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Triangle inequalities in international trade: The neglected dimension☆

Reto Foellmi [a,*], Christian Hepenstrick [b], David Torun [a,c]

[a] University of St.Gallen, Bodanstrasse 8, St. Gallen, 9000, SG, Switzerland
[b] Swiss National Bank, Börsenstrasse 15, Zurich, 8001, ZH, Switzerland
[c] UC San Diego, 9500 Gilman Dr, La Jolla, 92093, CA, United States

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ABSTRACT

Estimating trade costs is key to understanding the welfare effects of trade liberalizations. Cost minimization implies that the triangle inequality (TI) of international trade costs must hold for any three countries to avoid cross-border arbitrage. We show that re-routing opportunities might arise when trade costs change because a shipment through an intermediary becomes cheaper. The TI captures such re-routing opportunities. However, standard approaches to calculating the gains from trade liberalizations ignore this no-arbitrage condition. We outline an estimation routine that is model-consistent and respects the TI. Counterfactual exercises suggest that the welfare gains from re-routing after trade liberalizations can be substantial.

1. Introduction

An important driver of globalization is the reduction of trade barriers of any kind. It is a long-standing question how large these are and how much they impede the flow of goods, services, and ideas between countries. To determine the size of trade barriers in a world with many countries, we typically assume that trade costs are subject to a variant of the triangle inequality in Euclidean geometry. Trade costs between countries i and j must be lower than or equal to the trade costs between country i, an intermediate country k, and country j. The reason is simple: a cost-minimizing producer will send a product through the cheapest transportation channel.

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* Corresponding author.
E-mail addresses: reto.foellmi@unisg.ch (R. Foellmi), christian.hepenstrick@snb.ch (C. Hepenstrick), david.torun@unisg.ch (D. Torun).

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However central this assumption is, the literature typically ignores potential violations of the triangle inequality (TI) when studying shocks to the trade cost matrix. After trade costs change, re-routing opportunities might arise if a shipment through an intermediary becomes cheaper under counterfactual trade costs, which the TI would capture. Neglecting violations of the TI has profound consequences for the validity of trade models and, therefore, for their quantitative predictions of the (welfare) impact of trade liberalizations.

We must verify the TI whenever there is a change in trade costs even when focusing only on relative changes without measuring the level of trade costs—a powerful approach labeled "exact hat algebra", first introduced by Dekle et al. (2007) and now widespread in the literature.[1] To see this, consider a globalization step that results in an overall decrease of 10 percent of all bilateral trade costs. When using hat algebra, we do not need to know the initial level of trade costs. This procedure is only valid if the point of departure consists of trade costs that fulfill the TI, which should be the case following a no-arbitrage argument. But even when the TI holds initially, an overall reduction of 10 percent in trade costs could create violations of the TI that go unnoticed if we do not measure the initial level of trade costs. For example, let (initial) ad-valorem trade costs to export from country i to country j be equal to τ_{ij}. The triangle inequality for this trade relation reads $\tau_{ij} \leq \tau_{ik}\tau_{kj}$ for any potential intermediary country k. If we now assume that trade costs change to a factor $\gamma < 1$, such that the new trade costs equal $\gamma\tau < \tau$, the TI holds only if $\tau_{ij} \leq \gamma\tau_{ik}\tau_{kj}$. If γ is sufficiently small, this inequality is violated, implying a profitable re-routing opportunity for country pair ij.[2] Of course, this reasoning also applies if, e.g., we change only τ_{ik} while holding τ_{ij} and τ_{kj} constant.

To address the TI problem, this paper proceeds in two steps. First, we document that standard estimates of trade costs often violate the TI for many bilateral trade pairs and a large part of international trade volume. Using these estimates for counterfactual exercises would be inconsistent with the theory. The key message is that common approaches to calibrating trade costs do not take the TI into account and are, accordingly, not *guaranteed* to yield estimates that satisfy this no-arbitrage condition. Second, as a solution to the aforementioned finding, we provide two model-consistent methods to obtain trade costs that satisfy the TI in a standard quantitative framework. A basic premise to obtain logically consistent trade costs is an estimation that respects the TIs. The resulting trade costs can be employed to measure potential re-routing opportunities (i.e., TI violations) after trade-cost shocks.

We propose two methods to obtain trade costs that satisfy the TIs. For our baseline results, we first estimate trade barriers using the seminal approach developed by Waugh (2010). In our main method, we assume that alleged TI violations in these estimates are driven by bilateral preference shifters (BPS), because trade costs should satisfy the TI due to a no-arbitrage argument, as elaborated in Section 2. In trade theory, BPS and trade costs are typically isomorphic (i.e., trade barriers consist of trade costs and BPS), implying that a TI violation in estimated trade barriers could be driven by differences in BPS (which do not need to satisfy a TI).[3] We introduce a simple and fast iterative method to obtain TI-consistent trade costs while minimizing differences in BPS. This procedure does not require an additional estimation step once a set of trade barriers is estimated. Additionally, we present an alternative approach that imposes constraints to respect the TIs directly in the gravity regressions and neglects the presence of BPS. When we consider changes in trade costs, these estimates allow us to determine re-routing opportunities (captured via TI violations) endogenously.

A detailed examination of the TI has important quantitative implications for trade flows and welfare. In one of our counterfactual exercises, we look at a global proportional drop in trade costs of 25% as in Eaton and Kortum (2012). Importantly, counterfactual iceberg trade costs are never allowed to fall below one. Our estimates suggest that, after this shock, about 40% of the trade relations have at least one arbitrage opportunity (i.e., TI violation) and would thus be better off involving an intermediary. The trade-weighted share lies at 34%. In a framework à la Eaton and Kortum (2002) focusing on aggregate trade flows, this has substantial implications for the welfare gains that arise from re-routing. We find that almost all countries benefit from the option to re-route. The median country's real income growth increases from 19.4% to 29.7% when countries can exploit transportation arbitrage opportunities.[4] Moreover, our results suggest that accounting for such arbitrage opportunities after shocks to trade costs becomes more important the larger the shock size. This indicates a sort of "local stability" of the trade cost matrix. It is important to note that while we use the competitive Eaton–Kortum model to illustrate the triangle inequality's role in quantitative analyses, the logic underlying the TI relies on cost minimization, a principle independent of the market structure.[5]

In economic geography, it is argued that improving one segment of a transportation infrastructure can alter the shipping costs along the entire network. This concept is studied, e.g., in Allen and Arkolakis (2022), who analyze changes in the U.S. highway network. For instance, lower travel time between two cities may lead to changes in travel paths – re-routing – across the whole

[1] See, e.g., Costinot and Rodríguez-Clare (2014), Caliendo and Parro (2015), Eaton et al. (2016), Caliendo et al. (2019).

[2] Furthermore, we do not know whether trade costs hit their theoretical lower bound (i.e., $\tau_{ij} = 1$) after the trade-cost shock if we do not estimate their initial levels.

[3] In line with this reasoning, we document that intermediaries that would minimize transportation costs according to the estimated trade barriers share a border with the involved exporter or importer in almost 80% of the cases. We would expect consumers to (tend to) prefer goods produced by neighbors over products from countries farther away.

[4] In an earlier version of the paper, we also looked at a more complex version of the model by incorporating input–output linkages like Caliendo and Parro (2015). The underlying logic of re-routing and the method to obtain trade costs remain unchanged in such extensions. These additional results yield two main insights. First, in smaller samples, re-routing is less likely to be profitable. This is intuitive, since arbitrage opportunities are more likely the larger our set of potential intermediaries. Second, although we observe less re-routing with fewer countries in the sample, involving intermediaries tends to be highly profitable when sectoral linkages are included in the analysis. See Foellmi et al. (2022) for details.

[5] Qualitatively, the arguments we make also apply to models that have variable and fixed trade costs, such as the Melitz (2003) model (that additionally features imperfect competition). Chaney (2008, p.1711) states accordingly: "I also impose a triangular inequality to prevent transportation arbitrages: $\forall(i, j, k), \tau_{ik} \leq \tau_{ij}\times\tau_{jk}$". However, quantitative results would differ, as our trade cost estimates are a compound measure of iceberg and fixed costs through the lens of a Melitz (2003) and Chaney (2008) framework. The welfare gains from re-routing that we measure after a shock to trade costs (cf. Section 5) would, therefore, not necessarily be the same in those models.

network. Our paper argues that similar mechanisms implicitly exist in canonical international trade models when we consider the welfare effects of trade-cost changes. A related study in this regard is that of Ganapati et al. (2023), where the use of entrepôts creates incentives for indirect shipping routes.[6] In Section 6, we validate our approach by comparing it with studies that explicitly model and shock the transportation network à la Allen and Arkolakis (2022). Using leg-level (direct) trade costs from Ganapati et al. (2023), we show that accounting for re-routing (i.e., TI violations) after shocks to our reduced-form trade costs brings the counterfactual responses substantially closer to counterfactuals where we shock the explicit transportation network (i.e., the leg-level costs) and where, by construction, potential BPS play no role. This appears to be especially true for counterfactuals involving a few well-connected countries. The quantification suggests that our approach is conservative, in the sense that it yields a lower bound of the gains from changing the transportation network and exploiting re-routing opportunities.

While the TI has received little attention in quantitative trade models, it plays a central role in trade policy. An exporter from a third country i could have an incentive to ship a product to country j via country k, taking advantage of a favorable bilateral free trade agreement between countries k and j when there does not exist a similar treaty between i and j. Sophisticated rules-of-origin clauses in free trade agreements, typically based on value-added shares in each country, should preclude such trade deflection. However, Felbermayr et al. (2019) show that trade deflection to take advantage of tariff differentials is not profitable, as tariff differences do not outweigh increased transportation costs. Their argument underlies that the TI of trade costs should hold when we estimate trade costs, and that tariff differences (even if they could be exploited at all) are not sufficiently large to create violations of the TI.

This paper is organized as follows. In Section 2, we explain the theoretical reasoning behind the triangle inequality. Section 3 documents that standard trade cost estimates can suggest many arbitrage opportunities (i.e., TI violations). Section 4 details the estimation strategy. Section 5 discusses counterfactual exercises. Section 6 compares our predictions with those of frameworks that explicitly model the transportation network. Section 7 concludes.

2. The theoretical reasoning behind the TI

This section first outlines the theoretical arguments for why the common assumption of a holding triangle inequality (TI) is valid. It then discusses the implications of these arguments for counterfactual experiments.

Consider the following simple theoretical structure. The world consists of N countries and many goods. Each country purchases its products from the respective cheapest source in the world. This basic feature holds in a broad set of trade models; for instance, in a Ricardian trade model à la Eaton and Kortum (2002) (henceforth, EK).

Transportation sector. Trade is costly and takes place within a transportation sector that ships goods from country i to country j. The transportation sector is characterized by perfect competition. It uses the good that it is shipping as the only input, while no labor is employed in transportation. Following the literature, we assume that transportation costs are proportional to the marginal costs of the good: If marginal costs of production in country i equal c_i, the marginal costs of producing a good in country i and shipping the item directly to country j equal $\tilde{\tau}_{ij} c_i \geq c_i$, with $\tilde{\tau}_{ij} \geq 1$.[7] Thus, we make the common assumption that international trade entails constant ad valorem trade costs—known as "iceberg" trade cost (Samuelson, 1954). Trade costs are a c.i.f. measure, hence they account for trade costs from border i to border j. Therefore, it is consistent to set within-country trade costs $\tilde{\tau}_{jj} = 1$.[8] The measure $\tilde{\tau}_{ij}$ denotes the minimum cost to ship from country i to j *directly*. We do not assume that direct shipment is always cheapest, i.e., that the inequality $\tilde{\tau}_{ij} \leq \tilde{\tau}_{ik} \tilde{\tau}_{kj}$ holds. Rather, the competitive transportation sector figures out for each country pair the trade-cost minimizing route—be it direct or indirect, potentially through several intermediary countries.[9] In what follows, we solve for the cheapest route for all country pairs, which yields the optimal trade costs.

Optimal trade costs. Suppose there exists at least one intermediary k where $\tilde{\tau}_{ij} > \tilde{\tau}_{ik} \tilde{\tau}_{kj}$. We define

$$\tilde{\tau}^1_{ij} = \min_k \left\{ \tilde{\tau}_{ik} \tilde{\tau}_{kj} \right\}, \tag{1}$$

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[6] Other studies investigate the impact of backhauling, market power, or information frictions on shipping routes (see, e.g., Hummels et al. (2009), Behrens and Picard (2011), Wong (2022), Brancaccio et al. (2023)). However, there is a conceptual difference in the modeling of trade costs between models of international trade and those of economic geography. Economic geography, as exemplified in Allen and Arkolakis (2022), measures the transportation cost between two nodes. To reach a destination from a source location, the least-cost path along connecting nodes is calculated. In contrast, in standard international trade models, the optimal routing decision has already been taken on a micro level. Like in Eaton and Kortum (2002), the iceberg trade cost between two countries reveals the minimum achievable trade cost between them, after having optimally chosen the way to ship the product between the two countries. Hence, the TI for these iceberg trade costs also holds when the underlying route involves indirect shipments (cf. Section 2 for details).

[7] Allen and Arkolakis (2022) consider a transportation sector with route-specific, Fréchet-distributed shocks. As a result, all available routes are chosen in equilibrium with positive probability. Our trade-cost setup is deterministic, and hence, only one route is selected in equilibrium for a given country pair. We compare their approach to ours in Section 6 (Appendix A briefly outlines their transportation setup). Brancaccio et al. (2020) explicitly model a transportation sector with imperfect competition in partial equilibrium. In our modeling of the transportation sector in general equilibrium, following the literature on quantitative trade analyses, any changes in the transportation infrastructure are absorbed by the ad valorem trade cost.

[8] If within-country trade costs are non-zero (e.g., for retail distribution), total trade costs between i and j would amount to $\tilde{\tau}_{ij} \tilde{\tau}_{jj}$. This leaves the TI unchanged as we would have to compare $\tilde{\tau}_{ij} \tilde{\tau}_{jj} \leq \tilde{\tau}_{ik} \tilde{\tau}_{kj} \tilde{\tau}_{jj}$ in this case, assuming that within-country distribution costs have not to be paid in intermediate country k. For an analysis of internal trade frictions, see, e.g., Sotelo (2020).

[9] In the words of Eaton and Kortum (2005, p. 172), "arbitrage would eliminate violations of the TI since k would emerge as an entrepôt, so that [using our notation] $\tilde{\tau}_{ij} = \tilde{\tau}_{ik} \tilde{\tau}_{kj}$." When writing the TI in this common way, one assumes, on the one hand, that involving an intermediary k requires paying the full trade costs $\tilde{\tau}_{ik}$ and $\tilde{\tau}_{kj}$, and, on the other hand, that there are no additional costs of concatenation. Note further that multiple re-shipping via the same intermediary can never be optimal, as trade costs are theoretically bounded to satisfy $\tilde{\tau}_{ij} \geq 1$, and thus $\tilde{\tau}^x_{ij} \geq \tilde{\tau}_{ij}$ for any constant $x \geq 1$.

where $\tilde{\tau}^1_{ij} = \tilde{\tau}_{ij}$ when $\arg\min_k \left\{\tilde{\tau}_{ik}\tilde{\tau}_{kj}\right\} \in \{i, j\}$. When there is an intermediary k where it is cheaper to ship the product through, we have $\tilde{\tau}_{ij} > \tilde{\tau}^1_{ij} = \tilde{\tau}_{ik}\tilde{\tau}_{kj}$. To eliminate cross-border arbitrage, we derive a trade cost matrix where all country pairs satisfy the triangle inequality. For that aim, we replace trade costs that violate the TI with their updated value $\tilde{\tau}^1$ *iteratively*. It suffices to look at three-countries triangle violations. To see this, assume trade costs are lower if the good is shipped via two intermediaries k and k', but not if it is shipped via only one of them, i.e., $\tilde{\tau}_{ij} > \tilde{\tau}_{ik}\tilde{\tau}_{kk'}\tilde{\tau}_{k'j}$ but $\tilde{\tau}_{ij} < \tilde{\tau}_{ik}\tilde{\tau}_{kj}$ and $\tilde{\tau}_{ij} < \tilde{\tau}_{ik'}\tilde{\tau}_{k'j}$. Taking the former two inequalities together – obviously we get the identical result when using the latter inequality –, we see that the violation of the TI originates from a three-countries triangle violation. We obtain $\tilde{\tau}_{kj} > \tilde{\tau}_{kk'}\tilde{\tau}_{k'j}$, i.e., trade from k to j is cheaper via k'. In a violation where n intermediaries are involved, we apply the same reasoning to reduce the inequality to a violation where $n - 1$ intermediaries are involved. As the number of countries is finite, the number of potential multi-intermediary paths for a trade flow between countries i and j is finite as well.

Applying the procedure laid out in Eq. (1) to update trade costs, we obtain $\tilde{\tau}^2_{ij} = \min_k \left\{\tilde{\tau}^1_{ik}\tilde{\tau}^1_{kj}\right\}$. We repeat this until all violations of the three-countries triangle inequality are eliminated, and therefore, violations with $n > 1$ intermediaries are eliminated, too. As a result, the optimal trade cost, denoted by τ_{ij}, is a finite product of initial bilateral direct trade costs, which can be written as $\tau_{ij} = \tilde{\tau}_{ik_0} \cdot \tilde{\tau}_{k_0 k_1} \cdot \ldots \cdot \tilde{\tau}_{k_{n+1} j}$, where $k_0 = i$, $k_{n+1} = j$, and n denotes the number of intermediaries involved. When no intermediary is involved, we have $n = 0$, and trade costs read $\tau_{ij} = \tilde{\tau}_{ii} \cdot \tilde{\tau}_{ij} \cdot \tilde{\tau}_{jj} = \tilde{\tau}_{ij}$, because within-country trade costs equal one. This leads to the following definition.

Definition 1. We define $\tau_{ij} = \Pi^n_{u=0}\tilde{\tau}_{k_u k_{u+1}}$, where it holds for all $\{i, j\}$ that $\tau_{ij} = \min_k \left\{\tau_{ik}\tau_{kj}\right\}$ with $\arg\min_k \left\{\tau_{ik}\tau_{kj}\right\} \in \{i, j\}$. The index u runs from $u = 0$ to $u = n$, where $k_0 = i$ and $k_{n+1} = j$ with $n \geq 0$. No intermediary is involved when $n = 0$.

With the optimal trade cost τ_{ij}, there are no TI violations, i.e., $\tau_{ij} \leq \tau_{ik}\tau_{kj}$ $\forall (i, k, j)$, and we achieve τ after a finite number of iteration steps as in Eq. (1). The resulting updated trade cost between two countries follows an optimal trade trajectory along a finite set of countries. Hence, the (optimal) τ_{ij} denotes the cost-minimizing shipping route between countries i and j, either *directly or indirectly*. Consequently, the optimal marginal cost to produce a good in country i and ship it to j is equal to $\tau_{ij}c_i \leq \tilde{\tau}_{ij}c_i$. We summarize this insight in the following proposition.

Proposition 1. *Consider a trade cost matrix $\widetilde{T}$ with elements $\{\tilde{\tau}_{ij}\}$, where $i, j \in \{1, 2, \ldots, N\}$. There exists a unique trade cost matrix T with elements $\{\tau_{ij}\}$ where all trade costs satisfy the triangle inequality $\tau_{ij} \leq \tau_{ik}\tau_{kj}$, with τ_{ij} defined as in Definition 1.*

Proof. Existence is shown in the text. To see that T is unique, assume there exists a second matrix T' with at least one $\tau'_{ij} \neq \tau_{ij}$. Note that this would violate the definition of $\tau_{ij} = \min_k \left\{\tau_{ik}\tau_{kj}\right\}$. □

Counterfactuals. What does this result imply for the estimation of trade models? Standard gravity equations should contain the optimal values of trade costs τ, because of the no-arbitrage arguments leading to Proposition 1. No TI violation can occur, for cost-minimizing producers will select the cheapest route. If, for example, $\tau_{ij} = \tau_{ik}\tau_{kj}$, trade costs are the same whether trade takes place directly between i and j or involves the intermediary.[10]

What happens when we shock trade costs, τ, as is usually done in the standard trade literature? For instance, assume τ_{ik} drops to a factor $\gamma < 1$ such that a TI violation would occur: $\tau_{ij} > \gamma\tau_{ik}\tau_{kj}$. To eliminate the TI violation after the shock, we need to update trade costs iteratively like in Eq. (1). Suppose that after updating, the optimal counterfactual trade cost reads $\tau'_{ij} = \tau'_{ik}\tau'_{kj}$. Because of the reasoning above, we can simply replace the trade costs in the gravity equation τ_{ij} with τ'_{ij} to compute counterfactual trade flows. Therefore, when trade costs change, we use the updated counterfactual values, τ'_{ij}, to account for potential re-routing.

Corollary 1. *The gravity equations of trade flows must contain the optimal trade cost matrix T. When trade costs change, re-routing opportunities (i.e., TI violations) must be taken into account.*

Corollary 1 has relevant implications for quantitative studies of trade-cost changes. Many counterfactual experiments make use of the fact that workhorse trade models allow us to estimate relative changes in economic outcomes as a function of relative changes in trade costs and initial trade shares only. Thus, there is no need to calibrate the level of trade costs (or size-related parameters such as the state of technology and population size). This simple and powerful tool is known as "exact hat algebra", where the word "exact" refers to the fact that no approximations are involved in the estimation process (see Appendix A for an example). Consistent with the theoretical setup, one assumes that the TIs are satisfied in the initial equilibrium. However, as the level of trade costs is only implicitly present in standard structural (hat) formulae, we do not know whether, after a shock to the trade cost matrix, profitable re-routing opportunities arise.[11]

To see this, consider a trade pair where the TI holds initially, i.e., $\tau_{ij} < \tau_{ik}\tau_{kj}$. Let us retake our thought experiment from the introduction and assume there is an overall reduction of bilateral trade costs to a factor $\gamma < 1$. Obviously, there exists a value of γ such that $\gamma\tau_{ij} > \gamma^2\tau_{ik}\tau_{kj}$. The same logic applies if, e.g., we change only τ_{ik} while holding τ_{ij} and τ_{kj} constant. This implies that the

[10] It does not matter whether the physical trade flow between i and j goes through intermediary k. Recall that the transportation sector is perfectly competitive, and thus, there are no rents from being involved as an intermediary.

[11] Counterfactuals involving trade costs are unique in this respect. Other shocks, such as changes in technology parameters, will not encounter the issues discussed in this paper.

standard hat-algebra approach, relying solely on relative changes in trade costs, could lead to logically inconsistent results, since violations of the TI must be considered in simulations. In other words, the spillover effects of trade-cost changes through re-routing on the transportation sector are neglected. Moreover, we cannot be sure whether γ is small enough for τ_{ij} to hit its lower bound (i.e., $\tau_{ij} = 1$). To ensure a model-consistent counterfactual that accounts for re-routing, we therefore need to estimate the initial level of τ_{ij}, and after a shock, update the trade cost matrix as outlined above in case any TI is violated.[12]

Interestingly, considering the TIs implies that the trade elasticity need not be constant. For instance, if we have $\tau_{ij} = \tau_{ik}\tau_{kj}$ in the initial equilibrium, a rise in τ_{ij} only will not increase the shipping costs from i to j, since exporters from i can choose to ship via intermediary k in the counterfactual equilibrium.[13]

3. TI violations with standard trade cost estimates

Following the insights from Section 2, we need to calibrate the level of initial trade costs to verify whether TI violations arise after a shock to trade costs. This initial set of trade costs must satisfy the TIs to be consistent with the theory. In this section, we document that standard procedures for estimating iceberg trade costs do not necessarily yield estimates satisfying the TI. We call the resulting TI violations 'alleged' to emphasize that calibrated trade costs should satisfy the TIs due to the no-arbitrage arguments elaborated in Section 2. In Section 4, we proceed to explain these violations with bilateral preferences. The underlying off-the-shelf EK framework is standard in the literature and, thus, only briefly outlined in Appendix A.

Alleged TI violations. We will base our calibration in Section 4 on the seminal work by Waugh (2010). In what follows, we focus on the alleged TI violations suggested by this method's iceberg trade costs, while Online Appendix O.A discusses alternative specifications. To our knowledge, we are the first to plug standard estimates into the TIs to verify that they are satisfied.[14] The key insight is that common approaches to calibrating trade costs do not take the TI into account and are, accordingly, not guaranteed to yield estimates that satisfy this no-arbitrage condition.

The trade costs using the approach in Waugh (2010) stem from a standard gravity regression, with trade costs consisting of an exporter-specific component and 'gravity' measures of bilateral frictions (see Section 4 for details). We calculate trade costs for 127 countries in the year 2004 using the data described in Appendix B.[15]

For every pair, we plug trade costs into the TI and verify whether this no-arbitrage condition is violated for at least one intermediary country. The results are summarized in Table 1. We find a large number of alleged TI violations: 36% of trade relations could supposedly reduce their delivery costs by shipping via a third country, where most pairs have several potential intermediaries that are worth involving. There are 34 relations where we obtain trade costs below one, which would imply that trade costs could be pushed toward zero by re-shipping multiple times. But even when we set these trade costs equal to one, we see that 20% of trade relations would still have an alleged arbitrage opportunity. This does not only concern small relations, as 28% of total trade is affected (when trade costs are restricted to at least one). The potential savings for pairs with an arbitrage opportunity are substantial, with the average log-difference amounting to 22%.

Are the violations driven by only a handful of hubs? In Panel B of Table 1, we exclude the three intermediaries that would minimize trade costs for the most relations (Germany, Singapore, and Thailand) and rerun the regressions without them. The resulting estimates still feature many violations despite a notable decline. Even when the ten top hubs are excluded – the U.S. and China being among them – about 6% of trade pairs would be better off involving an intermediary (cf. Panel C). It is important to note that these hubs are not only the intuitive suspects (such as the Netherlands or Singapore).

Table D.2 in Appendix D provides more details on the affected exporters and their respective hubs. Trade costs are restricted to at least one for this analysis. In the second column, we list up to three hubs that supposedly help minimize the shipping costs of an exporter for at least one of its relations, with the main hub – causing most violations – being the first entry. One apparent feature is that exporters often share a border with their hubs. About 42% of these exporters share a border with their main hub (first entry in column two), while 67% of exporters with at least three hubs are neighbors of at least one of them. In general, hubs tend to be relatively close: for 85% of exporters, their main hub has a distance below the median distance to the remaining countries. Among the relations with a TI violation, the share of country pairs where the exporter and/or the importer share a common border with the intermediary is as high as 78%. Interestingly, important hubs like Germany and Thailand also have several alleged arbitrage opportunities as exporters. The third column in Table D.2 highlights significant heterogeneity among exporters. For some, the trade

[12] Note that the widely-used reference point of welfare losses under complete autarky is an exception. With $\tau_{ij} \to \infty \; \forall i \neq j$, there cannot be any violation of the TI. See Arkolakis et al. (2012) for a detailed discussion on welfare losses from autarky implied by standard trade models. More generally, whenever *all* trade costs are raised by the same factor (i.e., $\gamma > 1$ in the example above), we will not encounter violations if the initial trade cost matrix is consistent with the TIs.

[13] In our main specifications, following the literature on international trade, we will quantify shocks to the (optimal) trade cost τ_{ij} (see Section 5). In Section 6, we contrast our quantitative results with approaches that measure and shock $\tilde{\tau}_{ij}$. In Appendix A, we briefly discuss the theoretical similarities and differences between shocks to τ_{ij} (the standard target in the trade literature) and $\tilde{\tau}_{ij}$ (the *direct* underlying trade costs). We argue that the counterfactual trade costs after a trade-cost shock (and potential re-routing) cannot be larger than after a shock to $\tilde{\tau}$. In the special case where the shock is uniform across country pairs (i.e., shock by $\gamma \; \forall i \neq j$), the counterfactual trade costs are the same, irrespective of whether shocks directly affect trade costs or $\tilde{\tau}$. For further details, see Appendix A.

[14] In a recent study, Lee (2023) finds that their estimates, which are based on data on trade flows and prices, often violate the TI. Their approach to dealing with this issue is to prevent countries from exploiting re-routing opportunities. For the year 2004 – the year of our main results –, Lee's (2023) estimates suggest that about 11.5% of country pairs face at least one TI violation. Restricting our sample to 60 countries to match Lee's (2023) sample and re-computing our trade costs, we also obtained a share of TI violations around 11.5%. Therefore, the reason for the lower share of TI violations compared to Table 1 appears to stem from the smaller sample size. We are grateful to the author for sharing their estimates with us.

[15] The regression equation and the detailed results are discussed in Section 4 and summarized in Table D.1 of Appendix D.

Table 1
TI violations with standard trade cost estimates.

	Baseline	Restrict $t \geq 1$
Panel A: Full sample		
% of trade pairs with arbitrage opportunity	36%	20%
...trade-weighted	51%	28%
Top 10 hubs (desc. order):		
DEU SGP THA ARG CHN ARE USA MYS GBR PAN		
Panel B: Excl. top 3 hubs		
% of trade pairs with arbitrage opportunity	23%	13%
...trade-weighted	52%	22%
Panel C: Excl. top 10 hubs		
% of trade pairs with arbitrage opportunity	10%	6%
...trade-weighted	34%	19%

Notes. This table reports violations of the triangle inequality implied by iceberg trade cost estimates, t, that we compute using Waugh's (2010) method (see Section 4 for details on the estimation). The sample contains 127 countries in the year 2004. In the right-most column, we set $t = 1$ whenever we find $t < 1$. Panel A uses the full sample, the second row showing the share in total trade that has a potential arbitrage opportunity. Panels B and C exclude the three and ten main hubs, respectively, found in the full sample. A "hub" refers to an intermediary that allows for a cheaper delivery than the direct shipment between two countries. The results are discussed in Section 3.
Data. See Appendix B.

barriers suggest an alleged arbitrage opportunity for only a handful of countries. At the same time, other exporters could supposedly decrease their shipping costs to essentially their full set of partners. Some countries always have the same hub but many arbitrage opportunities (e.g., Canada and Malaysia), whereas others have few violations involving several hubs (e.g., Honduras and Portugal). There are only four countries without TI violations as exporters. Note from the fourth column that there is also some variation in the associated relative 'savings' (i.e., the log-difference between direct and indirect costs, conditional on the TI being violated), and that, in general, the relative savings potential tends to be large. The fifth column in Table D.2 lists the importers for which a given exporter could most decrease its shipping cost. These partner countries typically tend to be close to the involved hubs. Interestingly, we find exporters with few or many alleged violations across both lower- and high-income groups. The correlation between an exporter's number of TI violations and its log of total expenditure equals 0.22.

We illustrate these TI violations for three exporters (Norway, Nigeria, and India) in Figs. C.1–C.3 of Appendix C. Norway can allegedly decrease its trade costs to 14 destinations using six different intermediaries (marked with circles in Fig. C.1). The intermediaries (i) lay between Norway and the ultimate destinations, (ii) are relatively close to the importers, and (iii), apart from Thailand, share a common border with the importers. Fig. C.2 shows a similar pattern for Nigeria, with intermediaries always sharing a common border with the end destinations. India could supposedly save transportation costs by involving China in East Asia and the United Arab Emirates in the Persian Gulf region (see Fig. C.3). These maps highlight the findings from above: intermediaries are typically strong exporters (such as China and Germany) and are geographically close to the final destinations.

Alternative specifications. In Online Appendix O.A, we explore whether alternative specifications also yield apparent arbitrage opportunities. Specifically, we (i) change the set of covariates, (ii) add the error term in the regression to the trade costs, (iii) use PPML instead of OLS (Santos Silva and Tenreyro, 2006), (iv) look at multiple years, and (v) use the canonical method from Head and Ries (2001) – later adopted by Novy (2013) – instead of Waugh (2010). We find many TI violations throughout. In general, standard procedures do not guarantee that estimates satisfy this no-arbitrage condition. In the next section, we propose how to calibrate a theory-consistent trade cost matrix.

4. Obtaining theory-consistent trade costs

Section 2 explains why we need to calibrate the initial trade cost matrix, while Section 3 shows that trade costs from standard estimation procedures need not necessarily satisfy the TI. In this section, we develop two calibration methods to obtain theory-consistent trade costs. Our main method eliminates alleged TI violations using differences in bilateral preference shifters, while the alternative employs a constrained estimation.

Estimating trade barriers. We argue that an intuitive reason why calibrated trade costs may display TI violations is the presence of bilateral preference shifters (BPS). Importantly, BPS and trade costs are isomorphic in gravity equations (see, e.g., the discussion in Head and Mayer (2014)). As derived in Appendix A, in an EK environment, the gravity equation with bilateral preference shifters, α_{ij}, reads

$$\pi_{ij} = \frac{T_i w_i^{-\theta} \left(\tau_{ij}/\alpha_{ij}\right)^{-\theta}}{\sum_{k=1}^{N} T_k w_k^{-\theta} \left(\tau_{kj}/\alpha_{kj}\right)^{-\theta}}, \tag{2}$$

where π_{ij} is exporter i's share in importer j's total expenditure (including domestic expenditure shares, $i = j$), $T_i w_i^{-\theta}$ is a measure of country i's relative productivity, and θ the so-called trade elasticity. Therefore, increasing α_{ij} and τ_{ij} by the same proportion leaves trade shares unaffected. In other words, we cannot (empirically) distinguish whether country j imports more from i because it likes its products better than those of other exporters, or because shipping costs are relatively low. We will henceforth refer to τ_{ij}/α_{ij} as the *trade barrier* from i to j.

When running gravity regressions, the pair-specific variables yield a compound measure of the trade barrier τ_{ij}/α_{ij}, as we explain momentarily. This poses a challenge to identifying TI violations, since BPS do not need to satisfy a TI. For our main method, we assume that alleged TI violations – such as those presented in Section 3 – are driven by BPS, because trade costs should satisfy the TI due to a no-arbitrage condition as detailed in Section 2.[16] That is, an alleged TI violation where $\tau_{ij}/\alpha_{ij} > \tau_{ik}\tau_{kj}/(\alpha_{ik}\alpha_{kj})$ can be explained by a value of α_{ij} sufficiently smaller than $\alpha_{ik}\alpha_{kj}$. After outlining the (standard) estimation procedure, we introduce a simple algorithm to eliminate TI violations while minimizing the differences in BPS.

When estimating trade barriers, we follow the literature assuming that $\tau_{ij} \geq 1 \ \forall (i,j)$, with $\tau_{jj} = 1 \ \forall j$. We further normalize $\alpha_{jj} = 1 \ \forall j$. When scaling trade shares by the respective home shares, π_{jj}, and taking logs, Eq. (2) becomes

$$\log\left(\frac{\pi_{ij}}{\pi_{jj}}\right) = \log\left(T_i w_i^{-\theta}\right) - \log\left(T_j w_j^{-\theta}\right) - \theta \log\left(\tau_{ij}/\alpha_{ij}\right). \tag{3}$$

We calibrate trade barriers using Waugh's (2010) influential method. The reason we choose Waugh (2010) is threefold. First, these estimates help the model mimic empirically observed bilateral trade flows and prices. Second, it yields trade barriers even for country pairs without observed trade flows. Third, the calibrated trade barriers are entirely based on OLS coefficients, making the implementation straightforward.

A key assumption is the functional form imposed to estimate trade barriers τ_{ij}/α_{ij}.[17] In line with Waugh (2010), trade barriers are assumed to be a log-linear function of an exporter-specific shifter, ex_i, and bilateral dummy variables, that is,

$$-\theta \log\left(\tau_{ij}/\alpha_{ij}\right) = ex_i + \sum_{l=1}^{D} \beta^l d_{ij}^l, \tag{4}$$

where β^l is the coefficient on a dummy variable d_{ij}^l. Examples of frequently employed dummy variables are common border, common language, or distance bins. The shifter ex_i captures all exporter-specific aspects affecting trade barriers not picked up by the dummy variables.

Let $S_j^m := -\log\left(T_j w_j^{-\theta}\right)$, where the superscript m indicates that this term will be captured by an importer fixed effect (FE). Further, let $S_i^x := ex_i - S_i^m$, where the superscript x is chosen to indicate that the exporter FE will absorb this expression. By plugging Eq. (4) into Eq. (3), and using the definitions of S_i^x and S_j^m, we obtain our gravity regression

$$\log\left(\frac{\pi_{ij}}{\pi_{jj}}\right) = S_i^x + S_j^m + \sum_{l=1}^{D} \beta^l d_{ij}^l + \varepsilon_{ij}, \tag{5}$$

where ε_{ij} denotes the error term.

The dependent variable is directly observed in the data. The elements on the right-hand side of Eq. (5) are an exporter FE, an importer FE, and a set of bilateral dummy variables. The exporter-specific component of trade barriers in Eq. (4) is simply the sum of the exporting country's exporter and importer FEs, i.e., $ex_i = S_i^x + S_i^m$. According to the theory, in the absence of ex_i, the exporter and importer FEs would add up to zero. Empirical deviations from this theoretical target will thus add to τ_{ij}/α_{ij}. The higher the exporter-specific shifter, the lower the trade barriers. Finally, we set $\theta = 4.14$, Simonovska and Waugh's (2014) well-known estimate of the trade elasticity, whose approach uses trade costs estimated with the Waugh (2010) method. Note that the size of θ does not matter for the TI, but it will play a role in the welfare calculations below.

As in Waugh (2010), our baseline regression includes dummy variables indicating whether the country pair shares a common border and whether the geographical distance between two countries lies within a specific distance interval (cf. Table D.1). We run regression equation (5) on a sample of 127 countries in the year 2004 (the data are described in Appendix B). Table D.1 in Appendix D reports the coefficients.

Section 3 documents that the resulting trade barriers (and variations thereof) suggest numerous TI violations. However, using these calibrated trade barriers to verify TIs is only valid if one assumes away BPS differences – implicitly setting $\alpha_{ij} = 1 \ \forall (i,j)$ –, since BPS do not need to satisfy the TI. Instead, in our main approach outlined next, we determine differences in BPS that eliminate these apparent TI violations. Online Appendix O.B presents an alternative method to obtain theory-consistent trade costs, where we impose the TIs directly in the gravity regressions. This procedure yields the best fit conditional on trade barriers satisfying the TIs.

Extracting trade costs. In what follows, we introduce a simple and fast iterative method to obtain TI-consistent trade costs, which does not require an additional estimation step once we have a set of trade barriers. The resulting trade costs can then be used to compute counterfactuals while accounting for re-routing opportunities (as we do in Sections 5 and 6).

[16] The findings in Section 3 corroborate this assumption. Apparent TI violations are mostly created by nearby intermediaries, which tend to share a border with the importer. Therefore, low trade barriers to close trading partners – whose goods countries may favor – are likely due to a high value of α_{ij}. In Online Appendix O.B, we present an alternative method to eliminate TI violations that uses constrained regressions without relying on BPS. The results are consistent with this reasoning, as the impact of a common border on trade costs drops by 50% in the TI-constrained estimation.

[17] In Waugh (2010), BPS are not present in the discussion. But the procedure is unchanged even if one does not implicitly restrict $\alpha_{ij} = 1 \ \forall (i,j)$. Moreover, this approach is essentially equivalent to that in Eaton and Kortum (2002), except for having an exporter-specific shifter of trade costs rather than an importer-specific one (see Waugh (2010) for a discussion).

In particular, we propose to eliminate alleged TI violations by setting BPS such that the TI of trade costs holds for every triad. Let h_{ij} be the estimated value of trade barriers. We define $h_{ij} = t_{ij}/a_{ij}$. Therefore, t_{ij} and a_{ij} denote the calibrated values of τ_{ij} and α_{ij}, respectively. The TI for these estimates can be rewritten as $a_{ij}h_{ij} \leq a_{ik}h_{ik} \times a_{kj}h_{kj}$. We normalize $a_{jj} = 1\ \forall j$ and, for simplicity, assume $a_{ij} \leq 1\ \forall (i,j)$.[18] We will require $a_{ij}h_{ij} \geq 1$ to ensure $t_{ij} \geq 1$. Together, these constraints imply $a_{ij} \in [1/h_{ij}, 1]$. When $a_{ij} = 1$, trade barriers are purely trade costs. The central question is how to find a set of a_{ij} and, thus, t_{ij} that satisfies these constraints.

There are potentially many allocations of BPS that would eliminate the TI violations. A simple way to get TI-consistent trade costs is to update estimated trade barriers iteratively (starting with $a_{ij} = 1\ \forall (i,j)$) until there are no more TI violations. This procedure minimizes the differences in BPS conditional on trade costs satisfying the TIs and, therefore, essentially treats a_{ij} as a residual.[19] The solution algorithm consists of three main steps, each explained in more detail below.

I Estimate a set of trade barriers $\{h_{ij}\}_{i,j}$. Set $h_{ij} = \max\{1, h_{ij}\}\ \forall (i,j)$ and $h_{jj} = 1\ \forall j$. Set the initial values of BPS and trade costs as follows: $a_{ij} = 1\ \forall (i,j)$ and, thus, $t_{ij} = h_{ij}\ \forall (i,j)$. Go to Step II.

II Verify the TIs for all $\{t_{ij}\}_{i,j}$, i.e., $t_{ij} \leq t_{ik}t_{kj}\ \forall (i,k,j)$. If there are any TI violations, go to Step III. If all TIs are satisfied, stop.

III Update the BPS by setting $a_{ij} = \min_k\{t_{ik}t_{kj}\}/t_{ij}\ \forall (i,j)$. Update the trade costs by setting $t_{ij} = a_{ij}h_{ij}\ \forall (i,j)$. Return to Step II.

Step I simply states that we start by estimating trade barriers and setting them to at least one. As a first attempt, we equate trade costs t_{ij} and trade barriers h_{ij}. In Step II, we verify whether these trade costs satisfy the TIs. If there are no arbitrage opportunities, we are done. If there is at least one violation, we update trade costs according to Step III. That is, we set a_{ij} equal to the 'savings potential' from re-routing. We then update the trade costs using these new BPS values and return to Step II to verify the TIs.

This simple algorithm yields trade costs that satisfy the constraints above. The TIs are trivially satisfied due to Step II. Note that $\min_k\{t_{ik}t_{kj}\}/t_{ij} = 1$ if there is no TI violation from i to j and, therefore, $a_{ij} \leq 1$. Finally, because we set $h_{ij} \geq 1$, we start with $t_{ij} \geq 1$, which implies that $\min_k\{t_{ik}t_{kj}\} \geq 1$ and, hence, $a_{ij} \geq 1/h_{ij}$. In other words, the resulting trade costs satisfy the TIs and do not fall below one. Fig. C.4 of Appendix C plots the resulting trade costs, t_{ij}, against the estimated trade barriers, h_{ij}. The two are highly correlated, and, by construction, trade costs are weakly smaller than trade barriers.

With a theory-consistent trade cost matrix that entails no TI violations, we can ask how many re-routing opportunities (i.e., TI violations) arise after a shock to trade costs. We can further assess the welfare implications of exploiting these re-routing options. Section 5 provides a quantification. Section 6 then compares our quantitative results with the predictions of a framework that models an explicit transportation network.

5. The welfare implications of re-routing

How does the potential re-routing of trade flows impact the welfare gains from trade liberalizations? To understand the impact of the TI, we conduct counterfactual experiments where we lower trade costs. We compute welfare gains (i.e., relative changes in real income) using hat algebra as explained in Appendix A, and we do so in two ways.[20] First, we shock the trade cost matrix and do not verify whether TI violations arise (standard approach). Second, we check the TI and update trade costs whenever the TI is violated and, therefore, a new route allows for cheaper delivery of goods. The relative change in trade costs is then the *effective* drop in trade costs that materializes after the shock, which considers potential spillover (re-routing) effects. We do not allow trade costs to fall below one in either case.

Specifically, we set the initial value of τ_{ij} equal to the trade cost estimates t_{ij} from Section 4, such that the starting point features no arbitrage opportunities. For instance, let the counterfactual exercise be a proportional decrease in trade costs of 25%, where $\gamma = 0.75$ in this case using our notation from Section 2. Let $\hat{\tau}_{ij}$ denote the ratio of counterfactual to initial trade costs, τ'_{ij}/τ_{ij}. The first step sets $\hat{\tau}_{ij} = \gamma\ \forall i \neq j$ and computes the welfare gains as described in Appendix A.[21] These values of $\{\gamma\tau_{ij}\}_{i,j}$ contain only the *direct* impact of the trade-cost change. Therefore, as a second step, we verify whether the trade costs after this drop, $\gamma\tau_{ij}$, satisfy the TI. We update the trade cost matrix with elements $\{\gamma\tau_{ij}\}$ iteratively until there are no more TI violations, which follows Proposition 1 to obtain updated values such that $\tau'_{ij} = \min_k\{\tau'_{ik}\tau'_{kj}\}$. The welfare gains are then computed in the standard way but setting $\hat{\tau}_{ij} = \tau'_{ij}/\tau_{ij}$, i.e., we use the *effective* change in trade costs taking the option of re-routing explicitly into account. The standard equilibrium equations outlined in Appendix A are unaffected by this step (in line with Corollary 1). We would proceed analogously when predicting the consequences of a trade-cost increase.

Uniform drop in τ. We use the single-sector EK setup outlined in Appendix A and decrease global trade costs proportionally by 25%—an exercise conducted in Eaton and Kortum (2012).

[18] With this assumption, we will minimize the differences in BPS across countries conditional on the TIs and $h_{ij} \geq 1$ (essentially treating a_{ij} as a residual). We could interpret $a_{ij} \leq 1\ \forall (i,j)$ as a (weak) home bias. For evidence of a home bias in international trade and potential explanations, see, e.g., Wolf (2000), Hillberry and Hummels (2003), Yi (2010), Caron et al. (2014), Coşar et al. (2018), Egger et al. (2023).

[19] Additional data could help to identify BPS separately from trade costs (for a given set of trade barriers). For instance, Coşar et al. (2018) use data on prices, quantities, and product characteristics in the automobile industry to identify heterogeneity in consumer preferences across countries, while Crozet et al. (2012) employ data on prices and quality ratings of Champagne exports. Alternatively, by explicitly modeling the transportation network, Allen and Arkolakis (2022) develop a model that uses trade and traffic flows to identify trade costs. In Section 6, we demonstrate that our approach predicts counterfactual responses that are substantially closer to the predictions of the Allen and Arkolakis (2022) setup compared to those of standard hat algebra.

[20] Trade is unbalanced in the data, which is inconsistent with the theory. As a simple remedy, we first solve for the equilibrium that is closest to the data while ensuring balanced trade. Specifically, we set $\hat{\tau}_{ij} = 1\ \forall (i,j)$ and solve the equilibrium equations outlined in Appendix A. This equilibrium with balanced

Table 2
TI violations after a 25% drop in global trade costs.

	No restriction	Restrict $t \geq 1$
% of trade pairs with arbitrage opportunity	65%	40%
...trade-weighted	88%	34%
Distribution of potential savings:		
Q1: 7%, Median: 20%, Mean: 19%, Q3: 29%, Max: 69%		
Top 10 hubs (desc. order):		
THA FRA DEU BEL MYS NLD SGP ARG CHN ARE		

Notes. This table reports violations of the triangle inequality that emerge after we decrease global bilateral trade costs by 25%. The right-most column sets the new trade cost values equal to one if they drop below one. The second row shows the share in cross-border trade with at least one arbitrage opportunity. The third row refers to reductions in trade costs from re-routing (measured in log-differences) when there is an arbitrage opportunity (restricting $t \geq 1$). A "hub" denotes an intermediary that allows for a cheaper delivery than the direct shipment between two countries. The sample contains 127 countries. The results are discussed in Section 5.
Data. See Appendix B.

How many arbitrage opportunities arise? Table 2 reports the share of trade pairs with at least one violation of the TI after the shock. For 159 trade pairs (i.e., 1% of dyads), the trade costs would fall below one if we did not impose this lower bound, which is not possible in the standard hat-algebra procedure. But even with this restriction, the initial trade costs suggest that about 40% of trade pairs – or 34% of cross-border trade – can decrease their delivery costs by involving a third country in response to the shock. The implied savings potential for these relations (measured in log-differences) is large, as trade costs can drop by a further 19% on average, restricting $t \geq 1$. For a quarter of the trade relations, the *additional* decline is larger than the shock size ("Q3" in the third row of Table 2). Thus, the actual reduction in trade costs is considerably bigger for many pairs when accounting for potential spillover effects of the shock.[22]

Table D.3 of Appendix D zooms into the TI violations summarized in Table 2. There is substantial variation in the set of main hubs and the number of re-routing opportunities across exporters. Exporting countries encounter at least one TI violation for 57 importers on average, ranging from 7 to 125 (out of potentially 126). Hubs tend to be relatively close to the affected countries, with 28% of exporters sharing a border with their main hub. However, this is not always the case, since for 54% of the TI violations, the intermediary country is neither an adjacent neighbor of the exporter nor the importer.

Fig. 1 illustrates that these re-routing opportunities translate into substantial welfare gains. Almost all countries benefit from the option to re-reroute after this uniform globalization experiment. The losses for the three exceptions are negligible. This is intuitive because all exporters can decrease their delivery costs by involving an intermediary (cf. Table D.3 of Appendix D). Moreover, there is a positive relation between the average drop in the costs of exporting due to re-routing and the net welfare gain from re-routing (cf. Fig. C.5 of Appendix C). The median country's welfare gain increases from 19.4% to 29.7% when allowing for re-routing. However, the impact of re-routing is not simply linear, with notable heterogeneity across countries with similar "standard" welfare gains. Allowing countries to exploit arbitrage opportunities changes the ranking of the gains, as Fig. 1 shows.

Table D.4 in Appendix D lists the welfare changes in detail by country. The average increase in real income growth through re-routing is about 61%, ranging from −3% to 256%. To put the real-income changes into perspective, we can compare them to the loss from going to full autarky (i.e., $\tau_{ij} \rightarrow \infty \ \forall i \neq j$).[23] This is a widely used benchmark, not least because calculating it is straightforward (see Appendix A). The extra gains from re-routing are substantial relative to these benchmark values: On average, the real-income gain from involving intermediary countries equals about 91% of the absolute autarky loss (cf. Table D.4 in Appendix D for details). Although the magnitude of the latter strikes as large, it shows how, through the lens of the model, the implied welfare differences are sizable. This exercise suggests that it is quantitatively important to consider potential spillovers even in counterfactuals that involve uniform trade-cost changes.

Table 3 shows that verifying the existence of arbitrage opportunities becomes quantitatively more important the larger the trade-cost shock, suggesting that the trade cost matrix features some "local stability". Repeating the exercise from above for a 5% drop in global trade costs yields fewer re-routing opportunities (21% of dyads have one according to Online Appendix Table O.6). The median additional real income from re-routing is about 9% of the median overall welfare gain without re-routing. By contrast,

trade serves as the baseline for all our counterfactual exercises. A simple alternative to allow for trade imbalances is to add an additional parameter that matches net exports in the initial equilibrium (Dekle et al., 2007).

21 Technically, we set $\gamma_{ij} = \max\{0.75, 1/\tau_{ij}\}$ to avoid $\tau'_{ij} = \gamma\tau_{ij} < 1$. This procedure slightly differs from the standard hat-algebra approach, which would set $\gamma = 0.75 \ \forall i \neq j$. We need to impose the theoretical lower bound. Otherwise, we would obtain extreme results when allowing for re-routing.

22 Tables O.6 and O.7 of the Online Appendix show that also smaller shocks produce many arbitrage opportunities and that the set of major hubs remains stable across these symmetric shocks. In Tables O.8 and O.9 of the Online Appendix, we obtain results similar to Table 2 when estimating trade barriers (h_{ij}) using PPML and the Head and Ries (2001) method, respectively, instead of OLS. Table O.10 shows that estimates from our TI-constrained regressions, detailed in Online Appendix O.B, also predict many re-routing opportunities.

23 As is well known in the literature, the one-sector model generally yields relatively low gains from trade (see Costinot and Rodríguez-Clare (2014) and Ossa (2015) for a detailed discussion).

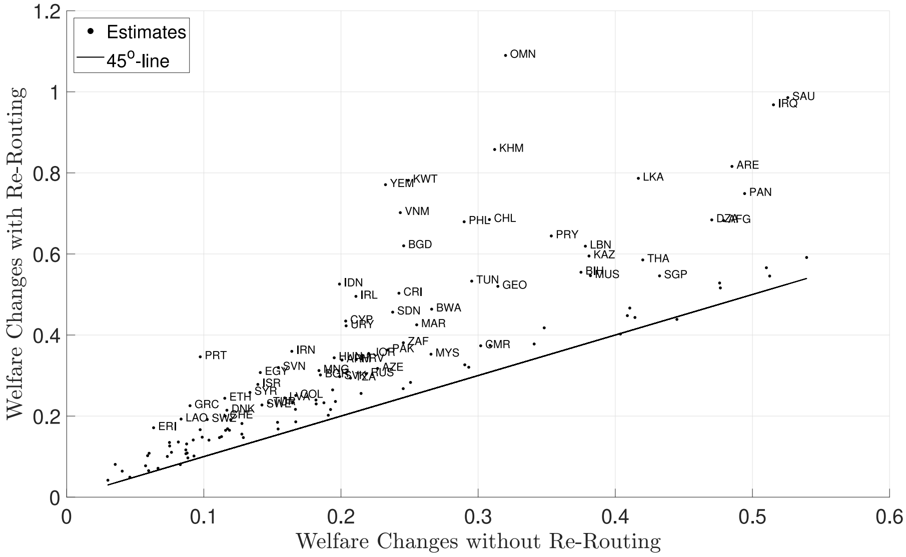


Fig. 1. Welfare changes after a 25% drop in global trade costs.
Notes. This figure depicts welfare changes after a drop in global trade costs of 25%. In one case, we do not allow for re-routing (standard approach); in the other, we allow for re-routing when the TI is violated. We do not allow trade costs to fall below one in either case. For illustrative purposes, country codes are shown only for above-median differences between the two axes. The results are discussed in Section 5.

Table 3
Welfare changes after a drop in global trade costs (Distribution).

Drop in trade costs	Distribution of net welfare changes from re-routing					Median welfare gain without re-routing
	Min.	Q1	Q2	Q3	Max.	
5%	0.0%	0.1%	0.2%	0.5%	4.3%	2.3%
10%	0.0%	0.3%	0.8%	1.5%	12.2%	5.2%
15%	0.1%	0.7%	1.9%	4.1%	25.9%	8.8%
25%	0.1%	3.7%	7.2%	16.6%	77.0%	19.4%
50%	2.4%	35.4%	66.9%	119.7%	370.4%	78.0%

Notes. This table reports the distribution of net welfare changes from re-routing (i.e., the absolute difference between gains with and without re-routing) after a decrease in global bilateral trade costs of 5%, 10%, 15%, 25%, or 50%. Q1, Q2, and Q3 refer to the first, second, and third quartiles. The right-most column reports the median real-income change without re-routing. See Section 5 for a discussion.

Table 4
TI violations after eliminating asymmetries in trade costs.

	No restriction	Restrict $t \geq 1$
% of trade pairs with arbitrage opportunity	86%	86%
...trade-weighted	31%	31%

Distribution of potential savings:
Q1: 41%, Median: 81%, Mean: 82%, Q3: 117%, Max: 285%
Top 10 hubs (desc. order):
THA MYS SGP USA DEU NLD BEL FRA ARE ARG

Notes. This table reports violations of the triangle inequality that emerge after eliminating asymmetries in trade costs (i.e., setting $\tau'_{ij} = \min\{\tau_{ij}, \tau_{ji}\}$). The right-most column sets the new trade cost values equal to one if they drop below one. The second row shows the share in cross-border trade with at least one arbitrage opportunity. The third row refers to reductions in trade costs from re-routing (measured in log-differences) when there is an arbitrage opportunity (restricting $t \geq 1$). A "hub" denotes an intermediary that allows for a cheaper delivery than the direct shipment between two countries. The sample contains 127 countries. The results are discussed in Section 5.

involving intermediaries creates a median net welfare change equal to 66.9% when we halve trade costs. In general, these statistics hide a lot of heterogeneity, as the more detailed results above show.

Asymmetric shock to τ. We also compute a counterfactual exercise with non-uniform trade-cost changes. Specifically, following Waugh (2010), we eliminate bilateral asymmetries in trade costs. We set the counterfactual trade costs equal to the minimum of the (potentially different) bilateral trade costs; formally, $\tau'_{ij} = \min\{\tau_{ij}, \tau_{ji}\}$. Note that trade costs cannot fall below one due to this shock, but nonetheless, the TI may not hold anymore.

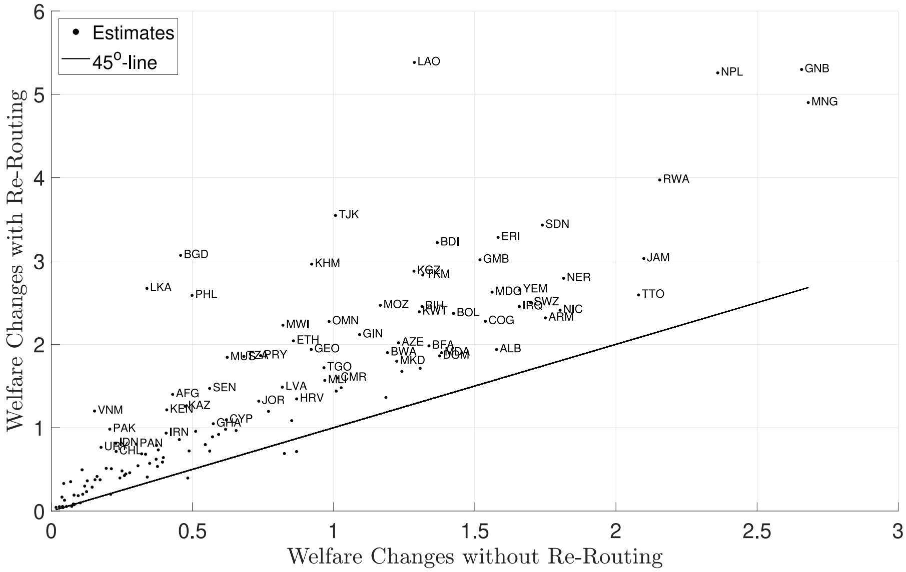


Fig. 2. Welfare changes after eliminating asymmetries in trade costs.
Notes. This figure depicts welfare changes after eliminating asymmetries in trade costs (i.e., setting $\tau'_{ij} = \min\{\tau_{ij}, \tau_{ji}\}$). In one case, we do not allow for re-routing (standard approach); in the other, we allow for re-routing when the TI is violated. We do not allow trade costs to fall below one in either case. Country codes are shown only for a subset of countries for illustrative purposes. The results are discussed in Section 5.

Table 4 shows that about 86% of the trade relations now face at least one arbitrage opportunity, with a substantial extra reduction of 82% on average. The main winners in this counterfactual scenario are mostly developing countries, reflected in a lower affected trade share compared to Table 2. Fig. 2 depicts the immense welfare gains for these countries. The median difference between the two welfare gains is equal to 45% of initial real income. The correlation between the initial average level of exporting costs and the net gain from re-routing is 0.57. Therefore, weaker exporters benefit not only from the direct trade-cost reduction to strong partners, but also from an indirect decline through re-routing, which is also highlighted by the set of top hubs in Table 4. Tables O.11 and O.12 of the Online Appendix list the arbitrage statistics and the welfare changes in detail by country.

6. Comparison to transportation network frameworks

We argue that re-routing opportunities must be taken into account in standard trade models after trade-cost shocks. Therefore, it is natural to compare our quantitative results to approaches from the economic geography literature that explicitly model the transportation network, thereby endogenizing the routing decision. Do the counterfactual predictions of our standard trade model get closer to those of such frameworks once we allow for re-routing?

We focus on the approach developed in Allen and Arkolakis (2022) (henceforth, AA22), who build a quantitative model with endogenous trade costs, which can be recovered by complementing data on trade flows with information on traffic flows. Appendix A briefly outlines their transportation setup. Ganapati et al. (2023) (henceforth, GWZ) apply this theory using international containerized trade and shipping flows to estimate leg-level transportation costs (i.e., the costs of shipping *directly* from country i to j). The resulting leg-level costs and the underlying trade data are publicly available on the authors' websites. After merging domestic trade flows for the year 2014 (GWZ's year of analysis) from our data, we are left with 129 countries. From here on, we use $\tilde{\tau}_{ij}$ to denote the leg-level transportation costs. With these estimates, we can ask what happens if we consider shocks to $\tilde{\tau}_{ij}$ rather than the trade cost τ_{ij} (the standard target in the trade literature). Importantly, by construction, $\tilde{\tau}_{ij}$ is unaffected by potential BPS.

With this in mind, we calculate three sets of trade costs. To obtain the first set of trade costs, we apply our approach from Section 4 to GWZ's trade data. We refer to the resulting trade costs as "traditional" trade costs to emphasize that we only use information on trade flows following the canonical gravity literature. For the second set, we compute the Leontief inverse of the leg-level transportation cost matrix to obtain trade costs following AA22, as explained in Appendix A. We refer to the resulting trade costs as the "multi-route" version, since every available shipping route is used with positive probability in their environment. Additionally, we obtain a third set of trade costs by calculating the least-cost route along $\tilde{\tau}$—the "single-route" version.[24]

These three sets of trade costs enable us to compute four types of counterfactual exercises (where τ and $\tilde{\tau}$ always refer to the estimated values in what follows):

[24] This is equivalent to setting $\tilde{\tau}_{ij}$ in Section 2 equal to GWZ's leg-level costs. Allen and Arkolakis (2014) develop a general-equilibrium model where country pairs use solely the least-cost route in the network.

Table 5
Welfare changes after a drop in trade costs (Different specifications).

Specification	Shock size	Distribution of welfare gains				
		Min.	Q1	Q2	Q3	Max.
Shock τ w/out Re-Routing	10%	0.3%	1.8%	3.0%	5.5%	17.7%
Shock τ with Re-Routing	10%	0.4%	2.4%	4.1%	9.4%	26.0%
Shock $\tilde{\tau}$ (Single-Route)	10%	0.6%	4.7%	8.2%	17.1%	54.9%
Shock $\tilde{\tau}$ (Multi-Route)	4.8%	1.0%	5.5%	9.2%	17.6%	51.5%
Shock τ w/out Re-Routing	25%	1.2%	6.8%	11.2%	19.7%	52.9%
Shock τ with Re-Routing	25%	1.7%	10.3%	17.7%	37.9%	94.7%
Shock $\tilde{\tau}$ (Single-Route)	25%	3.2%	35.0%	70.3%	124.0%	330.5%
Shock $\tilde{\tau}$ (Multi-Route)	7.7%	7.4%	47.6%	83.5%	132.4%	270.4%

Notes. This table reports the distribution of the welfare changes after a decrease in global bilateral trade costs of 10% and 25% across several specifications. The first specification changes traditional trade costs, τ, without accounting for re-routing opportunities (standard hat algebra). The second one allows for re-routing after the shock (our approach). The third specification shocks leg-level transportation costs, $\tilde{\tau}$, and computes the minimum-cost route for every country pair ('single-route'). The fourth variant changes $\tilde{\tau}$ and inverts the transportation cost matrix to obtain trade costs following Allen and Arkolakis (2022) ('multi-route'). For technical reasons, the shock size of the multi-route specification is smaller (details in the main text). Leg-level costs $\tilde{\tau}$ are taken from Ganapati et al. (2023). Q1, Q2, and Q3 refer to the first, second, and third quartiles. See Section 6 for a discussion.

(i) Shock the traditional τ_{ij} and do not allow for re-routing (standard hat algebra).
(ii) Shock the traditional τ_{ij} and allow for re-routing (our approach).
(iii) Shock $\tilde{\tau}_{ij}$ in the single-route version.
(iv) Shock $\tilde{\tau}_{ij}$ in the multi-route version.

In all these counterfactuals, we only adjust the set of trade costs (and shocks). The remaining structure outlined in Appendix A stays unchanged, allowing us to compare the welfare outcomes across these specifications. It is important to emphasize that (i) and (ii) shock the trade cost matrix, as is customary in the trade literature, while (iii) and (iv) consider changes to leg-level transportation costs. The question is whether the predictions in counterfactual (ii) are closer to (iii) and (iv) compared to those of counterfactual (i).[25] In other words, does accounting for the TI and re-routing after shocks capture forces that are similar to those contained in changes of the explicit transportation network? Importantly, in the multi-route version (iv), the same shock size has substantially larger effects than in the other specifications. Therefore, to facilitate comparability, we shock $\tilde{\tau}$ in counterfactual (iv) such that the average drop in τ is the same as in counterfactual (iii).[26]

Table 5 reports the distribution of welfare changes after a uniform drop in global trade costs of 10% and 25%, respectively. Confirming the results from Section 5, our method yields larger welfare gains compared to the standard hat-algebra approach along the entire distribution. Note that the numbers differ from Section 5 because here we use GWZ's trade data. The benefits from re-routing after shocks to the leg-level costs are even larger than what we predict via the TI in an otherwise standard setup. In fact, the median welfare gain after a 10% shock almost triples (doubles) in the single-route version relative to the standard approach (our method). Fig. C.6 of Appendix C plots the welfare changes underlying Table 5. It shows that standard hat algebra predicts lower welfare gains than the remaining specifications for all countries and that the welfare gains predicted by the four specifications are highly correlated (as confirmed by Table O.13 of the Online Appendix).

What happens when only a few (central) locations become better connected? GWZ highlight the role of important entrepôts in the transportation sector. Accordingly, we conduct a further counterfactual to connect our 'reduced-form' TI-based approach to their reasoning. That is, we decrease the export and import costs of the ten top hubs found in Table 1, leaving the remaining trade costs unchanged. Table 6 reveals that taking the TI seriously brings the predictions substantially closer (in terms of magnitude) to those of frameworks that explicitly shock and endogenize the transportation network. For instance, after a 25% shock, the median welfare gain in the single-route version is more than six times as large as in standard hat algebra, whereas it (only) doubles relative to our predictions. Fig. C.7 plots the underlying welfare changes. The correlations with the standard results are smaller than among the remaining methods (cf. Table O.14 of the Online Appendix).

[25] As argued in Appendix A, in the case of a uniform shock, counterfactuals (ii) and (iii) would predict the same changes in trade costs – and, hence, welfare – if we started from the same trade-cost levels. However, the traditional trade costs we estimate are considerably smaller than those implied by the single-route version. For instance, the median trade cost in the single-route specification is twice as large as the median of our traditional trade costs. In addition, the dispersion is larger as well: The inter-quartile range of the log of trade costs from the single-route version is more than 50% larger than for the traditional trade costs. The correlation between the log of these trade costs is 0.51.

[26] We abstract from potential scale economies in the shipping sector (see Ganapati et al., 2023). For large shocks, we cannot invert the transportation cost matrix in the multi-route version. Due to the differing underlying setup, the same shock size is not easily comparable to the other specifications—AA22 and GWZ use a shock size of only 1%. Inter alia, GWZ compare – in our notation – a counterfactual of type (i) to one of type (iv), calling the differences the "network effect". See Allen and Arkolakis (2022) for a discussion on invertibility.

Table 6
Welfare changes after a drop in trade costs (Different specifications—Hubs).

Specification	Shock size	Distribution of welfare gains				
		Min.	Q1	Q2	Q3	Max.
Shock τ w/out Re-Routing	10%	0.1%	0.5%	0.9%	2.0%	16.8%
Shock τ with Re-Routing	10%	0.2%	1.4%	2.3%	4.5%	21.7%
Shock $\tilde{\tau}$ (Single-Route)	10%	0.2%	1.7%	3.1%	6.5%	28.3%
Shock $\tilde{\tau}$ (Multi-Route)	4.9%	0.2%	1.8%	3.1%	6.6%	22.1%
Shock τ w/out Re-Routing	25%	0.3%	1.9%	3.4%	6.5%	53.7%
Shock τ with Re-Routing	25%	0.9%	6.5%	11.3%	21.9%	79.2%
Shock $\tilde{\tau}$ (Single-Route)	25%	1.2%	11.1%	22.6%	43.2%	155.8%
Shock $\tilde{\tau}$ (Multi-Route)	10.1%	1.3%	9.9%	18.6%	35.5%	104.7%

Notes. This table reproduces Table 5 but changing only the export and import costs of the top 'hubs' in Table 1 (i.e., ARG, CHN, DEU, GBR, MYS, PAN, SGP, THA, USA). ARE is missing in this dataset. Consult the notes to Table 5 for details and see Section 6 for a discussion.

In sum, accounting for TI violations after a trade-cost shock brings the welfare predictions substantially closer to those of frameworks that explicitly model and shock the transportation network. This seems to be especially true for counterfactuals involving a few well-connected countries. Therefore, the TI in canonical gravity setups captures forces that mimic spillovers in the transportation infrastructure (see also Section 2). Recall that our approach – based on a standard gravity setup – requires only data on trade flows, which is readily available for many countries, years, and industries. Having access to detailed data on shipping flows (e.g., the proprietary data used in GWZ) allows for a more elaborate depiction of the transportation network, as AA22 and GWZ show. Our quantitative results suggest that capturing re-routing via the TI yields a lower bound of the gains from changing and exploiting the transportation network.

7. Conclusion

We show that the triangle inequality (TI) of trade costs plays a crucial role in counterfactual analyses in general equilibrium trade models. Accounting for the TI implies that re-routing possibilities must be taken into account when trade costs change. In other words, we must consider the potential spillover effects of changing trade costs. Since this argument relies on (transportation) cost minimization, it is general and holds irrespective of the specific theoretical model and the empirical specification to estimate trade costs. For instance, a model with imperfect competition would yield different estimates of variable trade costs due to the presence of fixed market-access barriers. Similarly, pricing-to-market becomes relevant in a setup with non-homothetic preferences, and the estimated trade costs between countries of very different per capita incomes will likely be lower than in a model with homothetic preferences. However, also in such cases, the possibility of re-routing after trade-cost changes needs to be considered.

In this paper, we use the canonical Eaton and Kortum (2002) model and a variation of the Waugh (2010) approach to estimate trade costs to illustrate the argument above. We provide two methods to calibrate trade costs that satisfy the TI. Standard estimation procedures do not consider potential violations of the TI and can yield estimates that imply arbitrage opportunities. The latter are inconsistent with the theory and should thus not be employed in simulations.

We use our estimates to calculate the welfare gains that arise from re-routing after a shock to the trade cost matrix. Using both uniform and asymmetric reductions in trade costs, we show that counterfactual trade cost matrices can feature many arbitrage opportunities. That is, several trade pairs could further reduce their delivery costs by involving an intermediary country after the shock. Therefore, the effective drop in trade costs is larger for these dyads than the "direct" reduction in trade costs suggests. The TI – and, thus, re-routing – is quantitatively important in that welfare gains are substantially higher for many countries when we check for arbitrage opportunities. Finally, we compare our approach to studies that explicitly model the transportation network and show that accounting for re-routing after shocks to trade costs brings the counterfactual responses substantially closer to counterfactuals where we shock the explicit transportation network.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Model setup

The Ricardian framework we employ is picked off the shelf from well-known contributions in the literature. The only difference is our handling of trade cost (changes). In what follows, we briefly describe the Eaton and Kortum (2002) version with one sector and labor as the only input (see, e.g., Simonovska and Waugh, 2014). For a detailed discussion of the model, consult these papers.

Setup. This static world consists of N countries, indexed by i and j. There is a single tradable final-goods sector and a continuum of varieties indexed by $\omega \in [0,1]$. Labor is supplied inelastically by a measure of L_i consumers. The representative agent has CES utility over a bundle of final goods with elasticity of substitution $\sigma > 1$.

Firms operate in perfect competition and employ a constant returns to scale technology, where the cost of producing one unit of good ω in country i is given by $w_i/z_i(\omega)$. w_i is the economy's wage rate, and $z_i(\omega)$ denotes country i's efficiency in producing good ω, which is independently drawn from a Fréchet distribution

$$F_i(z) = \exp\left(-T_i z^{-\theta}\right).$$

For one unit of the good to arrive in destination j, producers in country i need to ship $\tau_{ij} \geq 1$ units, as described in Section 2. We normalize $\tau_{jj} = 1\ \forall j$ and assume that the triangle inequality holds, i.e., $\tau_{ij} \leq \tau_{ik}\tau_{kj}\ \forall (i,j,k)$.

Due to perfect competition, country i charges for good ω its marginal cost of production and transportation to consumers in j, that is,

$$p_{ij}(\omega) = \frac{\tau_{ij} w_i}{z_i(\omega)},$$

and consumers pick the source that offers the lowest price. The productivity distribution coupled with this pricing behavior yields the CES price index[27]

$$P_j = \left[\sum_{k=1}^{N} T_k \left(w_k \tau_{kj}\right)^{-\theta}\right]^{-\frac{1}{\theta}},$$

and the gravity equation

$$\pi_{ij} = \frac{X_{ij}}{X_j} = \frac{T_i\left(w_i\tau_{ij}\right)^{-\theta}}{\sum_{k=1}^{N} T_k\left(w_k\tau_{kj}\right)^{-\theta}}, \tag{A.1}$$

where π_{ij} is the so-called trade share, X_{ij} is the amount spent by country j's consumers on products from source i, and X_j is country j's total expenditure on final goods. In Section 4, we work with trade shares that are normalized by domestic absorption, that is,

$$\frac{\pi_{ij}}{\pi_{jj}} = \frac{T_i w_i^{-\theta}\tau_{ij}^{-\theta}}{T_j w_j^{-\theta}}.$$

To close the model, we assume that trade is balanced (i.e., every country has net exports equal to zero). As labor is the only source of income in this model, the set of wages satisfies the following condition

$$w_i L_i = \sum_{j=1}^{N} \pi_{ij} w_j L_j,$$

where we have $X_j = w_j L_j$.[28]

Hat algebra. How does the equilibrium change after a shock to trade costs? Let the value of a variable x in the counterfactual equilibrium be equal to x', and let $\hat{x} := x'/x$. Using this "hat-notation", we can depict changes in outcomes as a function of relative trade costs, $\hat{\tau}_{ij}$, and initial expenditure levels, X_{ij}. It is easy to show that the relevant set of equilibrium equations becomes

$$\begin{aligned}
\pi'_{ij} &= \frac{\pi_{ij}\left(\hat{w}_i\hat{\tau}_{ij}\right)^{-\theta}}{\sum_{k=1}^{N}\pi_{kj}\left(\hat{w}_k\hat{\tau}_{kj}\right)^{-\theta}} \\
\hat{w}_i X_i &= \sum_{j=1}^{N} \pi'_{ij}\hat{w}_j X_j.
\end{aligned}$$

After solving for the set of $\{\hat{w}_i\}_i$ that satisfies this equation system, we can calculate welfare changes (i.e., changes in real wages). More precisely, the gravity equation implies

$$\pi_{ii} = T_i\left(\frac{w_i}{P_i}\right)^{-\theta},$$

which means that welfare changes depend only on the trade elasticity, θ, and changes in the home share, π_{ii},[29]

$$\frac{\hat{w}_i}{\hat{P}_i} = \left(\hat{\pi}_{ii}\right)^{-\frac{1}{\theta}}.$$

[27] We abstract from constant terms which will be irrelevant to the entire discussion.

[28] A simple way to account for empirical trade imbalances would be to include an additional parameter that captures net exports in the initial equilibrium (see Dekle et al., 2007).

[29] For more details on this type of counterfactuals in quantitative trade models, see Costinot and Rodríguez-Clare (2014). For a discussion on the equilibrium's uniqueness, see Alvarez and Lucas (2007).

A useful benchmark is the real income loss from going to autarky (i.e., $\tau_{ij} \to \infty\ \forall i \neq j$). In that case, we obtain

$$\frac{\hat{w}_i^a}{\hat{P}_i^a} = \left(\pi_{ii}\right)^{\frac{1}{\theta}},$$

because we know that $\pi_{ii}^a = 1$, and thus $\hat{\pi}_{ii}^a = 1/\pi_{ii}$.

A note on shock sizes. In Section 2, we discuss why the standard assumption of a holding triangle inequality (TI) is valid. To that end, we introduced the *direct* trade cost between i and j, $\tilde{\tau}_{ij}$. Here, we briefly discuss the similarities and differences between shocks to τ_{ij} (the standard target in the trade literature) and $\tilde{\tau}_{ij}$ (the *direct* trade costs).

Let $\gamma \in (0,1)$, and consider a shock where the counterfactual direct trade costs equal $\tilde{\tau}'_{ij} = \gamma\tilde{\tau}_{ij}$. When we instead shock trade costs τ, the new value of trade costs (before re-routing) reads $\gamma\tau_{ij}$. The shock size is limited such that $\gamma\tilde{\tau}_{ij}$ and $\gamma\tau_{ij}$ do not fall below one. Moreover, let $\tau'_{ij,\tau}$ ($\tau'_{ij,\tilde{\tau}}$) be the counterfactual trade-cost value after a shock to τ ($\tilde{\tau}$) and potential re-routing. By definition, we have $\tau_{ij} \leq \tilde{\tau}_{ij}$ (because τ_{ij} measures the costs along the least-cost route, as explained in Section 2). Consequently, it must hold that $\gamma\tau_{ij} \leq \gamma\tilde{\tau}_{ij}$, and therefore, $\tau'_{ij,\tau} \leq \tau'_{ij,\tilde{\tau}}$. In words, the counterfactual trade costs after a trade-cost shock (and incorporating re-routing) must be smaller or equal to those after a shock to $\tilde{\tau}$.

In the special case when the shock is uniform across country pairs (i.e., shock by $\gamma\ \forall i \neq j$), it must hold that $\tau'_{ij,\tau} = \tau'_{ij,\tilde{\tau}}$. To see this, note that $\gamma\tau_{ij} \leq \gamma\tilde{\tau}_{ij}$, coupled with the fact that the counterfactual optimal value τ'_{ij} will follow a finite trajectory along the network, implies that we must obtain the same counterfactual trade cost levels.[30]

By contrast, in a non-uniform counterfactual experiment, the resulting trade costs might differ depending on whether we shock τ or $\tilde{\tau}$. For instance, if $\tau_{ij} = \tilde{\tau}_{ik}\tilde{\tau}_{kj} < \tilde{\tau}_{ij}$, changing only $\tilde{\tau}_{ij}$ has no effect as long as $\gamma\tilde{\tau}_{ij} > \tilde{\tau}_{ik}\tilde{\tau}_{kj}$. However, the counterfactual value is $\gamma\tau_{ij}$ if we shock the trade cost τ_{ij}. In such cases, it matters whether one changes the *direct* cost $\tilde{\tau}_{ij}$ or the route cost τ_{ij}.

In our main specifications, following the literature on international trade, we quantify shocks to the (optimal) trade cost τ_{ij} (see Section 5). In Section 6, we contrast our quantitative results with approaches that measure and shock $\tilde{\tau}_{ij}$.

Bilateral preference shifters. In international trade theory, bilateral preference shifters (BPS) and trade costs are isomorphic (see, e.g., the discussion in Head and Mayer (2014)). That is, one can explain larger trade flows from country i to j either with a higher utility obtained by households in j from consuming i's goods (i.e., a larger BPS for this country pair) or by lower trade costs (i.e., a lower value of τ_{ij}).

To see this, consider the setup above but suppose the representative household in country j has the following utility function

$$U_j = \left[\int_0^1 \left(\sum_{i=1}^N \alpha_{ij} q_{ij}(\omega)\right)^{\frac{\sigma-1}{\sigma}} \mathrm{d}\omega\right]^{\frac{\sigma}{\sigma-1}},$$

where $\alpha_{ij} > 0$ is a bilateral preference shifter (BPS) for the consumption of goods from country i, and $q_{ij}(\omega)$ is the amount of variety ω provided by i to j. Note that it still holds that there will only be one country exporting a specific variety ω to consumers in j.

The supply side is unaffected by this change in utility: Since we have perfect competition, prices are equal to marginal cost. However, consumers in j will now shop around the world to minimize prices divided by the respective BPS, where the ij-specific component is a function of τ_{ij}/α_{ij},

$$\min_i \left\{ \frac{\tau_{ij} w_i}{\alpha_{ij} z_i(\omega)} \right\}.$$

Following standard steps to solve the Fréchet integral (see Eaton and Kortum (2002)), we obtain the gravity equation with BPS

$$\pi_{ij} = \frac{X_{ij}}{X_j} = \frac{T_i \left(w_i\tau_{ij}/\alpha_{ij}\right)^{-\theta}}{\sum_{k=1}^N T_k \left(w_k\tau_{kj}/\alpha_{kj}\right)^{-\theta}}.$$

Increasing α_{ij} and τ_{ij} by the same proportion leaves trade shares unaffected. Finally, note that the hat-algebra equations above to compute counterfactual experiments are unchanged as long as we assume that trade-cost changes do not alter preference parameters.

Transportation network. Allen and Arkolakis (2022) show how to endogenize transportation costs in an EK-type environment. We briefly outline their setup, because we compare our results to their approach in Section 6. For detailed descriptions and derivations, consult Allen and Arkolakis (2022) (henceforth, AA22). To facilitate comparison with the above, we use our notation wherever possible.

Let the transportation network be represented by an $N \times N$ matrix $\mathbf{T} = [\tilde{\tau}_{kl} \geq 1]$, where $\tilde{\tau}_{kl}$ captures the ad-valorem cost of directly moving from k to l. There is a set of countably infinite possible routes from i to j, $\mathcal{R}_{ij}$, where moving from i to j along

[30] As an illustration, suppose that $\tau'_{ij,\tilde{\tau}} = \gamma^2\tilde{\tau}_{ik}\tilde{\tau}_{kj}$ (involving an intermediary), whereas $\tau'_{ij,\tau} = \gamma\tau_{ij}$. Now recall it must hold that $\tau'_{ij,\tau} \leq \tau'_{ij,\tilde{\tau}}$. Note that $\tau'_{ij,\tau} = \gamma\tau_{ij}$ is only possible if $\tau_{ij} = \tilde{\tau}_{ij}$. But this implies that $\gamma\tilde{\tau}_{ij} \leq \gamma^2\tau_{ik}\tau_{kj} \leq \gamma^2\tilde{\tau}_{ik}\tilde{\tau}_{kj}$, where the first inequality follows from the definition of $\tau'_{ij,\tau}$. If one of these inequalities were strict, this would contradict $\tau'_{ij,\tilde{\tau}}$ being the least-cost route. It follows that $\tau'_{ij,\tilde{\tau}} = \tau'_{ij,\tau}$ because, in general, $\tau'_{ij,\tau} \leq \tau'_{ij,\tilde{\tau}}$. As in Section 2, we can reduce such inconsistencies involving n intermediaries to three-countries TIs.

route r of length K_r incurs total costs of $\Pi_{k=1}^{K_r} \tilde{\tau}_{r_{k-1},r_k}$. Note that the length of a route is determined by the number of links crossed along the route. In AA22, the Fréchet shock is country-pair-route-specific (rather than only producer-specific) such that

$$p_{ij,r}(\omega) = w_i \frac{\Pi_{k=1}^{K_r} \tilde{\tau}_{r_{k-1},r_k}}{z_{ij,r}(\omega)}.$$

As a result, the probability that j buys a good from i using route $r \in \mathcal{R}_{ij}$ is given by

$$\pi_{ij,r} = \frac{T_i w_i^{-\theta} \left(\Pi_{l=1}^{K_r} \tilde{\tau}_{r_{l-1},r_l}^{-\theta} \right)}{\sum_{k=1}^{N} T_k w_k^{-\theta} \sum_{r' \in \mathcal{R}_{kj}} \left(\Pi_{l=1}^{K_{r'}} \tilde{\tau}_{r'_{l-1},r'_l}^{-\theta} \right)}.$$

Note that, due to the route-specific shocks, every route in the feasible set will be used with positive probability in equilibrium. As opposed to that, in our simple description of the transportation technology in Section 2, only the least-cost route is used. Summing over all routes, we obtain the same overall trade shares as in Eq. (A.1) when defining

$$\tau_{ij} := \left(\sum_{r \in \mathcal{R}_{ij}} \left(\Pi_{l=1}^{K_r} \tilde{\tau}_{r_{l-1},r_l}^{-\theta} \right) \right)^{-\frac{1}{\theta}}.$$

As a consequence of the route-specific shocks, these trade costs τ_{ij} do not necessarily obey the TI.

To derive an analytical solution for the transportation costs in equilibrium, let $\mathbf{A} := [\tilde{\tau}_{ij}^{-\theta}]$ be an $N \times N$ matrix with (i,j) element $\tilde{\tau}_{ij}^{-\theta}$. AA22 show that we can depict τ_{ij} as follows

$$\tau_{ij} = b_{ij}^{-\frac{1}{\theta}},$$

where b_{ij} is the (i,j) element of a matrix $\mathbf{B}$ determined by $\mathbf{B} := (\mathbf{I} - \mathbf{A})^{-1}$. In words, $\mathbf{B}$ is the Leontief inverse of the weighted adjacency matrix $\mathbf{A}$ (Allen and Arkolakis, 2022, p. 2922). This illustrates how a shock to link-level costs, $\tilde{\tau}$, can be directly mapped into bilateral trade costs, τ_{ij}, thereby incorporating the endogenous routing decision. AA22 further demonstrate how to use hat algebra in their environment by complementing data on bilateral trade with information on traffic flows, which avoids estimating $\tilde{\tau}$ (and is unaffected by potential BPS).

Appendix B. Data

We use the International Trade and Production Database for Estimation (ITPD-E). The ITPD-E provides bilateral trade flows and production data retrieved from several administrative data sources (see Borchert et al. (2021) for details). The production data is used to calculate domestic trade as well as trade shares. The dataset covers the years 2000–2016 and up to 243 countries and 170 industries. For each country pair, we sum over all industries to obtain aggregate bilateral trade flows. We include only countries that appear as both importers and exporters in a given year, and we drop countries with a total population below one million. We merge China and Hong Kong, as well as Belgium and Luxembourg, which is often done in the literature due to large shares of re-exports. Our main results use the year 2004.

The "gravity" covariates are taken from the widely-used CEPII Gravity database (Head et al., 2010). Specifically, we use the population-weighted distance between two countries, and indicators for whether a country pair has (i) a common border, (ii) a common official language, (iii) a common currency, (iv) a colonial link, or (v) a free trade agreement.

Appendix C. Additional figures

See Figs. C.1–C.7.

Appendix D. Additional tables

See Tables D.1–D.4.

Appendix E. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jinteco.2024.104018.

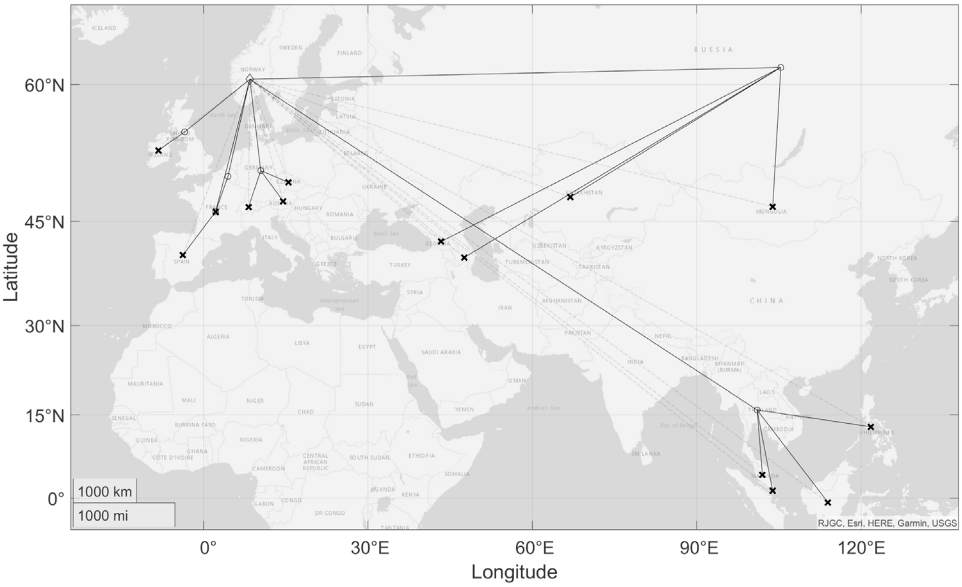


Fig. C.1. TI violations with standard trade cost estimates—Norway.
Notes. This figure illustrates the TI violations for Norway as an exporter. Trade barriers are computed with Waugh's (2010) method and restricted to at least one. We mark the exporter with a diamond, intermediaries with a circle, and importers (i.e., the final destination) with an x. The transparent dashed line draws the direct exporter–importer connection. See Section 3 for a discussion.
Data. See Appendix B.

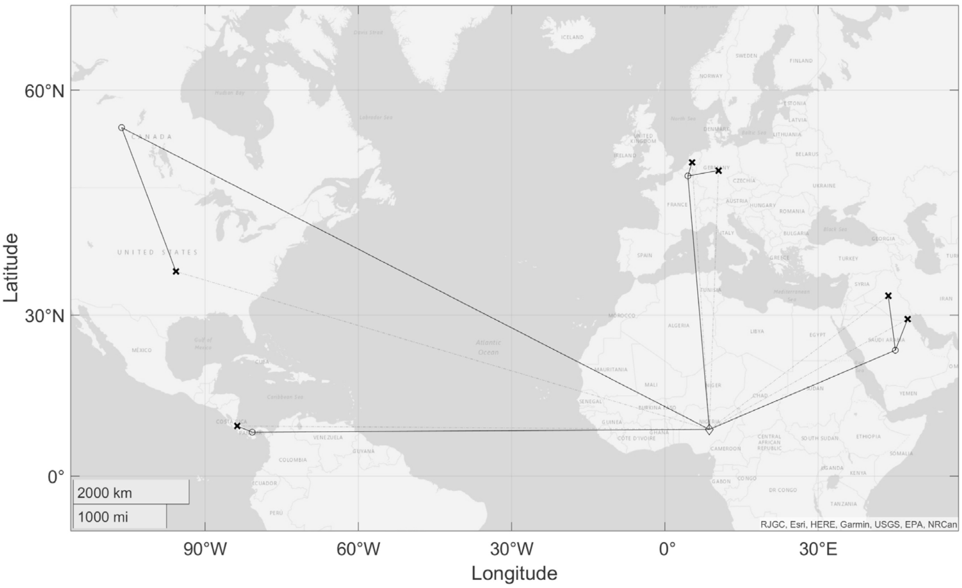


Fig. C.2. TI Violations with standard trade cost estimates—Nigeria.
Notes. This figure illustrates the TI violations for Nigeria as an exporter. Trade barriers are computed with Waugh's (2010) method and restricted to at least one. We mark the exporter with a diamond, intermediaries with a circle, and importers (i.e., the final destination) with an x. The transparent dashed line draws the direct exporter–importer connection. See Section 3 for a discussion.
Data. See Appendix B.

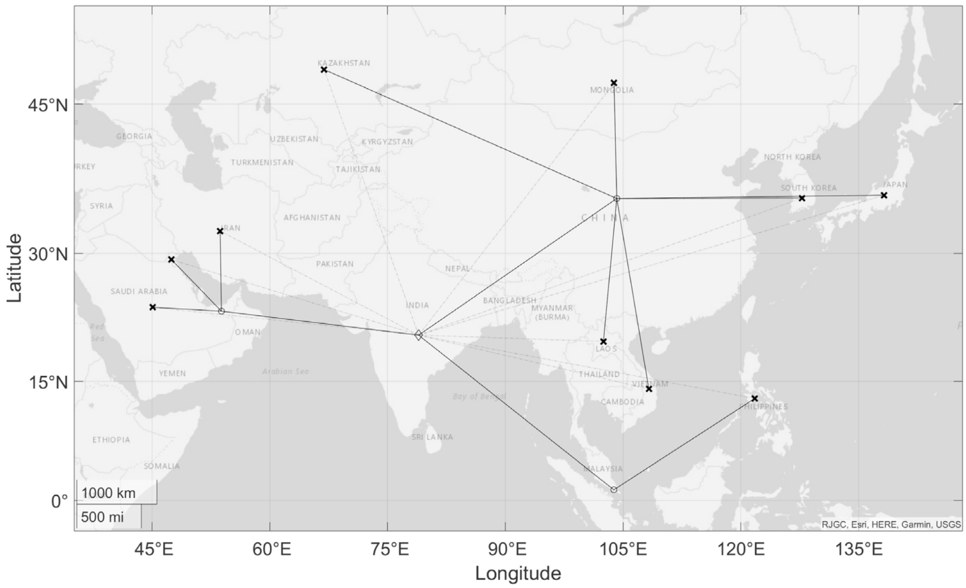


Fig. C.3. TI violations with standard trade cost estimates—India.
Notes. This figure illustrates the TI violations for India as an exporter. Trade barriers are computed with Waugh's (2010) method and restricted to at least one. We mark the exporter with a diamond, intermediaries with a circle, and importers (i.e., the final destination) with an x. The transparent dashed line draws the direct exporter–importer connection. See Section 3 for a discussion.
Data. See Appendix B.

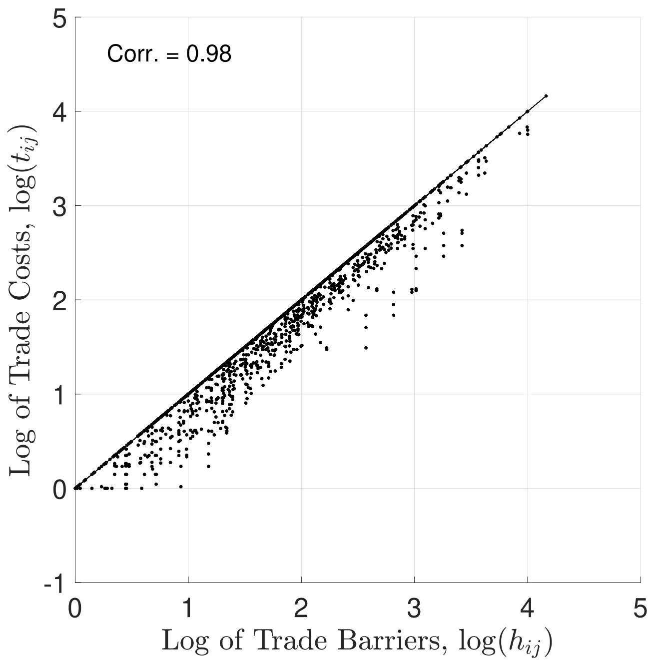


Fig. C.4. Trade barriers vs. Trade costs.
Notes. This figure depicts the log of estimated trade barriers, $h_{ij} = t_{ij}/a_{ij}$, against trade costs, t_{ij}. The solid black line is a 45-degree line, while "Corr". reports the correlation. We obtain trade costs by applying the algorithm summarized in Steps I to III. See Section 4 for a discussion.
Data. See Appendix B.

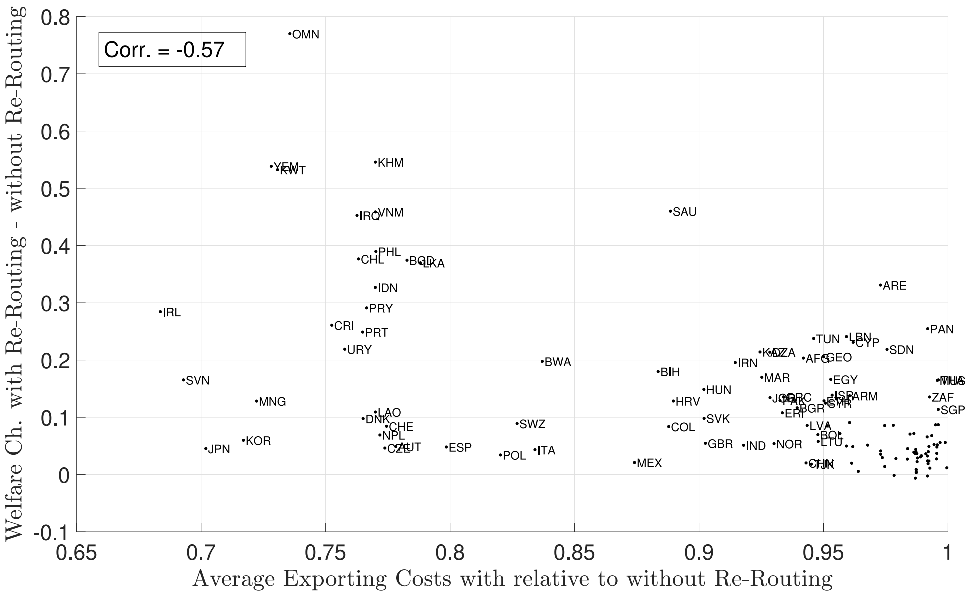
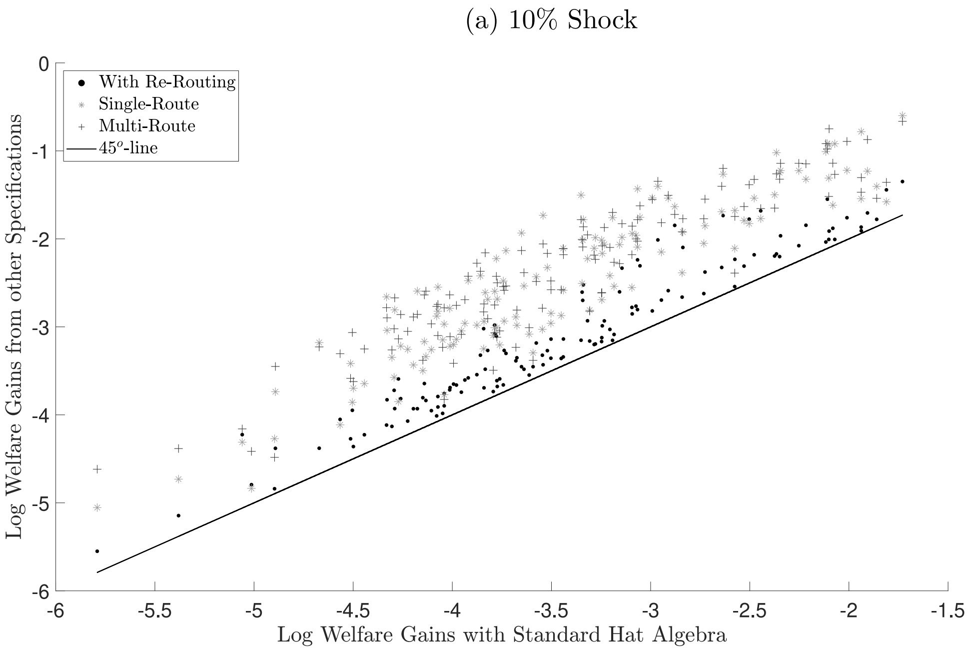


Fig. C.5. The impact of re-routing on trade costs and welfare after a 25% drop in global trade costs.

Notes. This figure relates the welfare gains from re-routing to the trade-cost reduction through re-routing after a drop in global trade costs of 25%. On the horizontal axis, we have the average ratio of trade costs after re-routing to trade costs without re-routing (both after the shock) for every exporter. The vertical axis refers to the net welfare gains from re-routing. Country codes are shown only for a subset of countries for illustrative purposes. The results are discussed in Section 5.



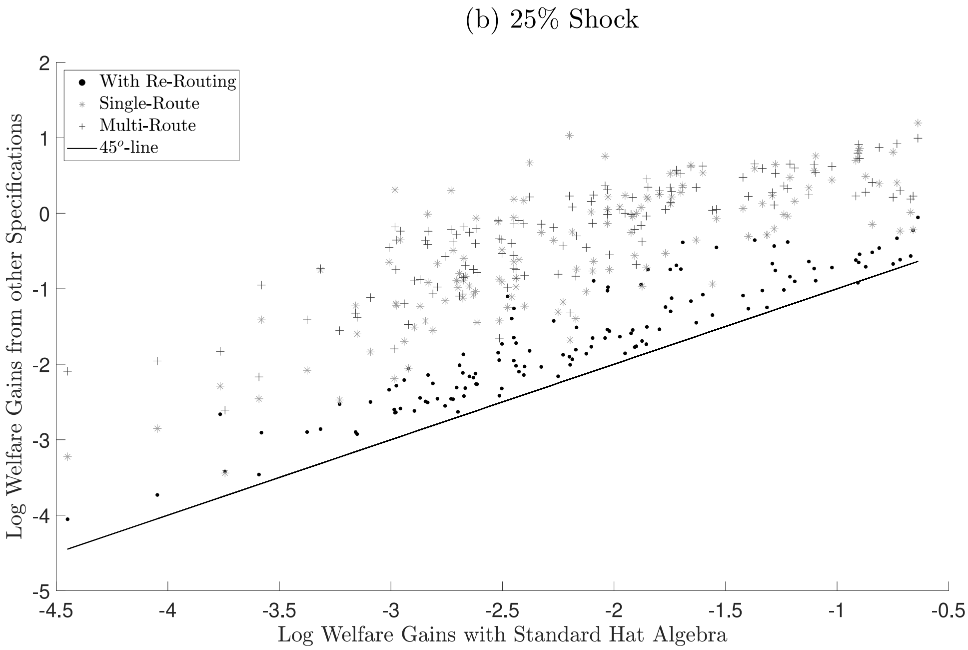


Fig. C.6. Welfare changes after a drop in trade costs (different specifications).
Notes. This figure plots the (log of) welfare gains underlying Table 5 in the main text. The horizontal axes contain the results from standard hat algebra (without re-routing), and the vertical axes the three remaining specifications. Consult the notes to Table 5 for details and see Section 6 for a discussion.

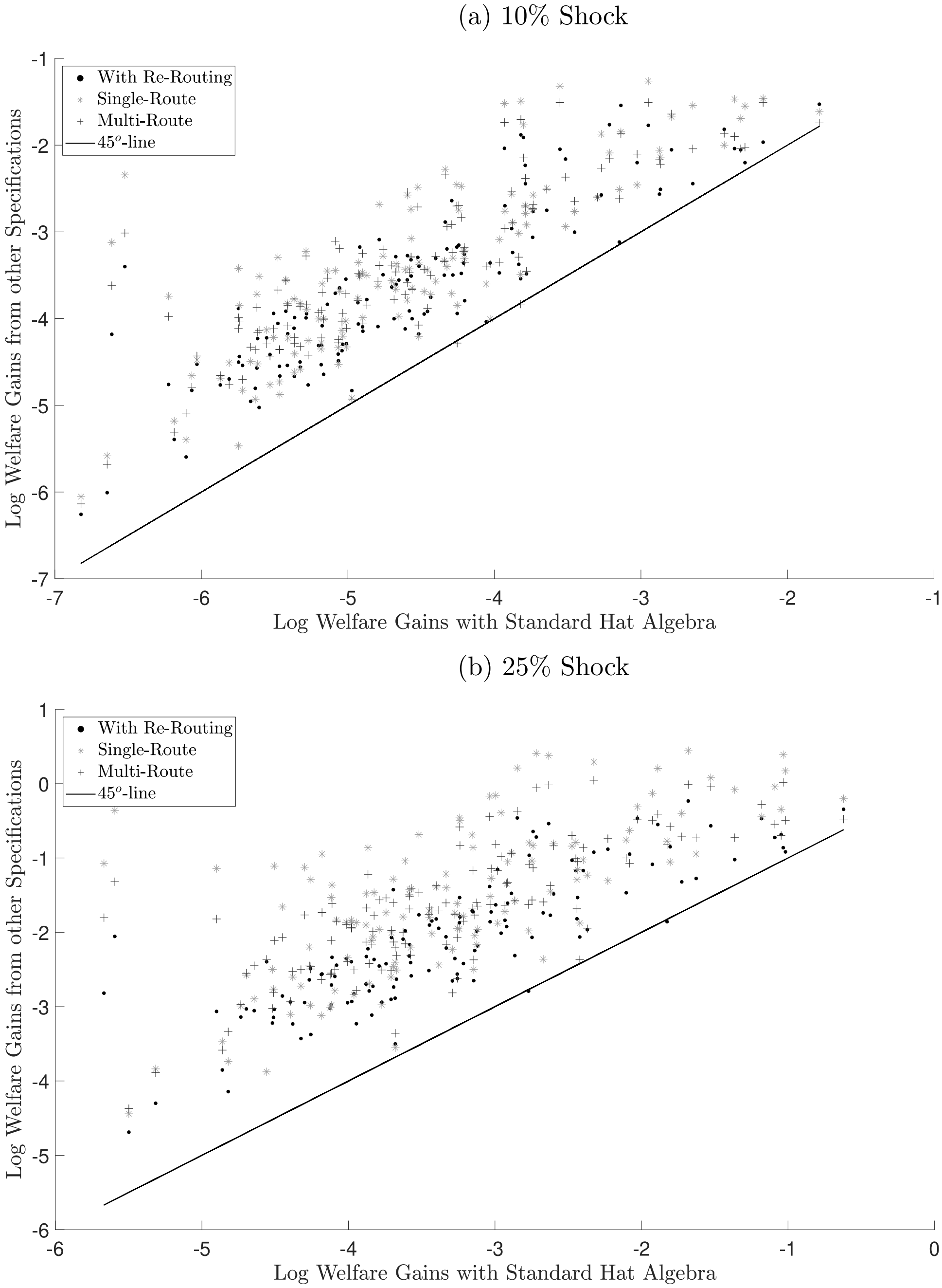


Fig. C.7. Welfare changes after a drop in trade costs (different specifications—hubs).
Notes. This figure plots the (log of) welfare gains underlying Table 6 in the main text. The horizontal axes contain the results from standard hat algebra (without re-routing), and the vertical axes the three remaining specifications. Consult the notes to Table 6 for details and see Section 6 for a discussion.

Table D.1
Coefficients from gravity regressions.

	OLS	PPML
Distance [0, 375)	−3.565***	−2.978***
	(0.352)	(0.621)
Distance [375, 750)	−4.323***	−3.099***
	(0.321)	(0.580)
Distance [750, 1500)	−5.415***	−3.964***
	(0.316)	(0.566)
Distance [1500, 3000)	−6.851***	−5.538***
	(0.311)	(0.582)
Distance [3000, 6000)	−7.861***	−6.246***
	(0.312)	(0.590)
Distance [6000, max.]	−8.532***	−6.455***
	(0.314)	(0.585)
Contiguity	1.260***	1.122***
	(0.118)	(0.215)
No. of observations	13,722	16,002

Notes. This table reports OLS and PPML results for the gravity equation (5) in Section 4. Robust standard errors are reported in parentheses. Regressions include importer and exporter fixed effects. Distance is weighted by population. Distance intervals are in miles. Trade flows are measured relative to domestic absorption. Dependent variable is absolute (log of) trade shares for PPML (OLS). The results are discussed in Section 3.

Data. See Appendix B.

*** significant at 1%-level.

Table D.2
TI violations with standard trade cost estimates—Details.

Exporter	Main hubs	TI violations	Mean rel. savings	Largest arbitrage opportunities
AFG	CHN, THA, ARE	10	0.24	KOR, JPN, MNG, MYS, IDN
ALB	SGP	2	0.16	IDN, PHL
ARE	SAU, DEU, IND	12	0.15	BEL, CHE, DNK, NLD, IRQ
ARG		0	0	
ARM	TUR, CAN, SAU	4	0.14	YEM, USA, BGR, GRC
AUS	CHN	1	0.16	MNG
AUT	DEU, THA, MYS	97	0.18	BEL, DNK, NLD, MAR, FRA
AZE	RUS, CAN, SAU	8	0.19	YEM, EST, FIN, LTU, LVA
BDI	SGP	1	0.16	PHL
BEL	DEU, FRA, THA	123	0.14	ESP, AUT, CZE, DNK, TUR
BFA	DEU	1	0.24	DNK
BGD	THA, SAU	6	0.27	MYS, IDN, PHL, SGP, YEM
BGR	TUR, GBR, SGP	6	0.15	IRL, IDN, IRN, ARM, GEO
BIH	DEU, SGP	6	0.22	BEL, DNK, NLD, FRA, IDN
BLR	RUS, FRA, SGP	4	0.16	ESP, KAZ, IDN, MNG
BOL	ARG, ZAF	2	0.19	URY, SWZ
BRA	DEU, ARG	3	0.31	CHL, DNK, POL
BWA	SGP, ZAF	3	0.18	SWZ, PHL, VNM
CAN	USA	125	0.16	MEX, COL, TTO, ALB, ARG
CHE	DEU, FRA, THA	122	0.16	CZE, DNK, POL, IRL, LTU
CHL	ARG, PAN	122	0.05	BRA, PRY, URY, CRI, CMR
CHN	THA, VNM	2	0.16	LKA, KHM
CIV	FRA, ITA	3	0.16	BEL, SVN, DEU
CMR	FRA, ARG	3	0.17	BEL, CHL, DEU
COG	SAU	2	0.16	IRQ, KWT
COL	PAN, ARG, DEU	8	0.16	CRI, CAN, URY, POL, HND
CRI	PAN, DEU	123	0.04	PER, TTO, COL, ECU, CHL
CYP	ITA, ARE, CAN	6	0.16	OMN, YEM, USA, NPL, CHE
CZE	DEU, THA, MYS	103	0.18	BEL, CHE, DNK, NLD, MAR
DEU	FRA, THA, BEL	19	0.14	ESP, OMN, YEM, MYS, ITA
DNK	DEU, THA, SAU	118	0.18	AUT, BEL, CHE, CZE, MAR
DOM		0	0	
DZA	CHN, ITA	2	0.17	SVN, KOR
ECU	FRA, PAN	5	0.12	CRI, BEL, CHE, DEU, ITA
EGY	ITA, SAU, CAN	6	0.06	USA, NPL, CHE, FRA, ARE
ERI	DEU, SAU, ARE	8	0.19	BEL, DNK, NLD, FRA, IRQ
ESP	FRA, CHN, SAU	26	0.19	BEL, DEU, ITA, CHE, BLR
EST	RUS, FRA, SAU	6	0.17	ESP, AZE, KAZ, YEM, IDN
ETH	SAU, IND	6	0.1	IRQ, KWT, NPL, ARE, JOR
FIN	RUS, ARE, FRA	8	0.18	OMN, ESP, AZE, GEO, KAZ
FRA	DEU, BEL, ITA	34	0.21	POL, NLD, AUT, CZE, DNK
GBR	NLD, THA, DEU	20	0.12	AUT, CZE, POL, DEU, FRA
GEO	RUS, TUR, ARE	7	0.18	OMN, YEM, FIN, NOR, USA
GHA	FRA, CAN	3	0.16	BEL, USA, DEU
GIN	FRA	2	0.17	BEL, DEU
GMB	BEL	1	0.24	DEU
GNB	BEL	2	0.24	DEU, NLD
GRC	TUR, SGP, NLD	7	0.11	IDN, PHL, IRN, GBR, ARM
HND	DEU, ITA, PAN	4	0.11	AUT, POL, COL, SVN
HRV	THA, DEU, FRA	6	0.14	DNK, SGP, IDN, PHL, ESP
HUN	SGP, BEL, NLD	4	0.15	FRA, IDN, PHL, GBR
IDN	SGP, MYS	125	0.4	KOR, PAK, LAO, PHL, ALB
IND	CHN, ARE, SGP	10	0.2	KOR, JPN, MNG, PHL, SAU
IRL	GBR, DEU, FRA	125	0.11	BGR, MDA, MKD, ROU, CHE
IRN	ARE, TUR, GBR	7	0.17	OMN, IRL, BGR, GRC, ERI
IRQ	SAU	10	0.23	YEM, ETH, SDN, ARE, OMN
ISR	ITA, ARE, CAN	5	0.14	OMN, USA, AUT, CHE, FRA
ITA	FRA, THA, DEU	15	0.15	ESP, BEL, DNK, CRI, MYS
JAM	PAN	1	0.1	COL
JOR	SAU, CAN	3	0.12	YEM, USA, ETH
JPN	CHN, THA, BEL	16	0.26	MNG, AFG, IND, KAZ, KGZ
KAZ	RUS, CHN, THA	22	0.2	JPN, KOR, MNG, VNM, FRA
KEN	CHN	1	0.16	KOR
KGZ	CHN, THA	9	0.22	JPN, KOR, MNG, MYS, IDN
KHM	THA	124	0.74	LKA, NPL, KAZ, OMN, BEL
KOR	CHN, THA	124	0.1	AFG, IND, PAK, TJK, KAZ
KWT	SAU, ARE, GBR	9	0.22	YEM, ETH, IRL, ERI, COG
LAO	THA	123	0.56	IDN, LKA, OMN, NZL, ZAF
LBN	ITA, ARE, CAN	4	0.16	OMN, USA, CHE, FRA

(continued on next page)

Table D.2 (*continued*).

Exporter	Main hubs	TI violations	Mean rel. savings	Largest arbitrage opportunities
LKA	THA	12	0.29	KHM, LAO, MYS, VNM, IDN
LTU	DEU, RUS, FRA	10	0.2	BEL, CHE, NLD, FRA, ESP
LVA	DEU, RUS, FRA	10	0.2	BEL, CHE, NLD, FRA, ESP
MAR	DEU, ARG	5	0.3	AUT, CZE, DNK, POL, CHL
MDA	FRA, GBR	2	0.27	IRL, ESP
MDG	SAU, CHN	3	0.16	IRQ, KWT, KOR
MEX	DEU, FRA, USA	5	0.15	CAN, AUT, CZE, POL, ITA
MKD	SGP, GBR	3	0.22	IRL, IDN, PHL
MLI	DEU	2	0.22	DNK, POL
MNG	CHN, CAN, THA	114	0.13	JPN, AFG, IND, KAZ, KGZ
MOZ	ARG, SGP	2	0.16	CHL, PHL
MUS	CHN	1	0.16	KOR
MWI	SAU, ARG, SGP	4	0.16	IRQ, KWT, CHL, PHL
MYS	SGP	125	0.68	AFG, ALB, ARE, ARM, AUS
NAM	ZAF	1	0.22	SWZ
NER	CAN, PAN	2	0.15	CRI, USA
NGA	BEL, SAU, CAN	6	0.18	DEU, NLD, IRQ, KWT, CRI
NIC	DEU, FRA, PAN	5	0.11	AUT, CZE, POL, COL, ITA
NLD	DEU, THA, BEL	122	0.13	AUT, CZE, FRA, TUR, POL
NOR	RUS, THA, DEU	14	0.2	AUT, CHE, CZE, FRA, IRL
NPL	IND, THA, CHN	20	0.21	KHM, MYS, VNM, JPN, IDN
NZL	THA, SGP	4	0.15	LAO, BGD, LKA, NPL
OMN	ARE	124	0.29	CYP, GEO, ISR, LBN, IRN
PAK	CHN, SGP, ARE	9	0.23	KOR, JPN, MNG, IDN, PHL
PAN	DEU, ITA	4	0.13	AUT, CZE, POL, SVN
PER	PAN	1	0.35	CRI
PHL	SGP, THA	117	0.15	IND, PAK, IDN, BGD, LKA
POL	DEU, RUS, SGP	25	0.2	FRA, BEL, CHE, DNK, NLD
PRT	ARG, DEU, ESP	3	0.23	POL, FRA, CHL
PRY	ARG, PAN	118	0.04	CHL, URY, CRI, AFG, ALB
ROU	GBR, SGP	2	0.25	IRL, IDN
RUS	CHN	4	0.13	KOR, JPN, LAO, VNM
RWA	SGP	1	0.16	PHL
SAU	ARE	5	0.16	AFG, IND, PAK, TJK, IRN
SDN	SAU, DEU, IND	5	0.12	IRQ, DNK, NPL, ARE, OMN
SEN	DEU	3	0.23	CZE, DNK, POL
SGP	THA, CHN	25	0.08	MNG, BGD, LKA, NPL, AFG
SLV	DEU, FRA, PAN	5	0.11	AUT, CZE, POL, COL, ITA
SVK	SGP, BEL, NLD	4	0.15	FRA, IDN, PHL, GBR
SVN	ITA, THA, FRA	12	0.12	FRA, DZA, MYS, CIV, IDN
SWE	DEU, BEL, FRA	8	0.18	AUT, CHE, FRA, ESP, YEM
SWZ	ZAF, SGP	4	0.17	BWA, NAM, PHL, BOL
SYR	ITA, TUR, CAN	5	0.09	USA, BGR, GRC, CHE, FRA
TGO	FRA, CAN	3	0.16	BEL, USA, DEU
THA	SGP, GBR, MYS	95	0.11	IRL, ALB, ARE, ARM, AUS
TJK	CHN, DEU, THA	14	0.24	KOR, JPN, MNG, BEL, CHE
TKM	FRA, GBR, SAU	3	0.2	YEM, IRL, ESP
TTO	PAN, USA	2	0.3	CRI, CAN
TUN	THA, CHN, PAN	7	0.15	CRI, KOR, MYS, VNM, IDN
TUR	DEU, SAU, CAN	8	0.19	BEL, NLD, FRA, YEM, USA
TZA	CHN	1	0.16	KOR
UKR	RUS, FRA, NLD	4	0.14	ESP, KAZ, MNG, GBR
URY	ARG	125	0.22	CHL, BOL, PRY, COL, AFG
USA		0	0	
VEN		0	0	
VNM	THA, CHN	122	0.26	LKA, NPL, KAZ, OMN, BWA
YEM	SAU	23	0.22	IRQ, KWT, ARM, AZE, CYP
ZAF	SGP, GBR	4	0.16	IRL, LAO, PHL, VNM

Notes. This table provides additional details on the summary statistics in Table 1. The sample contains 127 countries in the year 2004. "Main Hubs" are up to three intermediaries through which a given exporter can most often allegedly decrease its shipping costs (listed in descending frequency of involvement). "TI Violations" are the number of importers for which an alleged arbitrage opportunity exists. The fourth column reports average log-savings for relations with a TI violation. The last column lists for which importers a country has the largest relative drop in trade costs from involving an intermediary (up to five, in descending order). Trade costs are restricted to at least one. See Section 3 for a discussion.

Table D.3
TI violations after a 25% drop in global trade costs—Details.

Exporter	Main hubs	TI violations	Mean rel. savings	Largest arbitrage opportunities
AFG	MYS, ARE, CHN	69	0.08	LAO, VNM, YEM, BGD, AUS
ALB	CHE, MYS, TUR	18	0.14	PRT, BEL, DEU, NLD, DNK
ARE	SAU, BEL, IND	27	0.12	GBR, IRL, BGD, NOR, SWE
ARG	THA, FRA, BRA	15	0.01	VEN, BGD, CHN, ESP, GBR
ARM	TUR, ARE, RUS	46	0.1	BGR, GRC, ERI, EST, FIN
AUS	THA, BEL, CHN	19	0.05	PAK, AFG, KAZ, KGZ, TJK
AUT	BEL, DEU	120	0.26	TUR, ARE, ARG, ARM, AUS
AZE	RUS, FRA, ARE	34	0.14	EST, FIN, LTU, LVA, NOR
BDI	ARE, MYS, BEL	22	0.04	CHN, KOR, JPN, AFG, ARM
BEL	ITA, THA, ARE	36	0.05	PRT, ARM, GEO, SYR, CYP
BFA	FRA, MYS, TUR	17	0.06	LTU, LVA, NOR, SWE, MEX
BGD	MYS, IND	117	0.26	ALB, AUS, BDI, BGR, BIH
BGR	TUR, ITA, MYS	33	0.15	ARM, GEO, SYR, IRN, PRT
BIH	FRA, ITA, MYS	34	0.13	MAR, GBR, IRL, LTU, LVA
BLR	RUS, BEL, MYS	23	0.1	KAZ, MNG, TKM, MEX, ESP
BOL	ARG, ESP	108	0.06	MOZ, MWI, SWZ, BEL, CHE
BRA	ARG, BEL, VEN	92	0.06	DOM, HUN, LTU, LVA, NOR
BWA	ZAF	115	0.19	MOZ, AUS, CAN, CHN, COL
CAN	USA, PAN	124	0.03	ECU, BEL, CHE, DEU, DNK
CHE	BEL, NLD, DEU	119	0.26	PRT, ARE, ARM, AZE, BFA
CHL	ARG	123	0.28	AFG, ALB, ARE, ARM, AUS
CHN	THA, RUS, BEL	99	0.08	BDI, BWA, MOZ, MWI, NZL
CIV	BEL, MYS, CAN	17	0.11	GBR, IRL, HUN, LTU, LVA
CMR	BEL, THA, SAU	17	0.1	GBR, IRL, ARE, OMN, LTU
COG	THA, BEL, SAU	11	0.05	ARE, OMN, IRQ, KWT, COL
COL	PAN, VEN	116	0.13	HND, JAM, NIC, SLV, DOM
CRI	PAN	123	0.29	DNK, DOM, FRA, LAO, MYS
CYP	ITA, ARE, BEL	26	0.13	BEL, CHE, DEU, DNK, FRA
CZE	BEL, NLD, DEU	118	0.27	BDI, BGD, BRA, BWA, CAN
DEU	ITA, THA, ARE	36	0.05	PRT, ARM, GEO, SYR, CYP
DNK	FRA, DEU	123	0.27	ECU, BIH, HRV, HUN, LTU
DOM	MYS, BEL, VEN	17	0.03	ECU, COL, BRA, ESP, GBR
DZA	ITA, BEL, THA	36	0.16	LTU, LVA, NOR, SWE, BEL
ECU	BEL, MYS, PAN	29	0.06	DOM, SVN, ITA, BIH, HRV
EGY	ITA, BEL, MYS	29	0.14	ARE, OMN, POL, BEL, CHE
ERI	SAU, BEL, ARE	32	0.15	ARM, AZE, GEO, TKM, TUR
ESP	FRA, BEL, CHE	119	0.23	BIH, HRV, HUN, LTU, LVA
EST	RUS, FRA, THA	38	0.08	AZE, KAZ, MNG, ARM, TKM
ETH	ITA, SAU, MYS	24	0.16	ARE, JOR, OMN, AUT, BEL
FIN	RUS, BEL, THA	28	0.1	AZE, GEO, KAZ, MNG, ARM
FRA	ITA, BEL, ARE	34	0.05	PRT, ARM, GEO, SYR, CYP
GBR	BEL, ITA, NLD	113	0.11	PRT, BIH, HRV, HUN, LTU
GEO	TUR, RUS, ARE	50	0.11	FIN, NOR, BGR, GRC, ERI
GHA	BEL, THA, CAN	26	0.08	GIN, GBR, IRL, HUN, LTU
GIN	BEL, MYS, IND	20	0.11	GHA, GBR, IRL, BIH, HUN
GMB	DEU, MYS	22	0.05	HUN, LTU, LVA, NOR, SVK
GNB	BEL, MYS	14	0.08	HUN, LTU, LVA, NOR, SVK
GRC	ITA, TUR, MYS	38	0.16	ARM, GEO, SYR, IRN, PRT
HND	FRA, MYS, PAN	30	0.05	COL, PER, TTO, BIH, HRV
HRV	FRA, ITA, MYS	24	0.16	GBR, IRL, LTU, LVA, NOR
HUN	BEL, AUT, MYS	38	0.12	PRT, MAR, GBR, IRL, NOR
IDN	MYS	119	0.28	DNK, GBR, HRV, IRL, ITA
IND	ARE, MYS, CHN	98	0.09	KAZ, LAO, VNM, IRQ, YEM
IRL	GBR, BEL	125	0.28	BIH, HRV, HUN, LTU, LVA
IRN	ARE, TUR, FRA	106	0.09	BGR, ERI, GRC, IND, NPL
IRQ	SAU, ARE, BEL	104	0.21	IND, PAK, ERI, ARE, COG
ISR	ITA, ARE, BEL	33	0.13	POL, BEL, CHE, DEU, DNK
ITA	BEL, NLD, DEU	104	0.22	PRT, LTU, LVA, NOR, SWE
JAM	FRA, MYS, PAN	20	0.03	COL, PER, ECU, SLV, CHL
JOR	SAU, BEL, ARE	29	0.1	ETH, ARE, OMN, ERI, BGD
JPN	CHN, MYS, KOR	125	0.12	RUS, AFG, IND, KAZ, KGZ
KAZ	MYS, RUS, CHN	74	0.12	BLR, EST, FIN, LTU, LVA
KEN	ARE, BEL, MYS	20	0.03	JPN, AFG, GEO, IND, PAK
KGZ	THA, CHN, IND	59	0.07	LAO, VNM, AUS, NZL, JPN
KHM	MYS	119	0.28	GBR, HRV, IRL, ITA, NOR
KOR	CHN	123	0.29	ALB, ARE, ARM, AUS, AZE
KWT	SAU, ARE, BEL	123	0.2	COG, ERI, IND, MDG, MWI
LAO	MYS	119	0.28	AFG, ARG, AUT, BFA, BOL
LBN	ITA, THA, ARE	34	0.1	BEL, CHE, DEU, DNK, FRA

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Table D.3 (*continued*).

Exporter	Main hubs	TI violations	Mean rel. savings	Largest arbitrage opportunities
LKA	MYS	118	0.26	ARG, BOL, BRA, CAN, CHL
LTU	FRA, RUS, BEL	49	0.13	PRT, AZE, KAZ, MNG, DZA
LVA	FRA, RUS, MYS	48	0.14	PRT, AZE, KAZ, MNG, DZA
MAR	BEL, ESP, ITA	33	0.13	BIH, HUN, LTU, LVA, NOR
MDA	BEL, MYS, TUR	19	0.05	KAZ, MEX, ESP, PRT, MNG
MDG	THA, FRA, SAU	29	0.03	NAM, ARE, JOR, JPN, IRQ
MEX	USA	118	0.15	ALB, BFA, BGR, BIH, BLR
MKD	ITA, MYS, TUR	24	0.11	PRT, BEL, CHE, DEU, DNK
MLI	FRA, MYS, TUR	23	0.05	LTU, LVA, NOR, SWE, MEX
MNG	CHN	124	0.27	ALB, ARE, ARM, AUS, BGD
MOZ	MYS, BEL, ZAF	18	0.06	NAM, CHN, KOR, MNG, BOL
MUS	BEL, MYS, CHN	15	0.04	GBR, IRL, JPN, NOR, BGD
MWI	MYS, BEL, SAU	21	0.07	ARE, JOR, OMN, CHN, KOR
MYS	CHN, BEL, ZAF	7	0.07	NAM, AFG, JPN, KAZ, KGZ
NAM	ZAF, BEL, THA	20	0.07	MDG, MOZ, IDN, KHM, LAO
NER	BEL, CAN, MYS	17	0.08	ARE, OMN, LTU, LVA, NOR
NGA	FRA, SAU, MYS	18	0.12	GBR, IRL, ARE, OMN, LTU
NIC	THA, BEL, PAN	27	0.06	COL, PER, TTO, SVN, ITA
NLD	ITA, SGP, ARE	33	0.05	PRT, ARM, GEO, SYR, CYP
NOR	FRA, RUS, GBR	61	0.14	PRT, AZE, GEO, KAZ, MNG
NPL	MYS, IND, CHN	117	0.26	ALB, ARG, AUS, BDI, BGR
NZL	MYS, FRA, CHL	26	0.05	CHN, IND, KOR, MNG, PAK
OMN	ARE	125	0.28	ALB, AUT, BDI, BFA, BGD
PAK	ARE, MYS, CHN	83	0.09	LAO, VNM, IRQ, YEM, AUS
PAN	FRA, MYS, CHL	26	0.04	URY, ARG, BIH, HRV, HUN
PER	ESP, MYS, BEL	28	0.07	PRY, URY, ARG, HND, JAM
PHL	MYS	119	0.28	AFG, ALB, ARE, ARG, ARM
POL	BEL, RUS, NLD	100	0.25	ECU, AZE, CIV, CMR, GHA
PRT	BEL, ESP, NLD	55	0.2	HUN, LTU, LVA, NOR, SVK
PRY	ARG	124	0.27	AFG, ALB, ARE, ARM, AUS
ROU	ITA, MYS, TUR	25	0.12	PRT, BEL, CHE, DEU, DNK
RUS	CHN, DNK, FRA	29	0.08	LAO, VNM, JPN, MEX, KHM
RWA	ARE, MYS, BEL	22	0.04	CHN, KOR, JPN, AFG, ARM
SAU	ARE, BEL, TUR	107	0.13	NPL, AFG, IND, PAK, TJK
SDN	FRA, MYS, SAU	20	0.11	ARE, OMN, GBR, IRL, PRT
SEN	THA, BEL	19	0.06	HUN, LTU, LVA, NOR, SVK
SGP	BEL, CHN, MYS	16	0.03	NAM, AFG, JPN, KAZ, KGZ
SLV	BEL, MYS, PAN	28	0.06	COL, PER, TTO, SVN, ITA
SVK	BEL, THA, AUT	39	0.11	PRT, MAR, GBR, IRL, NOR
SVN	ITA, BEL	117	0.21	LVA, NOR, SWE, MEX, NIC
SWE	BEL, MYS, RUS	44	0.14	PRT, TUR, DZA, MAR, TUN
SWZ	ZAF	120	0.19	BOL, NAM, AFG, ALB, ARE
SYR	TUR, ITA, ARE	38	0.13	BGR, GRC, BEL, CHE, DEU
TGO	BEL, MYS, CAN	15	0.12	GBR, IRL, LTU, LVA, NOR
THA	FRA, CHN, MYS	19	0.03	NAM, AFG, JPN, KAZ, KGZ
TJK	MYS, ARE, CHN	66	0.09	LAO, VNM, YEM, GBR, IRL
TKM	RUS, ARE, BEL	26	0.11	ERI, BLR, EST, FIN, LTU
TTO	FRA, MYS, PAN	18	0.04	HND, NIC, SLV, COL, BGD
TUN	ITA, MYS, ARE	27	0.17	LVA, NOR, SWE, BEL, CHE
TUR	BEL, MYS, SAU	24	0.12	ARE, OMN, NOR, SWE, GBR
TZA	ARE, BEL, MYS	21	0.03	JPN, AFG, ARM, AZE, GEO
UKR	RUS, BEL, TUR	25	0.11	KAZ, MNG, GBR, IRL, MEX
URY	ARG	123	0.29	AFG, ALB, ARE, ARM, AUS
USA	MYS, BEL, PAN	15	0	ECU, BGD, CHN, IND, KOR
VEN	MYS, BEL, BRA	17	0.04	ARG, CHL, URY, ESP, GBR
VNM	MYS	119	0.28	GBR, HRV, IRL, ITA, NLD
YEM	SAU	118	0.22	ARE, ARM, AZE, CYP, GEO
ZAF	MYS, BEL	18	0.05	CHN, KOR, MNG, NOR, SWE

Notes. This table provides additional details on the summary statistics in Table 2. "Main Hubs" are up to three intermediaries through which a given exporter can most often decrease its shipping costs (listed in descending frequency of involvement). "TI Violations" are the number of importers for which an arbitrage opportunity exists. The fourth column reports average log-savings for relations with a TI violation. The last column lists for which importers a country has the largest relative drop in trade costs from involving an intermediary (up to five, in descending order). Trade costs are restricted to at least one. See Section 5 for a discussion.

Table D.4
Welfare changes after a 25% drop in global trade costs.

Country	(1) With re-routing	(2) No re-routing	(3) ((1)–(2))/(2)	(4) Autarky loss	(5) ((1)–(2))/|(4)|
AFG	0.68	0.48	0.42	−0.52	0.39
ALB	0.07	0.06	0.09	−0.03	0.18
ARE	0.82	0.49	0.68	−0.45	0.74
ARG	0.47	0.41	0.14	−0.32	0.17
ARM	0.34	0.20	0.69	−0.13	1.06
AUS	0.23	0.16	0.41	−0.09	0.74
AUT	0.16	0.12	0.42	−0.10	0.51
AZE	0.32	0.23	0.40	−0.13	0.67
BDI	0.06	0.04	0.58	−0.02	1.06
BEL	0.10	0.09	0.09	−0.12	0.07
BFA	0.20	0.19	0.06	−0.12	0.09
BGD	0.62	0.25	1.52	−0.16	2.40
BGR	0.30	0.18	0.63	−0.10	1.11
BIH	0.55	0.37	0.48	−0.26	0.68
BLR	0.40	0.40	0.00	−0.36	0.00
BOL	0.42	0.35	0.20	−0.24	0.29
BRA	0.08	0.06	0.35	−0.03	0.59
BWA	0.46	0.27	0.74	−0.63	0.31
CAN	0.17	0.12	0.44	−0.22	0.23
CHE	0.20	0.12	0.73	−0.10	0.83
CHL	0.68	0.31	1.22	−0.19	1.96
CHN	0.11	0.09	0.23	−0.05	0.38
CIV	0.45	0.41	0.10	−0.27	0.14
CMR	0.37	0.30	0.24	−0.17	0.42
COG	0.53	0.48	0.11	−0.37	0.14
COL	0.25	0.17	0.50	−0.09	0.90
CRI	0.50	0.24	1.08	−0.14	1.87
CYP	0.43	0.20	1.14	−0.12	1.97
CZE	0.16	0.12	0.39	−0.09	0.49
DEU	0.07	0.07	0.07	−0.06	0.07
DNK	0.21	0.12	0.84	−0.09	1.13
DOM	0.57	0.51	0.11	−0.37	0.15
DZA	0.68	0.47	0.45	−0.33	0.65
ECU	0.14	0.10	0.36	−0.06	0.61
EGY	0.31	0.14	1.18	−0.08	2.09
ERI	0.17	0.06	1.70	−0.04	2.92
ESP	0.11	0.06	0.80	−0.04	1.21
EST	0.26	0.21	0.19	−0.13	0.32
ETH	0.24	0.12	1.12	−0.07	1.91
FIN	0.15	0.11	0.32	−0.06	0.56
FRA	0.05	0.05	0.07	−0.05	0.07
GBR	0.14	0.08	0.67	−0.05	1.09
GEO	0.52	0.31	0.65	−0.21	0.99
GHA	0.26	0.19	0.36	−0.11	0.62
GIN	0.23	0.19	0.24	−0.12	0.39
GMB	0.28	0.25	0.13	−0.15	0.21
GNB	0.08	0.08	−0.03	−0.05	−0.05
GRC	0.23	0.09	1.51	−0.05	2.79
HND	0.55	0.51	0.06	−0.44	0.08
HRV	0.34	0.21	0.61	−0.12	1.08
HUN	0.34	0.20	0.76	−0.11	1.39
IDN	0.53	0.20	1.64	−0.14	2.41
IND	0.13	0.08	0.68	−0.05	1.10
IRL	0.50	0.21	1.35	−0.14	2.10
IRN	0.36	0.16	1.19	−0.10	1.91
IRQ	0.97	0.52	0.88	−0.46	0.99
ISR	0.28	0.14	1.00	−0.07	1.87
ITA	0.10	0.06	0.73	−0.04	1.09
JAM	0.38	0.34	0.11	−0.22	0.17
JOR	0.35	0.22	0.61	−0.15	0.90
JPN	0.08	0.04	1.28	−0.02	2.09
KAZ	0.59	0.38	0.56	−0.28	0.77
KEN	0.23	0.18	0.26	−0.12	0.42
KGZ	0.22	0.17	0.30	−0.12	0.41
KHM	0.86	0.31	1.75	−0.25	2.23
KOR	0.13	0.07	0.80	−0.05	1.28
KWT	0.78	0.25	2.14	−0.16	3.32
LAO	0.19	0.08	1.31	−0.12	0.94

(continued on next page)

Table D.4 (*continued*).

Country	(1) With re-routing	(2) No re-routing	(3) ((1)–(2))/(2)	(4) Autarky loss	(5) ((1)–(2))/|(4)|
LBN	0.62	0.38	0.64	−0.30	0.81
LKA	0.79	0.42	0.89	−0.36	1.04
LTU	0.24	0.18	0.32	−0.11	0.53
LVA	0.24	0.16	0.54	−0.10	0.90
MAR	0.43	0.26	0.67	−0.14	1.19
MDA	0.33	0.29	0.12	−0.19	0.19
MDG	0.37	0.31	0.21	−0.19	0.35
MEX	0.11	0.09	0.24	−0.06	0.37
MKD	0.14	0.09	0.53	−0.05	0.91
MLI	0.19	0.17	0.11	−0.11	0.18
MNG	0.31	0.18	0.70	−0.13	0.96
MOZ	0.24	0.20	0.20	−0.13	0.32
MUS	0.55	0.38	0.43	−0.27	0.61
MWI	0.15	0.11	0.32	−0.07	0.52
MYS	0.35	0.27	0.33	−0.22	0.39
NAM	0.44	0.44	−0.01	−0.45	−0.01
NER	0.18	0.15	0.20	−0.09	0.36
NGA	0.10	0.07	0.37	−0.04	0.71
NIC	0.44	0.41	0.07	−0.32	0.09
NLD	0.10	0.09	0.10	−0.10	0.09
NOR	0.18	0.13	0.42	−0.07	0.77
NPL	0.17	0.10	0.71	−0.07	0.94
NZL	0.13	0.09	0.50	−0.05	0.89
OMN	1.09	0.32	2.41	−0.29	2.66
PAK	0.36	0.23	0.55	−0.16	0.81
PAN	0.75	0.49	0.52	−0.47	0.54
PER	0.16	0.13	0.22	−0.07	0.38
PHL	0.68	0.29	1.34	−0.19	2.03
POL	0.11	0.08	0.45	−0.06	0.60
PRT	0.35	0.10	2.56	−0.05	4.81
PRY	0.64	0.35	0.82	−0.28	1.03
ROU	0.19	0.12	0.60	−0.07	1.09
RUS	0.30	0.22	0.39	−0.13	0.66
RWA	0.15	0.10	0.50	−0.06	0.79
SAU	0.99	0.53	0.87	−0.50	0.92
SDN	0.46	0.24	0.92	−0.15	1.50
SEN	0.22	0.19	0.12	−0.11	0.21
SGP	0.55	0.43	0.26	−0.54	0.21
SLV	0.52	0.48	0.08	−0.39	0.10
SVK	0.30	0.20	0.49	−0.11	0.87
SVN	0.32	0.15	1.07	−0.10	1.63
SWE	0.23	0.14	0.60	−0.08	1.09
SWZ	0.19	0.10	0.87	−0.17	0.54
SYR	0.26	0.13	0.93	−0.09	1.40
TGO	0.27	0.25	0.09	−0.15	0.14
THA	0.59	0.42	0.39	−0.41	0.40
TJK	0.15	0.13	0.14	−0.09	0.21
TKM	0.17	0.15	0.09	−0.09	0.16
TTO	0.32	0.29	0.09	−0.16	0.17
TUN	0.53	0.30	0.80	−0.16	1.44
TUR	0.23	0.15	0.58	−0.08	1.03
TZA	0.29	0.21	0.42	−0.13	0.66
UKR	0.12	0.09	0.34	−0.06	0.53
URY	0.42	0.20	1.07	−0.13	1.65
USA	0.04	0.03	0.39	−0.02	0.55
VEN	0.59	0.54	0.10	−0.46	0.11
VNM	0.70	0.24	1.89	−0.18	2.52
YEM	0.77	0.23	2.32	−0.17	3.21
ZAF	0.38	0.25	0.55	−0.15	0.93
Average	0.35	0.22	0.61	−0.17	0.91

Notes. This table reports the welfare changes after a decrease in global bilateral trade costs of 25%. Column (1) allows for re-routing after the shock, while Column (2) does not. Column (3) shows the relative increase in welfare gains due to re-routing. Column (4) reports, as a benchmark value, the real income loss from going to complete autarky (i.e., $\tau_{ij} \to \infty\ \forall i \neq j$). Column (5) shows the difference between Columns (1) and (2) scaled by the absolute value of Column (4). See Section 5 for a discussion of the results.

Data availability

Replication Package for "Triangle Inequalities in International Trade: The Neglected Dimension" by Foellmi, Hepenstrick, and Torun (Original data) (Mendeley Data)

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