How Far Goods Travel: Global Transport and Supply Chains from 1965-2020*

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Abstract

This paper considers the evolution of global transportation usage over the past half century and the implications for supply chains. Transportation usage is increasing in response to falling prices. Participation of emerging economies in world trade and increasing longer-distance trade between countries contribute to this increase, encouraging longer supply chains. We discuss technological advances over this period and their interactions with endogenous responses from transportation costs and supply chain linkages. Supply chains involving more countries and longer distances are more exposed to disruptions, highlighting the importance of considering the interconnectedness of transportation and supply chains in policymaking and future work.

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1 Introduction

The integration of countries and industries into global supply chains depends on cheap and efficient transport. We show how transport use and costs have evolved over the last 55 years, and establish their current and future implications for international trade and global supply chains. We find that increases in transport use is simultaneously driven by emerging markets and trade between countries that are further apart. We outline a set of issues to help future work integrate transportation economics with global value chains. In particular, we use data and the existing literature to highlight how more efficient transportation can influence the location and configuration of value chains.

Decreases in international transport costs are not only reflected in increasing trade flows and use of transport services, but transport costs themselves are endogenous to scale economies, technology adoption, and infrastructure investment. Furthermore, the transport sector interacts differentially across industries along supply chains. These interactions between transportation, trade, and supply chains have important implications for the resilience and vulnerability of international trade due to the upstream (closer to primary and raw material production) and downstream (closer to final consumers) nature of different stages of good production.

To this end, we first directly measure global transport use from 1965 to 2020. Specifically, we account for distance when measuring transport usage—goods being traded by countries that are further apart would mechanically use more transportation services. Real transport usage is measured in two ways: (1) by weight in ton-kilometers traveled as is standard in the transportation literature, and (2) by value in value-kilometers as is standard in the trade literature. We also account for the growth of the global economy during that time period by normalizing transport use by real global consumption. We show that normalized transport use has increased 100% and 160% over this period, by weight and value respectively. However, while normalized transport use by weight continued increasing after the 2007 Great Recession, transport use by value has substantially declined.

Second, we establish trends on global transport costs and show that it has decreased over this same period. We do this by calculating the cost to ship a dollar's worth of goods for one kilometer each year, relying on national account and trade data. We show that transport costs have declined over the last half century by 33-39% and 48-62%, by weight and value respectively. The cost of shipping relatively heavier goods has fallen less than the cost of shipping relatively higher value goods.

Third, we consider the implications of the interaction between transport and the global economy. We start with the participation of emerging economies in the global trading market over this time period. While about one-third of world trade originated from developing countries in 2002, by 2011 this share has increased to about half (UNCTAD, 2013). We focus on one important emerging economy, China, and its contribution to the overall increases in transportation usage. Since 1990, China accounted for the entirety of the relative global transport use increase by weight. Given that weight-based transport use is a proxy for raw materials and intermediate goods (goods that are more upstream in the production process), this suggests that China plays a prominent role upstream in supply chains during this period. We also decompose transport usage into trade that takes place over short distances (less than 5,000km, essentially within-region trade), medium distances (5,000km-10,000km, like Asia-Europe trade), and long distances (more than 10,000km, like Asia-North America trade). Longer distance trades—both medium and long distances—account for most of the increase in transport use, compared to shorter distance trade. Taking both of these points together, we show that the efficient technological advancement in transport can encourage supply chains—for goods to be shipped to and from emerging countries like China, and over longer distances. Both these aspects show that countries are more interconnected and integrated in recent decades. Additionally, we consider the composition of goods that contribute to these increases in transport use—intermediate inputs and raw materials by weight, and manufactured goods by value.

Then, we consider a number of transport technology and infrastructure changes over this time period that contribute to the decreasing transport cost and increasing transport use trends. These include the introduction of container and jet airplane technology, greater exploitation of economies of scale in shipping contributing to a hub and spoke trade network, improvements in global transport infrastructure, and innovations in the logistics management system contributing to "just-in-time" deliveries and door-to-door freight services. Crucially we highlight that while supply chains respond endogenously to transportation costs changes, transportation costs themselves also respond endogenously to these technology and infrastructure changes. In particular, we highlight the just-in-time inventory management system pioneered by Toyota Motor Corporation and the reliance of such production on cheap and reliable transportation.

Taking stock, we show that potential interactions between transportation and supply chains can impact the resiliency and vulnerability of supply chain networks going forward. While downstream goods may face fewer direct risks, they are still indirectly exposed to potential disruptions due to their reliance on upstream goods for production—upstream goods are more exposed since they require more transportation services and travel further. We highlight future avenues for research linking supply chains and changes in transportation costs with an emphasis on the resiliency and vulnerabilities for trade flows.

Telephone and smartphone production as illustrative examples To motivate key points in this paper, we start with two examples spanning a century. Built in 1905, the Western Electric Hawthorne Works factory in Cicero IL manufactured 43,000 varieties of telephone apparatus for the parent Bell telephone monopoly (Weber, 2002; Lantz, 2014). It employed 40,000 people over 100 buildings connected by 10 miles of private railroad track. While this factory did source a few raw materials from remote locations, it manufactured many intermediate components, such as vacuum tubes and transistors internally, before distributing finished telephone equipment across the country. While the US did have have an efficient internal railroad system then, transport costs were still substantial and excessive back-and-forth transport links were not common. These locations effectively made handsets from Bakelite, rubber, and metal in a single location for the entire US.

The factory operated until 1986, and large portions of the grounds were dynamited in 1994 to build a Home Depot and Sam's Club (Pelton, 1994). A vertically integrated factory in a high cost location near final customers no longer make financial sense in an age of globalization and low transport costs.

The supply chain for the telephone's modern equivalent, a smartphone, is quite different. Consider a bestselling handset, the Apple iPhone. Apple's Research and Design activities take place in the United States, while its development and engineering activities take place in the United States and Taiwan (including within its largest manufacturing partner, Foxconn). Production directly involves six countries in addition to any further upstream manufacturers; designed in the US, key components are manufactured in Japan, Korea, Taiwan, and China, with final assembly in China and India (Table 6, Dedrick and Kraemer (2017)). Samsung's smartphone production process is even more involved; while design takes place in South Korea, manufacturing and assembly span the globe.[1]

Unlike Western Electric, Apple's direct subcontractors do not manufacture many of the components used and only assemble the final product before shipment around the world. With the exact mix depending on the model, components such as memory, microprocessors, optics, batteries, and screens are manufactured in both nearby Asian countries (for example in South Korea, Taiwan, Japan, Malaysia, Vietnam) or even in the US, Mexico, or EU.

These locations are connected today by frequent and reliable air freight and container shipping networks, compressing space and enabling supplier networks between far-apart countries. While common today, the breadth and extent of such networks for intermediate goods did not exist in heyday of Western Electric. Today's companies simply use much

[1]Manufacture of key components for the Samsung smartphone takes place in South Korea, Japan, and the US, while the final assembly takes place in Korea, Vietnam, China, India, Brazil, and Indonesia (Dedrick and Kraemer, 2017).

more transport services in the process of making their products. The expansive use of global networks by Apple is not just a function of reduction in government imposed trade barriers, but also a function of declining transportation costs (Harley, 1988; Hummels, 2007). Harley (1988) documents that in 1890 it would cost nearly $200 per ton to ship goods from California to Europe in 2020 dollars. A century later in 2020, the cost would be less than $2 per ton using a standard bulk ship.

2 Transport Use Over Time

World trade has exploded since the end of World War II, accounting for a larger share of total world production and consumption.[2] The World Trade Organization (WTO) reports that 2021 world trade is 43 times larger in volume in 2021 than in 1950 (World Trade Growth, 1950-2021). We first link this increase in global trade to increases in the use of global transport services—to not only ship more goods, but to ship them further as well.

Specifically, we examine the usage of transportation services as primarily consisting of two components: (1) the amount of goods that are transported, and (2) how far these goods are transported. The first component can be reasonably approximated by international trade flows. The second measure is important to incorporate as goods that are shipped further require more transportation. This transport use measure captures what is often missing in traditional trade measures—the role of distance. If trade increases, but only between nearby countries and between locations that are far apart, then the global need for transportation may only marginally increase. But if trade between distant locations increases, then transportation needs will dramatically increase. Including distance directly captures transport use.

We measure transportation usage in two ways. The first method uses the weight of transported goods—as most transportation costs are primarily priced in either weight or volume (Hummels and Skiba, 2004; Irarrazabal, Moxnes and Opromolla, 2015; Wong, 2022).[3] This method is a way to directly measure real transportation usage, which is more reflective of the transport of raw materials, such as grain, coal, ore, or crude oil. These goods are more likely to be inputs into production (as opposed to final goods). The second way is to better align transportation usage with traditional trade (as opposed to transportation) statistics,

[2]We primarily use gross-output to measure world trade, value-added measures dampen this increase as world production has further fragmented over time. For example, Johnson and Noguera (2012) shows that the US-China 2004 trade imbalance is about 30-40 percent smaller when measured in value-added terms.

[3]Nearly all bulk cargo transport costs are in tons. Containers are priced by volume (Twenty-foot equivalent units, TEUs) up to a binding maximum tonnage, with exceptions for cargo with special handling needs like refrigeration (also known as reefers).

by considering the value of goods multiplied by the distance travelled. This value measure places more emphasis on the transport of machinery, automobiles, and electronics which are closer to final consumption goods. It also broadly lines up with iceberg trade costs, the opportunity cost of time, and ad-valorem tariffs. Studying the trends of these two measures over this time period allows us to better understand transportation usage and trade, as well as reconcile the differences between the two.

For the approximately 200 countries with available trade statistics from 1965-2020 in the NBER-UN Comtrade and CEPII BACI databases (Feenstra et al., 2005; Gaulier and Zignago, 2010),[4] we measure usage of transport as follows:

$$\begin{aligned} \text{Transport Use}_t &= \text{Total Trade Transported (tons or \$)} \times \text{Distance Transported (km)} \\ &= \sum_o \sum_d X_{odt} \times D_{od} \;\; \text{where} \;\; o, d \in N \end{aligned} \tag{1}$$

where X_{odt} is the total amount of trade between origin country o and destination country d in year t measured in tons or dollars, and D_{od} is the population-weighted great circle (as-the-crow-flies) distance between these countries measured in kilometers from the CEPII Gravity database.[5] The underlying databases convert currencies into current US Dollars. All values are converted into year 2000 US Dollars using price index data from the World Input-Output Database (WIOD) database (Timmer et al., 2015), Penn-World Tables, and BEA US GDP deflators.

While data on the value of trade is available over our entire sample period, weight data is only widely available after 2000. WIOD price index data and BACI price/weight data from 1995-2000 are used to backwards impute weight data from prices. For natural resources from 1970-1985, weight and quantity data from the US Energy Information Administration (EIA) and the Organization of the Petroleum Exporting Countries (OPEC) are used to impute weights from prices, as the WIOD price index data is only available for a subset of countries. Full data details are in the appendix.

Figure 1 shows that over the last five decades, international transportation usage has dramatically increased. By weight, that there has been a more than ten-fold increase in transport use over this period (Figure 1a). The amount of transport use was about 7.1 trillion ton-kms in 1965, and by the end of our period it is about 78 trillion ton-kms. There is a 14-fold increase when measuring transport use in value terms (Figure 1b). The amount

[4]Data from the end of World War II to 1965 is problematic due to the rapid pace of decolonization from European powers, including now-defunct countries such as the USSR and Yugoslavia. Aggregate totals are adjusted to the composite World Input-Output Database (WIOD) databases (both the long run and 2016 release, Timmer et al. (2015)) to line up with Section 3. See the data appendix for full details.

[5]Lacking data on the specific route and mode used for transportation between all these countries, the great circle or haversine distance is an informative approximation.

of transport use was less than 4,000 trillion dollar-kms in 1965, peaks at 67,000 trillion dollar-km in 2011 (more than 16-fold increase), and by the end of our period is more than 57,000 trillion dollar-km (more than 14-fold increase). The steep upward trends in both panels suggest a large increase in transport use over this time period, also reflecting the growth of the global economy during the same time.

Both trends mirror each other from 1965 to right before the Great Recession. After 2008, the weight measure of transport usage (in ton-kilometers) continues its rapid growth but this trend is not matched by the value measure in dollar-kilometers. This suggests that there is either less trade of higher value-to-weight goods after this period or that these goods are being transported over shorter distances relative to lower value-to-weight goods. Transport for lower value-to-weight goods, such as raw materials, continues its upward trend. We will revisit the diverging trends in transport usage by weight and value at the end of this section.

Next, we account for the rapid growth in the world economy and normalize total transportation usage by real global consumption. This real transport use measure, detailed below, captures the cumulative distance traveled by intermediate inputs in production, in addition to the distance traveled by the final good to its ultimate destination for consumption:

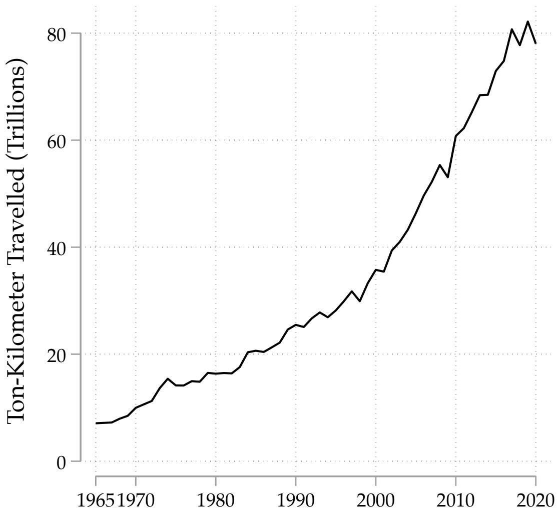
$$\begin{aligned} \text{Real Transport Use}_t &= \frac{\text{Total Trade Transported (tons or \$)} \times \text{Distance Transported (km)}}{\text{Total Gross Domestic Product}} \\ &= \frac{\sum_o \sum_d X_{odt} \times D_{od}}{\sum_o \text{GDP}_{ot}} \quad \text{where} \;\; o, d \in N \end{aligned} \tag{2}$$

where all elements in the numerator replicate Equation (1) between origin country o and destination country d in year t. In addition to the data from the aggregate measures of trade and transportation from above, WIOD data is used for country-level GDP from 1965-2014, and the Penn World Table (Feenstra, Inklaar and Timmer, 2015) (2015-2019) and UN statistics (2020) for GDP data from 2015-2020. See the appendix for full details.

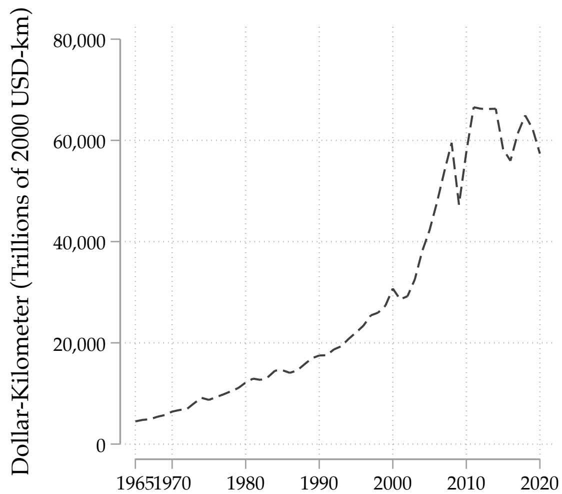
Figure 1c shows that real transport use in weight has more than doubled over the past 50 years, from 0.67 ton-km per dollar of real GDP in 1965 to 1.35 ton-km per dollar of real GDP in 2020. This shows that while the world economy is rapidly growing over this time period, not all of the increase in transport use is driven by that growth. As previously mentioned, these goods are more reflective of the transport of raw materials that are more likely to be inputs into production. This increasing trend is roughly linear over the entire time period. When using value measures, this increase in normalized transport use is even larger than the weight measure—more than tripling from 1965 to 2007, before declining nearly 20% from the peak (Figure 1d). Similarly, this shows that transport use is increasing above and beyond the growth in the world economy. As mentioned previously, this value measure is a closer

Figure 1: Transport Use, 1965-2020

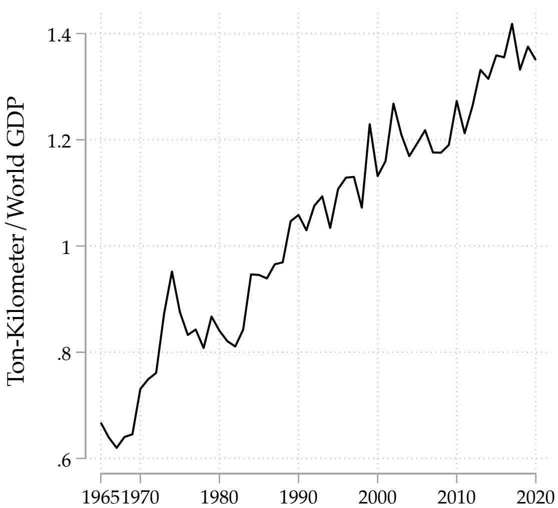
(a) By Weight and Distance



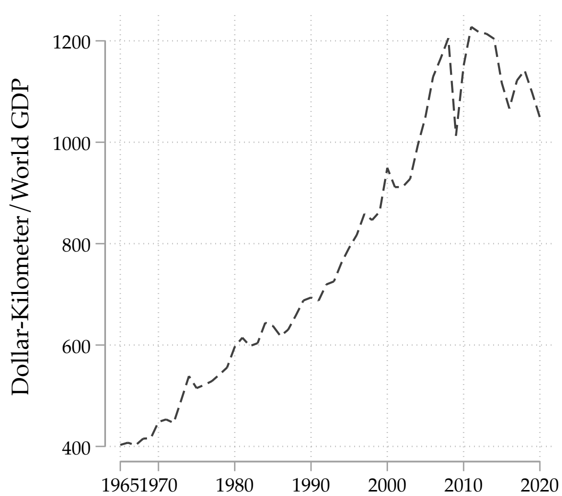
(b) By Value and Distance



(c) By Weight and Distance (Normalized)



(d) By Value and Distance (Normalized)



Notes: Figures 1a and 1b measure the distance shipped of goods, weighted by metric tons and real 2000 US Dollars respectively (Equation 1). Figures 1c and 1d normalize these figures relative to the sum of the gross domestic product of all countries to calculate real transport use (Equation 2). All monetary values converted to 2000 USD. Source: BACI, WIOD, UN-NBER-Combtrade, PWT, and associated output deflators.

approximation for the transport of final goods. We look into the distinction between final and intermediate goods in further detail in Section 4.

Trade versus Transportation

With these measure of transportation usage, we revisit conventional trade statistics, as international trade and transportation usage are intrinsically linked—international trade in goods cannot take place without transportation. In Figure 2, we plot the growth of our two normalized transportation usage measures (in weight-distance and value-distance from Figures 1c and 1d respectively) against the growth of more conventional trade measures, trade values and trade weights as a share of global output.[6] Since the more conventional trade measures do not account for distance, the comparison between these trade and transportation measures allows us to highlight the role of distance over this period—are more goods being shipped to countries that are further apart?

The growth of normalized transport usage in dollar-distance (gray dashed line) roughly echoes the growth of trade value as share of global output (orange triangles)—more than tripling by 2007 relative to 1965, before decreasing. Towards 2020 the growth is less than 2.5 times since 1965. In terms of value, goods are being shipped more to both nearby and distant locations.

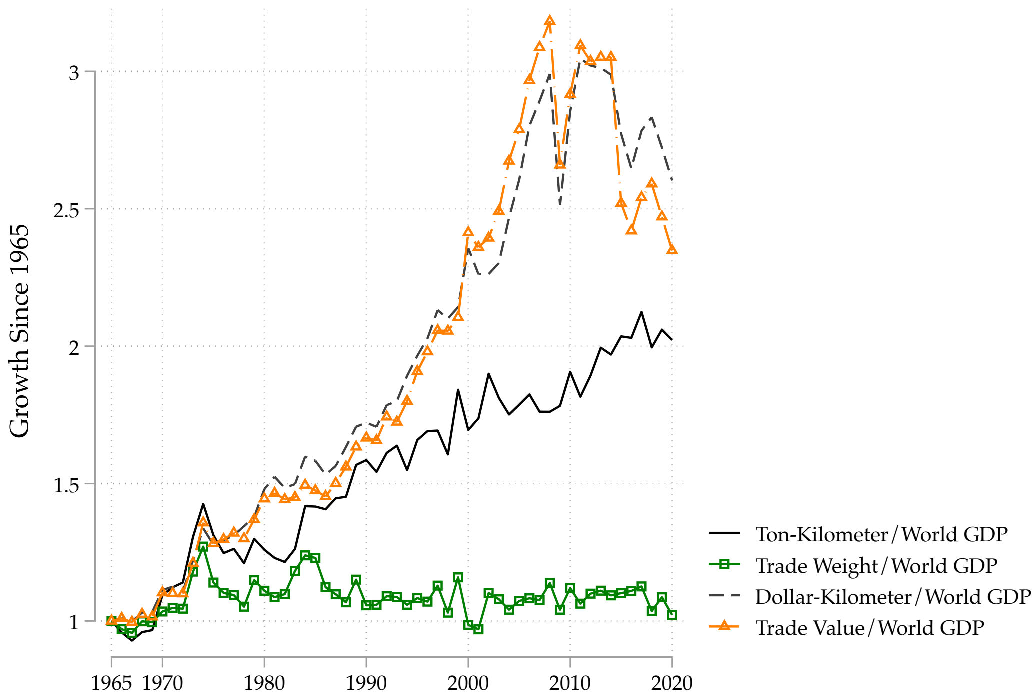
On the other hand, the growth of normalized transport usage in weight-distance (black solid line) is quite different from with the growth of trade weight as a share of global output (green squares). Both series diverge pretty early on in our sample period. As mentioned before, transport usage in weight-distance steadily increases at a slower rate and more than doubles by 2020 (compared to the dollar-distance measure). However, as a share of the global economy, the aggregate amount of tonnage shipped has stayed relatively constant from 1965 to 2020 at around 0.24 to 0.26 shipped tons per $1,000 of real World GDP. Relative to the global economy, nations are not trading significantly more goods by weight over this time period. However, when nations do trade these goods, they are transported over increasingly further distances.

We characterize three points from the trends in Figure 2:

1. **Parallel then divergent trends:** The growth in trade value and weight parallel each other until 1990. After 1990, the growth in value accelerates through 2007 and then subsequently collapses. Meanwhile, growth in weight continues steadily throughout this period, largely unaffected by the 2008 recession.

[6] Following Johnson and Noguera (2012) one can re-frame the value portion of this exercise using value added. This dampens growth by 10-25%.

Figure 2: TRANSPORT USE, 1965-2020



Notes: All series are normalized with respect to its 1965 value and can be read as growth since 1965. The black line is the normalized transportation use measured in ton-kms from Figure 1c. The dashed gray line is the normalized transportation use measured in dollar-kms from Figure 1d. The green squares are the total weight shipped relative to World GDP. The orange triangles are the value shipped relative to World GDP. All monetary values converted to 2000 USD. Source: BACI, WIOD, UN-NBER-Comtrade, PWT, and associated output deflators.

2. **By weight, goods are shipped longer distances:** Growth of transport use in weight is increasing, while trade in weight is roughly constant over the entire time period. The critical implication is that heavier goods are increasingly shipped further distances every year.

3. **By value, goods are shipped everywhere equally by distance:** For valuable shipments, countries are shipping everywhere equally by distance. Growth occurs 1965 to 2007, but decreases following the 2007 recession (Eaton et al., 2016).

These points highlight a central tension that exists at the intersection of transportation and international trade. Specifically, how each literature measures transport costs and how these measures are then linked to trade outcomes. The pricing structure in transportation is often at the per-unit level, e.g. one ton or a container of goods. These transport prices/costs are also equilibrium outcomes jointly determined with trade and transport use, in addition to also be reflective of scale economies, congestion, technology adoption, and infrastructure investment. While there are important exceptions, transport costs are typically treated as exogenous in the trade literature—approximated by distance empirically and by the iceberg functional form theoretically. The trade literature also typically focuses on the value of trade flows and not on weight. While the collapse of trade value following the Great Recession is clearly visible, transportation usage barely changes. Nations are cutting back on purchasing higher value-to-weight goods like foreign electronics relative to overall consumption, but trade in lower value-to-weight goods which are more reflective of raw materials like coal or oil continue to grow. We find important and potentially economically meaningful differences in transport use and trade flows—by value and weight—over the past 55 years, and these differences deserve further scrutiny.

3 Transport Cost Over Time

Both usage and total expenditures are equilibrium outcomes, dependent on the price or cost of transportation. For now we take transportation costs as given, but will return to a discussion on endogenous costs. We show two approximations of aggregate global trade costs over the from 1965 to 2014.

Instead of focusing on a subset of transport costs, which often do not include costs at the origin or destination, we use both our aggregate measure of transportation usage from the previous section, as well as the total expenditures in the transportation sector to recover the price to ship either a ton or real dollar of goods for one kilometer.[7] We then return to the share accounted for by transportation in the overall economy—a function of both usage and the price for transportation services.

In order to compare the cost of transport over this long period, we calculate the cost to transport one ton or one real dollar of goods for one kilometer in each year t as:

$$\begin{aligned}\text{Transport Cost}_t &= \frac{\text{Spending on Transport (\$)}}{\text{Total Trade (tons or \$)} \times \text{Distance Transported (km)}} \\ &= \sum_o \sum_d \frac{T_{odt}}{X_{odt} \times D_{od}} \quad \text{where } \; o, d \in N\end{aligned} \tag{3}$$

where T_{odt} is the amount of spending on transport between an origin country o and destination country d in year t measured in real dollars, X_{odt} is the total amount of trade value between these countries measured in either tons or dollars, and D_{od} is the distance between these countries measured in kilometers.

There are two issues taking equation (3) directly to the data. First, while aggregate

[7] We refrain from using spot-market ore self-reported transportation prices, but rather use national accounting and aggregate industry data to measure expenditures.

data on transportation expenditures is widely available in gross output and value added terms, such data is rarely differentiated by whether the expenditures are for domestic or international trade. Second, while data on the value of internal trade flows are available for a subset of countries, data on distances covered internally are hard to come by—especially over our extended time period.[8]

We address these issues in two different ways. First, we consider the scenario where all aggregate transportation spending was on international trade (numerator in Equation (3)). Since we are dividing this spending by the use of transport internationally (international trade multiplied by distance between countries, the denominator in Equation (3)), we are calculating a lower bound on the time trend of international trade costs.

Second, we approximate domestic transport use by assuming that the internal distance transported is unchanged over time.[9] We consider this an upper bound for international trade costs—while internal trade distances may have increased, it is seems plausible that it would increase at a slower rate than international trade distances. For the numerator in Equation (3), we use data on transportation and storage expenditures from the WIOD database (ISIC codes I60-I63 (rev 3) and H49-H52 (rev 4)). While we consider storage and warehousing as an important part of transportation costs, the data has the undesirable feature of including passenger transportation as a component.[10] For the denominator, we use international trade data from Section 2. For internal domestic trade, we use the population-weighed internal distance from the CEPII gravity database multiplied by the the gross value of internal trade. For weight, we use the average weight of that country's exports.

For the same set of countries, transport costs have decreased over the past 50 years globally from 1965 to 2014 (Figure 3a). In aggregate, weight-based measure of transportation costs from 1970 to 2015 have fallen by 33-39%. Value based measures have fallen by 48-62%. The cost of shipping heavier items has fallen less than the cost of shipping high-value items.

This is consistent with Hummels (2007) documenting a dramatic decline in transportation costs from 1950 to 2007 using direct data on prices paid for a consistent set of transportation

[8]An internationally traded shipment will involve both domestic and international transport services. While not our focus here, domestic transport and distribution costs are nontrivial. Anderson and Van Wincoop (2004) estimates that domestic distribution cost can be 55 percent of producer prices, more than two times larger than estimated international transport costs (21 percent). Atkin and Donaldson (2015) shows that intranational trade costs can be especially high in developing countries and finds that the effects of distance on trade costs within Nigeria and Ethiopia are 4-5 times larger than in the US. Van Leemput (2021) finds that internal trade barriers account for 40% of total trade barriers for Indian states with large variations depending on their distance to the closest port.

[9]Due to data availability, our sample is restricted to 24 countries with complete data over our time period in this section.

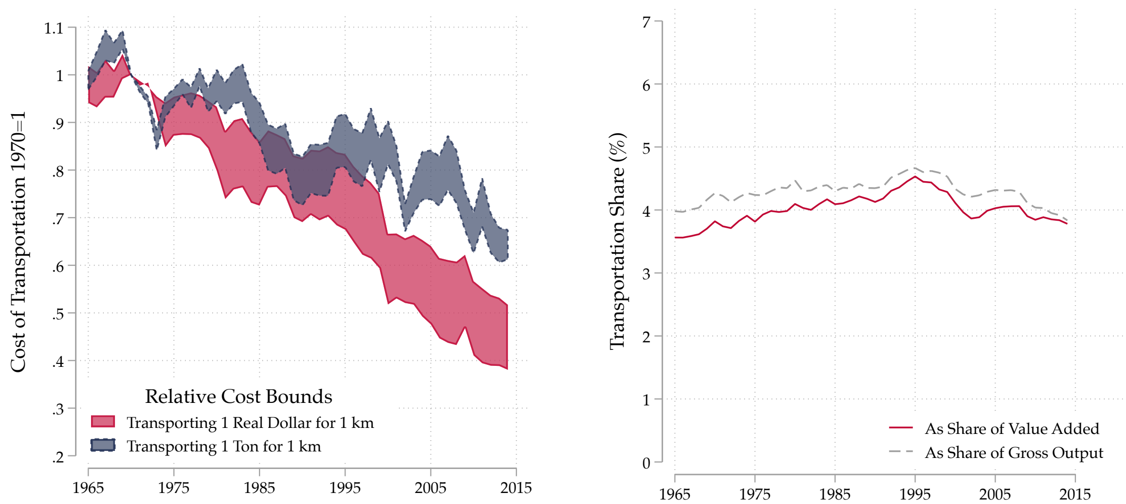
[10]A richer analysis would decouple passenger and freight transportation; however detailed US BEA value added data imply that passenger transportation expenditures follows a similar trend to freight transportation and accounts for less than 20% of the sector.

modes.[11] It is important to document this declining trend for both the transport of goods by value and weight, as they provide different perspectives. The cost to transport one ton of good for one km has decreased by about 40 percent over this period (gray dotted lines, Figure 3a). This understates Ardelean et al. (2022) who documents that dry-bulk freight rates have decreased by 71% between 1985-2020.

Interestingly, this trend exhibits a significant amount of volatility from 1975-1985, reflecting increases in the price of oil due to OPEC supply restrictions. Additionally, the cost of transporting a dollar's worth of goods for one km has decreased by about half over this period (red solid lines, Figure 3a). This declining trend for a dollar of good means that this cost decline does not just apply to bulky goods, but also all other transported goods.

Figure 3: Transport Costs and Aggregate Spending, 1965-2014

(a) Transportation Costs (b) Transportation Economic Share



Notes: Figure 3a is calculated according to Equation 3. Normalized to 1 in 1970. These figures use a consistent sample of 24 countries representing 90% of world GDP. The time period for the World Input-Output Database (WIOD) ends at 2014 which restricts our sample Timmer et al. (2015). For an alternative measure of Figure 3b, see the Appendix A2 for UN data until 2020.

As the dollar cost trends decrease faster than the weight trends, this data lines up with analysis from Harrigan (2010), where cheaper airfreight and containerization allows for the shipment of higher value goods, even if ocean bulk freight rates show less price movement. Before we touch on the input-output and supply chain implication of this, we first consider the magnitudes of the price declines and what it means for the total value added of the transportation sector.

[11] Hummels (2007) also highlights difference in quality and the endogenous selection of different modes of transport.

Using theory-based measures of aggregate trade costs that include all frictions to trade (as opposed to this accounting based measure of transportation) Novy (2013) finds US trade costs declined on average by about 40 percent between 1970 and 2000 and Jacks, Meissner and Novy (2011) find a decrease of 16 percent 1950-2000.[12] Head and Mayer (2013) attempt to line up trade costs with transportation and freight costs. To rationalize aggregate trade costs from reported transportation costs in standard trade models, they find that 50-90% of trade costs are generally unobserved.[13]

A related aspect of trade costs are trade elasticities. Transport costs make up just one component in trade elasticities (trade policy, for example, is another important component). Some studies find a decrease in the elasticity of trade to distance, while most point to little change or a modest increase over the last half century (Anderson and Van Wincoop, 2004; Disdier and Head, 2008; Brun et al., 2005; Leamer and Levinsohn, 1995). Berthelon and Freund (2008) shows that homogeneous goods, bulky goods, and high tariff goods became significantly more distance sensitive. More study is needed to understand the link between transportation cost and trade elasticity trends.

While transport costs have fallen and the global economy uses more transport services, is it spending more on transport services as a whole? We calculate global transport spending as a share of total gross output for the same time period from 1965-2015 using the WIOD databases. The expenditure share on transport for these countries have mostly stayed constant: started around 4 percent in 1965 and increased to more than 4.5 percent by 1995, before declining back to 4 percent in 2015 (Figure 3b).

Gross output measures capture the flows of goods every time these goods cross a border. These measures include the cost of inputs as well as the value added to the product by each country, leading to double counting (Johnson and Noguera, 2012). An alternative measure of transport spending considers the value added of goods from 1965-2015. The value added expenditure share for transport is (1) slightly lower than the gross share, but (2) mirrors gross output throughout the entire time period (Figure 3b).[14]

[12] See Head and Mayer (2014) for a survey.

[13] Studies such as Anderson and Van Wincoop (2004) and Burstein, Neves and Rebelo (2003) also note that direct transportation costs are a limited portion of overall distribution costs, with wholesaling (Ganapati, 2018; Chatterjee, 2019) and retailing margins of 50%.

[14] Redding and Turner (2015) show that US domestic transportation value added fell in the US over this period, from 4.0% of GDP to 3.0% of GDP, however due to the nature of global shipping, many international transportation costs to the US are attributed to other countries; the US may have simply outsourced it.

Production and Trade Responses to Decreased Transport Costs

We show that transport costs decreased between 30-60 percent over the past 50 years (Figure 3a). How much we utilize transport services is an equilibrium response to the price or cost of transport. One plausible outcome is that producers are incentivized to rely less on geographically concentrated production and instead to use more transport services to source their inputs from other locations within the same country or in other countries. Declines in trade costs have been attributed to many aspects of international trade, such as the geographic location of economic activity and fragmentation of supply chains (Antràs and Chor, 2022; Redding, 2022). This decrease in transport cost could be contributing to global value chains with intermediate production.

These transport cost decreases give rise to the classic proximity-concentration trade-off: firms can choose to expand production horizontally across borders in order to maximize proximity to foreign customers, or concentrate their production in one location in order to benefit from scale economies and exporting instead to these foreign destination.

As transport costs fall, all else equal, we would predict that these multinational firms would choose to pursue the latter option by exporting directly from a smaller set of concentrated locations. Using data on US multinational corporations operating in 27 countries, Brainard (1997) finds empirical evidence of this trade-off—exports of multinationals increase relative to overseas production as transport costs decrease. Helpman, Melitz and Yeaple (2004) include 11 less developed countries and finds the same empirical pattern of firms substituting exports for FDI sales when transport cost is low.[15] They subsequently introduce this proximity-concentration trade-off into a multi-country and multi-sector model with heterogeneous firms. Essentially, as trade costs fall, firms are going to utilize more transport, resulting in the share of transport costs over time to be ambiguous—consistent with our finding in Figure 3b. Next, we focus on decomposing utilization of transport.

4 Decomposing Transport Use

What has contributed to the dramatic increases in transportation usage since 1965? We focus on three factors: (1) increasing participation of emerging economies in global trade like China, (2) increasing trade between countries that are further apart (longer-distance trade), and (3) the composition of traded goods—upstream versus downstream goods and natural resources versus manufactured goods.

[15] Bernard et al. (2020) find a related phenomenon when firms offshore only low quality products, products with lower price to weight ratios (and echoed in Lashkaripour (2020)).

4.1 Rise of Emerging Economies and China

Developing countries have been increasing their participation in world trade, accounting for about 40 percent of world exports in 2020 (UNCTAD, 2022). East Asian countries are the main drivers of this increase. Additionally, one of the biggest changes of the last 30 years to global trade has been the opening of China to both inbound and outbound trade. Focusing on China as an important example of emerging economies, we consider the how much of the rise in transportation usage is accounted for by both intermediate and final good shipments to China. Essentially, what share of transport use growth over this period is due to trade with China?

We recompute Equation (2) to exclude both incoming and outgoing trade with China in the numerator, as well as excluding Chinese GDP from world GDP in the denominator. This metric is akin to considering a world without China, however we don't allow for trade diversion and just assume the trade vanishes, along with Chinese GDP vanishing.[16]

We first consider the role of China in real transportation usage considering the ton-kilometers of goods (Figure 4a). Between 1965 and the 1990s, the real transport usage with and without China is relatively similar. In 1965, one dollar of real output represents 0.67 ton-kilometers of transportation usage. By 1990, both the global average and the average without China, rose to 1.06 and 1.10 ton-km respectively for one dollar of output. After that, China accounts for almost the entirety of the relative physical transportation usage increases. At this point the two trends diverge.[17] By 2020, the global average with China had increased by 28% since 1990, but the average excluding China had instead fallen by 9%. By the weight of goods, the growth of post-1990 transportation usage largely reflects the growth of China—to the near exclusion of many other trends.

Considering value, the dollar-distance trends with and without China mostly increase in tandem (Figure 4b), although we do see a divergence starting in 1990 that is much smaller and slower than the weight-distance trend. By 2007, the distance traveled for one dollar of final good consumption was 1165 dollar-km, while the number without China was 976 dollar-km. However following the great recession, both numbers, with and without China faced a similar decline to 1049 dollar-km and 853 dollar-km respectively.

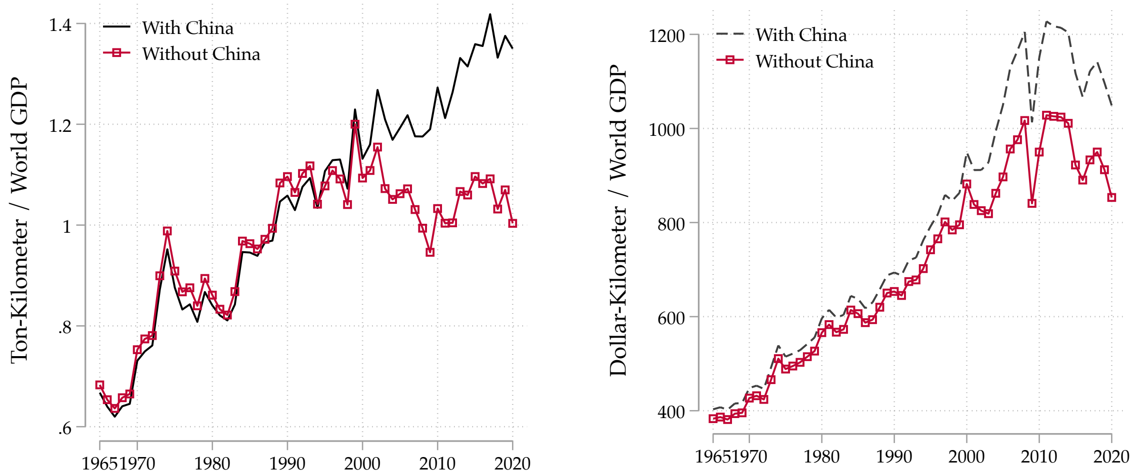
How do we rationalize these differential trends? Part of it represents China's growth trajectory. In 1990, input-output tables and trade statistics show China importing and exporting raw materials and other similar low-value, but high-weight products. These trends

[16] A fuller experiment would be to embed China in a model that simultaneously computes both trade flows, as well as transportation usages - as in Ganapati, Wong and Ziv (2021).

[17] Starting in the 1990s, China implemented a number of reforms as part of their economic transformation, see Brandt and Rawski (2008) and Feenstra and Wei (2010) for a review on the impact of these reforms.

Figure 4: The Role of Emerging Economies, Focusing on China, 1965-2020

(a) Transport Use by Weight and Distance (b) Transport Use by Value and Distance



Notes: The real transport use measured in ton-distance, indicated by the black line in Figure 4a, is reproduced from Figure 1c for comparison. The real transport use measured in ton-distance *excluding China*, indicated by the red line with squares in Figure 4a, is calculated by recomputing Equation (2) to exclude both incoming and outgoing trade in weight with China in the numerator, as well as excluding Chinese GDP from world GDP in the denominator. The real transport use measured in dollar-distance, indicated by the black line in Figure 4b, is reproduced from Figure 1d for comparison. The real transport use measured in dollar-distance *excluding China*, indicated by the red line with squares in Figure 4a is calculated by recomputing Equation (2) to exclude both incoming and outgoing trade in value with China in the numerator, as well as excluding Chinese GDP from world GDP in the denominator. See Figure 1 notes and the Data Appendix for further details.

continued unabated through the great recession, necessitating the use of more and more transport services; especially to and from China, which continued to grow. However, China also started exported and importing high-value, low-weight goods. Trade in these goods mirrored the rest of the world and leveled off following 2007. The collapse in trade values after 2007 is not a China-specific trend (Baldwin and Evenett, 2009; Eaton et al., 2016).

This echoes the fact that while trade in raw materials and natural resources is as strong as ever; especially as production requires geographically concentrated mineral supplies; the same doesn't seem to be true for higher value production. These items, which may be relative cheap (in terms of their value) to transport, may face changes in the proximity-concentration trade-off. Their production requires only capital and other raw materials. As it becomes cheaper for those raw materials to be imported, production locations may be more reflective of where final demand is located.[18]

[18] We also can decompose this by final and source trading partners for China to look at the role of China with trade with the US/EU and then with other developing countries. China's trade with other developing countries with under 15K/year in GDP per capita accounts for 52% of the weight-kilometers in 2020. In

4.2 Longer-Distance Trade

Next, we focus on the distance between countries and how it has contributed to the increase in transport usage. Most of the growth in real transport usage in weight is due to trade between countries that are further apart (longer-distance trade). Figure 5 breaks down our two metrics for real transportation usage from Figure 2 into three sub-components that total the aggregate figures. We consider transportation usage of shorter distance trade under 5,000 kilometers, medium distance trade from 5,000 to 10,000 kilometers, and very long distance trade over 10,000 kilometers. The short distance bin, within 5,000km, typically includes country pairs that are in the same region (for example, countries within the East Asia region, the European Union, or North America). The medium distance bin (5,000-10,000km) typically includes Asian-European countries while the long distance bin includes Asia-North America countries. As mentioned before, the transport use of all three distance bins add up to the aggregate transport use measure previously presented in Figure 2.

In 1965, all three distance bins account for rough similar amounts of transport usage (The bins in increasing distance accounted for 25%, 40% and 34% of the aggregate). However, since the mid-1980s, the transport use by countries that are further apart increases by much more than the short-distance countries. Overall, short-distance countries increases transport use in weight by 45% from 1965 to 2020, while longer-distance countries more than doubled their transport use—medium-distance countries increased by 114% and long-distance countries by 129%. Digging into the underlying data, much of the increase stems from raw material shipments, often originating from OPEC countries, Australia, and Brazil. These raw materials are often bound for processing and usage in distant locations, especially China—which helps explain the divergences in Figure 2 between the total tons shipped and the ton-kilometer metric of transportation usage.

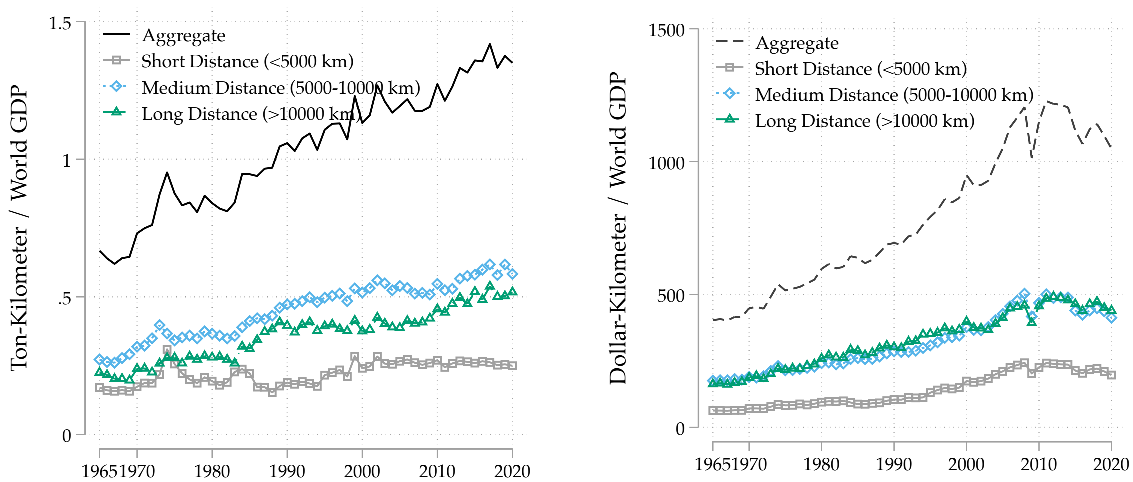
When considering the transportation usage in value, Figure 5b highlights a different story. There are large increases across all three distances from 1965-2020. Shipments for short-distances increased by 211%, medium-distances by 134%, and long-distances by 170%. The rough similarity of these trends highlights the near identical growth paths of trade value and transport use by value in Figure 2 over our entire time period (The bins in increasing distance in 1965 accounted for 16%, 44% and 40% of the aggregate. In 2020, the figures stood at 19%, 39%, and 42% respectively).

Taking stock of both Figures 5a and 5b, while heavier and lower value goods are being traded between countries that are further apart, lighter and higher value goods are being traded more to both locations that are nearby and far apart. This observation provides

contrast, Chinese trade in value with the same set of countries only accounts for 32% of dollar-miles

Figure 5: The Role of Longer Distance Trade, 1965-2020

(a) Transport Use by Weight and Distance (b) Transport Use by Value and Distance



Notes: The real transport use measured in ton-distance, indicated by the black line with circles in Figure 5a, is reproduced from Figure 1c for comparison. The remaining 3 lines in Figure 5a are calculated by breaking down the real transport use measure in weight into three sub-components that total the aggregate figures: transportation usage of shorter distance trade under 5,000 kilometers (gray line with squares), medium distance trade from 5,000 to 10,000 kilometers (blue line with diamonds), and very long distance trade over 10,000 kilometers (green line with triangles). The real transport use measured in dollar-distance, indicated by the black line with circles in Figure 5b, is reproduced from Figure 1d for comparison. The remaining 3 lines in Figure 5b are calculated by breaking down the real transport use measure in value into three sub-components that total the aggregate figures: transportation usage of shorter distance trade under 5,000 kilometers (gray line with squares), medium distance trade from 5,000 to 10,000 kilometers (blue line with diamonds), and very long distance trade over 10,000 kilometers (green line with triangles). See Figure 1 notes and the Data Appendix for further details.

interesting implications when considering that longer-distance trade can have more potential for transport disruptions and delays. Longer-distance trade often have to cross many more choke points, like the Suez and Panama Canals, as well as the Straits of Malacca and Hormutz. The obstruction of the Suez Canal for six days in March 2021, and its subsequent supply chain disruptions, serves as a illustrative example of how longer-distance trade can be more subjected these potential disruptions.

4.3 Composition of Trade

Emerging economies (such as China) and longer-distance trade have played a disproportionate role in contributing to the rise of transportation usage over the past 50 years, particularly for transport use measured in ton-kilometers. This raises the question of what these goods actually are—where are they on the value chain?

We study the how the composition of trade has contributed to transport use over this period in two ways, by highlighting (1) the role of final and intermediate good consumption (Figure 6), and (2) the role of raw materials and manufactured goods (Figure 7).

Final vs Intermediate Goods In Figure 6, we decompose Figure 2 into use for intermediate and final good consumption.[19] Similar to our decomposition in Section 4.2, the transport use of both types of goods add up to the aggregate transport use measure.

First, intermediate goods use accounts for the majority of transport use by weight, accounting for 85-90% of transport use over the whole time period (Figure 6a). We also find that the increase in transport use in ton-kilometers over this period primarily reflects growth in intermediate good consumption, which increased by 83% over this time span. Final good consumption transportation usage, starting at much lower levels, increased dramatically by 246% over this same period. This effect of this increase on overall transportation use is limited, as final goods today only account for 17% of transportation usage, and whose share has held steady since the early 2000s and fallen since 2010.

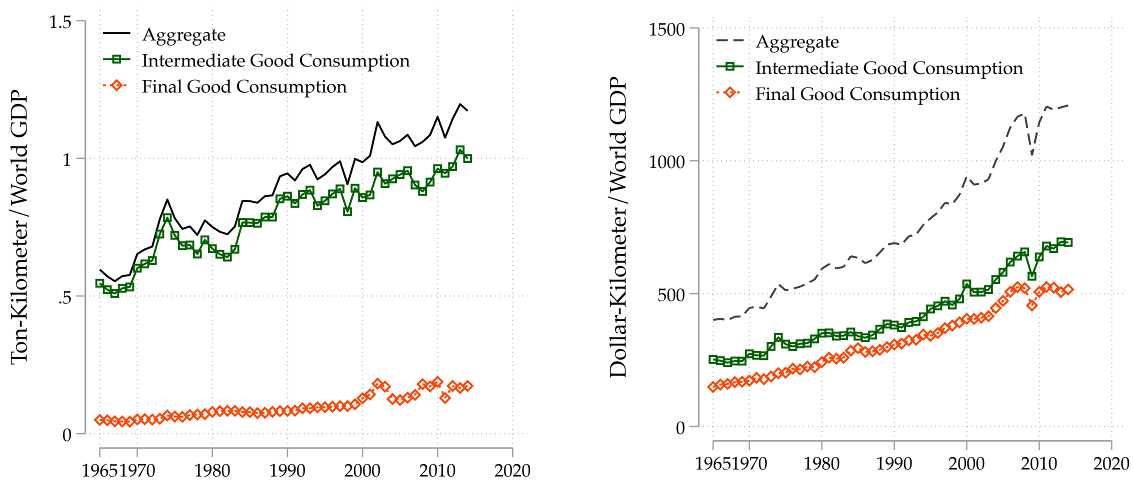
Figure 6b highlights the growth in transportation usage by value, broken down by final and intermediate goods consumption. The transport use of intermediate goods account for roughly 60% of aggregate transport use throughout this period, which is consistent with Johnson and Noguera (2012) finding that intermediate goods account for two-thirds of 2004 global trade in value. The transport use trends are initially in parallel for both intermediate and final goods, with final good transport usage increasing 246% and intermediate good transport usage rising 174%. However, since 2008, all growth has been in intermediate good usage, as the proportion accounted for by final goods has fallen since 2008. Our finding, that intermediate goods consumption has contributed to the large increase in transport use by value, is consistent with Hummels, Ishii and Yi (2001) who finds a 30 percent increase between 1970-1990 in the value of imported inputs used in producing exported goods for 10 OECD and four emerging market countries (three-fifths of world trade).[20] As final goods typically have higher value-added and the transport usage for final goods have increased by much more than intermediates up until 2008, our results are also broadly consistent with the negative correlation between distance and bilateral ratio of value added to gross exports in Johnson and Noguera (2017) from 1970-2009.

[19] This data ends in 2014, the last year of our WIOD global input-output database that allows us to separate final goods from intermediate good consumption.

[20] See Hillberry and Hummels (2008) for analysis considering only domestic US trade and intermediate goods.

Figure 6: THE ROLE OF FINAL VS INTERMEDIATE GOODS, 1965-2014

(a) Transport Use by Weight and Distance (b) Transport Use by Value and Distance



Notes: We end in 2014 due to data availability. The WIOD global input-output database ends in 2014 and we require I-O tables to separate final goods from intermediate good consumption. The real transport use measured in ton-distance, indicated by the black line with circles in Figure 6a, is reproduced from Figure 1c for comparison. The remaining two lines in Figure 6a are calculated by breaking down the real transport use measure in weight into two sub-components that total the aggregate figure: final and intermediate good consumption (green line with squares and yellow line with diamonds respectively). The real transport use measured in dollar-distance, indicated by the black line with circles in Figure 6b, is reproduced from Figure 1d for comparison. The remaining two lines in Figure 6b are calculated by breaking down the real transport use measure in value into two sub-components that total the aggregate figure: final and intermediate good consumption (green line with squares and yellow line with diamonds respectively). See Figure 1 notes and the Data Appendix for further details.

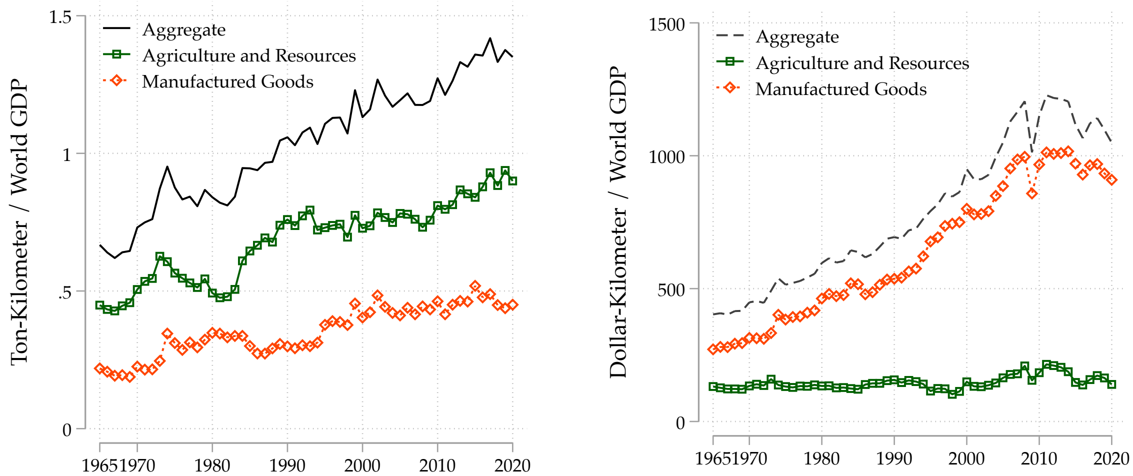
Raw Materials vs Manufactured Goods The distinction between intermediate and final goods can be ambiguous, so as an alternative we consider goods that are "raw materials", agricultural and natural resource products (ISIC categories A and B), from manufactured products. Similar to our final goods decomposition, the transport use of both raw materials and all other goods add up to the aggregate transport use measure.

Figure 7a shows the role played in weight-based measures of transportation usage. While raw materials make up a higher share of aggregate transport use by weight throughout this period (accounting for 66% of the weight-distance measure in 2020), both raw materials and manufactured goods equally contributed to the growth from 1965 to the early 2000s, especially as refined petroleum and mineral products have high weights and low values. However since 2000, manufactured goods no longer contribute to the growth in ton-kilometers compared to the growth of the global economy, all growth is due to natural resources.

Considering the value-distance of shipped goods in Figure 7b, the increase in transport use by value over this period is entirely driven by manufactured goods, who account for 87%

Figure 7: The Role of Natural Resources vs Manufactured Goods, 1965-2020

(a) Transport Use by Weight and Distance (b) Transport Use by Value and Distance



Notes: The real transport use measured in ton-distance, indicated by the black line with circles in Figure 7a, is reproduced from Figure 1c for comparison. The remaining two lines in Figure 7a are calculated by breaking down the real transport use measure in weight into two sub-components that total the aggregate figure: agricultural and natural resource products (ISIC categories A and B, green line with squares), and manufactured products (orange line with diamonds). The real transport use measured in dollar-distance, indicated by the black line with circles in Figure 7b, is reproduced from Figure 1d for comparison. The remaining two lines in Figure 7b are calculated by breaking down the real transport use measure in value into two sub-components that total the aggregate figure: agricultural and natural resource products (ISIC categories A and B, green line with squares), and manufactured products (orange line with diamonds). See Figure 1 notes and the Data Appendix for further details.

of all dollar-distance in 2020. This is a dramatic increase from 1965 when manufactured goods only accounted for 67% of all dollar-distance in 1965. While manufactured good transportation use in value grew 135%, natural resource use grew just 6%. While raw materials are a required input in much of economic production, reflected by their dominance of transportation usage in ton-kilometers, they constitute a smaller and smaller share of total trade values.

The manufactured goods driving the transport use by weight growth in Figure 7a are very different from the goods driving the transport use by value growth (Figure 7b). Delving into the underlying data, lower value-to-weight manufactured goods like chemicals and refined petroleum products and base metals drive Figure 7a, while Figure 7b is driven by higher value-to-weight manufactured goods like electronics and automobiles.

Our finding that raw materials dominate the transport use growth by weight, but not the transport use growth by value is consistent with Fally and Sayre (2018). While primary commodities—intensive in natural resources, which is captured in our raw material goods—only account for a modest 16 percent of world trade by value, they show that these commodities are used as inputs into all production processes, are difficult to find substitutes for, and can be supplied by only a few countries. As the world economy grows, it makes sense that these raw materials would be shipped further and further distances since they are import inputs into all production processes and can only be supplied by a few countries. Our finding is also consistent with Berthelon and Freund (2008) who employs a gravity equation framework and finds that homogeneous and bulky goods have become significantly more distance sensitive between 1985-2005 (increase in their elasticity of trade to distance).[21] As trade costs fall, Antràs and De Gortari (2020) shows that it is optimal to locate downstream production to final good consumers, while it is less important for upstream production. This logic is echoed in the trend of upstream production traveling further in the last decade, while downstream production's transportation usage fell.

Having decomposed the drivers of increased transportation usage, we now turn to both the drivers of the increases and their supply chain implications.

5 Innovations and Implications for Supply Chains

We have established two main results so far. First, transport use has increased while transport costs have decreased over the past 50 years—the amount of transportation services used is an equilibrium response to how costly transportation is. Second, this increased demand for transportation is driven by emerging economies like China participating in world trade, longer-distance trade between countries that are further apart, and differences at where products lie along the value chain. Each of these factors can contribute to global supply chains and further drive demand for transportation services. There are important distinctions in transport use trends when comparing them to conventional trade statistics. This dichotomy can speak both to how transportation and trade interact, and has implications for global supply chains.

In this section, we consider a number of transport technology and infrastructure changes over the last 50 years that have affected the mechanics of global trade and contributed to our findings. Many of these technologies require large investments, differentially affect parts of value chains, and result in endogenous transportation costs responses. We conclude by highlighting one particular innovation that is the result of the interactions of the technological advances—"Just in Time" manufacturing—and how it too interacts with supply chains.

[21] Raw materials are more likely to be homogeneous and bulky (lower value-to-weight ratio).

5.1 Transport Technology and Infrastructure Innovations

Global trade is conducted using land, sea, and air; all of which have had improvements in the last 50 years. Transport costs have fallen, but unequally across modes (Hummels, 2007; Ardelean et al., 2022). In particular, two technologies have exhibited extraordinary cost decreases; containerized and air freight.[22] Both of these technologies may exhibit scale economies, but they only interact with subset of traded goods that have relatively higher values and lower weights/volumes compared those used to ship upstream raw materials. Furthermore, better computing technology and efficiency in logistics allows companies to coordinate large volumes of shipments and to offer door-to-door freight delivery services. The trade and transport networks, as a result of these technological improvements, further connects ports, countries, and production processes. Transportation infrastructure improvements that increase efficiencies of these networks can generate even larger effects.

There is an extensive literature that indirectly looks at the impacts of transport costs on various economic outcomes (see Redding and Turner (2015), for a recent survey, which also shows how the spatial literature accounts for endogenous transportation costs). Domestic trade costs have also received substantial attention (see Glaeser and Kohlhase (2003) considering the decoupling of domestic freight and passenger costs and Coşar (2022) for a review on the overland transport cost literature). Our aim is to look at the drivers of changes in these international transport costs over the last five decades and their implications up and down supply chains.

Containerization Many of the differences in trends between weight-based and distance-based measures come down to a particular new technology, containerization of both land- and sea-based transportation. Containerization refers to the standardization of a 40-foot long reusable steel box that can be loaded onto purpose-built trains, trucks, and ships; easily transferring between the various modes required to get from origin to destination.

Modern, container technology was introduced in 1956, triggering complementary technological and logistical innovations that has revolutionized the transport industry and international trade (Bernhofen, El-Sahli and Kneller, 2016; Levinson, 2016). Without containerization, the globalization of production would not have been possible (UNCTAD, 2022). Examples of complementary technological innovations include the creation of the modern intermodal transport system, shipping capacity increases through larger ships, and delivery time reductions through intermodal cargo movements between ships, trains and trucks. While the first user of containerization is the United States, almost 90 percent of countries

[22] Hummels (2007) documents that the cost of air transport fell more than 10 times between 1955-2004 (Figure 1), and the container price index declined between 1985-2004 (Figure 4).

had built container-handling infrastructure at their ports by 1983 (Rua, 2014).

The nature of containerization implies high fixed costs and minimal marginal costs as highlighted by Coşar and Demir (2018). Since container cost is typically per-unit, Hummels and Skiba (2004) shows per-unit transactions cost lowers the relative price of, and raises the relative demand for, high-quality goods with higher unit values. Containerization also makes it easier for multimodal transportation to take place—it's much easier to have a crane move a container from ship to rail or truck at intermodal terminals like ports (Fuchs and Wong, 2022). While containerization increases local economic activity (Brooks, Gendron-Carrier and Rua, 2021), there can be a crowding out effect from container seaport development since they require large swaths of land (Ducruet et al., 2020).

Air Transport Our period of study starts at the beginning of the Jet Age and continues through the development of air freight as both an independent industry, as well as a complement to passenger travel (Proctor, Machat and Kodera, 2010).[23]

Reliable and frequent air transport networks have made it especially easy to coordinate the production of sensitive high-value products across global transport chains. Hummels and Schaur (2013) highlights how time is a valued characteristic of trade. Increased air connectivity have positive impacts on local economic activity including population and income (Blonigen and Cristea, 2015; Feyrer, 2019), industrial activity (Redding, Sturm and Wolf, 2011), as well as business links and the movement of capital (Campante and Yanagizawa-Drott, 2018). Additionally, it can have indirect positive effects on trade (Cristea, 2011; Poole, 2016; Yilmazkuday and Yilmazkuday, 2017). Air transport can also be employed to smooth demand volatility due to its faster speed (Hummels and Schaur, 2010).

Interaction between Transport Modes and Supply Chains Focusing on these two major technological changes, we revisit our main results and highlight their implications for the global supply chains. First we start by asking: what kinds of goods are transported by containers and air, and where are they on the supply chain?

Looking just at US trade imports of NAFTA in 2019, containerized vessels account 45% of value and 29% of weight (Census Bureau). Air accounts for 38% of value but less than 1% of weight, while bulk shipments account for 18% value but 71% of weight.[24] Between these

[23] Passenger travel time decreased by 29% on average between 1951-1966, with much larger decreases for airports that are further apart—41% for airports more than 2000km apart (Pauly and Stipanicic, 2021). Using the start of the Jet Age and patent citations, they find that the decreased air travel time between locations increases knowledge diffusion and creation.

[24] Similar patterns hold for 2019 US exports outside of NAFTA: containerized vessels account for 26% of export value and 16% of export weight, air account for 46% of exports by value but less than half a percent by weight, and bulk exports are 28% of export value but 84% of export weight.

three modes of transport, goods that travel by air have the highest value-to-weight ratio, followed by containers, and then bulk shipments.[25]

As goods move down the supply chain, their value-to-weight ratio rapidly changes.[26] Bringing back our earlier example, a smartphone may require tons of coal and oil to generate electricity, bauxite to create aluminum enclosures, lithium ore for batteries, and sand to make silicon. These raw materials have very low value-to-weight ratios and are transported via bulk shipping. Once assembled, however, a smartphone, even including packaging, may be under 250 grams and take up less than a liter of volume. This final product has a much higher value-to-weight ratio and is often transported via air instead.

As such, the technological improvements from containerization and air transport have revolutionized the shipment of high-value final goods and downstream manufactured products, but have minimal impact on the trade of raw materials and upstream manufactured products which rely heavily on bulk and pipeline transport. Revisiting Figure 3 helps put this into context. Trade costs using dollars have fallen between 50-60% over our time period, while trade costs using physical weight has only fallen 35-45%. This suggests that technological innovations have decreased trade costs disproportionately for higher value goods far down the value chain; but not as much for goods further upstream. These technological improvements have heterogeneous impacts across the value chain. It is important to take this into account when trying to understand the impacts from these innovations on the interaction between transportation and supply chains.[27]

Since containerized and airborne shipments have higher value-to-weight ratios, we see the impact of these innovations on value-based transport use and trade. Both the transport use in dollar and trade value grew dramatically over the past 50 years, indicating that goods are being transported more to both nearby and distant locations (Figure 2). Furthermore, transport use from final goods more than doubled (Figure 6b) and downstream manufactured goods (compared to raw materials) contributed disproportionally to transport use growth (Figure 7b). These innovations have an outsized impact on goods with higher value-to-weight

[25] We omit discussion of pipelines versus tankers, but not that pipelines are offer substantially cheaper shipping, but are only built in response to high expected usage.

[26] This is directly seen in aggregate trade data correlating measures of upstreamness with unit values

[27] In related literature, Shapiro (2021) looks at another component of trade cost, tariffs and non-tariff barriers, finding that barriers are lower on dirty and more upstream industries—that are heavier with lower value-to-weight ratios—relative to clean and more downstream industries. Blanchard, Bown and Johnson (2017) also finds that governments set lower bilateral tariffs where global value chain linkages are the strongest. Our finding also echoes papers highlighting the important interaction between transportation and the environment when considering policy changes. Cristea et al. (2013) finds that elimination of tariff preferences between nearby trading partners will increase trade from partners further away, proportionally increasing air transport use and greenhouse gas emissions. Lugovskyy, Skiba and Terner (2022) finds that a proposed regulation to cap emissions from maritime shipping can incentivize a subset of goods to be transported by air instead, increasing overall emissions and overturning the initial goal of the regulation.

ratio that are more downstream.

In contrast, the transport use by weight is driven by bulk transportation for heavy goods with lower value-to-weight ratios. As these innovations have made it easier to transport goods that are more downstream, upstream supply chains will also be impacted. Raw materials are required for downstream production, and the data shows that they are travelling further, even if their total shipments in weight are unchanged (Figure 2). Even though final good shipments are becoming relatively cheaper, we shipping raw materials further. Figure 7a further reinforces this point by showing that raw materials make up a higher aggregate share of transport use by weight over the past 50 years, and in the last 2 decades contributes to all of the increase in transport use by weight.[28]

Looking only at oceanic shipping, this is echoed in the relative breakdown of the global shipping fleet. Ships that only carry bulk goods, including agriculture, natural resources, and refined petroleum products, account for 75% of the global shipping fleet by tonnage. Container ships—the ships that carry significant amount of consumer goods—only account for 13.2% of the global shipping. In tons loaded—containers account for less than 2 million tons laded—out of more than 10 million tons (UNCTAD-Clarksons Research 2021).

5.2 Endogenous Transportation Costs

As discussed earlier, transport costs are equilibrium outcomes jointly determined with trade and transport. While not comprehensive, we highlight a series of broad topics that capture the forces that can affect trade costs, often creating network effects, feedback loops, and endogenous investment to lower transport costs.

Scale Economies Scale economies imply that as volume increases, trade cost fall. This can create a feedback loop (either internal or external to a firm), further lowering trade costs. One critical area with visible natural scale economies has been in containership technology, which we highlight.

There has been a significant increase in the size of containerships over the years (Cullinane and Khanna, 2000). While the total containerized fleet capacity increased 8 times between 1996-2021, the number of containerships only increased by 3 times—this large size increase is concentrated among a smaller number of ships (Ardelean et al., 2022). Since crew size and fuel costs does not increase proportionally with ship sizes, larger ships can take advantage of the cost savings from its larger capacity and are more profitable.[29] The first containerships

[28] Intermediate goods also drive almost all of this increase (85-95%, Figure 6a).

[29] The CEO of container shipping firm Maersk explained in 2013 that their decision to build larger ships, like the Maersk Triple-E ships with capacities of 18,000 TEUs, is "primarily a cost-saving initiative" (Milne,

were modified bulk vessels or tankers since converting existing ships were cheaper and less risky as the container technology was still not widely adopted. Capacities were about 500-800 TEUs. By the start of the 1970s, the first fully cellular containerships dedicated to transporting containers were introduced. These containerships had 2-4 times the capacities of the converted containerships (Rodrigue, 2020). By the end of our sample period in 2015, the largest containership that was built that year has a capacity that is at least 24 times the size of the first containerships—19,000 TEUs and nearly as big as four football fields laid end-to-end.[30]

Outside container shipping, scale economies also play a crucial role in other aspects of transport logistics including distribution networks (Holmes and Singer, 2018; Ganapati, 2018). However, it isn't clear that all aspects of the trade network have the same level of either scale economies or their inverse—congestion effects (see Allen and Arkolakis (2022) in a domestic context Fajgelbaum and Schaal (2020) with labor mobility and Redding and Turner (2015) for context in an urban economics setting).

Related to scale economies is the discussion of market power. Larger markets induce entry, driving down markups and prices, even if costs are constant (Bresnahan and Reiss, 1991; Berry and Reiss, 2007). As absolute demand for transportation services increases, entry can further amplify the affect at entrants help discipline costs. In transportation, Hummels, Lugovskyy and Skiba (2009) and Asturias (2020) show large effects of market entry on reducing prices in international shipping. Ignatenko (2021) and Ardelean and Lugovskyy (2020) considers the effects on price discrimination. In domestic distribution, Atkin and Donaldson (2015) and Ganapati (2018) also find large market size effects. More entrants and competition leads to lower prices. These effects are also related to the next area with potential endogenous transport costs, when the network itself underlying trade is related to demand for trade.

Transport and Trade Networks Interdependencies in transportation technologies create networks which further links locations, above and beyond their trade and supply chain relationships. Largely driven by scale economies in container shipping, the container trade network is a hub and spoke system where majority of trade is shipped indirectly—the median shipment to the United States stops at two additional countries before its destination (Ganapati, Wong and Ziv, 2021). Bulk shippers transport goods directly but have to search

2013). Fuel costs for these ships are about \$300 to \$400 lower per container for a round trip between Asia and Europe which, once multiplied with its capacity of 18,000 TEUs, come up to a substantial \$5-\$7 million.

[30] As an example, MSC Oscar is the largest ship built at the start of 2015 with a capacity of 19,000 TEUs. To put the capacity of this ship in perspective, it can carry 39,000 cars, 117 million pairs of sneakers, or more than 900 million cans of dog food (Stromberg, 2015).

for loading opportunities after delivering their cargo, generating network effects between neighboring countries (Brancaccio, Kalouptsidi and Papageorgiou, 2020). Improving access within these networks, like the 2016 Panama Canal expansion, can generate large trade returns (Heiland et al., 2019).

This connection between countries also arises from round-tripping—containerships, trucks, and air transport have fixed schedules like buses going back and forth between large trading partners in a round trip. This introduces joint transportation costs which links transport supply between locations (Wong, 2022). In the case of imbalance trade routes, this is known as the backhaul problem. This logistic feature of round-tripping can shape the location of economic activity in the presence of agglomeration (Behrens and Picard, 2011) and create backfiring effects from protectionist import tariffs (Ishikawa and Tarui, 2018; Hayakawa, Ishikawa and Tarui, 2020; Wong, 2022), particularly in the case of imbalanced trade (Jonkeren et al., 2011; Tanaka and Tsubota, 2016; Friedt and Wilson, 2018).

These network effects in transportation means that benefits from technological innovations or infrastructure improvements can be amplified even further through endogenous transport costs, or that local disruptions could have a much larger effect.

Trade Facilitation: Logistics Management Technology and Door-to-Door Freight Forwarding Trade facilitation generally includes policies that lower administrative barriers to trade by primarily streamlining administrative processes, like filing of shipment documents at border crossings, which in turn decreases the management cost of supply chains (see Carballo, Schaur and Martincus (2018) for a review on the trade facilitation literature). While explicit trade costs in terms of freight are well established, Head and Mayer (2013) point out that estimates from Feyrer (2021) and Allen (2014) imply that 50%-90% of trade costs that are associated with distance travelled are unobserved—suggesting that the returns to trade facilitation improvements can be large. However, the logistics and transportation industry has many examples that highlight some of these costs that economists view as “missing". We highlight two, one involving logistic management technology and second the paid services of freight forwarders.

While logistics were initially applied to military operations, its most significant impact is on production, distribution, and consumption (see Talley and Riggs (2018) for an overview of the logistics of international trade and Hesse and Rodrigue (2004) for an overview of the literature on logistics and freight distribution). Better computing technology and efficiency in logistics allows companies to coordinate large volumes of shipments to different locations, port authorities to manage these shipments through their ports, or shipping carriers keep better track of containers on their ships. One example of this is the introduction of the cargo booking documents systems INTTRA which was introduced in the early 2000s (Talley and Riggs, 2018). It allows non-vessel owning carriers and freight forwarders to book cargo on ships, as well as access voyage schedules. Another example is the introduction of the Society for Worldwide Interbank Financial Telecommunication (SWIFT) messaging system in the 1970s which allows for efficient and secure transfer of funds by banks between importers, exporters, and transportation intermediaries, lowering their financial transaction costs.

Transportation intermediaries like freight forwarders are responsible for cargo pickup, documentation, transport, and delivery from the beginning to the end of the value chain (see Blum, Claro and Horstmann (2018) for an overview of on the literature on intermediaries and trade costs). They pick up the container holding the goods from the exporter, transports it to the port, do all the necessary paperwork, coordinate with a ship carrier for transport to the port of destination, and eventually delivers it to the address of the importer. Previously, a trader would have to deal with coordinating their own transport from origin to origin port, a ship carrier from origin port to destination port, customs officials to clear their goods,[31] then transport from destination port to destination. With a freight forwarder, they only have to interface with one company. Container technology has contributed to the growth of freight forwarders and large-scale services were offered starting in the early 1970s (UNCTAD, 2018). By 2018, major container shipping lines who only provide port-to-port service have largely disappeared from the market. Such middlemen roles are not new, and in other settings they are instrumental in facilitating trade especially to more remote consumers and markets (Atkin and Donaldson, 2015; Ahn, Khandelwal and Wei, 2011; Ganapati, 2018; Startz, 2016; Grant and Startz, 2022).

With research showing how firms make forward-looking export decisions (Morales, Sheu and Zahler, 2019), the interaction of these choices with either relationship-specific capital or sunk costs in freight forwarders and logistics technologies may act in way to amplify trade effects.

Transportation Infrastructure In addition to trade policy changes, policy makers can invest in transportation infrastructure to directly improve access to trade. The quality of transport infrastructure has been shown to be directly proportional to transport costs (Limao and Venables, 2001), and port efficiency can play a major role in facilitating trade flows (Clark, Dollar and Micco, 2004; Blonigen and Wilson, 2008; Feenstra and Ma, 2014; Blonigen and Wilson, 2018). Such endogenous investments, like railroad networks, pipelines, and high-capacity expressways, can have large benefits and result in direct decreases on transport costs (Coşar and Demir, 2016; Donaldson, 2018; Fan, Lu and Luo, 2019; Asturias, García-Santana

[31] Processing times can be very costly as highlighted by Carballo et al. (2021*b*).

and Ramos, 2019). As transport use continue to rise and trade between countries that are further apart continue to grow (Figure 5), transport infrastructure investments play a increasingly important role in facilitating this expansion.

A newer set of papers consider transportation infrastructure with endogenous transportation costs and investment. In road networks Fajgelbaum and Schaal (2020) and Allen and Arkolakis (2022) highlight how congestion endogenously determine transportation costs and characterize methods to recover costs and determine optimal investments. These investments shape the nature of production and supply chains. Subsequent work extend these framework to include two or more transport networks with transport mode and route choices (Fan, Lu and Luo, 2019; Jaworski, Kitchens and Nigai, 2020; Fuchs and Wong, 2022). In the case of emerging economies, such infrastructure improvements could have even larger welfare impacts (Asturias, García-Santana and Ramos, 2019; Bonadio, 2021; Carballo et al., 2021*a*).

5.3 Just-in-time production and inventory system

We now highlight the mechanism of one of the examples above–Just-in-time deliveries (JIT) (also called lean manufacturing). The JIT system is a strategy that aligns input orders from suppliers directly with production schedules, so that the inputs are received only as needed for the production process. The JIT system have resulted in smaller, more frequent shipments to reduce warehousing costs at the receivers' end. This, in turn, has increased demands on shipment costs and reliability to ensure the uninterrupted implementation of planned production processes. At the same time, JIT has led to a changing relationship between transport and warehousing costs (most famously and well documented in the case of Toyota, which significantly reduced warehouse and inventory costs).[32] As this system is adopted by more and more businesses, the need to hold inventory on-site decreases. We start by establishing this trend for the US.

Figure 8 reports the inventory to sales ratio trends from the Census Bureau.[33] This ratio measures the amount of inventory that businesses hold relative to their sales. A higher ratio indicates that businesses hold more merchandise relative to their sales in a period. Figure 8a reports this ratio for the manufacturing, which is the longest publicly available time series

[32] Toyota Production System: achieving the complete elimination of all waste in pursuit of the most efficient methods, and Moore, Scott "A Profile of Toyota's Production System", Harvard Business School Case Study W90C18-PDF-ENG

[33] The Census Bureau reports this data based on three surveys: the Manufacturers' Shipments, Inventories, and Orders Survey, the Monthly Wholesale Trade Survey, and the Monthly Retail Trade Survey. More recent data, from 1992 onward, is based on the North American Industry Classification System (NAICS) while historic data was based on the Standard Industrial Classification (SIC) codes. The SIC was phased out in 1997 by US statistical agencies. See (Fort and Klimek, 2018) for a discussion on the how the classification change impacted the measurement of US economic activity.

from January 1958 onwards.

The average manufacturing inventory to sales ratio was around 1.7 before 1990. Since then, there has been steady decrease in the amount of inventory that businesses hold—the average ratio is about 1.3 between 2000-2019. This is an average decrease of about 24 percent.[34] We do note that the manufacturing industry is shrinking as a share of GDP over this period—its value added share of GDP was 25% in 1960 (BEA) and by 2019 it was about 11% (BEA).

Figure 8b reports this ratio for the retail industry, where there is more muted but similar downward trend. The average was around 1.7 before 1990 and it decreased to about 1.5 between 2000-2019. An 11 percent decrease. The value added of the retail industry accounted for 6.8% of GDP in 1981 (BEA). There are similar declines using the total series reported by the Census (Figure 8c).

As an alternative, we look into estimates of logistics expenditures broken into inventory or warehouse spending, and transport spending from the Council of Supply Chain Management Professionals (CSCMP).[35] The inventory or warehouse spending estimates, as a percent of GDP, are similar in magnitude to transport in 1980 (around 7.6% and 7.4% respectively as seen in Appendix Figure A1). While both the Census and CSCMP inventory decreases have decreased, the decrease in CSCMP inventory costs is much sharper at 67%.[36]

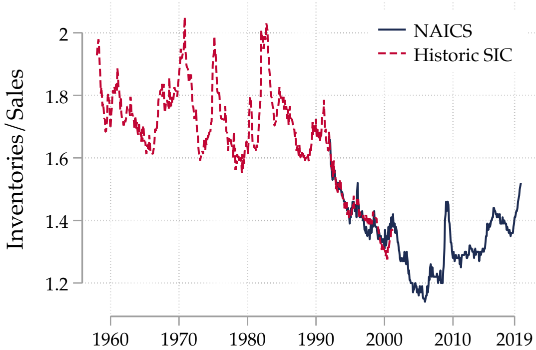
Transport costs have not just fallen, but they are endogenous in multiple ways; scale economies play a role; as more countries trade, matching friction decrease, competition on providers increases, and feedback loops abound. Simultaneously countries can invest in infrastructure and technologies and firms can invest in production and transportation technologies. Production technologies can change in a way that reduces dependence on inventory costs, substituting them with transportation usage. With this all in mind, we turn to considering a set of issues involving the interaction of global value chains and the transportation network.

[34] Focusing on 2008-2010 at the height of the trade collapse, Alessandria, Kaboski and Midrigan (2011) shows that firm inventory holdings are much higher in response to persistent negative shocks. For developing countries, the cost of trade is much larger and inventory can serve as a buffer for these costs (Alessandria, Kaboski and Midrigan, 2010). Carreras-Valle (2021) studies the recent reversal of the declining trend in the manufacturing industry since 2005 and how much of it can be attributed to the longer delivery times and delays from sourcing foreign inputs that are further away.

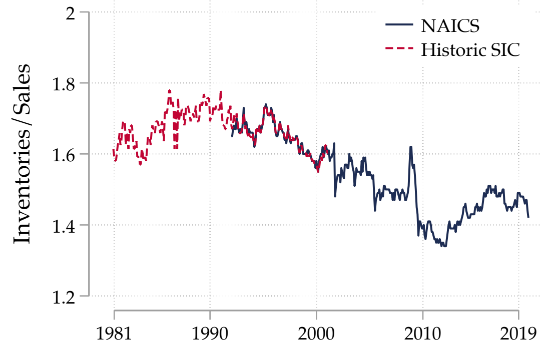
[35] See Federal Highway Administration (2005) for discussion on the estimates.

[36] Domestic transport spending also decreased but by a smaller rate 32%.

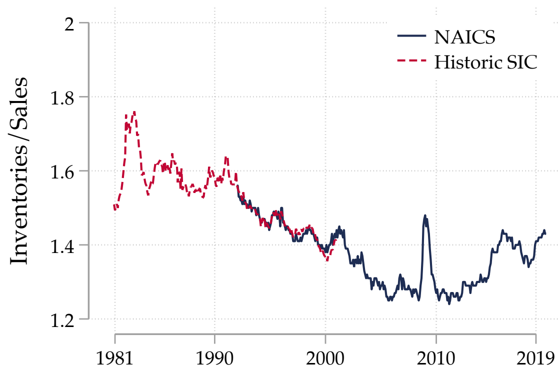
Figure 8: Inventory to Sales Ratio



(a) Manufacturing, 1958-2019



(b) Retail, 1981-2019



(c) Total, 1981-2019

Note: The historic SIC data is normalized relative to the recent NAICS data. NAICS data for all three panels is from the Manufacturing & Trade Inventories and Sales data page. In Figure 8a, historic SIC data for Manufacturing is from the Census Manufacturing Branch under the Historical Time Series. In Figure 8b, historic SIC data for Retail is from the Census Retail Indicator Branch under the Historical Data section. In Figure 8c, the historic SIC series is constructed using the historic manufacturing, retail, and wholesale data. Historic SIC data for Wholesale is from the Wholesale Indicator Branch under the Time Series Data (Prior to NAICS) section. The shorter time period in retail and total series is due to lack of digitized data on the Census Bureau website. See Data Appendix for further details.

6 Going Forward: Resiliency and Vulnerabilities

We now consider the factors contributing to resiliency and vulnerability in transportation networks and their implications for supply chains, both today and in context of changes over the last 50 years.

Resiliency and Vulnerability Factors What are the features of transportation networks that lend themselves to either resiliency and/or vulnerability? In particular, how does the trade network interact with the transport network to either propagate or dampen shocks? We highlight a series of characteristics at the intersection of transportation and supply chains that warrant further investigation:

- **Longer Distance Trade** Goods are transported over increasingly longer distances (Figure 5), often travelling indirectly to their destination, which further lengthens their trips. Longer shipment distances are mechanically more vulnerable to transportation disruptions since potential shocks can affect more locations. On top of this, there is a second level of risk: disruptions to transport networks can propagate through the network and spillover to non-directly affected countries.

- **More Diverse Production Locations** Even though the share of the world economy dedicated to physical goods is falling (see Appendix Figure A2), the importance of the transportation sector has stayed constant over the past 50 years (Figure 3b). As manufactured goods production becomes increasingly fragmented and moves to lower cost/efficient production locations (Figure 4), such production necessarily relies on a larger and larger proportion of transportation services.

  Goods along the value chain are being produced by more diverse sets of countries, and these countries are further apart. Disruptions of transport at any of these locations would affect production of these goods, potentially distorting downstream markets depending on substitutability among locations.

- **Goods Composition Along Value Chains** Different types of goods, depending on their positions in the value chains, are being transported different distances. While final goods consumption may appear to be closer to home and less risky due to less exposure, they still require upstream inputs in their production and the riskier upstream would increase their exposure. Their ultimate reliance on trade and transport requires analysis of the entire value chain and alternatives. While air transport may be considered to have a lower risk in terms of time delays, compared to ocean shipping through the Suez Canal, air goods are produced using goods that are shipped by ocean and may be ultimately exposed to the ocean disruption as well.

The resiliency of modern supply chains and networks is a growing area of research, especially in the context of shocks in production. There is a tradition of considering disasters shocks on a variety of macroeconomic and microeconomic outcomes (Barro, 2006; Hendricks and Singhal, 2005; Boustan, Kahn and Rhode, 2012).

We focus on the related study of shocks that look at transportation and production along supply and value chains. This encompasses a wide set of potentially issues. They may be trade policy-related (Brexit or sanctions on Russia), or global events that directly affect production and transportation (natural disasters or climate-change-related). There are a series of paper that study these shocks independently, for example Boehm, Flaaen and

Pandalai-Nayar (2019) considers the role played by earthquakes and how shocks propagate upstream, and Feyrer (2021) looks at the closure of the Suez canal on aggregate trade flows.

However, we want to focus on the intersection of the two, how do transportation shocks interact with the supply chain? Khanna, Morales and Pandalai-Nayar (2022) looks at manufacturers during COVID-lockdowns and highlights the role of multiple sourcing. Besedeš and Murshid (2019) study the impact of the eruption of the Icelandic volcano Eyjafjallajökull that closed European air space. The role played by European airports in facilitating global connectivity meant that the disruption to European airspace had far-reaching effects that affected inter-regional travel between non-European destinations.

Allowing for scale and congestion effects in transportation technology and endogenous development of infrastructure can either amplify or dampen the effects of both transportation and non-transportation trade shocks. But, much more work needs to be done here. While papers such as Fajgelbaum and Schaal (2020); Allen and Arkolakis (2022); Ganapati, Wong and Ziv (2021); Brancaccio, Kalouptsidi and Papageorgiou (2020) consider endogenous responses of transportation costs to shocks, they are highly limited to looking at just fragments of both the transportation network and the value chain; none of the papers can integrate the upstream and downstream effects across modes of transport.

Such effects may be instrumental in searching for the the "bullwhip" effect (Fransoo and Wouters, 2000; Lee, Padmanabhan and Whang, 1997; Cachon, Randall and Schmidt, 2007), where small perturbations upstream in a production chain are amplified downstream and become major issues. This may interact with the potential variation in production functions downstream and upstream. Upstream production may use input products with a limited set of globally dispersed substitutes, while downstream may face different many alternative, but geographically concentrated substitutes. This result in uneven effects of disruptions.

Transportation networks are not only longer today, but they also feature round-trip and hub-and-spoke networks. Container, cargo air, and truck transport go back and forth between fixed locations on round trips (like buses). With these fixed schedules routes, any disruption on one part of their route can affect the entire round trip (Swanson, 2021). A disruption to one leg of a trip, not only affects goods on that leg, but can cascade throughout the network. The same containership that transits the Suez canal going from Spain to Singapore, continues onward to Shanghai and Seoul. Additionally, larger and larger ships are built to take advantage of the per unit cost savings. These large ships concentrate the hub and spoke system further, and utilize the multimodal transport network more, resulting in further international links between countries which spills over into domestic intranational links between cities or regions as well.

Similarly, disruptions or congestion to one mode of transport can have spillover effects to other modes of transport (Berger, 2022), although these networks may have resilience built in through the existence of potentially multiple equilibrium. In the long run, transportation networks (as opposed to just the trade network) can reorient and affect the winner and losers from trade (see Fujita and Ogawa (1982) in an Urban Economics context).

Many of these issues are illustrated in the following case study. While JIT is extremely efficient and can save on inventory expenditure, unexpected events can paralyze entire production networks. The vulnerability of Toyota's supply chains was exposed in February 1997 due to a fire a Japanese-owned parts supplier Aisin. Because Aisin was the sole supplier of a crucial break valve for all Toyota's vehicles and the JIT system meant that only one day's worth of valves was in immediate stock, this fire caused a ripple effect which shut down the entire Toyota production for almost a week (Nishiguchi and Beaudet, 1998).[37] Most Toyota assembly plants at the time only kept a hold only 2-3 days' worth of stocks at hand. All assembly plants took about 2 weeks before getting back up to full production and the fire cost Toyota about 160 billion yen in revenue. While this incident could potentially highlight that JIT leaves firm production networks extremely vulnerable to unexpected shocks, Toyota and other firms interviewed by Nishiguchi and Beaudet (1998) did not consider abandoning JIT due to the expense of holding large inventories for each component. Instead, Toyota focused on developing flexibility within their firm in order to better response to future issues like this.

Trends Going Forward A related question is whether transportation networks are more or less resilient and/or vulnerable to disruptions today compared to 50 years ago. Simply put, more goods are traded to further locations, consumers are more globally distributed, but there may be more production sources. But long run trends are clouded by changes in not just transportation, but also production and consumer preferences, as well as the frequency and magnitude of disruptions.

For example, the Suez canal has been a perennial flashpoint, first connecting the British and French colonial empires, then serving as an essential oil conduit, to today forming the backbone of Asia-Europe trade. Is this link more vulnerable today? More generally, are supply chains today more or less vulnerable? Mechanically it would appear to be so, as goods increasingly transit many choke points as well as production locations. Figure 5 highlights increasingly longer distance travel, which mechanically may mean that trade is more vulnerable especially as it is infeasible to ship oil via air (Figure 7). However, little research has touched on long run trends here and little is known concretely.

[37] Nishiguchi and Beaudet (1998) details how Toyota's collaborative response, in the presence of JIT system, helped mitigate the ultimate fallout from the fire crisis

A recent turn to protectionism in parts of the world (Fajgelbaum et al., 2020) is fighting against continued improvements in transportation costs. But transportation and value chain linkages can work towards continued openness (Blanchard, Bown and Johnson, 2017). The study of protectionism and transport also interact with market power and market access, of which we know very little of.[38]

7 Conclusion

Countries, and cities within countries, are more interconnected than in earlier decades as a result of the interaction of efficient transport and supply chains. While this interconnectedness can leave supply chains and transport networks potentially more vulnerable to disruptions, it does not necessarily mean we should start looking inward in terms of production processes and decrease transport use. Even Toyota, after the crisis, did not consider moving away from JIT citing cost concerns and noting that any production system is vulnerable to unexpected crises (Nishiguchi and Beaudet, 1998). Instead, we emphasize that it is extremely important to understand how local disruptions can have far and wide-reaching trade and welfare consequences for the world economy through this interaction. When policy makers think about trade policy changes or tackling climate change issues, they should be taking into account how these policy issues can have amplifying consequences as a result of this interaction. As trade interacts with global value chains (Antràs and Chor, 2022; Antràs, 2020), so does transportation and infrastructure.

[38] Much of the work here lies in intra-national studies Chatterjee (2019) and Atkin and Donaldson (2015).

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A Appendix

A.1 Data Appendix

Our dataset of transportation usage and trade costs extends from 1965 to 2020 and requires the use of multiple sources. We start with two major sources of trade statistics.

BACI Database For 1995-2020, we use the BACI database from Centre d'Etudes Prospectives et d'Informations Internationales (CEPII). This database reports values on quantities (in weight) and value for all bilateral trading relationships in the underlying UN Comtrade database. The researchers at CEPII correct underlying data to a consistent classification nomenclature, imputing data when necessary. We use the 2022 release of this data in 1992 Harmonized System nomenclature.

NBER-UN Comtrade Data For complete trade data in value from 1965-2000, we use the NBER-UN Comtrade database compiled by Feenstra et al. (2005).

For the overlap period from 1995-2000, we take the BACI values as given and line up the UN Comtrade data adjusting by the average difference in the datasets between 1995 and 2000. We perform similar procedures wherever there is an overlap, taking the newer data levels as correct and adjusting up and downward by the period of overlap.[39]

For various denominators and supply-chain statistics, we turn to alternative sources of data.

World Input–Output Database (WIOD) We use the combined Long-Run and updated World Input–Output Database (WIOD) to cover valued added and gross output statistics from 1965-2014. While the datasets only contain detailed statistics for 24 and 43 countries, that cover over 90% of would output, with the remainder of countries consolidated in a "Rest of World" Aggregates.[40]

We additionally use the WIOD to provide sectoral level price deflators from 1965-2014.

Penn World Tables and UN National Accounts Databases For aggregate GDP and global price deflators, we use data from the Penn World Tables Version 11 (PWT) from 2014-2019 at the aggregate level, and from the United Nations Statistics Division (UNSD) National Accounts Main Aggregates database for aggregates and sectoral level data not

[39] Please see the Stata subroutine 'splice' in our replication package.

[40] As an alternative, for data from 1995-2021, we also can use the OECD Input-Output Database. Due to differences in dataset design and industrial codes, we refrain from merging the two.

covered by the PWT. Due to differences in measurement of sectoral output between the UNSD and the WIOD, we refrain from extending our time-series on transportation costs and value added beyond 2014.[41] Just for 2019 and 2020, we additionally use the US Bureau of Economic Analysis GDP price indices assessed through the FRED database.

Value to Weight Conversions prior to 1995 After 1995, we directly use weight data from the BACI database. Prior to 1995, we backwards impute weights using BACI data and aggregate price series from the WIOD database. To do so, we use price index data from the WIOD.

This works well, except for natural resource and oil shipments from 1973-1985. We directly use oil price and oil import data from 1973-1985 to adjust quantity data over that time period for those exports and imports. We use oil price and shipment data from OPEC, as well as import statistics from the US Energy Information Administration to recover real shipment weights.

We concord all data to ISIC Rev. 3 (Prior to 2000) and ISIC Rev. 4 (After 2000) codes at the level of aggregation in the WIOD Database (2-digit sectoral aggregates). We uses concordances from the UN Trade Statistics Division.

Gravity Data For all countries we use population-weighted distance data from the CEPII Gravity Database (the 2022 revision).

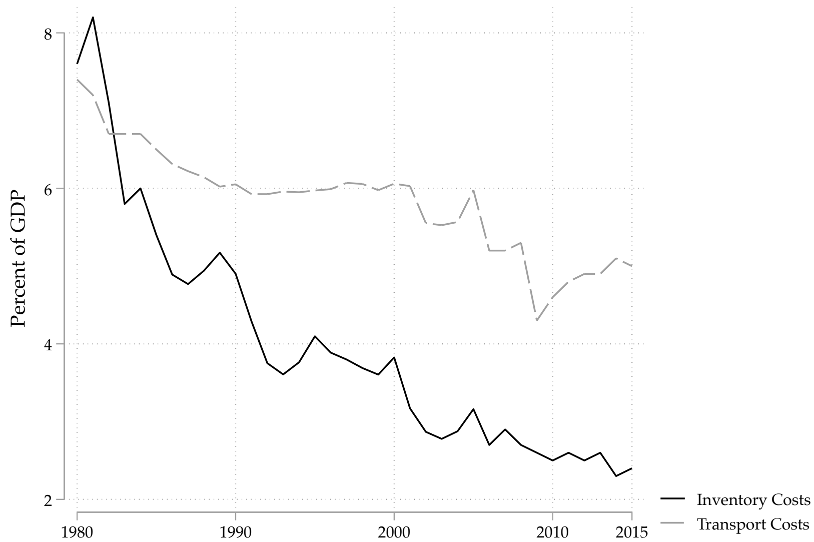
Inventory to Sales Ratio The Census Bureau reports this data based on three surveys: the Manufacturers' Shipments, Inventories, and Orders Survey, the Monthly Wholesale Trade Survey, and the Monthly Retail Trade Survey. More recent data, from 1992 onward, is based on the North American Industry Classification System (NAICS) while historic data was based on the Standard Industrial Classification (SIC) codes. The historic SIC data for Manufacturing is from the Census Manufacturing Branch under the Historical Time Series section. The historic SIC data for Retail is from the Census Retail Indicator Branch under the Historical Data section. Historic SIC data for Wholesale is from the Wholesale Indicator Branch under the Time Series Data (Prior to NAICS) section. The SIC was phased out in 1997 by US statistical agencies and is normalized relative to the recent NAICS data. NAICS data is from the Manufacturing & Trade Inventories and Sales data page. The shorter time period in retail and total series is due to lack of digitized data on the Census Bureau website.

[41] Appendix Figure A2 shows how UN Data conflates communication services with transportation, making it difficult to continue the time series.

Value Added as a percent of GDP The BEA reports historic data from 1947-1997 while BEA reports more recent data from 1998-2021.

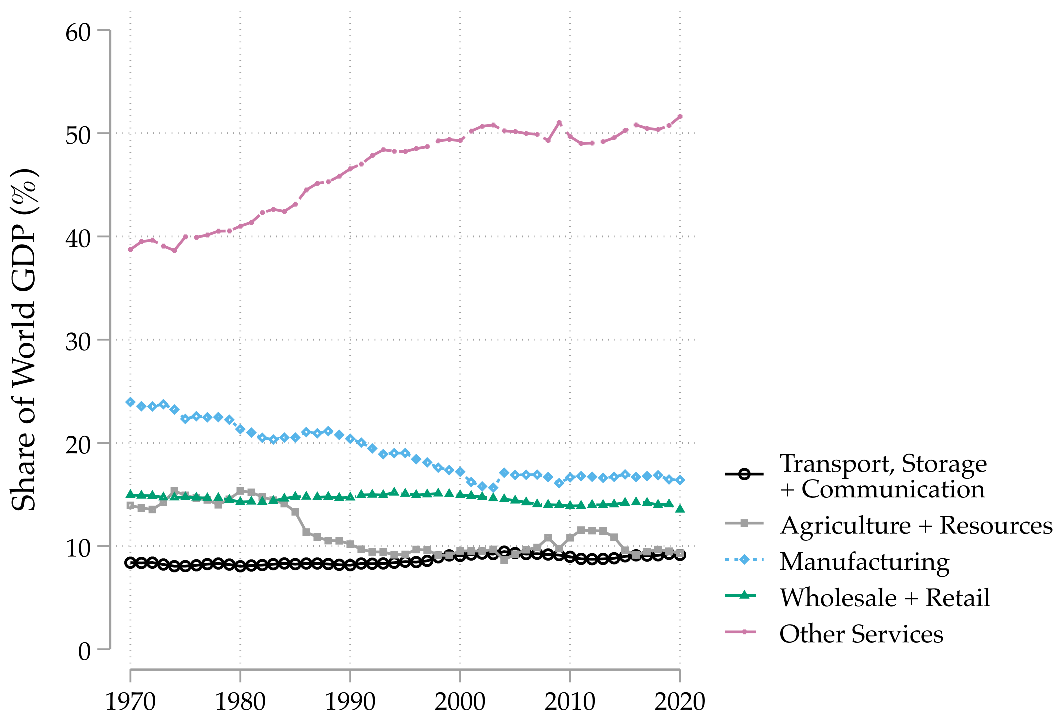
A.2 Additional Figures

Figure A1: Inventory and Transport Costs, 1980-2015



Notes: Digitized series of the annual *State of Logistics Report* of the Council of Supply Chain Management Professionals. The Council of Supply Chain Management Professionals produces annual estimates of logistics expenditure for the United States. See Federal Highway Administration (2005) for discussion on the estimates. Logistics expenditure are broken down into inventory/warehousing, transport, and administrative. Administrative spending make up a very small portion of GDP and are omitted here.

Figure A2: Global Sector Value Added, 1970-2020



Notes: This chart breaks down global GDP into components, transportation (including storage and communication), natural resources (agriculture, forestry, and mining), manufacturing, retail/wholesale distribution, and all other services. While the value added from manufacturing and resources is falling, the value added from transportation continues to stay constant. However, unlike the WIOD data used in the main text, this time series mixes communications and other transportation services. Sourced from UN Economic Data.