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Digital network centrality and the structure of goods trade

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Abstract
This paper studies how digital infrastructure is associated with the spatial structure of international trade in goods. We embed data availability into a structural gravity framework, conceptualizing it as an information friction that interacts with geographic distance and equilibrium market access. Using the topology of the global subsea cable network, we construct country-level measures of digital network position. We find that countries with greater digital network embeddedness, particularly on the exporter side, exhibit lower distance elasticities of trade. Other dimensions of digital connectivity are more closely associated with multilateral resistance, highlighting distinct channels through which digital infrastructure affects goods trade.

Keywords: digital network centrality; spatial integration; international trade; subsea cable networks
JEL codes: R12, D85, F14, R11

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1 Introduction

International digital infrastructure has become a central component of the global economy. By enabling the rapid transmission of data across borders, it supports finance, logistics, cloud computing, and the coordination of global value chains, while increasingly shaping productivity, innovation, and the diffusion of data-intensive technologies. At the same time, the economic implications of digital infrastructure extend beyond the digital sector itself: by facilitating access to information, coordination, and matching, digital connectivity has the potential to alter how firms overcome geographic barriers and engage in international exchange. Despite its growing importance, however, the role of digital infrastructure in the geography of goods trade remains only partially understood, particularly once countries' positions within global digital networks are taken into account.

This paper examines how digital infrastructure that enables cross-border data flows affects the spatial structure of international trade in goods. We focus on a central but underexplored question: how does data availability across countries, proxied by their positions in the global digital infrastructure network, weaken distance-related information frictions and shape market access in general equilibrium? Studying goods trade provides a non-obvious but important margin for addressing this question, because digital infrastructure affects goods trade primarily through information, coordination, and matching frictions rather than through the direct delivery of the traded product itself. Our starting point is that data, unlike goods, are non-rival and inexpensive to replicate, and are transmitted through digital networks whose topology matters for economic outcomes. As a result, traditional notions of distance and trade costs developed for physical goods are insufficient to capture how digital connectivity influences international trade, motivating a network-based approach to measuring data availability.

We approach this question by embedding data availability into the structural gravity model of trade. In this framework, bilateral trade depends on relative trade costs scaled by outward and inward multilateral resistance terms that summarize equilibrium market access. Rather than revisiting gravity as a methodological contribution, our objective is to introduce countries' positions in the global digital infrastructure network as a new structural object within gravity, and to study how different dimensions of digital network position reshape both the sensitivity of trade to geographic distance and equilibrium market access. In this sense, the paper complements and goes beyond existing broadband–trade studies by moving from country-level measures of digital adoption to network-based measures of digital infrastructure topology.

Empirically, we combine bilateral goods trade data with detailed information on the global network of subsea cables that forms the physical backbone of international data transmission. Trade flows are drawn from standard international trade datasets, while countries' positions in the global digital infrastructure network are constructed from the topology of the international subsea cable system. From this network, we derive country-level measures of digital network position that capture different dimensions of connectivity, including higher-order embeddedness, scale of direct connectivity, and topological roles within the network. We then estimate augmented gravity equations in which geographic distance enters both directly and interacted with exporter- and importer-side digital centrality, allowing the distance elasticity of trade to vary systematically with countries' positions in the global digital network. In a second step, we relate digital network position to exporter–time and importer–time fixed effects from the gravity model, which retain their interpretation as outward and inward multilateral resistance. This approach preserves the core structure of the gravity framework while introducing a network-based channel through which digital infrastructure reshapes the spatial organization of goods trade.

Our analysis delivers three main findings. First, countries that occupy more central positions in the global digital infrastructure network exhibit significantly lower distance elasticities of trade, indicating that digital connectivity weakens the trade-reducing effect of geographic distance. Second, this attenuation effect is driven primarily by exporter-side network embeddedness, consistent with an improved ability to serve geographically remote markets. Third, higher-order measures of network embeddedness (particularly eigenvector centrality) play a dominant and robust role in attenuating distance sensitivity, while other dimensions of digital network position capture complementary channels. In particular, measures reflecting the scale and structure of direct digital connectivity are more closely associated with equilibrium market access, as summarized by multilateral resistance, and their relevance differs between exporter- and importer-side access. To provide an intuitive benchmark for economic magnitude, we translate the estimated distance–centrality interactions into equivalent changes in physical distance, illustrating how improvements in digital network position can substantially reduce the effective cost of long-distance trade.

The remainder of the paper is organized as follows. Section 2 reviews the related literature. Section 3 develops a conceptual framework embedding data availability into structural gravity. Section 4 presents the empirical specification and hypotheses. Section 5 describes the data and the construction of digital network centrality measures. Section 6 reports the main empirical results. Section 7 concludes by summarizing the findings and discussing their economic significance, including an intuitive distance-equivalent interpretation.[1]

2 Related Literature

Our analysis builds on the structural gravity framework introduced by Anderson (1979) and formalized by Anderson and van Wincoop (2003), and on the interpretation of distance in gravity equations as capturing information frictions rather than purely physical transport costs. Early contributions emphasize the role of networks in reducing search and matching frictions in international exchange (Rauch, 1999; Rauch and Trindade, 2002). Subsequent work demonstrates that information frictions alone can generate gravity-type trade patterns (Allen, 2014) and that reductions in such frictions attenuate the trade-reducing effect of geographic distance (Steinwender, 2018). These mechanisms are embedded in general-equilibrium settings such as Allen and Arkolakis (2017) , who show how information frictions shape market access and multilateral resistance. Recent methodological contributions further refine gravity estimation in high-dimensional settings, highlighting issues related to multi-dimensional panels, aggregation, and fixed effects (Baltagi et al., 2024; Breinlich et al., 2024).

A large empirical literature studies the role of digitalization in trade by proxying digital acces-

[1] Details of this exercise are provided in Online Appendix C.

sibility with country-level indicators such as Internet penetration, communication costs, or indices of digital regulation. These measures are consistently found to correlate with trade flows and trade costs (Freund and Weinhold, 2004; Fink et al., 2005; Clarke and Wallsten, 2006; Goldfarb and Tucker, 2019; van der Marel and Ferracane, 2021). This literature, however, typically treats countries as isolated units of connectivity and abstracts from the networked nature of global data transmission. More recent work documents that digitalization has a stronger impact on trade in services than in goods, consistent with the idea that ICT reduces coordination and transaction costs in information-intensive activities (Yin and Choi, 2025). Related studies further show that digital connectivity, particularly when combined with supportive regulatory frameworks, lowers trade costs and has especially large effects on digitally deliverable services (Herman and Oliver, 2022; Bellucci et al., 2025; Casalini and López González, 2019). While informative, these approaches largely overlook how the topology of digital infrastructure shapes effective access to information in a multilateral setting.

Insights from network theory suggest that access to information, spillovers, and economic opportunities depends on network position rather than on simple measures of connectivity intensity (Jackson, 2008; Bloch et al., 2023). While this literature often emphasizes eigenvector-type measures to capture higher-order network embeddedness, other centrality measures capture complementary dimensions of connectivity (such as scale, redundancy, or brokerage) that may affect economic outcomes through distinct channels. In line with this perspective, recent empirical work shows that the physical backbone of global data transmission, and most notably subsea cables, affects coordination costs, firm behavior, and trade in physical goods (Hjort and Poulsen, 2019; Akerman et al., 2022). A related body of work in economic geography examines the spatial organization, governance, and uneven development of global Internet and submarine cable infrastructures (Malecki, 2002; Tranos, 2011; Tranos and Nijkamp, 2013).

Beyond these general geographies of connectivity, a parallel strand highlights the geopolitical and strategic dimensions of digital infrastructure. Submarine cables are not neutral conduits but critical assets embedded in political power relations, with landing points and routes acting as strategic chokepoints in the global information economy. Work in geography and political economy shows how cable networks are entangled with state strategy, security concerns, and competing development imaginaries, underscoring the geopolitical stakes of physical network layout (Starosielski, 2015; Malecki and Wei, 2009; Farrell and Newman, 2019). Closely related, an earlier literature on network vulnerability and critical infrastructure protection studies how network topology conditions robustness to random failures and targeted disruptions. This perspective is developed most prominently in the work of Gorman (2005), who show how redundancy, centralization, and topological structure shape the ability of networks to sustain flows under stress. Together, these studies provide a conceptual foundation for treating digital infrastructure topology as economically consequential rather than purely technical.

Methodologically, our approach relates to a tradition of network analysis in economic geography that explicitly constructs and compares centrality measures for large-scale digital infrastructure networks. Using closely related Internet backbone and subsea cable data, Tranos (2011) develops alternative centrality metrics and demonstrates how different topological positions correspond to distinct regional roles within the European Internet network. Closely related, Tranos and Nijkamp (2013) revisit the "death of distance" hypothesis by jointly modeling cyber, physical, and relational proximities, showing that network-based measures of connectivity capture dimensions of economic interaction that are distinct from, yet complementary to, geographic distance. Extending this framework, Tranos et al. (2014) apply centrality measures to global and Chinese Internet networks, illustrating how digital urban connectivity and hierarchical network positions shape spatial interaction patterns across regions and countries. Together, these studies provide a direct methodological precedent for our use of network centrality measures, while our contribution differs in embedding such measures into a structural gravity framework and interpreting them as determinants of multilateral information accessibility in international trade.

Our paper is most closely related to Jeon and Rysman (2025), who use gravity-type regressions with detailed routing data to construct bilateral, path-based measures of digital distance and study international trade in data and digital services. By contrast, we embed country-level measures of digital network position into a structural gravity framework to examine how digital infrastructure shapes both distance sensitivity and equilibrium market access in international trade in goods. More broadly, much of the existing literature relates digital connectivity to trade volumes or market access levels, whereas our approach explicitly distinguishes between how network position affects the sensitivity of trade to geographic distance and how it shapes equilibrium market access in general equilibrium.

Finally, our interpretation of network centrality as a proxy for data availability connects to the growing economics literature on the value of data and digital privacy. Coyle and Manley (2024) review empirical methods for valuing data as an economic asset, highlighting substantial heterogeneity across contexts and uses. Complementarily, Goldfarb and Que (2023) show how privacy regulation and data governance can act as modern trade frictions, potentially offsetting the distance-attenuating effects of digital infrastructure. These perspectives underscore that the economic implications of digital centrality depend not only on physical connectivity but also on institutional and regulatory environments.

Taken together, these literatures motivate an approach that treats digital infrastructure not merely as a country attribute or a bilateral trade cost, but as a networked object shaping multilateral access to information in general equilibrium. Our contribution is to operationalize this perspective by constructing country-level measures of digital network centrality from the global subsea cable system and embedding them into a structural gravity framework for goods trade. This allows us to study how digital network embeddedness reshapes distance sensitivity and multilateral resistance, and to provide an economically interpretable link between the topology of digital infrastructure and the spatial organization of international trade.

From a broader perspective, the paper contributes to a long-standing research trajectory within *Spatial Economic Analysis* that emphasizes connectivity, spatial interaction, and network structure as fundamental determinants of economic integration. Over the past two decades, contributions to the journal have moved beyond treating distance as a reduced-form friction, highlighting instead the role of spatial embeddedness, spillovers, and infrastructure networks in shaping economic outcomes (Fratesi et al., 2025a,b,c). By embedding digital infrastructure topology into a structural gravity framework, the present paper follows this tradition and extends it to the analysis of international trade in a digitally connected world.

3 Conceptual Framework

Let X_{ij} denote exports from origin i to destination j. In a standard structural gravity system with CES preferences and iceberg trade costs (Anderson and van Wincoop, 2003; Head and Mayer, 2014), bilateral exports satisfy

$$X_{ij} = \frac{Y_i E_j}{Y_W} \left(\frac{\tau_{ij}}{P_i \Pi_j} \right)^{1-\sigma}, \tag{1}$$

where Y_i is income in i, E_j is expenditure in j, Y_W is world income, $\sigma > 1$ is the elasticity of substitution, $\tau_{ij} \geq 1$ is the bilateral iceberg trade cost, and P_i and Π_j are outward and inward multilateral resistance (MR) terms. These terms are equilibrium objects that summarize countries' average market access across all trading partners and are shaped by the entire structure of trade costs rather than by any single bilateral link.

3.1 Data Availability and Information Frictions

Improvements in data availability affect trade primarily by reducing information-related trade costs rather than by altering physical distance directly. Greater data availability in exporter i and importer j lowers a broad class of informational frictions relevant for international exchange, including uncertainty about demand conditions, regulatory environments, and partner reliability. In gravity models, such frictions enter naturally as components of iceberg trade costs and can generate gravity-type trade patterns even in the absence of physical transport costs (Allen, 2014).

Crucially, information frictions are typically amplified by geographic distance. When data availability improves, these distance-amplified frictions are reduced disproportionately for more distant trading partners, weakening the sensitivity of trade flows to distance. In equilibrium, this mechanism flattens the distance–trade relationship and attenuates the distance elasticity of trade, consistent with empirical evidence that reductions in information frictions diminish the trade-reducing effect of distance (Steinwender, 2018).

To formalize this mechanism, decompose iceberg trade costs into a physical and an information component:

$$\tau_{ij} \equiv \tau_{ij}^{\text{phys}} \cdot \tau_{ij}^{\text{info}}, \tag{2}$$

where

$$\ln \tau_{ij}^{\text{phys}} = \alpha_d \ln \text{dist}_{ij} + \alpha_b \, \text{border}_{ij} + \alpha_\ell \, \text{lang}_{ij} + \cdots, \tag{3}$$

with $\alpha_d > 0$. The term dist_{ij} refers to bilateral distance, while border_{ij} and lang_{ij} tell whether countries share a common border and a common language respectively. The ellipsis collects additional standard time-invariant bilateral trade-cost determinants commonly used in gravity models (such as colonial ties, historical links, or other geographic and institutional frictions) that are orthogonal to the role of geographic distance emphasized here.

Let D_i and D_j denote data availability in exporter i and importer j. In the empirical analysis, data availability should be interpreted as a latent equilibrium object that can be proxied by different measures of digital network position depending on the channel of interest: higher-order network embeddedness is most relevant for distance attenuation, while broader connectivity characteristics may shape overall market access. The information-cost component is modeled as

$$\begin{aligned} \ln \tau_{ij}^{\text{info}} = \kappa_0 - \kappa_o \ln D_i - \kappa_d \ln D_j + \kappa_m \ln \text{mis}_{ij} + \kappa_{dist} \ln \text{dist}_{ij} \\ - \kappa_{o,dist} \ln D_i \ln \text{dist}_{ij} - \kappa_{d,dist} \ln D_j \ln \text{dist}_{ij}, \end{aligned} \tag{4}$$

where mis_{ij} captures other bilateral sources of information mismatch (such as institutional, regulatory, or cultural differences) that affect information costs independently of geographic distance and data availability. In the empirical implementation, they will not be separately observed but absorbed by standard bilateral controls and fixed effects, as in conventional gravity specifications.

Equations (2)–(4) imply that distance affects trade not only through physical transport costs but also through distance-amplified information frictions. The partial elasticity of trade with respect to distance, holding MR fixed, is

$$\frac{\partial \ln X_{ij}}{\partial \ln \text{dist}_{ij}} = (1-\sigma)\left[\alpha_d + \kappa_{dist} - \kappa_{o,dist}\ln D_i - \kappa_{d,dist}\ln D_j\right]. \tag{5}$$

If $\kappa_{o,dist}, \kappa_{d,dist} > 0$, higher data availability makes the distance elasticity less negative, attenuating the trade-reducing effect of distance.

Data availability also affects MR terms because MR aggregates trade costs across all partners. Higher D_i lowers information costs of reaching many destinations, improving exporter market access and reducing outward MR P_i (Donaldson and Hornbeck, 2016). Higher D_j lowers costs for many foreign suppliers to serve j, reducing inward MR Π_j, with especially large gains for distant suppliers when information frictions rise with distance (Allen, 2014; Steinwender, 2018). In equilibrium, higher data availability is associated with lower distance sensitivity and improved market access as reflected in multilateral resistance, consistent with the structural gravity framework.[2]

3.2 Country Centrality in Global Digital Networks

Which network measure best captures economically relevant access to digital resources depends on the channel through which digital connectivity affects trade. In this paper, we distinguish between higher-order network embeddedness, which shapes how distance-related information frictions operate, and broader dimensions of digital network position, which may influence overall market access in general equilibrium.

Among standard centrality measures, eigenvector-type centrality provides the most appropriate proxy for digital network embeddedness. Eigenvector centrality assigns greater weight to connections with highly connected partners, thereby capturing a country's integration into the core of the global digital network. In digital contexts, such embeddedness is naturally associated with cumulative data spillovers, interoperability, and participation in global digital ecosystems, where

[2] In heterogeneous-firm gravity models (Melitz, 2003; Chaney, 2008; Helpman et al., 2008), lower information costs also facilitate entry into distant markets, reinforcing the attenuation of distance elasticities and reducing multilateral resistance at the extensive margin.

access depends not only on the number of connections but also on their quality and systemic importance. For this reason, eigenvector centrality is particularly well suited to capturing multilateral data availability and the attenuation of distance-amplified information frictions.

Other centrality measures capture complementary but conceptually distinct dimensions of digital network position. Degree centrality primarily reflects the scale and redundancy of direct digital connectivity, measuring how many physical or logical connections a country maintains to the global network. Betweenness centrality captures brokerage and potential chokepoint positions, reflecting control over routing paths rather than broad access to data. Closeness centrality measures average network proximity or latency and is therefore sensitive to the overall reachability of the network. While these measures do not directly proxy cumulative data availability, they may affect trade through alternative channels, such as capacity, resilience, routing dependence, or exposure to network bottlenecks.

The preference for eigenvector-type centrality as a measure of embeddedness is grounded formally in network theory and network economics. Foundational work shows that when access to resources or information depends on the centrality of one's neighbors, eigenvector and related measures capture network position more appropriately than simple connectivity counts (Bonacich, 1987; Jackson, 2008). Recent theoretical results further formalize this insight by demonstrating that eigenvector and Katz centrality emerge as the relevant objects in environments with complementarities, spillovers, and reinforcement effects (Bloch et al., 2023). These features closely characterize data availability in digital networks, where access is cumulative and amplified through connections to highly connected hubs.

This distinction aligns naturally with the structural gravity framework. Outward and inward multilateral resistance summarize overall market access in general equilibrium rather than bilateral proximity (Anderson and van Wincoop, 2003; Yotov, 2022). Eigenvector centrality can therefore be interpreted as a digital analogue of multilateral information access that is especially relevant for understanding how geographic distance constrains trade. At the same time, broader measures of digital network position, such as degree, betweenness, and closeness, may influence equilibrium market access through channels related to scale, redundancy, and network structure. Accordingly, we take country i's eigenvector centrality EC_i as a proxy for its digital embeddedness and data availability, while retaining alternative centrality measures to capture complementary dimensions of digital connectivity that play distinct roles in shaping trade outcomes.

4 Empirical Specification

The conceptual framework yields three main testable hypotheses linking countries' positions in the global digital infrastructure network to trade outcomes. These hypotheses distinguish between (i) the sensitivity of bilateral trade to geographic distance and (ii) overall market access in general equilibrium, and allow different dimensions of digital network position to operate through distinct channels.

H1 (Distance attenuation through digital network embeddedness): Countries that are more embedded in the core of the global digital infrastructure network, as measured by eigenvector centrality, face a less negative elasticity of bilateral trade with respect to geographic distance. This attenuation effect is expected to be stronger on the exporter side, reflecting exporters' ability to serve geographically distant markets when information and coordination frictions are mitigated.

H2 (Digital network position and multilateral market access): Countries' positions in the global digital infrastructure network are associated with their overall market access in general equilibrium, as summarized by outward and inward multilateral resistance. In particular, exporter-side market access is expected to be closely related to the scale and redundancy of direct digital connectivity, while importer-side market access may also reflect higher-order network integration.

H3 (Distinct mechanisms across centrality measures): Conditional on digital network embeddedness, alternative centrality measures capture distinct mechanisms with potentially different implications for trade. Weighted degree reflects the scale and redundancy of direct digital connections and is therefore expected to matter more for overall market access than for distance attenuation. Betweenness centrality captures brokerage or chokepoint positions and may be negatively associated with market access if it proxies vulnerability or routing dependence, while closeness centrality reflects average network proximity and may exhibit less stable relationships in sparsely connected parts of the network.

Consistent with these hypotheses, we allow different dimensions of digital network position to affect distance sensitivity and multilateral resistance through separate channels. Higher-order network embeddedness, as captured by eigenvector centrality, is expected to matter most for attenuating distance-related trade frictions (H1), while broader measures of digital network position, such as the scale and structure of direct connectivity, may play a more prominent role in shaping overall market access in general equilibrium (H2 and H3).

To translate these hypotheses into an empirical gravity framework suitable for panel estimation, let X_{ijt} denote exports from country i to country j at time t. Following the structural gravity literature, we estimate trade flows using Poisson pseudo-maximum likelihood (PPML), which is consistent with theory and robust to heteroskedasticity and zero trade flows (Santos Silva and Tenreyro, 2006).

4.1 Baseline structural gravity

The baseline specification is:

$$X_{ijt} = \exp\left[\beta_1 \ln \text{dist}_{ij} + \mathbf{B}_{ij}\gamma + \alpha_{it} + \delta_{jt}\right] \cdot \varepsilon_{ijt}, \tag{6}$$

where $\ln \text{dist}_{ij}$ denotes geographic distance, $\mathbf{B}_{ij}$ includes standard time-invariant bilateral controls (contiguity, common language, colonial ties, etc.), α_{it} and δ_{jt} are exporter–time and importer–time fixed effects capturing outward (P_i) and inward (Π_j) multilateral resistance, and ε_{ijt} is a multiplicative error term. Exporter–time and importer–time fixed effects load negatively on outward and inward multilateral resistance, P_i and Π_j respectively, so that higher estimated fixed effects correspond to lower multilateral resistance and improved market access in general equilibrium.

4.2 Distance sensitivity

To test hypothesis H1, we use eigenvector centrality as the empirical proxy for countries' embeddedness in the global digital infrastructure network and for data availability relevant to the attenuation of distance-related trade frictions, while other centrality measures capture complementary dimensions of network position. Let EC_{it} and EC_{jt} denote exporter- and importer-side eigenvector centrality at time t. We augment (6) as follows:

$$X_{ijt} = \exp\Big[\beta_1 \ln \text{dist}_{ij} + \beta_2 \ln \text{dist}_{ij} \times EC_{it} + \beta_3 \ln \text{dist}_{ij} \times EC_{jt} + \mathbf{B}_{ij}\gamma + \alpha_{it} + \delta_{jt}\Big] \cdot \varepsilon_{ijt}. \quad (7)$$

Under H1, we expect $\beta_2 > 0$ and $\beta_3 > 0$, indicating that higher digital network embeddedness attenuates the trade-reducing effect of geographic distance. This specification captures the idea that greater access to global data and information networks weakens distance-amplified trade frictions, particularly in long-distance transactions.

4.3 Multilateral access

Hypothesis H2 predicts that digital network position also affects trade through multilateral rather than purely bilateral channels. Because exporter–time and importer–time fixed effects absorb all country–time determinants of trade that operate symmetrically across partners, this hypothesis is evaluated in a second step by examining whether estimated fixed effects from the baseline gravity specification correlate with measures of digital network position:

$$\widehat{\alpha}_{it} = \theta_t + \rho\, EC_{it} + \mathbf{Z}_{it}\eta + u_{it}, \qquad \widehat{\delta}_{jt} = \theta_t + \rho'\, EC_{jt} + \mathbf{Z}_{jt}\eta' + v_{jt}, \quad (8)$$

where $\mathbf{Z}_{it}$ includes country-level controls such as income, population, and institutional quality.

Under H2, we do not require eigenvector centrality to be the sole or dominant determinant of multilateral resistance. Rather, we expect digital network position more broadly to be associated with improved market access, reflecting the cumulative effects of long-run digital infrastructure investments on countries' equilibrium trading opportunities.

4.4 Alternative network measures

To test hypothesis H3, we compare eigenvector centrality with alternative measures of network position that capture distinct dimensions of digital connectivity. In the distance-sensitivity specification, we extend (7) by including interactions based on alternative centrality measures, illustrated here with betweenness centrality (BC_{it}, BC_{jt}):

$$\begin{aligned} X_{ijt} &= \exp\Big[\beta_1 \ln \text{dist}_{ij} + \beta_2 \ln \text{dist}_{ij} \times EC_{it} + \beta_3 \ln \text{dist}_{ij} \times EC_{jt} \\ &\quad + \beta_4 \ln \text{dist}_{ij} \times BC_{it} + \beta_5 \ln \text{dist}_{ij} \times BC_{jt} + \mathbf{B}_{ij}\gamma + \alpha_{it} + \delta_{jt}\Big] \cdot \varepsilon_{ijt}. \end{aligned} \tag{9}$$

In the multilateral-resistance mapping, we extend (8) as:

$$\begin{aligned} \widehat{\alpha}_{it} &= \theta_t + \rho\, EC_{it} + \mu\, BC_{it} + \mathbf{Z}_{it}\eta + u_{it}, \\ \widehat{\delta}_{jt} &= \theta_t + \rho'\, EC_{jt} + \mu'\, BC_{jt} + \mathbf{Z}_{jt}\eta' + v_{jt}. \end{aligned} \tag{10}$$

Under H3, eigenvector centrality is expected to be the primary proxy for digital network embeddedness and thus for distance attenuation, while alternative measures capture complementary mechanisms. Accordingly, we expect β_2 and β_3 to be positive and economically meaningful, whereas β_4 and β_5 may differ in sign or significance depending on whether brokerage positions facilitate or hinder trade. In the second-stage regressions, ρ and ρ' summarize the association between embeddedness and multilateral resistance, while μ and μ' capture the role of brokerage positions in the digital network. These specifications can be analogously enriched with weighted degree centrality (Deg_{it}) and closeness centrality (CC_{it}) to explore the roles of, respectively, the scale of direct digital connectivity and average network proximity.

5 Data

This section describes the data sources and construction of the main variables used in the empirical analysis. We combine bilateral trade data with detailed information on the global subsea cable network to measure countries' positions in international digital connectivity.

5.1 Goods Trade

Bilateral trade flows are drawn from the BACI database compiled by CEPII, which provides harmonized country–country merchandise trade data constructed from UN Comtrade by reconciling mirror flows and correcting reporting inconsistencies. Trade flows are measured in current U.S. dollars and are widely used in empirical gravity analyses.

In this paper, BACI trade flows constitute the dependent variable X_{ijt} in the gravity regressions. We focus on aggregate merchandise exports between country pairs in order to align the trade data with country-level measures of digital infrastructure and network centrality. The empirical analysis covers the period 2015–2020, reflecting the intersection between the availability of consistent trade data and the coverage of the global subsea cable dataset.

We exclude landlocked countries, whose centrality in the subsea cable network is mechanically zero in the absence of terrestrial cable data. For countries with geographically distant overseas territories, such territories are excluded from the regression sample to avoid measurement error in bilateral distance, but are retained as nodes in the construction of the global cable network so that centrality measures fully capture countries' digital positions. This leaves us with 136 countries and thus 816 country-year data points given that we cover 6 years.

Although the paper studies digital infrastructure and data availability, the outcome variable is trade in physical goods. The contribution therefore lies not in measuring digital trade flows directly, but in exploring how countries' positions in the global digital infrastructure network shape information frictions, distance sensitivity, and market access in goods trade.

5.2 Subsea Cables and Network Centrality

Measures of digital network centrality are constructed from the network of subsea cables, which constitute the physical backbone of global data transmission. The primary source is TeleGeography's *Submarine Cable Map*, which provides information on global subsea fiber-optic cables, including routes, landing points, Ready-for-Service (RFS) dates, and operational status.[3]

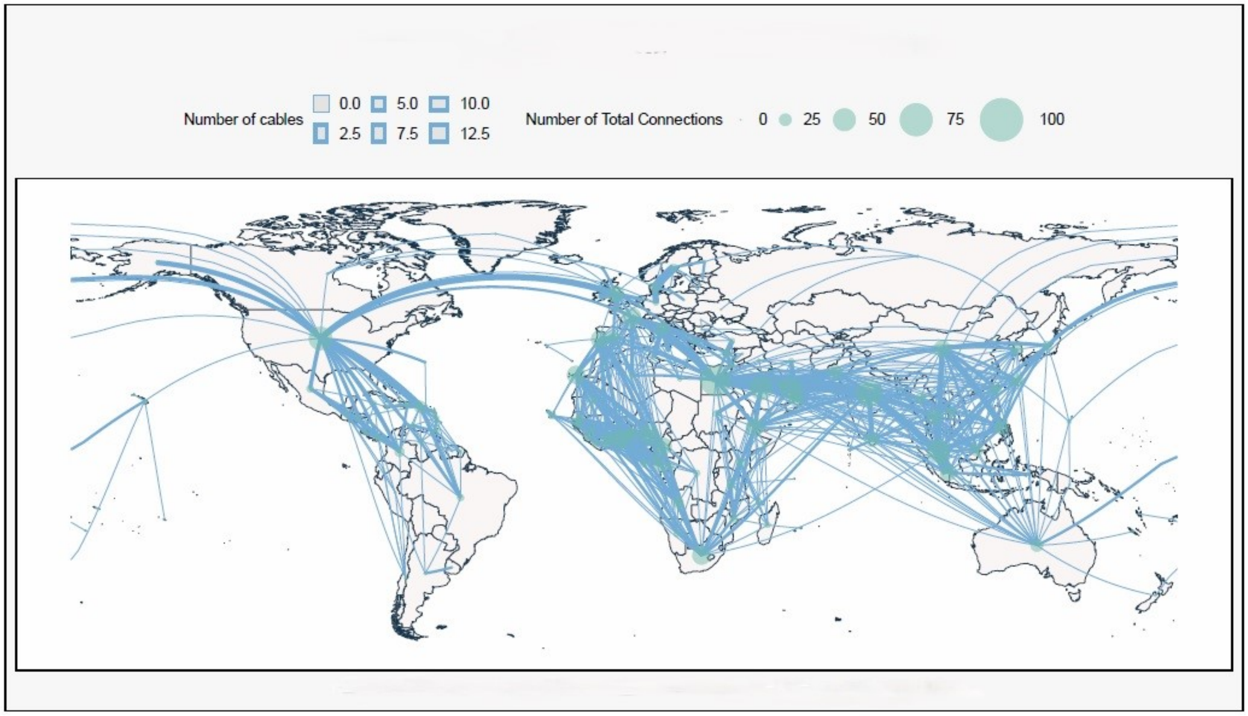

Figure 1: Subsea Cable Network 2015

Notes: Nodes represent countries (or aggregated territorial units), and edges represent active direct subsea cable connections. A node's size is proportional to the total number of its active direct connections, and an edge's thickness reflects the total number of its active cables.

Countries (or aggregated territorial units) are treated as nodes in a global digital network, and subsea cables are treated as edges connecting these nodes. Two countries are considered directly connected if at least one active subsea cable links them without passing through a third country. The network is modeled as undirected, reflecting the bidirectional nature of modern fiber-optic transmission. Using cable-level RFS dates, the network is reconstructed annually by including

[3] See Online Appendix A for additional details.

only cables that are operational in each year t. The empirical analysis focuses on the period 2015–2020. Let A_{ijt} denote the weighted adjacency matrix in year t, where each element represents the strength of the digital connection between countries i and j. Edge weights are constructed primarily from the number of active subsea cables connecting a given pair of countries, capturing both capacity and redundancy in digital connectivity. Additional details on the construction of edge weights and the role of cable length are provided in Online Appendix A.

Figures 1 and 2 visualize the global subsea cable network in 2015 and 2020. While the set of nodes and bilateral links is largely stable over this period, edge weights and node sizes evolve as countries add or reinforce cable connections. As we will discuss below, this intensive-margin evolution leads to meaningful changes in countries' positions within the global digital network, even in the absence of new country entries.

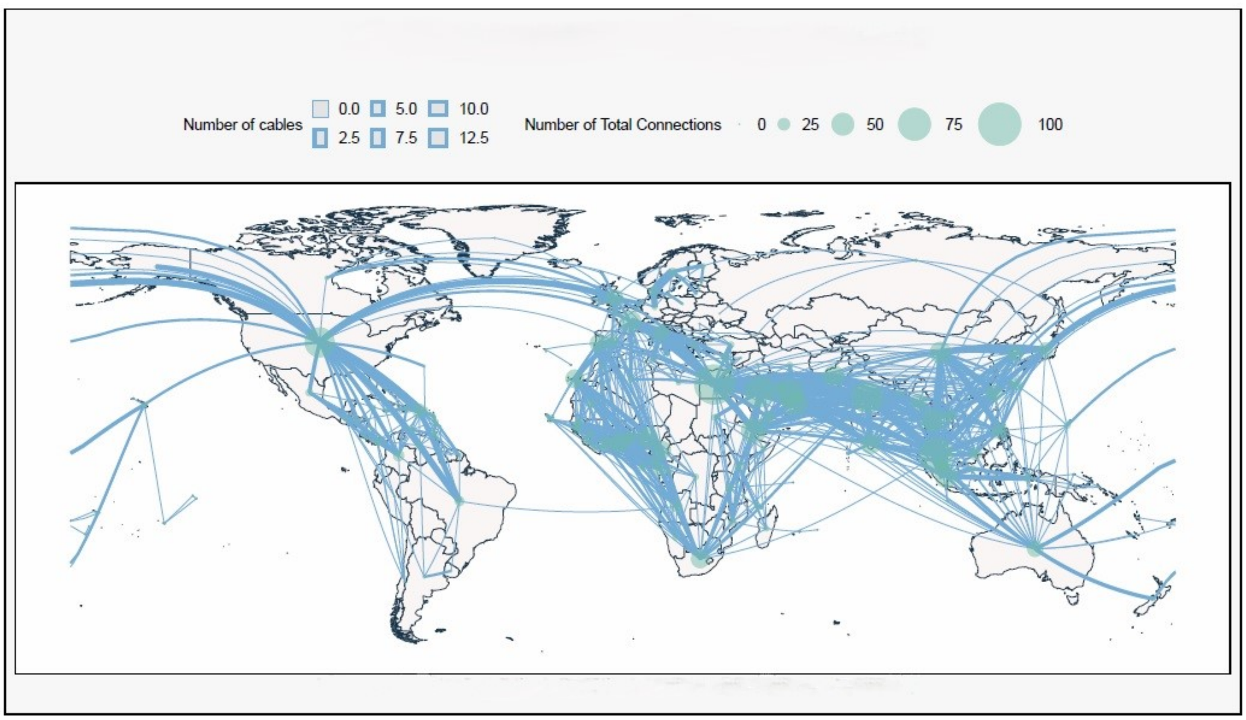

Figure 2: Subsea Cable Network 2020

Notes: Nodes represent countries (or aggregated territorial units), and edges represent active direct subsea cable connections. A node's size is proportional to the total number of its active direct connections, and an edge's thickness reflects the total number of its active cables. Changes in node size and edge thickness with respect to Figure 1 reflect the intensive-margin evolution of digital connectivity.

From the adjacency matrix A_{ijt}, we compute standard network centrality measures at the country–year level. Weighted degree centrality (Deg_{it}) captures the scale and redundancy of direct digital connections. Betweenness centrality (BC_{it}) measures a country's role as an intermediary in network paths, while closeness centrality (CC_{it}) captures average network proximity. Our main measure of digital accessibility is eigenvector centrality, denoted by EC_{it}:

$$EC_{it} = \frac{1}{\lambda_t} \sum_j A_{ijt} EC_{jt},$$

where λ_t is the largest eigenvalue of the adjacency matrix in year t. As discussed above, eigenvector centrality captures a country's embeddedness in the core of the global digital network and reflects access to the global data infrastructure as a whole rather than purely bilateral connectivity. We thus interpret EC_{it} as the most appropriate country–year measure of data availability and multilateral digital accessibility. Eigenvector centrality enters the gravity regressions through interactions with geographic distance, $\ln(\text{dist}_{ij}) \times EC_{it}$ and $\ln(\text{dist}_{ij}) \times EC_{jt}$, allowing the distance elasticity of trade to vary systematically with exporters' and importers' positions in the global digital network. Alternative centrality measures are used in robustness checks to distinguish embeddedness from direct connectivity, brokerage, and network proximity.[4]

Table 1 reports descriptive statistics for the global subsea cable network. Panels A and B document substantial heterogeneity across countries in network structure and centrality, while Panel C shows that network centrality evolves meaningfully over time even in the absence of new country entries. This intensive-margin variation underpins the empirical identification strategy, which exploits within-country changes in digital network centrality.

6 Centrality, Distance and Resistance

This section presents the main empirical results linking countries' positions in the global digital infrastructure network to trade patterns. The analysis proceeds in two steps. First, we examine

[4]see Online Appendix B for additional details and formal definitions.

Table 1: Descriptive Statistics: Global Subsea Cable Network

	Mean	Std. Dev.	Min	Max	Obs.
Panel A. Network Structure					
Number of active cables per country	16.9	18.0	4.0	26.0	801
Number of connected partner countries	11.2	9.9	3.0	18.0	801
Average cable length (km)	2435.8	1762.3	776.7	3713.2	801
Panel B. Network Centrality Measures					
Eigenvector centrality (EC_{it})	0.13	0.23	0.002	0.14	798
Weighted degree centrality (Deg_{it})	7.9	8.2	1.9	12.1	798
Betweenness centrality (BC_{it})	0.02	0.06	0.00	0.01	798
Closeness centrality (CC_{it})	0.25	0.07	0.20	0.28	798
Panel C. Network Dynamics (2015–2020)					
Change in EC_{it}	-0.02	0.09	-0.04	0.00	134
Change in Deg_{it}	1.6	2.9	0.00	1.6	134
Change in BC_{it}	0.002	0.02	0.00	0.00	134
Change in CC_{it}	0.005	0.07	0.005	0.02	134
Change in number of cables	3.7	6.5	0.0	4.0	134

Notes: The table reports descriptive statistics for the inter-country subsea cable network used to construct the digital network centrality measures. Panels A and B report pooled country–year statistics. Panel A reports: the number of cables connecting a given country to the network; the number of connected partner countries, defined as the number of distinct countries with which a given country has at least one direct, active subsea cable connection in a given year; and the average cable length, defined as the average length of all cables connecting a given country to the network. Panel B reports eigenvector, weighted degree, betweenness, and closeness centrality computed from the weighted, undirected adjacency matrix of active subsea cables. Panel C reports within-country changes between 2015 and 2020, highlighting the intensive-margin evolution of the network.

whether digital network centrality attenuates the trade-reducing effect of geographic distance in structural gravity regressions, as documented in Table 2. Second, we assess whether digital centrality operates through a multilateral market-access channel by relating it to outward and inward multilateral resistance, as shown in Table 3. The empirical analysis is designed to characterize structural associations between digital network position and equilibrium trade outcomes rather than to identify short-run causal effects of marginal infrastructure changes. Digital network centrality reflects long-lived investments (such as subsea cable landings and backbone expansions) that evolve slowly over time and are shaped by geography, historical ties, and strategic considerations. While Panel C of Table 1 shows that digital network centrality exhibits meaningful within-country variation over time, providing identifying variation for the distance–centrality interactions in the gravity regressions reported in Table 2, the correlations with multilateral resistance documented in Table 3 primarily reflect cross-sectional differences. This is consistent with the interpretation of both digital network centrality and multilateral resistance as persistent, slow-moving equilibrium objects shaped by long-run infrastructure investments. Within the structural gravity framework, the estimated coefficients should therefore be interpreted as reduced-form elasticities capturing how equilibrium trade patterns covary with digital network topology through information and coordination frictions.

Table 2 reports Poisson pseudo–maximum likelihood estimates of augmented gravity equations in which the elasticity of trade with respect to geographic distance varies with countries' positions in the global digital infrastructure network. Column (1) reports the baseline structural gravity specification with standard bilateral controls and exporter–time and importer–time fixed effects. Column (2) implements specification (7) by introducing interactions between distance and exporter and importer eigenvector centrality, our preferred measure of multilateral digital embeddedness. In line with the hypothesis that digital infrastructure mitigates distance-related information frictions, both exporter- side and importer-side eigenvector centrality significantly attenuate the negative effect of distance on trade, with the effect being economically larger and more precisely estimated on the exporter side.

Columns (3) and (4) compare eigenvector centrality to alternative network measures in partial specifications, while column (5) includes all centralities jointly. Across specifications, exporter eigenvector centrality remains positive, statistically significant, and stable in magnitude, and importer eigenvector centrality remains significant at conventional levels. By contrast, alternative centrality measures display more heterogeneous patterns once considered jointly: some coefficients lose significance, others change sign, and their magnitudes are less stable across specifications. This behavior is consistent with substantial collinearity among centrality measures and with the interpretation that they capture distinct mechanisms, such as scale and redundancy of direct connectivity (degree), brokerage or chokepoint exposure (betweenness), and network proximity (closeness), rather than a single underlying dimension of digital accessibility. Taken together, the results in Table 2 indicate that higher-order network embeddedness, as captured by eigenvector centrality, plays a central and robust role in weakening the trade-reducing effect of geographic distance. This finding supports the interpretation of eigenvector centrality as a proxy for multilateral data availability and information spillovers that become increasingly valuable as geographic separation grows.[5]

To further interpret these results through the lens of structural gravity, Table 3 relates digital network centrality to exporter–time and importer–time fixed effects obtained from the baseline gravity specification. As these fixed effects absorb all country–time determinants of trade that operate symmetrically across partners, they retain the standard structural interpretation as outward and inward multilateral resistance in the sense of Anderson and van Wincoop (2003), summarizing overall market-access conditions in general equilibrium. By contrast, when distance–centrality interactions are included directly in the first-stage gravity equation, part of the effect of digital network position is explicitly modeled as a bilateral trade-cost shifter that varies with distance. In that case, the resulting exporter–time and importer–time fixed effects no longer capture total multilateral resistance, but rather multilateral resistance net of the distance attenuation channel. Using these conditional fixed effects in the second stage would therefore address a different question (whether digital network centrality affects market access beyond its impact on bilateral distance-related frictions) and would not correspond to the standard multilateral resistance concept derived from structural gravity.

Column (1) of Table 3 relates multilateral resistance to eigenvector centrality alone. On the importer side (Panel B), eigenvector centrality is positively and significantly associated with lower inward multilateral resistance, consistent with improved access to foreign markets. On the exporter side (Panel A), however, the corresponding coefficient is smaller and not statistically significant. Columns (2)–(4) extend the analysis to alternative centrality measures and joint specifications.

[5] Online Appendix Table D.1 reports specifications with each interaction entered separately. Signs and magnitudes are broadly stable, indicating that instability in Table 2 reflects overlap across centrality measures rather than fragility of the distance-attenuation effect. The exporter eigenvector interaction remains positive and statistically significant across specifications in the main table.

Table 2: Digital Network Centrality and Distance Sensitivity in Trade

	(1) Baseline	(2) Eigenvector	(3) Alternatives (1)	(4) Alternatives (2)	(5) All Centralities
$\ln(\text{dist}_{ij})$	-0.7286***	-0.7867***	-0.7458***	-0.7585***	-0.7822***
	(0.0308)	(0.0310)	(0.0344)	(0.0345)	(0.0344)
$\ln(\text{dist}_{ij}) \times EC_{it}$		0.1004***	0.1068***		0.1679***
		(0.0246)	(0.0270)		(0.0406)
$\ln(\text{dist}_{ij}) \times EC_{jt}$		0.0643***	0.0877***		0.0884**
		(0.0200)	(0.0218)		(0.0367)
$\ln(\text{dist}_{ij}) \times Deg_{it}$				0.0593*	-0.1383***
				(0.0351)	(0.0463)
$\ln(\text{dist}_{ij}) \times Deg_{jt}$				0.0737**	-0.0411
				(0.0323)	(0.0484)
$\ln(\text{dist}_{ij}) \times BC_{it}$			-0.0225**	-0.0567***	-0.0028
			(0.0094)	(0.0149)	(0.0163)
$\ln(\text{dist}_{ij}) \times BC_{jt}$			-0.0416***	-0.0746***	-0.0442**
			(0.0133)	(0.0196)	(0.0223)
$\ln(\text{dist}_{ij}) \times CC_{it}$				0.0914***	0.1184***
				(0.0337)	(0.0360)
$\ln(\text{dist}_{ij}) \times CC_{jt}$				0.0410	0.0645**
				(0.0321)	(0.0319)
Bilateral controls	Yes	Yes	Yes	Yes	Yes
Exporter–time FE	Yes	Yes	Yes	Yes	Yes
Importer–time FE	Yes	Yes	Yes	Yes	Yes
Observations	105,194	105,194	105,194	105,194	105,194
Pseudo R^2	0.94185	0.94380	0.94438	0.94401	0.94501

Notes: PPML estimates of augmented gravity equations. EC_{it}, Deg_{it}, BC_{it}, and CC_{it} denote exporter eigenvector, weighted degree, betweenness, and closeness centrality, respectively. Interaction terms capture how digital network position attenuates the trade-reducing effect of distance. Column (1) is the baseline structural gravity. Column (2) considers eigenvector centrality. Column (3) considers eigenvector centrality and betweenness centrality jointly. Column (4) includes the alternative centrality measures jointly. Column (5) includes all centrality measures jointly. All centrality measures have been demeaned and normalized by the sample-wise standard deviation, so that the main distance effect can be interpreted as the effect at the mean and interaction coefficients have a comparable order of magnitude. We use as bilateral controls contiguity, shared colonial history, common language, free trade agreement, common legal system and common religion. Standard errors clustered at the pair level are shown in parentheses. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 3: Digital Network Centrality and Multilateral Resistance

	(1) Eigenvector	(2) Alternatives (1)	(3) Alternatives (2)	(4) All Centralities
Panel A. Exporter-side (Outward MR / Exporter–time FE)				
EC_{it}	0.0716	0.1152		-0.0614
	(0.0741)	(0.0708)		(0.1095)
BC_{it}		-0.1442**	-0.2206***	-0.2334***
		(0.0604)	(0.0731)	(0.0724)
CC_{it}			-0.1463*	-0.1506*
			(0.0856)	(0.0859)
Deg_{it}			0.2725***	0.3349**
			(0.0890)	(0.1365)
Country controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	926	926	926	926
R^2	0.91779	0.91935	0.92154	0.92164
Within R^2	0.89005	0.89214	0.89507	0.89520
Panel B. Importer-side (Inward MR / Importer–time FE)				
EC_{jt}	0.0959**	0.0852*		0.0791
	(0.0485)	(0.0488)		(0.0737)
Deg_{jt}			0.1201*	0.0397
			(0.0642)	(0.0882)
BC_{jt}		0.0355	0.0142	0.0306
		(0.0385)	(0.0392)	(0.0448)
CC_{jt}			-0.0763	-0.0707
			(0.0638)	(0.0635)
Country controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	926	926	926	926
R^2	0.95040	0.95053	0.95071	0.95093
Within R^2	0.92017	0.92038	0.92067	0.92103

Notes: This table reports second-stage regressions relating exporter–time and importer–time fixed effects from the *baseline* structural gravity specification to measures of digital network centrality. Because the fixed effects are obtained from a gravity model without distance–centrality interactions, they retain the standard interpretation as outward and inward multilateral resistance (market access). EC_{ct} denotes eigenvector centrality, while Deg_{ct}, BC_{ct}, and CC_{ct} denote weighted degree, betweenness, and closeness centrality, respectively. Column (1) considers eigenvector centrality. Column (2) considers eigenvector centrality and betweenness centrality jointly. Column (3) compares eigenvector centrality to alternative network measures. Column (4) includes all centrality measures jointly. Positive coefficients indicate that higher digital network centrality is associated with lower multilateral resistance. All centrality measures have been normalized by the sample-wise standard deviation, so that the interaction coefficients have a comparable order of magnitude. We use as country controls the WTO membership status, the European Union membership status, the log of remoteness index, log GDP, and log GDP per capita. Standard errors clustered at the country level are shown in parentheses. * p<0.05, ** p<0.01, *** p<0.001.

Two patterns stand out. First, exporter-side multilateral resistance is most robustly associated with the scale and redundancy of direct digital connectivity, as captured by weighted degree, which enters positively and significantly in both the standalone and joint specifications. Second, exporter betweenness centrality is consistently negative and statistically significant. In our data, countries with high betweenness centrality include major intercontinental routing hubs such as the United States, Egypt, France, and the United Kingdom. These countries host key landing points along strategic corridors (e.g., the North Atlantic routes or the Red Sea–Suez gateway linking Europe and Asia) and therefore lie on a large share of shortest paths in the global subsea network. This structural position may confer brokerage advantages but can also expose countries to congestion risks or routing dependence, helping explain why higher betweenness is associated with weaker exporter-side market access in the multilateral-resistance regressions. On the importer side, eigenvector centrality remains positively associated with market access in parsimonious specifications but becomes smaller and statistically insignificant once alternative measures are included.

Overall, the results in Table 3 suggest that correlations with multilateral resistance reflect a broader set of connectivity characteristics than those governing distance sensitivity alone, with direct connectivity scale playing a particularly important role for exporter-side market access.[6]

Taken together, Tables 2 and 3 highlight a clear distinction between the channels through which digital network position affects trade. Table 2 shows that eigenvector centrality (capturing embeddedness in the core of the global digital network) plays a dominant role in attenuating the trade-reducing effect of geographic distance. This channel operates through the marginal sensitivity of bilateral trade to distance and is consistent with the interpretation of eigenvector centrality as a proxy for multilateral information availability and spillovers that are especially valuable in long-distance transactions. By contrast, Table 3 indicates that overall market access, as summarized by multilateral resistance, is less tightly linked to eigenvector centrality on the exporter side and is in-

[6]Online Appendix Table D.2 reports multilateral-resistance regressions with each centrality measure entered separately. The qualitative patterns of Table 3 are preserved: degree retains a positive coefficient on the exporter side, betweenness remains negatively associated, and eigenvector centrality remains positive on the importer side. Coefficient attenuation in the fully saturated model thus reflects overlap across measures rather than instability of the underlying relationships.

stead more strongly associated with the scale and redundancy of direct digital connectivity, as well as with other topological features such as betweenness. This pattern suggests that while embeddedness in the digital core is central to weakening distance-related information frictions, overall market access also reflects the extensive capacity and structural position of countries within the digital network.

One final methodological comment concerns closeness centrality. While this measure is well behaved for most countries, it can be problematic for nodes with very sparse connectivity. For such countries, only a limited subset of the network is reachable, and because closeness centrality is computed solely over reachable nodes, the measure can be highly sensitive to the addition of new connections. In particular, new links may expand the set of reachable countries to include very distant nodes, mechanically increasing average path length and thereby reducing closeness centrality. As a result, the metric can exhibit counterintuitive movements. For example, when Fiji became connected to the global subsea cable network through a new cable in 2019, its closeness centrality declined rather than increased, as the new connection granted access to a large number of previously unreachable but geographically distant countries.

7 Conclusion

This paper has examined how digital infrastructure shapes the spatial organization of international trade in goods. Focusing on data availability as a source of information and coordination frictions, we have shown that countries' positions in the global digital infrastructure network play a systematic role in determining both the sensitivity of trade to geographic distance and countries' overall market access in general equilibrium.

The paper's central contribution is to introduce digital network position as a structural object in the gravity model of trade. Rather than treating digitalization as a purely local technology or access shock, we model it as a networked phenomenon whose topology matters for economic outcomes. Using the global subsea cable network to construct country-level measures of digital network position, we find that countries occupying more central positions in the digital network face a substantially weaker trade-reducing effect of distance. This attenuation is driven primarily by exporter-side network embeddedness and is most robust for eigenvector centrality, which captures integration into the core of the global digital network rather than simple connectivity or brokerage alone.

We further show that digital network position is associated with lower outward and inward multilateral resistance, consistent with a market-access interpretation of digital infrastructure. Importantly, different dimensions of network position play distinct roles in shaping market access: while higher-order embeddedness is central to attenuating distance-related frictions, broader features of digital connectivity (such as the scale and structure of direct connections) are more closely associated with equilibrium market access. This pattern indicates that distance attenuation explains an important share, but not all, of the relationship between digital network position and market access, pointing to broader general-equilibrium channels through which digital connectivity reshapes trade patterns.

To convey the economic magnitude of these effects, Table 4 translates the estimated distance–centrality interactions into intuitive "distance-equivalent" benchmarks. Using the coefficients from the distance-sensitivity specifications, we compute the reduction in physical distance that would generate the same change in the distance component of the gravity equation as a one–standard-deviation increase in exporter and importer eigenvector centrality. The magnitudes reported in Table 4 suggest that, for representative intercontinental trade routes (such as Europe–North America, Europe–East Asia, or Europe–Oceania) improvements in digital network embeddedness correspond to very large reductions in effective trade distance across specifications. Because the interaction effect scales with $\ln(\text{dist}_{ij})$, these distance-equivalent effects are largest for geographically distant pairs, consistent with the interpretation that digital network embeddedness primarily attenuates distance-amplified information frictions. While these calculations should not be interpreted as literal substitutes for geography, they provide an intuitive benchmark illustrating that improvements in digital connectivity can have economically large effects on long-distance trade.[7]

Table 4: Distance-equivalent effect of a +1 s.d. increase in eigenvector centrality

Distance bin	Col. (1)	Col. (2)	Col. (3)	Col. (5)
4,000 km (Europe–Sub-Saharan Africa)	0.0%	82.3%	88.5%	93.4%
6,000 km (Europe–North America)	0.0%	83.7%	89.7%	94.2%
8,000 km (Europe–East Asia / North America–South America)	0.0%	84.7%	90.4%	94.8%
10,000 km (Europe–East Asia / North America–East Asia)	0.0%	85.4%	91.0%	95.1%
12,000 km (Europe–South America)	0.0%	86.0%	91.4%	95.4%
16,000 km (Europe–Oceania)	0.0%	86.8%	92.0%	95.8%

Notes: Each entry reports the percent reduction in bilateral distance dist_{ij} that yields the same change in the distance term as a $+1$ standard-deviation increase in *both* exporter and importer eigenvector centrality. Calculations use the coefficients on $\ln(\text{dist}_{ij})$, $\ln(\text{dist}_{ij}) \times EC_{it}$, and $\ln(\text{dist}_{ij}) \times EC_{jt}$ from the corresponding columns of Table 2, evaluated at the representative distance shown. Column (1) includes no eigenvector-centrality interactions and therefore implies a zero distance-equivalent benchmark by construction. Distance bins correspond to rounded great-circle distances between population-weighted country centroids for major intercontinental trading regions, following standard practice in CEPII gravity datasets.

Taken together, these findings have several implications. Conceptually, they underscore that digital infrastructures are not merely technical backbones of the digital economy but fundamental spatial determinants of international economic integration. Empirically, they highlight the value of exploiting the topology of global digital infrastructure networks—rather than relying solely on reduced-form proxies such as Internet penetration or regulatory indices—to study the economic effects of data availability. From a policy perspective, the results imply that investments in digital infrastructure and the governance of cross-border data flows can have far-reaching consequences for trade integration, particularly for geographically distant or peripheral economies.

More broadly, the paper reinforces the importance of incorporating network structure into spatial economic analysis. As data-intensive technologies continue to diffuse and global digital infrastructures expand, understanding how network topology interacts with geography will be essential for explaining future patterns of trade, production, and economic development.

[7] Details are provided in Online Appendix C.

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Appendix A: Construction of the Subsea Cable Network Dataset

This appendix describes the construction of the inter-country network of subsea cables used to compute digital network centrality measures.

Sources and scope. The subsea cable data was originally retrieved from the GitHub repository `https://github.com/bunam/submarine_cable_map`, which keeps a version of the dataset publicly available from the Telegeography Git-Hub repository in 2022, subject to the CC BY-NC-SA 3.0 license. The dataset covers the universe of subsea cables recorded by TeleGeography as of 2022, including planned and under-construction cables. The analysis restricts attention to cables that were ready for service before 2020, ensuring that all connections used to compute centrality correspond to operational infrastructure. We complemented the geographic data of the cables with additional information available on the freely available TeleGeography's *Submarine Cable Map* (`https://www.submarinecablemap.com/`), which provides comprehensive information on the global network of subsea fiber-optic cables, including cable routes, landing points, Ready-for-Service (RFS) dates, and operational status. We kindly thank Telegeography for the permission to use the dataset and the information contained in the cable map.

Definition of nodes. The network is constructed at the level of countries or territorial areas. Territorial areas are defined as geographic units under the same political authority that lie within 100 kilometers of one another. This aggregation rule ensures that closely connected territories (such as mainland–island configurations) are treated as a single node when they effectively share digital infrastructure. Each node is assigned a geographic centroid, which can be used for visualization and for computing great-circle distances between nodes.

Definition of edges. Edges in the network correspond to direct subsea cable connections between pairs of nodes. Two nodes are considered connected if at least one subsea cable links them without passing through a third country or territorial unit. This definition isolates direct bilateral digital connections and avoids conflating them with indirect routing through transit hubs. When multiple cables connect the same pair of nodes, these connections are aggregated. The strength of the edge between nodes i and j is defined as the total number of distinct subsea cables directly connecting them. This aggregation captures both capacity and redundancy in bilateral digital connectivity and highlights countries that act as major connection hubs or chokepoints in the global data network.

Temporal reconstruction. Cable-level RFS dates are used to reconstruct the evolution of the global subsea cable network over time. Each cable enters the network in the year in which it becomes operational and remains active thereafter. Using this information, a sequence of annual networks is constructed, allowing the topology of the global data network to be traced over time. For the empirical analysis in the main text, centrality measures are computed using the network as observed from 2015 to 2020.

Adjacency matrix and weighting. Bilateral cable connections are organized into an undirected, weighted adjacency matrix A_t, where each element A_{ijt} summarizes the strength of direct subsea connectivity between countries i and j in year t. Edge weights are designed to reflect primarily the number and redundancy of active direct subsea cables connecting a given pair of countries. Cable-level information on geographic length is incorporated only through a deliberately weak penalty (a_w=0.05), so that differences in cable length have a marginal effect on the resulting weights. This design choice ensures that network centrality captures connectivity intensity and redundancy rather than precise transmission distances, which are accounted for explicitly in the gravity specification.

Centrality measures. Standard network centrality measures are computed from the adjacency matrix. These include weighted degree centrality, betweenness centrality, closeness centrality, and eigenvector centrality (see Appendix C for definitions). Eigenvector centrality is emphasized in the empirical analysis as the main proxy for multilateral digital accessibility, as it assigns greater weight to connections with highly connected nodes and captures embeddedness in the core of the global data network rather than purely bilateral connectivity.

Visualization and geographic representation. For visualization purposes, the network is plotted on a world map using great-circle paths to represent subsea cable routes. This procedure accounts for the spherical shape of the Earth and ensures an accurate depiction of long-distance connections, including cables that cross the International Date Line. Node size in these visualizations is scaled by the total number of cable connections.

Overall, this dataset provides a physically grounded representation of the global digital infrastructure, allowing countries' positions in the subsea cable network to be mapped into network centrality measures that proxy multilateral access to global data transmission capacity. The resulting world data network is visualized in Figures 1 and 2 at the beginning (2015) and the end (2020) of the observation period respectively. The line connecting two nodes is based on the coordinates of their centroids and shows the great-circle path considering the earth as rounded rather then flat. The size (radius) of a node represents the number of its total connections. An important feature of the network over this period is that, while the number of nodes is essentially constant, their radius changes. Analogously, the number of edges is rather stable, but their strength evolves. This implies that countries' network centrality can still evolve even though there are virtually no country pairs connected for the first time

Appendix B: Alternative Network Centrality Measures

This appendix describes the alternative network centrality measures used in the empirical analysis and explains how they differ conceptually from eigenvector centrality. All measures are computed on the weighted, undirected inter-country network of subsea cable connections described in Appendix A, with adjacency matrix elements A_{ijt} representing the strength of the digital connection between countries i and j in year t.

Weighted degree centrality. Weighted degree centrality measures the total strength of a country's direct digital connections. It is defined as

$$Deg_{it} = \sum_{j} A_{ijt}.$$

This measure captures the scale and redundancy of a country's immediate access to the digital infrastructure network, reflecting how many direct subsea cable links it has and how intensively it is connected to its neighbors. Unlike eigenvector centrality, weighted degree does not account for the connectivity of a country's partners and therefore does not capture higher-order network effects or embeddedness in the global digital core.

Betweenness centrality. Betweenness centrality measures the extent to which a country lies on the shortest paths between other pairs of countries in the network. Let σ_{jk} denote the total number of shortest paths between countries j and k, and let $\sigma_{jk}(i)$ denote the number of those paths that pass through country i. Betweenness centrality is defined as

$$BC_{it} = \frac{2\sum_{j\neq i}\sum_{k\neq i,j}\frac{\sigma_{jk}(i)}{\sigma_{jk}}}{(N-1)(N-2)}.$$

where N is the number of countries connected to the network. This measure captures a country's potential role as a routing hub or chokepoint in the global digital network. A country with high betweenness centrality may exert control over data routing or enjoy strategic importance as an intermediary, even if it is not highly connected overall. Betweenness centrality therefore reflects brokerage rather than embeddedness and does not directly measure multilateral access to global digital infrastructure.

Closeness centrality. Closeness centrality measures how close a country is, on average, to all other countries in the network. Let d_{ij} denote the length of the shortest path between countries i and j, where path length is defined using the inverse of edge weights so that stronger connections imply shorter distances. Closeness centrality is defined as

$$CC_{it} = \left(\frac{\sum_{j\neq i} d_{ij}}{N-1}\right)^{-1}.$$

This measure captures average network proximity and reflects how quickly information or data can reach a country from the rest of the network. While closeness centrality is informative about latency and reachability, it does not distinguish between being connected to peripheral versus highly central partners and therefore does not capture the cumulative spillovers associated with embeddedness in the network core.

Comparison with eigenvector centrality. Eigenvector centrality differs from the measures above by assigning greater weight to connections with highly connected countries. It is defined as the solution to

$$EC_{it} = \frac{1}{\lambda_t} \sum_j A_{ijt} \, EC_{jt},$$

where λ_t is the largest eigenvalue of the adjacency matrix in year t. This recursive definition implies that connections to well-connected countries contribute more to centrality than connections to peripheral ones. As a result, eigenvector centrality captures a country's embeddedness in the core of the global digital network and reflects access to the global data infrastructure as a whole rather than purely bilateral connectivity.

In the empirical analysis, weighted degree, betweenness, and closeness centrality are used as alternative measures to assess whether the results attributed to eigenvector centrality can be explained by simpler notions of connectivity, brokerage, or proximity.

Appendix C: Distance-Equivalent Effects of Digital Network Centrality

This appendix provides an intuitive mapping between changes in digital network centrality and changes in physical distance implied by the estimated distance–centrality interactions in the gravity model. The purpose of this exercise is not to reinterpret digital centrality as a literal substitute for geographic distance, but to construct transparent distance-equivalent benchmarks that help gauge the economic magnitude of the estimated distance-attenuation effects.

The mapping exploits the interaction structure of the baseline distance-sensitivity specification reported in Table 2. In particular, the estimated gravity equation can be written as

$$\ln X_{ij} = \cdots + \beta_1 \ln dist_{ij} + \beta_2 \left(\ln dist_{ij} \times EC_{it}\right) + \beta_3 \left(\ln dist_{ij} \times EC_{jt}\right) + \cdots,$$

where EC_{it} and EC_{jt} denote exporter- and importer-side eigenvector centrality, respectively. Because eigenvector centrality is demeaned and normalized by its sample-wise standard deviation, a one-unit increase in EC_{it} or EC_{jt} corresponds to a one–standard-deviation increase in centrality.

Consider a simultaneous one–standard-deviation increase in both exporter and importer eigenvector centrality. Holding all other components of the gravity equation fixed, this change alters the contribution of the distance term by $(\beta_2 + \beta_3) \ln dist_{ij}$. To express this effect in intuitive units, we define the *distance-equivalent reduction* as the percentage decrease in physical distance that would generate the same change in the distance component of the gravity equation through the baseline distance coefficient β_1 alone. Formally, letting $dist'_{ij}$ denote the counterfactual distance that yields the same change in trade, the implied ratio satisfies

$$\frac{dist'_{ij}}{dist_{ij}} = dist_{ij}^{(\beta_2+\beta_3)/\beta_1},$$

so that the distance-equivalent effect is given by $100 \times \left(1 - dist'_{ij}/dist_{ij}\right)$.

Two assumptions underlie this mapping. First, in computing the distance-equivalent benchmarks we abstract from any impact that changes in digital centrality may have on outward and inward multilateral resistance terms. This is appropriate because the objective of the exercise is to isolate the distance-attenuation channel captured by the interaction terms, and because the corresponding fixed-effect regressions indicate that this channel does not drive the market-access results. Second, the mapping evaluates the distance-attenuation effect relative to a baseline in which digital centrality does not affect the distance component of trade costs, ensuring that the benchmark isolates the role of geographic distance and the estimated coefficients.

Table 4 reports these distance-equivalent reductions for benchmark bilateral distances of 2,000 km, 5,000 km, and 10,000 km, using the eigenvector-centrality interaction coefficients from Columns (1), (2), (3), and (5) of Table 2. Column (1), which includes no eigenvector-centrality interactions, implies a zero distance-equivalent effect by construction. Columns (2) and (3), which focus on eigenvector centrality in parsimonious and partially augmented specifications, yield substantial distance-equivalent reductions that increase with distance, reflecting the fact that the interaction effect scales with $\ln dist_{ij}$. Column (5), which includes all centrality measures jointly, produces even larger distance-equivalent benchmarks, illustrating how the mapping becomes more sensitive when multiple, correlated network measures compete within the same specification.

The main message of Table 4 is that improvements in digital network embeddedness (as measured by eigenvector centrality) can have economically large effects on long-distance trade by attenuating distance-amplified information frictions. At the same time, these calculations should be interpreted as illustrative distance-equivalent benchmarks rather than literal distance substitutions, as digital centrality operates by reshaping information and coordination costs rather than by altering geography itself.

Appendix D: Robustness to Alternative Centrality Specifications

This appendix presents additional specifications in which alternative measures of digital network centrality are entered separately in the distance-sensitivity and multilateral-resistance regressions. These tables complement the joint specifications reported in the main text.

To address concerns about potential multicollinearity among alternative centrality measures, Table D.1 reports specifications in which each distance–centrality interaction is included separately. When entered individually, the interaction terms retain their expected signs and broadly similar magnitudes relative to the baseline specification. The instability observed in the fully saturated model of Table 2 therefore reflects overlap across centrality measures rather than sensitivity of the distance attenuation effect to model specification. In particular, the attenuation effect associated with exporter eigenvector centrality remains positive and statistically significant across all specifications.

Table D.1: Digital Network Centrality and Distance Sensitivity in Trade

	(1) Degree	(2) Betweenness	(3) Closeness
$\ln(\text{dist}_{ij})$	-0.7742***	-0.7101***	-0.7976***
	(0.0328)	(0.0350)	(0.0322)
$\ln(\text{dist}_{ij}) \times Deg_{it}$	0.0633***		
	(0.0178)		
$\ln(\text{dist}_{ij}) \times Deg_{jt}$	0.0259		
	(0.0163)		
$\ln(\text{dist}_{ij}) \times BC_{it}$		-0.0012	
		(0.0099)	
$\ln(\text{dist}_{ij}) \times BC_{jt}$		-0.0212	
		(0.0133)	
$\ln(\text{dist}_{ij}) \times CC_{it}$			0.0994***
			(0.0223)
$\ln(\text{dist}_{ij}) \times CC_{jt}$			0.0359*
			(0.0193)
Bilateral controls	Yes	Yes	Yes
Exporter–time FE	Yes	Yes	Yes
Importer–time FE	Yes	Yes	Yes
Observations	105,194	105,194	105,194
Pseudo R^2	0.94252	0.94201	0.94276

Notes: PPML estimates of augmented gravity equations. Deg_{ct}, BC_{ct}, and CC_{ct} denote weighted degree, betweenness, and closeness centrality for country c at time t (exporter i or importer j). Interaction terms capture how digital network position attenuates the trade-reducing effect of distance. We use as bilateral controls contiguity, shared colonial history, common language, free trade agreement, common legal system and common religion. Standard errors clustered at the pair level are shown in parentheses. * p<0.05, ** p<0.01, *** p<0.001.

To further assess the role of potential multicollinearity among centrality measures in the multilateral resistance regressions, Table D.2 reports specifications in which each centrality measure is entered separately. The results confirm the patterns documented in Table 3. In particular, weighted degree centrality retains a positive coefficient on the exporter side, while betweenness centrality remains negatively associated with exporter-side market access. On the importer side, eigenvector centrality remains positively related to inward market access in parsimonious specifications. These findings again indicate that the attenuation of some coefficients in the fully saturated specification reflects overlap across network measures rather than instability of the underlying relationships.

Table D.2: Digital Network Centrality and Multilateral Resistance

	(1) Degree	(2) Betweenness	(3) Closeness
Panel A. Exporter-side (Outward MR / Exporter–time FE)			
Deg_{it}	0.0712		
	(0.0764)		
BC_{it}		-0.1104**	
		(0.0457)	
CC_{it}			-0.0726
			(0.0745)
Country controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	926	926	926
R^2	0.91773	0.91838	0.91778
Within R^2	0.88997	0.89084	0.89003
Panel B. Importer-side (Inward MR / Importer–time FE)			
Deg_{jt}	0.0924*		
	(0.0517)		
BC_{jt}		0.0605*	
		(0.0326)	
CC_{jt}			-0.0208
			(0.0559)
Country controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	926	926	926
R^2	0.95020	0.94980	0.94943
Within R^2	0.91986	0.91921	0.91861

Notes: This table reports second-stage regressions relating exporter–time and importer–time fixed effects from the *baseline* structural gravity specification to alternative measures of digital network centrality. Deg_{ct}, BC_{ct}, and CC_{ct} denote weighted degree, betweenness, and closeness centrality, respectively. All centrality measures have been normalized by the sample-wise standard deviation. We use as country controls the WTO membership status, the European Union membership status, the log of remoteness index, log GDP, and log GDP per capita. Standard errors clustered at the country level are shown in parentheses. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.