Spatial Trade with Transportation Markets*

Busra Ariduru† Germán Pupato‡

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Abstract

Iceberg costs are pervasive in trade and geography models, but rule out equilibrium transportation prices. We develop a spatial model with competitive transportation markets. Truckers select routes subject to idiosyncratic costs, generating upward-sloping supply on each route. As cost heterogeneity vanishes, transportation supply becomes perfectly elastic and our theory converges to a spatial model with iceberg costs that nests Costinot et al. (2012) and a version of Allen and Arkolakis (2014). We derive a welfare decomposition that highlights the role of endogenous transportation prices and characterize analytically how transportation markets propagate and amplify local cost shocks via general equilibrium effects. We combine an original dataset of freight rates with Freight Analysis Framework shipment data across 129 North American regions to study the elimination of the Interstate Highway System, the harmonization of interstate trucking regulations, the closure of the U.S.–Canada border, and the adoption of autonomous trucks. Transportation markets amplify welfare effects by 13–29% relative to the iceberg benchmark.

Keywords: transportation markets, iceberg costs, trade costs, trucking, freight, infrastructure, borders

JEL Codes: F14, F15, R13, R41

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†Department of Economics, Toronto Metropolitan University; eariduru@torontomu.ca

‡Department of Economics, Toronto Metropolitan University; gpupato@torontomu.ca

1 Introduction

Transportation costs are central to many topics in economics, from agglomeration (Krugman, 1991) and border effects (Anderson and Van Wincoop, 2003) to transportation infrastructure (Donaldson, 2018) and the welfare gains from economic integration (Arkolakis et al., 2012). The stakes are high: in 2017, 19.8 billion tons of goods worth $18.9 trillion flowed through the U.S. transportation network, including 2.3 billion tons traded internationally (Bureau of Transportation Statistics, 2021).

In modeling transportation costs, the literature has widely adopted the *iceberg assumption* (von Thünen, 1826; Samuelson, 1954), now a standard feature in quantitative trade and economic geography models. Treating transportation costs as exogenous cost shifters, this 'trick of the genre' (Krugman, 1998, p.164) sidesteps modeling a transportation industry and enhances analytical tractability.

The iceberg assumption, however, is not without challenges. Empirically, iceberg costs are incompatible with the existence of additive components in transportation costs; e.g., Hummels and Skiba (2004) and Bosker and Buringh (2020). Conceptually, local shocks to iceberg costs can have only local effects on transportation costs, ruling out potentially relevant propagation channels of economic shocks. For example, under the iceberg assumption, the cost of shipping from Chicago to New York City must be independent of both changes in U.S.–Canada border regulations and road infrastructure improvements between Houston and Los Angeles.

We address these shortcomings by treating transportation costs as equilibrium prices that respond endogenously to economic shocks. We build a multi-region, multi-sector spatial trade model with competitive transportation markets for each origin-destination pair—a distinct market for each directional route, or N^2 markets across N regions. Transportation supply is modeled as a discrete choice problem in which truckers select optimal routes subject to fundamental and idiosyncratic costs. We interpret fundamental costs as route-specific shipping costs determined by geography, infrastructure quality, transportation technology, and border regulation. We investigate how transportation markets shape the impact of fundamental cost shocks on the spatial distribution of transportation costs and social welfare.

We derive three analytical results. First, we show that our theory nests workhorse spatial trade models with iceberg costs. As idiosyncratic cost heterogeneity vanishes, the supply of transportation services becomes perfectly elastic in all transportation markets and the equilibrium converges to a spatial model with iceberg costs that nests Costinot et al. (2012) and a version of Allen and Arkolakis (2014). We label this limiting case the *Iceberg Limit* equilibrium. It provides a benchmark for assessing how transportation markets propagate fundamental cost shocks, relative to the standard iceberg formulation.

Second, we derive a welfare formula that decomposes the effects of fundamental cost shocks into two sufficient statistics: changes in internal trade shares and changes in internal transportation prices. While the former channel is conventional in the literature, the latter is unique to our model and highlights the welfare implications of endogenizing transportation costs. Our welfare formula converges to the ACR formula of Arkolakis et al. (2012) in the Iceberg Limit.

Third, we show that transportation markets amplify the impact of local fundamental cost shocks on the distribution of transportation prices via general equilibrium effects. With symmetric regions and industries, a reduction in the fundamental cost of shipping across regions triggers a reallocation of transportation demand away from internal markets and an increase in transportation supply in all markets, reducing equilibrium prices in *all* transportation markets. In contrast, iceberg cost shocks in the Iceberg Limit do not propagate beyond a direct effect on the local transportation market.

To quantify the model, we use data from the Freight Analysis Framework (FAF5) and Statistics Canada to measure the value of bilateral truck shipments for 128 U.S. locations and a single, aggregate Canada. Because shipment values in the FAF5 are net of freight charges, we assemble an original dataset of shipping prices to and from every location in the FAF5 data.

A central step in parameterizing the model is estimating the elasticity of transportation supply, the parameter that disciplines our departure from the iceberg formulation. The empirical challenge is the simultaneity of transportation prices and quantities. We address this with 2SLS, using an instrument based on each destination's geographical remoteness—a demand shifter that we show is a first-order approximation of the destination's multilateral resistance term, derived from the gravity equation that governs transportation demand.

The 2SLS estimation yields a supply elasticity of 7.9 for the typical transportation market in the dataset. We estimate fundamental shipping costs by including splines for driving time and distance and dummies for state and U.S.–Canada borders as controls in the 2SLS estimation. As expected, the estimated fundamental costs increase monotonically but non-linearly in time and distance. We find that the U.S.–Canada border effect is not statistically different from the state border effect.

After checking the calibrated model's fit, we present four counterfactual exercises, each targeting a component of fundamental costs: (i) the elimination of the Interstate Highway System (IHS, infrastructure); (ii) the harmonization of interstate trucking regulations (domestic border regulation); (iii) the closure of the U.S.–Canada border (international border regulation); (iv) the adoption of fully autonomous trucks (transportation technology). In each exercise, we compare the baseline model with endogenous transportation prices to the Iceberg Limit, holding constant all parameters other than the transportation supply elasticity.

We find that transportation markets amplify fundamental cost shocks. Across the four exercises, the average change in equilibrium transportation costs is 30–57% larger in absolute value in the baseline than under the Iceberg Limit. These effects propagate to welfare: baseline welfare effects are 13–29% larger in absolute value than under the Iceberg Limit. Each experiment highlights a distinct facet of the amplification: IHS elimination propagates into internal transportation markets that are not directly shocked (-0.22% vs -0.17%); interstate-regulation harmonization spills over to Canadian transportation prices via a terms-of-trade deterioration (U.S. welfare: $+0.67\%$ vs $+0.52\%$); closing the U.S.–Canada border raises domestic transportation prices endogenously—a channel typically absent in the literature (-0.32% vs -0.28%); and autonomous trucks deliver welfare gains equivalent to a uniform 14% TFP shock in the manufacturing sector ($+2.03\%$ vs $+1.57\%$).

We decompose baseline welfare changes to gauge the contribution of transportation markets. Changes in internal transportation prices account for 27–44% of the total welfare change. In the Iceberg Limit, this channel can only be activated exogenously—when internal iceberg costs are directly shocked—and is exactly zero in three of our four exercises. Policy evaluations based on the iceberg assumption may therefore understate the welfare consequences of infrastructure investment, border regulation, and technology adoption.

Related Literature. Our paper builds on a large literature that uses quantitative trade models to study trade costs in international trade and economic geography, including Eaton and Kortum (2002), Anderson and Van Wincoop (2003), Alvarez and Lucas (2007), Allen and Arkolakis (2014), Redding (2016), and Caliendo et al. (2018), among many others; Redding and Turner (2015) and Redding and Rossi-Hansberg (2017) provide surveys. In these papers, trade costs are exogenous and follow the iceberg formulation. Matsuyama (2007) argues this is not an innocuous assumption but a substantive restriction on the mechanisms through which trade costs affect the economy.

A growing literature endogenizes transportation costs in trade models through imperfect competition (Hummels et al., 2009; Ishikawa and Tarui, 2018; Asturias, 2020; Hafner et al., 2023; Allen et al., 2024b). We focus on the trucking industry in North America, where extreme carrier fragmentation makes perfect competition with free entry the natural starting point, and embed it in a multi-sector spatial model that nests a class of workhorse trade and geography models with iceberg costs. This lets us study analytically and quantitatively how transportation markets shape the propagation of local cost shocks across space, relative to the standard iceberg formulation.

Building on Behrens and Picard (2011), Wong (2022) develops an Armington trade model of the round-trip effect in maritime trade, where a shock to transportation costs on a route also affects the price in the opposite direction. This approach features perfectly elastic transportation supply functions, constraining the propagation of local cost shocks—e.g., precluding changes in domestic relative transportation prices in response to border regulation changes, a mechanism active in our paper. Coşar et al. (2024) study the long-run effects of US transportation productivity growth in a competitive model that partially endogenizes transportation costs, with exogenous relative prices for any given origin.

A recent literature develops rich models of the transportation industry—featuring search frictions, dynamic carrier decisions, matching, and congestion—to study trade patterns, efficiency and infrastructure investment in maritime shipping; see Brancaccio et al. (2020, 2023, 2024). Yang (2024) models truckers' dynamic route choices with home preference and studies how the spatial distribution of drivers shapes interstate trucking costs. In this literature, the production side (the quantity and value of shipments) is exogenous. We adopt a more parsimonious description of the transportation industry but embed it in general equilibrium to study how transportation cost shocks amplify beyond the industry.

Finally, our work is distinct from and complementary to two strands of the literature. The first embeds optimal-route choice in quantitative spatial models, as in Allen and Arkolakis (2022) and Ganapati et al. (2024): a local infrastructure shock reshapes iceberg costs across many origin–destination pairs by redirecting traffic to alternative paths through the network. In our theory, by contrast, the price of shipping along the direct route between two locations is determined in equilibrium, so a local infrastructure shock propagates to transportation prices throughout the economy through general-equilibrium adjustments — without invoking the long detour walks that drive spatial propagation in this literature. The second strand, exemplified by Alessandria et al. (2010), derives an implicit iceberg cost from fixed transaction costs and lumpy inventory management. Whereas this approach revisits the iceberg assumption along a dynamic dimension, ours focuses on a spatial one.

Outline. Section 2 introduces the model. Section 3 derives three analytical propositions and illustrates the amplification mechanism with a numerical example. Section 4 describes the data, estimation, and calibration. Section 5 presents four counterfactual exercises. Section 6 concludes. The online Appendix is organized in three parts: Appendix A contains technical derivations, the algorithm used to compute baseline and counterfactual equilibria, and proofs of all propositions; Appendix B documents data, estimation, identification, and calibration; and Appendix C provides institutional background on interstate and U.S.–Canada trucking regulations, and additional counterfactual results.

2 Theoretical Framework

The economy has N locations (regions or cities) in two countries, $N-1$ in the U.S. and 1 in Canada. There are J tradable goods and one non-tradable good, all produced under perfect competition with constant returns to scale. The production of tradable goods requires workers and transportation services in fixed proportions. The non-tradable good is produced solely with labor. Each location has an endowment of residential land and each country has an endowment of workers. Labor is mobile within, but not across, countries. All goods, services, and inputs are supplied competitively. We denote any particular location by n or i and sort U.S. locations from 1 to $N-1$. We denote any particular tradable good by $j \geq 1$ and the non-tradable good by $j = 0$.

Consumer Preferences. The preferences of workers living in location $n \in \{1, ...N\}$ are described by a two-tier utility function that depends on the consumption of goods (C_n^j) and the use of residential land (H_n):

$$U_n = \prod_{j=0}^{J} \left(\frac{C_n^j}{\alpha^j} \right)^{\alpha^j} \left(\frac{H_n}{1-\alpha} \right)^{1-\alpha}, \quad \sum_{j=0}^{J} \alpha^j \equiv \alpha, \tag{1}$$

where $\alpha^j > 0$ for all j and $0 < \alpha < 1$.

The consumption index for each tradable good, C_n^j for $j \geq 1$, is defined over the consumption of a fixed continuum of symmetric varieties $\omega^j \in [0, 1]$:

$$C_n^j = \left[\int_0^1 c_n^j(\omega^j)^{\frac{\sigma^j - 1}{\sigma^j}} d\omega^j \right]^{\frac{\sigma^j}{\sigma^j - 1}}, \quad \sigma^j > 1, \ j \geq 1,$$

where σ^j is the constant elasticity of substitution between varieties of good j. The corresponding dual price index is:

$$P_n^j = \left[\int_0^1 p_n^j(\omega^j)^{1-\sigma^j} d\omega^j \right]^{\frac{1}{1-\sigma^j}}, \ j \geq 1. \tag{2}$$

The non-tradable good is homogeneous with price P_n^0. The aggregate consumption price index in location n is

$$P_n^{-\alpha} = \prod_{j=0}^{J} \left(P_n^j \right)^{-\alpha^j}.$$

Technology and Production. Tradable goods are produced with labor and delivered to consumers with transportation services provided by trucks. We assume no substitution between production and transportation. The output of variety ω^j of good j produced in

i and shipped to n is:

$$q_{ni}^{j}(\omega^{j}) = \min\left(\frac{L_{ni}^{j}(\omega^{j})}{\varphi_{i}^{j}}, k_{ni}^{j}(\omega^{j})\right) z_{i}^{j}(\omega^{j}),\ j \geq 1, \tag{3}$$

where parameter φ_i^j determines the (efficient) proportion of workers $L_{ni}^j(\omega^j)$ and trucks $k_{ni}^j(\omega^j)$ allocated to this technology. $z_i^j(\omega^j)$ is the idiosyncratic total factor productivity, independently drawn from a Fréchet distribution with scale parameter A_i^j and shape parameter θ^j.

Under perfect competition, the cost to a consumer in location n of purchasing one unit of variety ω^j from location i is:

$$p_{ni}^{j}(\omega^{j}) = \frac{\varphi_{i}^{j} w_{i} + t_{ni}}{z_{i}^{j}(\omega^{j})},\ \ j \geq 1, \tag{4}$$

where w_i denotes the wage in i and t_{ni} is the transportation price per unit of output shipped from origin i to destination n. Transportation prices are determined endogenously in transportation markets, described below.

Trade Shares and Price Indices. Consumers in location n source each good from the lowest-cost supplier to that location. Using (4) and the properties of the Fréchet distribution, the share of n's expenditure on varieties of good j purchased from i is:

$$\pi_{ni}^{j} = \frac{A_{i}^{j}\left[\varphi_{i}^{j} w_{i} + t_{ni}\right]^{-\theta^{j}}}{\sum_{s=1}^{N} A_{s}^{j}\left[\varphi_{s}^{j} w_{s} + t_{ns}\right]^{-\theta^{j}}},\ \ j \geq 1. \tag{5}$$

After solving for price distributions across varieties, the price of tradable good j in location n is

$$P_{n}^{j} = \Gamma^{j}\left(\sum_{i} A_{i}^{j}(\varphi_{i}^{j} w_{i} + t_{ni})^{-\theta^{j}}\right)^{-\frac{1}{\theta^{j}}},\ j \geq 1, \tag{6}$$

where $\Gamma^j \equiv \Gamma\big((\theta^j + 1 - \sigma^j)/\theta^j\big)^{1/(1-\sigma^j)}$ and $\Gamma(\cdot)$ is the Gamma function.

The price of the non-traded good is

$$P_{n}^{0} = \frac{w_{n}}{A_{n}^{0}}. \tag{7}$$

Demand for Transportation. Because tradable goods require transportation, consumer demand generates demand for transportation. The output of variety ω^j shipped from i to n has the standard CES form

$$q_{ni}^{j}(\omega^{j}) = \alpha^{j} X_{n} (P_{n}^{j})^{\sigma^{j}-1} p_{ni}^{j}(\omega^{j})^{-\sigma^{j}},\ j \geq 1,$$

where X_n denotes total consumer expenditure in n. The Leontief technology (3) determines the number of trucks required to haul $q_{ni}^{j}(\omega^{j})$ units. Integrating across varieties ω^j yields the demand for transportation services from i to n for tradable good j:

$$k_{ni}^{j} = \frac{\alpha^{j} X_{n} \pi_{ni}^{j}}{\left(\varphi_{i}^{j} w_{i} + t_{ni}\right)},\ j \geq 1. \tag{8}$$

Supply of Transportation. We assume that transportation is a homogeneous service supplied competitively under free entry. A fringe of potential entrepreneurs can build trucks to haul tradable goods from any location i by incurring a sunk entry cost f_i per truck.[1] Upon entry, trucker r solves a discrete choice problem to determine the optimal shipping route by selecting the destination n that maximizes profits, taking transportation prices t_{ni} and wage w_i as given:

$$\max_{n \in \{1,\ldots,N\}} \ \Pi_{ni}(r) = t_{ni} - w_{i} c_{ni} + w_{i} \epsilon_{ni}(r) \nu,$$

where c_{ni} is an exogenous fundamental cost, $\epsilon_{ni}(r)$ is an idiosyncratic cost shock and parameter $\nu > 0$ controls the dispersion of cost heterogeneity. Note the trucker's problem is independent of the particular tradable good transported, so transportation markets are not segmented by industry.[2]

The fundamental cost c_{ni} is central to the comparative statics and counterfactuals below. We interpret c_{ni} broadly, capturing route-specific average shipping costs related to distance, terrain features, road infrastructure, transportation technology, and compliance costs derived from international and intranational border regulations. The term $\epsilon_{ni}(r)$ captures trucker r's idiosyncratic cost deviation from the route-specific average, c_{ni}. We assume that entry, fundamental, and idiosyncratic shipping costs are measured in units of labor in the origin i.[3]

[1] In our application, f_i is calibrated per truck-shipment from the free-entry condition. The natural interpretation is the fixed cost incurred regardless of route destination, including dispatch and load-planning, loading at the origin, shipment paperwork (freight tendering, bills of lading), and brokerage matching fees, alongside the amortized per-trip share of license, registration, and insurance.

[2] This assumption resonates well with our experience collecting shipping price data for the U.S. and Canada. Shipping quotes depend exclusively on the origin, destination, dimensions, and weight of the goods transported. With few exceptions (e.g., hazardous materials or perishable goods), all tradable goods can be carried in standard commercial trucks.

[3] This is the natural counterpart of the standard iceberg assumption, under which extra output must be produced at the origin before it dissipates in transit. In both formulations, the resources consumed by transportation are drawn entirely from the origin. This assumption ensures that our model nests the standard iceberg formulation as a special case (Proposition 2), which serves as the benchmark for the counterfactual exercises in Section 5.

To solve for the supply of transportation and free entry condition, we assume that initial uncertainty about idiosyncratic shipping costs is resolved after entry. After incurring the entry cost but before selecting the optimal shipping route, trucker r draws $\epsilon_{ni}(r)$ independently from a Gumbel distribution $F(\epsilon) = \exp[-\exp(-\epsilon - \bar{\gamma})]$, where $\bar{\gamma}$ is the Euler–Mascheroni constant.

The share of trucks supplying transportation services from i to n is:

$$\frac{k_{ni}}{k_i} = \frac{e^{\frac{t_{ni}}{w_i \nu} - \frac{c_{ni}}{\nu}}}{\sum_{h=1}^{N} e^{\frac{t_{hi}}{w_i \nu} - \frac{c_{hi}}{\nu}}}, \tag{9}$$

where k_{ni} is the number of trucks that haul tradable goods from i to n and k_i is the total number of trucks built in i.

Free entry implies that, in equilibrium, the expected ex-ante profits (inclusive of the entry cost) of truckers must be equal to zero:

$$w_i f_i = w_i \nu \left[\log \sum_{n=1}^{N} e^{\frac{t_{ni}}{w_i \nu} - \frac{c_{ni}}{\nu}} \right]. \tag{10}$$

The degree of cost heterogeneity across trucks, determined by ν, is inversely related to the elasticity of transportation supply. From the supply function (9) and free entry condition (10), $\partial \log k_{ni} / \partial (t_{ni}/w_i) = \nu^{-1}$. Hence ν^{-1} is the partial semi-elasticity of transportation supply with respect to the relative transportation price. Alternatively, $\partial \log k_{ni} / \partial \log t_{ni} = \nu^{-1}(t_{ni}/w_i)$ is the price elasticity of transportation supply.

Trade Balance. Trade balance in location n requires expenditure to equal total income. Total income is the sum of labor income ($w_n L_n$, where L_n is local population of workers) plus income from residential land ($r_n H_n$, where r_n denotes the price of land). Since consumer expenditure on land is rebated locally as a lump-sum transfer, $r_n H_n = (1 - \alpha) X_n$. Therefore, the trade balance condition in location n is:

$$\alpha X_n = w_n L_n. \tag{11}$$

Market Clearing. With N locations, there are N^2 transportation markets, indexed by origin and destination. Transportation markets clear when

$$k_{ni} = \sum_{j=1}^{J} k_{ni}^{j}, \tag{12}$$

for all origins $i \in 1, ..., N$ and all destinations $n \in 1, ..., N$.

The non-tradable sector employs a constant fraction α^0/α of the location's total employment L_i.[4] The labor market clears when the remaining fraction of workers is employed in the production and transportation of tradable goods:

$$\left(1-\frac{\alpha^0}{\alpha}\right) w_i L_i = \sum_{n=1}^{N}\sum_{j=1}^{J} \alpha^j \pi_{ni}^j X_n. \quad (13)$$

The right-hand side of (13) uses the fact that revenue from shipping tradable goods produced in location i is fully paid to local workers, since all shipping costs (entry, fundamental, and idiosyncratic) are measured in units of labor in the origin location.

Land market clearing under trade balance requires:

$$r_n H_n = \left(\frac{1-\alpha}{\alpha}\right) w_n L_n. \quad (14)$$

Population Mobility. Labor is freely mobile across the $N-1$ U.S. locations. In equilibrium, workers are indifferent between residing in any two locations. This requires $u_n = u$, for $n = 1, ..., N-1$, where

$$u_n = \frac{w_n}{\alpha P_n^{\alpha} r_n^{1-\alpha}}$$

is real income per worker.[5] Let $\bar{L}$ denote the U.S. labor endowment. Combining the mobility condition with the population constraint, $\bar{L} = \sum_{n=1}^{N-1} L_n$, we obtain the population shares of U.S. locations:

$$\frac{L_n}{\bar{L}} = \frac{H_n\left(\frac{w_n}{P_n}\right)^{\frac{\alpha}{1-\alpha}}}{\sum_{i=1}^{N-1} H_i\left(\frac{w_i}{P_i}\right)^{\frac{\alpha}{1-\alpha}}}, \quad (15)$$

for $n = 1, ..., N-1$. The population share of location n is increasing in its real wage and land endowment, relative to other U.S. locations. In Canada ($n = N$), the population is exogenous and equal to the country's labor endowment, L_N.

Equilibrium. Given parameters for preferences $\{\alpha, \alpha^j, \sigma^j\}$, technology $\{A_i^j, \theta^j, \varphi_i^j\}$, factor endowments $\{H_n, \bar{L}, L_N\}$ and shipping costs $\{c_{ni}, \nu, f_i\}$ for all sectors, locations, and countries, a *competitive equilibrium with transportation markets* is a collection of transportation prices $\{t_{ni}\}$, factor prices $\{w_n, r_n\}$, goods prices $\{P_n^j\}$ and allocations $\{L_n, X_n, k_n, k_{ni}, k_{ni}^j, \pi_{ni}^j\}$ that satisfy equilibrium conditions (5) to (15).[6]

[4] In location i, expenditure on the non-tradable goods is $\alpha^0 X_i$. Imposing trade balance implies that the demand for workers in the non-tradable sector is $(\alpha^0/\alpha)L_i$.

[5] u_n is the indirect utility function of an individual consumer; i.e. $u_n \equiv U_n/L_n$, where U_n is defined in (1). Under trade balance, nominal income per capita in location n is w_n/α.

[6] Derivations of the equilibrium conditions are in Appendix A: prices (6), trade shares (5), and the population mobility condition (15) in Appendix A.1; transportation demand (8), supply (9), and free

Proposition 1. *There exists $\bar{\nu} > 0$ such that, for all $\nu \in [0, \bar{\nu})$, the competitive equilibrium with transportation markets exists and is locally unique.*

Proof. See Appendix A.5. □

Our proof of Proposition 1 relies on the implicit function theorem, perturbing from a tractable limit of the model, $\nu \to 0$, and requiring only a generic regularity condition (strictly weaker than uniqueness) that is verified at our calibrated parameters by direct computation of the Jacobian of the equilibrium system.[7]

3 Analytical Results

This section presents three propositions that highlight key properties of our theory.

3.1 A Special Case: The Iceberg Limit

Consider a sequence of equilibria resulting from reductions in ν, the degree of cost heterogeneity across trucks, holding all other parameters of the model constant. As $\nu \to 0$, the transportation supply functions become perfectly elastic, pinning down transportation prices. Inverting the transportation supply (9) under free entry (10) yields

$$\frac{t_{ni}}{w_i} = c_{ni} + f_i, \text{ as } \nu \to 0, \tag{16}$$

in any active transportation market (i.e. $k_{ni} > 0$ in the limiting equilibrium).[8] Using this result, we re-write the equilibrium conditions (5) to (15) to characterize the limiting equilibrium with perfectly elastic transportation supply functions (Appendix A.3). We use the term Iceberg Limit to denote the limiting case $\nu \to 0$ of our model, reserving the term *baseline* exclusively for the case $\nu > 0$ of finite transportation supply elasticities.

The key property of the Iceberg Limit is that relative transportation prices are exogenous; the following result shows that it nests workhorse spatial trade models with iceberg trade costs.

entry (10) in Appendix A.2.

[7]The usual approaches to existence and uniqueness in trade and geography models do not apply to our setting. The spectral-radius sufficient condition of Allen et al. (2024a) does not hold in our model. The Perron–Frobenius argument on a pair of transpose-linked linear integral operators that Allen and Arkolakis (2014) use in their Theorem 1 requires the single-sector CES gravity structure, which is broken by our J coupled sectoral operators; their Theorem 2 reduces the nonlinear system to a single Hammerstein integral equation under symmetric trade costs, which is violated by our directionally asymmetric fundamental costs. The gross-substitutes approach of Alvarez and Lucas (2007) requires reducing the system to a wage-only excess demand function, which cannot be done in closed form when transportation prices are endogenous. Appendix A.5 contains the full proof, the precise statement of the regularity condition, and the numerical verification.

[8]Intuitively, without uncertainty about idiosyncratic shipping costs, every active transportation market needs to be equally profitable for truckers. Free entry then pins down (16), the unique relative transportation price that guarantees zero profits (inclusive of entry costs) in each transportation market.

Proposition 2. *The Iceberg Limit equilibrium with exogenous relative transportation prices given by* (16) *is isomorphic to:*

(i) the multi-sector Ricardian model of Costinot et al. (2012) with iceberg costs $\tau^j_{ni} \equiv \varphi^j_i + c_{ni} + f_i$*, if* L_n *is exogenous and* $\alpha^0 = 0$*.*

(ii) the spatial trade model of Allen and Arkolakis (2014) with no local spillovers and iceberg costs $\tau_{ni} \equiv \varphi_i + c_{ni} + f_i$*, if* $J = 1$ *and* $\alpha^0 = 0$*.*

Proof. See Appendix A.6. □

Proposition 2 enables a clean assessment of the role of transportation markets in the propagation of fundamental cost shocks vis-à-vis the standard iceberg cost formulation. In our counterfactual analysis, we feed the same shock to the baseline model and the Iceberg Limit and contrast their comparative statics. According to Proposition 2, the two settings differ only in a single parameter governing the elasticity of transportation supply, ν, while all other parameters—preferences, technology, endowments, and geography—remain identical.

3.2 Welfare Decomposition

Transportation markets generate a new channel through which economic shocks impact welfare. A central goal of our counterfactual experiments is to assess whether this channel amplifies or dampens welfare effects studied in the literature under the assumption of iceberg costs.

We first obtain an expression for welfare changes arising from a small counterfactual change in fundamental costs. Manipulating the population mobility condition and the population constraint yields:

$$d\ln u = \alpha \sum_{n=1}^{N-1} \left(\frac{L_n}{\bar{L}}\right) d\ln\left(\frac{w_n}{P_n}\right).$$

With a mobile population, the welfare change is a population-weighted average of real wage changes across locations.[9] We obtain an expression for the real wage in location n by inverting (5) and using the sectoral price index (6). For any tradable good j, this yields:

$$\frac{w_n}{P^j_n} = (\Gamma^j)^{-1}(A^j_n)^{\frac{1}{\theta^j}}(\pi^j_{nn})^{-\frac{1}{\theta^j}}(\tau^j_{nn})^{-1},\ j \geq 1,$$

where π^j_{nn} is location n's share of expenditure on locally produced goods and τ^j_{nn} is an *endogenous* internal iceberg cost, defined below. The real wage in location n follows from

[9] w_n/P_n measures the real wage in terms of tradable and non-tradable goods (i.e. excluding residential land); we refer to this ratio as the real wage.

aggregating this expression across goods using $P_n^{-\alpha} = \prod_{j=0}^{J} (P_n^j)^{-\alpha^j}$. Collecting these results:

Proposition 3. *Let τ_{nn}^j be the endogenous internal iceberg cost for tradable good $j \geq 1$ in location n, where*

$$\tau_{nn}^j \equiv \varphi_n^j + \frac{t_{nn}}{w_n}.$$

Then the welfare change arising from (small) counterfactual changes in fundamental costs $\{c_{ni}, \forall n, i\}$ can be written as

$$d\ln u = \sum_{n=1}^{N-1} \left(\frac{L_n}{\bar{L}}\right) \sum_{j=1}^{J} -\alpha^j \left(\frac{1}{\theta^j} d\ln(\pi_{nn}^j) + d\ln(\tau_{nn}^j)\right). \tag{17}$$

Proof. See Appendix A.7. □

Expression (17) highlights two sufficient statistics that summarize the welfare effects of changes in transportation costs. These are driven by changes in (i) internal trade shares, π_{nn}^j; and (ii) internal iceberg costs, τ_{nn}^j.

The first channel is familiar from the literature that builds on Arkolakis et al. (2012). For the Iceberg Limit without internal geography (i.e. population concentrated at a single point in space), equation (17) simplifies to the ACR welfare formula for a class of multi-sector, perfectly competitive trade models with (exogenous) iceberg costs.

The second channel is a distinct consequence of introducing transportation markets. The endogenous internal iceberg costs, τ_{nn}^j, are linear in internal relative transportation prices, t_{nn}/w_n, and operate as sufficient statistics for the impact of transportation markets on local real income and aggregate welfare. This channel is inactive in the Iceberg Limit and, more generally, in any quantitative trade model that imposes iceberg trade costs as primitives.[10]

3.3 Amplification of Fundamental Cost Shocks

A distinct feature of our theory is that a local shock to fundamental costs—say, improving road infrastructure or reforming border regulation between two specific locations i and n—will impact equilibrium transportation prices in all other markets in the economy. In contrast, under the standard iceberg assumption (Iceberg Limit), the impact is restricted to the local transportation price between i and n, since infinite transportation supply elasticities pin down prices in all other transportation markets.

To trace the propagation of a local fundamental shock to all transportation markets, consider the market clearing condition (12) for shipping from origin i to destination n in

[10] Such models can activate this second channel only exogenously, by shocking parameter τ_{nn}^j.

the baseline model ($\nu > 0$). Equating demand (8) and supply (9) under free entry (10) and trade balance (11), and setting $\varphi_i^j = \varphi_i$ for ease of exposition, yields:

$$k_i e^{\left(\frac{t_{ni}}{w_i} - c_{ni} - f_i\right)/\nu} = \frac{1}{\alpha} \frac{w_n}{w_i} L_n \frac{\sum_{j \geq 1} \alpha^j \pi_{ni}^j}{\varphi_i + \frac{t_{ni}}{w_i}}. \tag{18}$$

A shock to fundamental cost c_{ni} has a direct effect on local transportation supply and indirect effects that spread to all other transportation markets via general equilibrium changes in demand and supply shifters. Equation (18) shows three demand shifters: the relative wage (w_n/w_i), the destination's population size (L_n), and the destination's aggregate expenditure share on goods from i ($\sum_{j \geq 1} \alpha^j \pi_{ni}^j$). The supply shifter is the total stock of trucks that transport goods produced from origin i (k_i).

We characterize the comparative statics analytically by imposing symmetry across locations and sectors while maintaining differences in fundamental costs between internal transportation markets ($i = n$) and external markets ($i \neq n$).[11] In this setting, relative wages and populations are constant, leaving one demand shifter and one supply shifter in each transportation market. The following result shows how general equilibrium effects amplify a local fundamental cost shock beyond the local transportation market.

Proposition 4. *In the symmetric baseline model, if $c_{ni} > c_{ii}$ for all origins i and destinations $n \neq i$, then a reduction in external fundamental costs c_{ni} implies:*

1. *Transportation prices decline in all markets: $dt_{ni} < dt_{ii} < 0$.*
2. *Demand reallocates towards external markets: $d\pi_{ii} < 0 < d\pi_{ni}$.*
3. *Supply increases in all markets, for sufficiently large N: $dk_i > 0$.*

Proof. See Appendix A.8. □

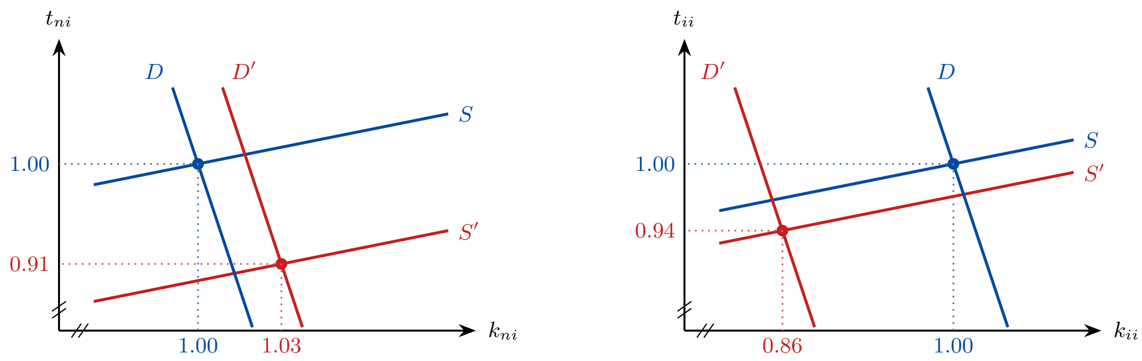
Numerical Example. We illustrate Proposition 4 with a numerical comparative statics exercise under symmetry, with two types of transportation markets: internal (within a location) and external (between locations).[12] Figure 1 plots the supply and demand curves in both markets following a 10% reduction in external fundamental costs, comparing the baseline model in panel (a) with the Iceberg Limit in panel (b).

In the baseline model, the local reduction in the external fundamental cost lowers relative transportation prices in all markets, with the decline in the external price (9.3%) exceeding that in the internal price (5.9%).[13] The shock propagates to the internal market through general equilibrium effects: the stock of trucks at each origin expands by 2.4%, increasing internal supply, while consumers substitute toward external suppliers,

[11] The symmetric equilibrium is defined in section A.8 of the Appendix.
[12] Parameter values are provided in Appendix A.9.
[13] Under symmetry, we normalize $w_i = 1$ for all locations i.

Figure 1: A Reduction in the External Fundamental Cost under Symmetry

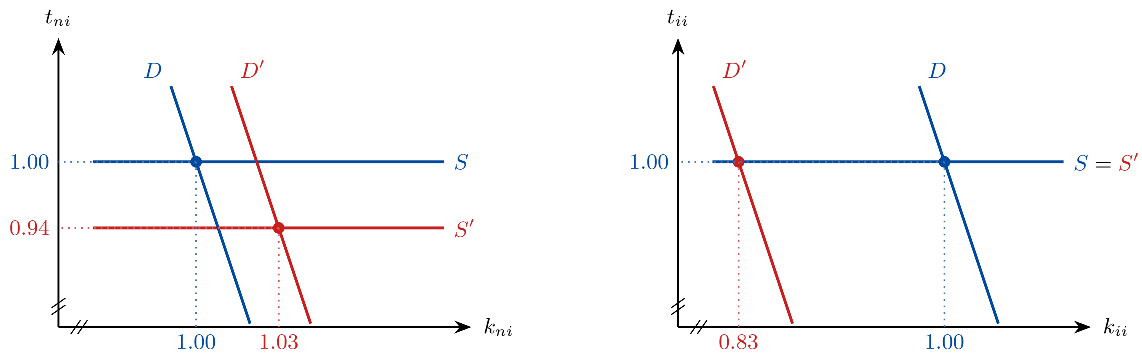
(a) Baseline: Endogenous Transportation Prices



External Transportation Market

Internal Transportation Market

(b) Iceberg Limit: Exogenous Transportation Prices



External Transportation Market

Internal Transportation Market

Note: The figure shows the impact of a 10% reduction in the external fundamental cost, c_{ni} for $i \neq n$, on transportation markets with symmetric locations and sectors. Plots of prices t against quantities k for external (ni) and internal (ii) transportation markets. Axes are rescaled so that initial equilibrium prices and quantities equal 1. Panels (a) and (b) correspond to the baseline model ($\nu > 0$) and the Iceberg Limit ($\nu \to 0$), respectively. Blue curves and dots denote the initial equilibrium; red curves and dots denote the post-shock equilibrium. Primed labels (D′, S′) indicate post-shock curves.

decreasing internal demand. In the Iceberg Limit, exogenous transportation prices confine the shock to the external market: the external price declines by just 6.0%—65% of the baseline decline—and the internal price is unchanged.

Welfare increases by 0.38% in the baseline model compared to 0.33% in the Iceberg Limit, an amplification factor of 1.2. The additional welfare gain is partly driven by a 0.10% decline in the endogenous internal iceberg cost, the new welfare channel identified in Proposition 3. Section 5 confirms these amplification effects in a fully calibrated, asymmetric version of the model.

4 Parameterization

We estimate two parameters central to our counterfactual exercises: ν, that governs cost heterogeneity across trucks and determines the partial semi-elasticity of transportation supply; and c_{ni}, the route-specific fundamental costs. The former disciplines the departure of our baseline model ($\nu > 0$) from the Iceberg Limit ($\nu \to 0$) and, by virtue of Proposition 2, from a class of quantitative trade models with iceberg costs. The latter determine the fundamental cost shocks that we will explore in Section 5.

The remaining model parameters are standard in the literature and not central to a comparison between the baseline model and the Iceberg Limit. We calibrate them by deliberately relying on values and methods drawn from past studies to ensure our results are not driven by methodological innovations in calibration.

4.1 Data

The U.S. Motor Carrier Act of 1980 and the Canadian Motor Vehicle Transport Act (MVTA) of 1987 deregulated freight rates, eased entry requirements, and removed route restrictions in their respective countries.[14] The North American trucking industry has since become atomistic: as of 2017, 1.54 million motor carriers were registered with the U.S. Federal Motor Carrier Safety Administration (FMCSA) alone, of which 99.7% operated 100 or fewer power units and 95.1% operated ten or fewer (Federal Motor Carrier Safety Administration, 2026). This fragmentation motivates our assumption of perfect competition with free entry in transportation markets.

Our primary data source is the Freight Analysis Framework (FAF5) regional database,

[14]The U.S. Motor Carrier Act of 1980 (Pub. L. No. 96-296) eliminated the Interstate Commerce Commission's (ICC) authority to set freight rates through collective rate bureaus, replaced the "certificate of public convenience and necessity" entry standard—which required applicants to prove that existing carriers could not adequately serve the market—with a "fit, willing, and able" standard, and removed the geographic route restrictions that had confined individual carriers to ICC-approved corridors. The Canadian MVTA of 1987 replaced the same "public convenience and necessity" entry test with a fitness standard, discontinued rate regulation, and lifted route restrictions on extra-provincial carriers; intra-provincial deregulation was completed by 2000 under the Agreement on Internal Trade.

produced by the Bureau of Transportation Statistics (BTS) and the Federal Highway Administration (FHWA). We compute tonnage and value of truck shipments by sector and transportation market, for 16 tradable commodities and 128 major metropolitan areas and states of the contiguous U.S. and aggregate Canada in 2017.[15] We supplement this dataset with tonnage and value of truck shipments by sector within Canada from the 2017 Canadian Freight Analysis Framework (CFAF) produced by Statistics Canada.[16] We work with 16 tradable sectors and 1 service sector, classified according to the North American Industry Classification System (NAICS) [17]. Table 1 maps the key model variables to their empirical counterparts. We measure the quantity of transportation services k_{ni}^j with the weight of shipments (in tons) reported in the FAF5, a physical measure of the volume of goods hauled by trucks. A limitation of FAF5 is that values are reported net of freight charges, which motivates the independent measurement of transportation prices t_{ni}, described below. We combine these sources to measure expenditure X_{ni}^j as the value of shipments from i to n at consumer prices.

Table 1: Summary of the Main Data Requirements

Variable	Measurement	Main Source
X_{ni}^j	Value by commodity type	FAF5 and CFAF
k_{ni}^j	Weight by commodity type	FAF5 and CFAF
t_{ni}	Transportation prices	Schneider
L_i	Employment	BEA and StatCanada
w_i	Nominal wages	FAF5, BEA, StatCanada

Note: This table maps key model variables to their empirical counterparts and corresponding data sources.

To measure transportation prices, we collected freight rate quotes in 2022 from Schneider, one of the major shipping brokers in the U.S. and Canada with 64,000 qualified carrier relationships and \$6.6 billion of operating revenue.[18] We deliberately hold

[15]We treat Canada as a single aggregate region because bilateral truck-shipment data across disaggregated U.S. and Canadian regions are not available: FAF5 reports U.S.–Canada international flows at the U.S.-region level but only at the country level on the Canadian side, while CFAF reports within-Canada flows at the provincial level but treats the U.S. as a single foreign destination.

[16]Commodities are classified at the 2-digit level of the Standard Classification of Transported Goods (SCTG), listed in Table 3 of Appendix B.6. FAF5 regions are listed in Table 4 of Appendix B.6. The FAF5 shares the same regional definitions as the Commodity Flow Survey. In addition, FAF5 integrates additional data sources to estimate volumes of shipments from industries that are not covered by the CFS, including foreign trade. The CFAF covers twelve manufacturing sectors; see Appendix B.4 for details.

[17]We match the tradable sectors in Caliendo et al. (2018) except Agriculture from Caliendo and Parro (2015). We provide the full list of sectors in Appendix B.6.

[18]The brokerage layer is a direct consequence of the carrier-side fragmentation discussed above: with hundreds of thousands of small operators, shippers face an information problem that brokers solve by aggregating capacity and matching loads to carriers. This intermediation layer is itself competitive, with 25,000 active property brokers registered with the FMCSA (Federal Motor Carrier Safety Administration, 2026).

constant a number of shipment parameters throughout the data collection process, to consistently measure price variation for a *homogeneous* transportation service.[19] Given multiple quotes from different truckers, we use the lowest as the transportation price for each market. We deflate all quotes using a U.S. truck industry (producer) price index from the Bureau of Labor Statistics (BLS) to account for a 52% rise in trucking prices between 2017 and 2022 (see Appendix B.1 for details on the data collection). We validate the cross-route structure of our price data against an independent government-collected benchmark in Appendix B.2, where we also show that the estimated transportation supply elasticity and the counterfactual welfare changes are invariant to additive and multiplicative measurement error in observed t_{ni}.[20]

We use a theory-consistent approach to measure the nominal wage w_i in each location (Appendix B.5). Given employment L_i, sourced from the Bureau of Economic Analysis (BEA) Regional Economic Profiles for U.S. locations and Statistics Canada for Canada (Appendix B.5), and the total value of outgoing tradable goods from i, $X_i^{\text{out}} \equiv \sum_{j=1}^{J} \sum_n X_{ni}^j$, labor-market clearing (13) together with trade balance imply that $w_i L_i = X_i^{\text{out}} + \alpha^0 X_i$, the sum of tradable and non-tradable labor income. We use this identity to recover $w_i = (X_i^{\text{out}} + \alpha^0 X_i)/L_i$. We source travel distances for U.S. and U.S.–Canada routes, as well as for internal routes in Canada, from two datasets: (i) ArcMap and (ii) FAF5 and CFAF. We obtain travel time from ArcMap.[21]

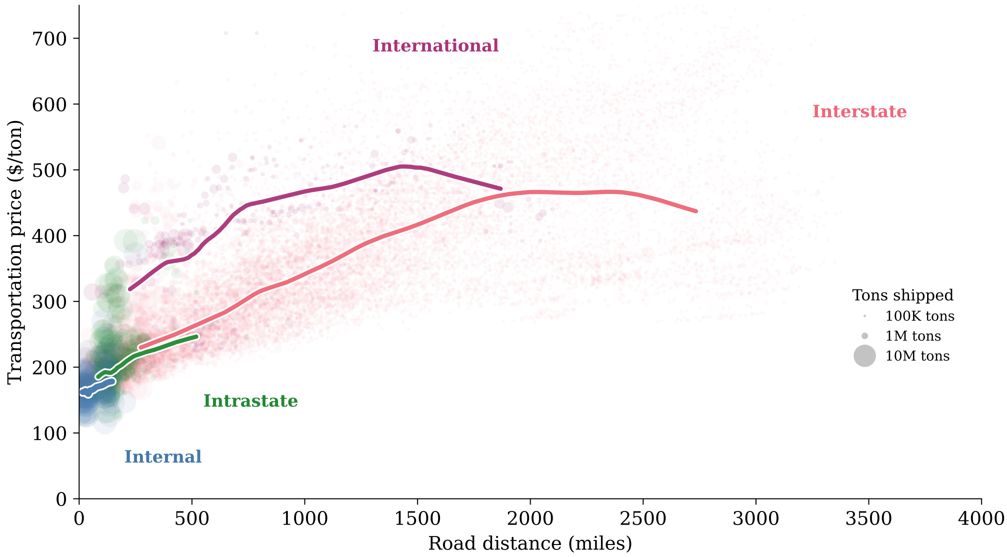
Of the 129^2 = 16,641 potential transportation markets, 16,498 have positive truck flows and form the estimation sample. We classify transportation markets into four types: *internal* markets (origin and destination are the same location), *intrastate* markets (origin and destination in the same state), *interstate* markets (origin and destination in different states), and *international* markets (origin and destination on opposite sides of the U.S.–Canada border). Figure 2 plots the Schneider transportation prices against road distance for each market type. Bubble area is proportional to tons shipped: the largest bubbles concentrate in internal and short-distance markets, with a long tail of small interstate markets at higher prices.

[19] In all cases, the requested quotes consisted of a less-than-truckload service two business days in advance of the intended shipment date. The shipment description was set to a generic "manufacturing goods". The pallet dimensions were set to the standard 48x40x72 inches. The shipment weight was set to 2,987 lbs, equal to the weight of the median value in the FAF5 database. The origin was set to "business address without loading dock and with lift gate", while the destination was set to "residential address with lift gate".

[20] The benchmark is the U.S. Department of Agriculture (USDA) *Fruit and Vegetable Truck Rate Report*, which collects spot-market rates on a comparable set of origin-destination lanes. Unlike our Schneider quotes, the USDA data hold no shipment parameter constant: commodity mix (up to 22 produce items per entry), load weight, trailer size, and carrier type all vary across the underlying transactions. Despite this heterogeneity, the Pearson correlations on standardized prices are 0.45 in 2017 (148 matched lanes) and 0.63 in 2022 (122 matched lanes).

[21] To construct route-specific fundamental costs as in (20), we use FAF5 distances for U.S. and U.S.–Canada routes and CFAF distances for internal Canadian routes, supplemented by travel times from ArcMap. The instrumental variable IV_{ni}, as defined in (21), is constructed from the same FAF5 and CFAF distances.

Figure 2: Transportation Prices from Schneider Freight Rate Quotes



Note: Each bubble represents a transportation market. The vertical axis is the transportation price t_{ni} in \$/ton, deflated to 2017 prices. Prices are collected from Schneider for a standardized shipment (see text for details). Bubble area is proportional to tons shipped (FAF5), capped at the 99th percentile. Solid curves are LOESS smoothers fitted separately to each market type. Market types: internal (origin = destination), intrastate (different locations, same state), interstate (different states), international (U.S.-Canada).

Table 2: Descriptive Statistics for Trade and Transportation, by Market Type

	Market Type (#O-D pairs)	Transportation Prices ($)	Total Tons (Million)	Total Value (Million $)	Distance (Miles)
U.S.	Internal (128)	168	8,062	6,175,035	56
	Intrastate (330)	219	1,442	1,741,015	208
	Interstate (15,783)	266	2,275	5,629,033	1,247
International	CA to U.S. (128)	368	64	162,992	832
	U.S. to CA (128)	392	73	225,513	875
Canada	Internal (1)	371	654	1,595,372	251
Total		205	12,570	15,528,960	1,210

Note: The number of origin-destination pairs for each route type is shown in parentheses. Transportation prices represent the ton-weighted average dollar price per ton. Total Value is the value of shipments net of freight charges. Distances are unweighted averages of road distance from FAF5 for U.S. and U.S.–Canada markets and from CFAF for the internal Canadian market.

Table 2 reports averages by market type. Total trade volume is 12,570 million tons, with an average transportation cost of \$205 per ton. Cross-border rates are the highest in the table despite shorter average distances than U.S. interstate: \$368 per ton from Canada and \$392 per ton to Canada over 832 and 875 miles, against \$266 per ton over 1,247 miles for U.S. interstate. Internal Canadian trade sits at \$371 per ton over 251 miles. U.S. internal markets carry 64% of total trade tons.

4.2 Estimation of the Transportation Supply Elasticity

We invert the transportation supply function (9), impose the free entry condition (10), and link fundamental costs to distance, time, and borders. This yields the following estimating equation:

$$\frac{t_{ni}}{w_i} = \nu \log\left(\frac{k_{ni}}{k_i}\right) + \tilde{c}_{ni} + \gamma_i + u_{ni}, \tag{19}$$

where we decompose fundamental costs as $c_{ni} = \tilde{c}_{ni} + u_{ni}$, with $\tilde{c}_{ni}$ capturing the component systematically linked to road distance, travel time and border crossings (international and interstate). The residual u_{ni} captures unobserved fundamental costs and provides the structural interpretation for the error term. Equations (9) and (10) imply an origin fixed effect, denoted by γ_i in (19).

We adopt a flexible specification for observable fundamental costs, with a spline function for road distance and travel time and a variable intercept for transportation markets that span international or interstate borders:

$$\begin{aligned}\tilde{c}_{ni} = &\sum_{q=1}^{5} \delta_{\text{dist},q} \max\{\text{dist}_{ni} - \rho_{\text{dist},q},\, 0\} + \sum_{q=1}^{5} \delta_{\text{time},q} \max\{\text{time}_{ni} - \rho_{\text{time},q},\, 0\} \\ &+ \delta_{\text{US-CAN\_border}} \cdot \text{US-CAN\_border}_{ni} + \delta_{\text{STATE\_border}} \cdot \text{STATE\_border}_{ni}.\end{aligned} \tag{20}$$

Knots $\rho_{\text{dist},q}$ and $\rho_{\text{time},q}$ split the support of road distance and travel time into empirical quintiles. The truncated-power basis $\max\{x - \rho_q, 0\}$ generates a continuous piecewise-linear function of x; the coefficients $\delta_{\text{dist},q}$ and $\delta_{\text{time},q}$ measure the slope changes at each knot. US-CAN_border is a binary variable equal to 1 if origin i and destination n are on different sides of the U.S.–Canada border and 0 otherwise. Similarly, STATE_border is a binary variable equal to 1 if origin i and destination n are in different U.S. states and 0 otherwise.[22]

Consistent estimation of ν in (19) requires addressing simultaneity: relative transportation prices t_{ni}/w_i and truck shares k_{ni}/k_i are jointly determined by supply and demand in transportation markets. Identifying the supply elasticity requires a demand

[22]Equation (20) omits an intercept. Appendix B.9 shows that this normalization is inconsequential for the counterfactual analysis in Section 5.

shifter. Our instrumental variable, IV_{ni}, exploits variation in relative remoteness across destinations:

$$IV_{ni} = \sum_{\ell \neq i} \text{dist}_{n\ell}. \tag{21}$$

Intuitively, demand for transportation from i to n increases with the remoteness of n from alternative suppliers $\ell \neq i$. This logic is rooted in the model's structure. Formally, transportation demand (8) satisfies the assumptions underlying structural gravity (Head and Mayer, 2014). We interpret IV_{ni} as a first-order approximation to the destination's multilateral resistance term, evaluated at a symmetric equilibrium. Appendix B.8 provides the details.

4.3 Main Empirical Results

We estimate the inverse supply function (19) with the route-specific fundamental cost specification (20) and the instrumental variable (21). Table 3 reports the results. Columns (1) and (2) report OLS estimates without and with origin fixed effects, respectively. Column (3) shows the first-stage results and Column (4) reports our preferred 2SLS estimates.

Transportation Supply Elasticity. The OLS specifications yield a negative and significant coefficient on the truck share, which is consistent with simultaneous equations bias. The 2SLS estimation identifies the slope of the supply curve by shifting demand through the remoteness instrument. In the first stage, the instrument predicts the truck share k_{ni}/k_i, with a partial F-statistic on the excluded instrument of 143.72—well above the Stock and Yogo (2005) 10% critical value of 16.38. The second stage recovers a positive and significant estimate of ν, equal to 0.103. From Section 2, this implies a price elasticity of transportation supply of 7.9, evaluated at the sample mean of $\overline{t_{ni}/w_i} = 0.82$.

Fundamental Costs. We construct fundamental costs from equation (20), using the estimated coefficients along with data on travel time and distance. Because the estimating equation (19) includes origin fixed effects, only within-origin variation in $\tilde{c}_{ni}$ is identified, not the level of fundamental costs. Appendix B.9 formally shows that this is inconsequential: the equilibrium depends on c_{ni} and f_i only through their sum $c_{ni} + f_i$; without loss of generality, we set $c_{ni} = \tilde{c}_{ni}$ and pin down $c_{ni} + f_i$ with the origin-specific free entry condition. The counterfactual shocks Δc_{ni} in Section 5 are also unaffected by this normalization because each shock is constructed from identified regression coefficients and route-level observables.

The estimated distance spline exhibits a steeper marginal cost of distance for short routes and flattens beyond 1,867 miles (the fourth knot), where the fifth spline segment is small and statistically insignificant. The time coefficients are positive and significant across the first four segments, with a similar flattening at the longest travel times. Because road distance and travel time are nearly collinear (correlation 0.99), we interpret spline coefficients as capturing the joint effect of route length through two complementary proxies. Both border dummies are positive and statistically significant in the 2SLS specification. The state border coefficient (0.164) exceeds the U.S.–Canada border coefficient (0.126), though their difference is not statistically significant at the 5% level.

To gauge economic significance, we convert the estimated coefficients to \$/ton at the sample-average wage. At the sample mean (1,210 miles, 18.3 hours), each additional 100 miles of road distance—with the associated 1.5 additional hours of travel time—raises estimated fundamental costs by \$29.6 per ton. The state border coefficient corresponds to a premium of \$80.7/ton on interstate relative to intrastate transportation markets, and the U.S.–Canada border coefficient to a premium of \$62.0/ton. Expressed in distance-equivalent terms, a state border crossing adds the same cost as 273 additional miles of travel, and a U.S.–Canada border crossing the same as 209 additional miles.

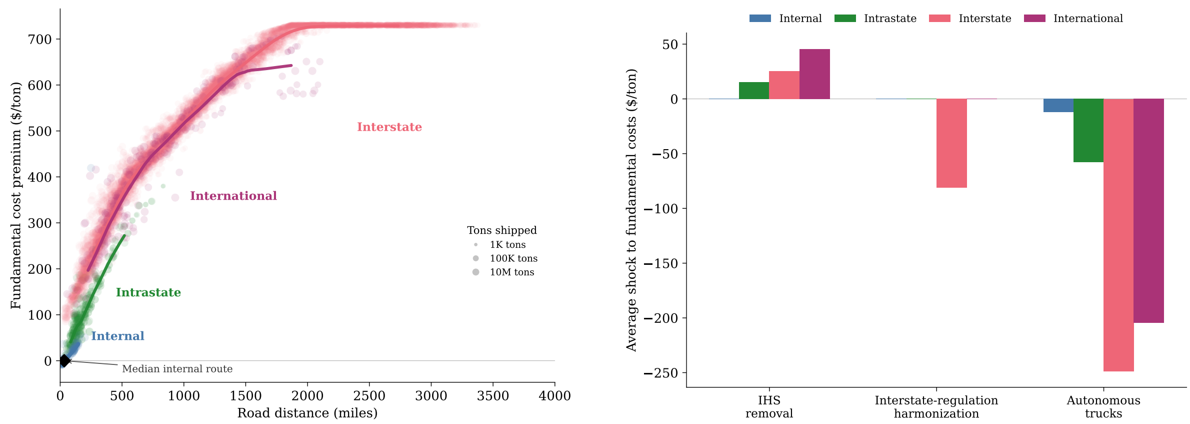
Figure 3, panel (a), plots the fundamental cost premium for each route—the cost difference from the median internal route—against road distance. Panel (b) previews the counterfactual exercises of Section 5, plotting the average shock to fundamental costs scaled by the sample average wage, $\bar{w} \cdot \Delta\tilde{c}_{ni}$, by market type. The IHS elimination raises fundamental costs by \$45.6/ton on international and \$25.4/ton on interstate transportation markets; interstate-regulation harmonization eliminates the \$80.7/ton state-border premium on interstate markets; and autonomous trucks reduce fundamental costs across all market types, from \$11.9/ton on internal markets to \$248.7/ton on interstate ones.

Robustness Checks. Because the instrument varies primarily across destinations, the main threat to validity is that remote destinations may have systematically higher unobserved fundamental costs—for instance from poor local infrastructure. Destination fixed effects would absorb this variation but are infeasible: $IV_{ni} = \sum_{\ell} \text{dist}_{n\ell} - \text{dist}_{ni}$, so the instrument net of destination fixed effects reduces to $-\text{dist}_{ni}$, which is already controlled for by the distance spline. We therefore expand the baseline specification with destination-level controls. These include employment L_n, bridge condition and deficiency rates from the 2017 National Bridge Inventory (NBI), and pavement quality and lane-miles from the 2017 Highway Performance Monitoring System (HPMS).[23] Appendix B.10 shows that adding destination-specific employment, road, or bridge infrastructure controls yields $\hat{\nu} \in [0.121, 0.167]$, with the instrument remaining strong in all cases (partial $F > 53$). Controlling for these destination-specific characteristics thus *increases* $\hat{\nu}$, the direction opposite to what omitted-variable bias would imply.

[23]NBI controls are aggregated from 612,677 individual bridge records to 128 FAF5 regions; HPMS controls from 6.8 million road segments to 127 FAF5 regions, both via a county-to-FAF5 concordance. See Appendix B.10 for data construction details, summary statistics, and full regression results.

Appendix B.10 reports $\hat{\nu}$ under alternative specifications, varying the construction of the instrument, the functional form of fundamental costs (20), and the estimation sample. Across all specifications, the estimate of $\hat{\nu}$ ranges from 0.086 to 0.135—implying a price elasticity of transportation supply between 6.1 and 9.5, compared with the baseline 7.9. The weak-IV-robust Anderson–Rubin test rejects $\nu = 0$ at the 5% level under alternative clustering schemes (Table 8, rows 20–21). Alternative instruments based on travel time rather than distance yield similar estimates ($\hat{\nu} = 0.097$). Replacing the piecewise linear splines with a quadratic specification or dropping either distance or time from the controls leaves the estimate essentially unchanged, consistent with ν being identified from IV-driven demand shifts rather than from the parameterization of fundamental costs. Restricting the sample to U.S.-only routes, trimming distance extremes, or trimming the tails of the transportation price or tonnage distributions likewise has negligible effects.

Figure 3: Estimated Fundamental Costs and Counterfactual Shocks



(a) Fundamental Cost Premium (b) Counterfactual Shocks

Note: Both panels convert estimated fundamental costs to \$/ton using the sample-average wage $\bar{w}$. Panel (a) displays the fundamental cost premium $\bar{w} \cdot (\tilde{c}_{ni} - \tilde{c}_{\text{ref}})$ for each origin-destination pair, where $\tilde{c}_{\text{ref}}$ is the median internal route (32 miles). Bubble area is proportional to tons shipped (FAF5), capped at the 99th percentile. Solid curves are LOESS smoothers fitted separately to each market type. Panel (b) displays the average counterfactual shock $\bar{w} \cdot \Delta\tilde{c}_{ni}$ by market type for three experiments: IHS elimination (Section 5.1), interstate-regulation harmonization (Section 5.2), and autonomous trucks (Section 5.4). The border closure experiment (Section 5.3) is omitted because counterfactual fundamental costs on international routes are set to infinity.

Table 3: Structural Estimation of Transportation Supply

	OLS	OLS	First Stage	2SLS
Dependent Variable				
	t_{ni}/w_i	t_{ni}/w_i	$log(k_{ni}/k_i)$	t_{ni}/w_i
Truck share: $log(k_{ni}/k_i)$	$-.0060^{***}$	$-.0069^{***}$		$.1029^{***}$
	(.0021)	(.0012)		(.0198)
Distance Spline (in thousands of miles)				
Distance $\leq$ 0.540	$-.150^{*}$	$-.200^{***}$	-7.253^{***}	$.596^{***}$
	(.086)	(.054)	(.408)	(.148)
0.540 $<$ Distance $\leq$ 0.880	$-.069$	-.106	-3.063^{***}	$.239^{***}$
	(.115)	(.073)	(.367)	(.088)
0.880 $<$ Distance $\leq$ 1.264	.145	.028	-3.143^{***}	$.315^{***}$
	(.095)	(.064)	(.430)	(.093)
1.264 $<$ Distance $\leq$ 1.867	$.194^{**}$	.089	-1.010^{**}	$.153^{*}$
	(.093)	(.056)	(.516)	(.084)
1.867 $<$ Distance	.111	.009	.460	$-.084$
	(.142)	(.111)	(.517)	(.147)
Time Spline (in hours)				
Time $\leq$ 8.72	$.025^{***}$	$.033^{***}$	$-.047^{**}$	$.039^{***}$
	(.006)	(.004)	(.027)	(.005)
8.72 $<$ Time $\leq$ 13.51	$.031^{***}$	$.032^{***}$	$.070^{***}$	$.023^{***}$
	(.008)	(.005)	(.026)	(.005)
13.51 $<$ Time $\leq$ 19.04	$.017^{***}$	$.020^{***}$	.035	$.019^{***}$
	(.007)	(.004)	(.026)	(.005)
19.04 $<$ Time $\leq$ 27.71	$.013^{**}$	$.015^{***}$	$-.042$	$.020^{***}$
	(.006)	(.004)	(.036)	(.006)
27.71 $<$ Time	$-.000$	.005	$-.060^{**}$	.012
	(.010)	(.007)	(.035)	(.010)
Border Dummies				
US-CAN border	$.130^{***}$	$.202^{***}$	1.065^{***}	$.126^{**}$
	(.049)	(.032)	(.260)	(.051)
STATE border	.004	-.024	-1.550^{***}	$.164^{***}$
	(.045)	(.029)	(.175)	(.040)
IV				
			$7.15e-06^{***}$	
			$(5.96e-07)$	
Origin FE	N	Y	Y	Y
Observations	16,498	16,498	16,498	16,498
R^2	0.368	0.789	0.484	0.491
First-stage F-statistic			143.72	

Note: The dependent variable is t_{ni}/w_i, where t_{ni} is the transportation price in millions of \$/ton and w_i is the origin wage in millions of \$/worker; the ratio is rescaled by 1/1000 to reduce trailing zeros in coefficient estimates. Distance is road distance in thousands of miles; time is travel time in hours. The instrumental variable (IV) is a demand shifter, as defined in Equation (21). Robust standard errors clustered at the state-pair level (1,275 clusters) in parentheses. The first-stage F-statistic is the partial F on the excluded instrument; the Stock and Yogo (2005) critical value for 10% maximal IV size is 16.38. * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$. Robustness checks are reported in Appendix B.10.

4.4 Calibration Strategy

We calibrate the model to 128 U.S. FAF5 regions and 1 Canadian region (129 locations), with 17 sectors: 16 tradable and 1 service (full list in Appendix B.6). Table 4 summarizes the calibration strategy.

Table 4: Calibration Strategy

Parameter	Description	Strategy / Source
θ^j	Sectoral trade elasticities	Caliendo et al. (2018), Caliendo and Parro (2015)
α	Non-residential expenditure share	Redding (2016)
α^j	Sectoral expenditure shares	Caliendo et al. (2018)
φ_i	Labor requirement per truck	Inverting transportation demand (8)
f_i	Sunk entry cost	Free entry condition (10)
H_i	Land endowment	Population mobility condition (15)
A_i^j	Productivity	Inverting trade shares (5)

Note: Parameters above the line are taken from the literature; their values are reported in Table 5 in the Appendix. Parameters below the line are recovered by inverting model equations given data and estimated parameters (ν, $\tilde{c}_{ni}$) from Section 4.2.

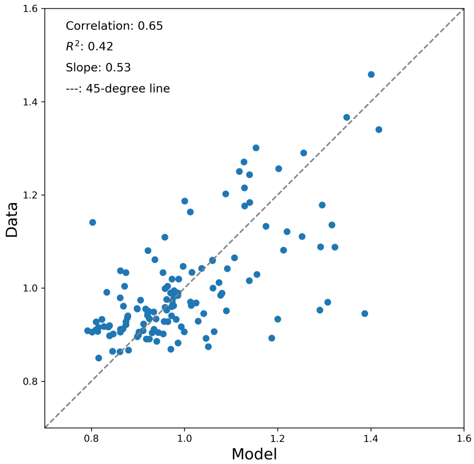
Parameters from the Literature. Sectoral trade elasticities θ^j are taken directly from Caliendo et al. (2018), with Agriculture from Caliendo and Parro (2015). Sectoral expenditure shares α^j are computed adapting the procedure of Caliendo et al. (2018) to our slightly different sectoral aggregation (Appendix B.7). Parameter values are reported in Table 5 of the Appendix. In our calibration, tradable goods account for a share $\alpha - \alpha^0 = 0.153$ of U.S. aggregate expenditure. From Redding (2016), residential land absorbs a fraction $1 - \alpha = 0.25$. Non-tradable services make up the residual share, $\alpha^0 = 0.597$. Because our counterfactual shocks affect only the tradable sectors, placing these sectors in the context of the rest of the economy is essential for interpreting our welfare magnitudes.

Parameters from model inversion. The remaining parameters are recovered by inverting model equations, given observed data and the estimated parameters ν and $\tilde{c}_{ni}$ from Section 4.2. The labor per truck requirement, φ_i, is recovered by inverting the demand for transportation (8): the value per ton shipped from i to n in sector j equals $\varphi_i^j w_i + t_{ni}$. We aggregate across destinations and sectors to obtain a location-specific φ_i (Appendix B.5). The sunk entry cost f_i is computed from the free entry condition (10), which requires zero expected profits for truckers, given observed transportation prices and estimated fundamental costs. Land endowments H_i are recovered from the population mobility condition (15), matching observed relative population shares across U.S. locations (Appendix B.7). Productivity parameters A_i^j are recovered by inverting the trade share equation (5) to match observed bilateral trade shares by origin, destination, and sector (Appendix B.7), given calibrated input costs $\varphi_i w_i + t_{ni}$ and trade elasticities θ^j.

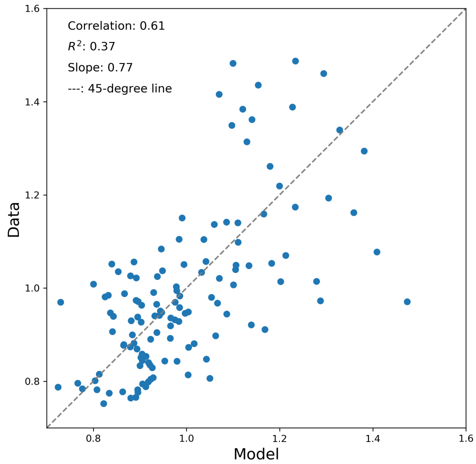
4.5 Model Fit

Figure 4 plots inbound and outbound transportation prices generated by the calibrated model against their empirical counterparts, with correlations of 0.65 and 0.61, respectively.

Figure 4: Model Fit - Inbound and Outbound Transportation Prices



(a) Inbound, $N^{-1}\sum_i t_{ni}$



(b) Outbound, $N^{-1}\sum_n t_{ni}$

Note: For any destination n, we construct average inbound transportation prices as $N^{-1}\sum_i t_{ni}$. Similarly, for any origin i, we construct average outbound transportation prices as $N^{-1}\sum_n t_{ni}$. For a unit-free comparison, we normalize model and empirical prices by their corresponding mean across all pairs of locations.

As an additional check, the calibrated model generates a transportation sector of plausible size. Transportation in the model is a general technology for delivering goods from producers to consumers, so its empirical counterpart should encompass a broad set of transportation services. The Transportation and Warehousing industry (NAICS 48–49) accounts for 3.2% of U.S. value added in 2017 and 3.5% in 2022.[24] The calibrated model generates a transportation share of 4.4%.[25] The model overstates this benchmark by one percentage point, but the comparison is conservative: the NAICS 48–49 category excludes in-house logistics and other delivery-related activities that fall within the scope of the model's transportation technology. We view this as a reasonable fit of a moment not targeted by the calibration.

5 Counterfactual Exercises

We now present four counterfactual exercises that highlight the role of transportation markets in propagating fundamental cost shocks to equilibrium prices and welfare. Each

[24] https://fred.stlouisfed.org/series/VAPGDPT.

[25] Through the lens of the model, we compute $\sum_{n=1}^{N-1}\sum_{i=1}^{N-1} t_{ni}k_{ni}/\sum_{n=1}^{N-1} X_n$, for U.S. locations.

experiment targets a distinct component of the estimated fundamental costs $\tilde{c}_{ni}$: highway infrastructure (Section 5.1), state borders (Section 5.2), the U.S.–Canada border (Section 5.3), and transportation technology (Section 5.4).[26] As panel (b) of Figure 3 illustrates, these shocks vary widely in geographic incidence and magnitude. In each case, we compare outcomes under the baseline model ($\nu = 0.103$) with those under the Iceberg Limit ($\nu \to 0$), holding all other parameters constant. This design isolates the contribution of ν: any difference in counterfactual outcomes is attributable to the finite transportation supply elasticity alone, since recalibrating other primitives across models would conflate it with their contribution. In all cases, we compute equilibria using the algorithm in Appendix A.4.

We summarize the results of each counterfactual exercise in a four-panel figure (Figures 5–8). Panels (a) and (b) plot equilibrium changes for every transportation market, under the baseline and Iceberg Limit, respectively: the percentage change in the iceberg cost ($\tau_{ni} \equiv \varphi_i + t_{ni}/w_i$) against the percentage change in truck quantities (k_{ni}).[27] A kernel density along the right edge of each panel shows the distribution of iceberg-cost changes across markets, with a dashed line at the truck-weighted mean. Panel (c) plots the percentage change in the supply and demand shifters in each transportation market in the baseline model, according to (18): the supply shifter (k_i) on the vertical axis and demand shifters (w_n/w_i, L_n, and $\sum_{j\geq 1} \alpha^j \pi^j_{ni}$) on the horizontal axis (see Appendix C.5 for the derivation). A horizontal line marks the percentage change in the aggregate stock of trucks in the U.S. Panel (d) plots the welfare decomposition of Proposition 3 across the 128 U.S. locations, with the U.S. aggregate and Canada bubbles highlighted.

Across all four experiments, the figures reveal a recurring pattern: transportation markets in the baseline model amplify the impact of fundamental cost shocks on transportation prices, showing that the analytical amplification property derived under symmetry in Proposition 4 extends to the asymmetry of our quantitative exercises (on average, across markets). In the Iceberg Limit, panels (b) show unshocked markets clustered at $\Delta\tau_{ni}/\tau_{ni} = 0$ and the density spiking at zero; in the baseline, panels (a) show iceberg costs adjusting endogenously on all markets. The wedge is entirely due to the finite transportation supply elasticity: the GE shifters in panels (c) operate in both models, but only the baseline propagates them into endogenous iceberg cost adjustments.

Table 5 summarizes the welfare effects across all four experiments using the decomposition from Proposition 3. It reports the two sufficient statistics from (17): the internal trade share component, $\sum_n (L_n/\bar{L}) \sum_{j\geq 1} (\alpha^j/\theta^j) d \ln \pi^j_{nn}$, which captures changes in internal expenditure shares; and the internal iceberg cost component, $(\alpha - \alpha^0) \sum_n (L_n/\bar{L})\, d \ln \tau_{nn}$,

[26]Donaldson (2025) surveys the welfare evaluation of transport-infrastructure improvements and transport-policy changes; our four exercises are instances of these two types of shock.

[27]We introduce the familiar iceberg costs as auxiliary variables, and report them instead of relative transportation prices. This is without loss of generality, since there is a one-to-one mapping between them.

which is exogenous in the Iceberg Limit but endogenous in the baseline model. In all four experiments, the baseline generates larger welfare effects than the Iceberg Limit in absolute value, with amplification factors ranging from 1.13 to 1.29. The internal iceberg cost channel is the source of this amplification: it is zero in the Iceberg Limit for the three experiments that do not directly shock internal transportation markets and substantially larger in the baseline for the one that does (autonomous trucks). Table 5 also reports a TFP-equivalent shock for each model and experiment: for autonomous trucks, a welfare change of 2.03% is equivalent to a uniform TFP increase across tradable sectors of 14.0% in the baseline but only 10.7% in the Iceberg Limit, an amplification factor of 1.31.

Table 5: Welfare Amplification Effects in the U.S. across Experiments

	I. Eliminating IHS	II. Harmonizing Interstate Reg.	III. U.S.–Canada Border Closure	IV. Autonomous Trucks
Welfare (%)				
Baseline	−0.22	0.67	−0.32	2.03
Internal trade share	0.15	−0.48	0.18	−1.35
Internal iceberg cost	0.06	−0.18	0.14	−0.65
Iceberg Limit	−0.17	0.52	−0.28	1.57
Internal trade share	0.18	−0.52	0.28	−1.42
Internal iceberg cost	0	0	0	−0.15
Amplification factor	1.25	1.29	1.13	1.29
Equivalent TFP Shock (%)				
Baseline	−1.4	4.5	−2.1	14.0
Iceberg Limit	−1.1	3.4	−1.8	10.7
Amplification factor	1.25	1.30	1.13	1.31

Note: Welfare is decomposed following Proposition 3 into two sufficient statistics: internal trade share and internal iceberg cost. Results expressed in percentage changes. *Amplification factor* is the ratio of the baseline to the Iceberg Limit effect. The equivalent TFP shock is the uniform productivity shift r such that the sectoral Fréchet scale parameters $A_i'^j = (1+r)^{\theta^j} A_i^j$ generate the same welfare change as the counterfactual experiment.

We now turn to the detailed results of each experiment. Appendix C.6 presents the spatial distribution of real-income effects for each of the four counterfactuals.

5.1 Eliminating the Interstate Highway System

The IHS, authorized by the Federal-Aid Highway Act of 1956 and built over the subsequent three decades, comprises 49,000 miles—just over 1% of total U.S. road mileage—yet carries one quarter of all vehicle miles traveled and over 20% of combination truck traffic.[28] In a spatial trade model with iceberg costs, Allen and Arkolakis (2014) estimate

[28]FHWA, *Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance*, 23rd Edition (2018), Chapter 1. Duranton et al. (2014) document the relationship between highway mileage and the volume of goods shipped across U.S. cities.

the welfare impact of eliminating the IHS in the U.S..[29] Our exercise revisits this counterfactual with transportation markets, isolating the amplification effects that operate through the endogenous transportation price channel.

The Shock. We simulate the elimination of the IHS by recalculating travel times and distances using ArcGIS's Network Analyst tool applied to the North American road network, excluding all interstate highway segments.[30] Eliminating the IHS increases average interstate travel time by 26% and average interstate distance by 7%, with no impact on internal markets. The recalculated travel metrics are substituted into the fundamental cost function (20), keeping the estimated coefficients unchanged. The shock is concentrated on interstate and international markets, with the largest increases in the Midwest (3.4% to 3.8%) and smaller effects on the coasts.[31]

Propagation through Transportation Markets. On average across all transportation markets, iceberg costs rise endogenously by 1.85% in the baseline, compared to a 1.42% exogenous change in the Iceberg Limit—an amplification factor of 1.30. Because the IHS elimination raises fundamental costs exclusively on interstate and international markets, this experiment provides a clean visualization of the propagation mechanism: internal markets are unshocked, so internal iceberg cost adjustments are attributable to general equilibrium effects operating across transportation markets.

Panel (b) of Figure 5 shows that the distribution of iceberg cost changes in the Iceberg Limit concentrates around zero, with $\Delta\tau_{ni}/\tau_{ni} = 0$ for internal markets. In Panel (a), iceberg costs in the baseline rise by 0.5% at the internal medoid and 0.6% on average across internal markets. Panel (c) traces the underlying baseline mechanism: transportation demand reallocates away from interstate and international markets toward local suppliers, and the U.S. truck stock contracts by 1.6% on average, generating a decrease in transportation supply in *every* transportation market.

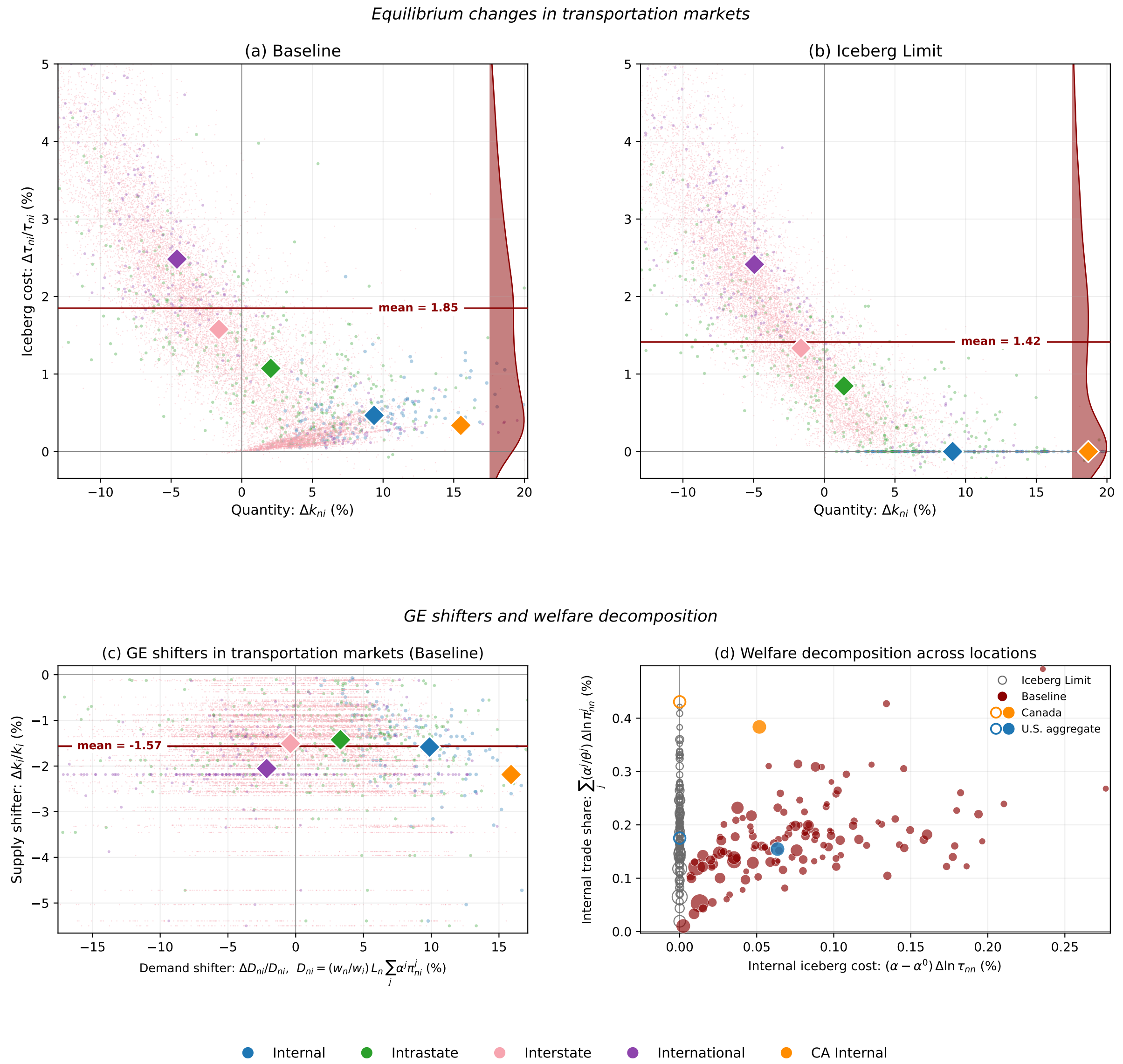
Welfare. U.S. welfare declines by 0.22% in the baseline compared to 0.17% in the Iceberg Limit—an amplification factor of 1.25 (Table 5). Panel (d) makes the source of this amplification visible by location: in the Iceberg Limit, all 128 U.S. locations sit on the vertical axis; in the baseline, the cloud spreads to the right, and the U.S. aggregate (blue) at $(0.06, 0.15)$ attributes 29% of the welfare decline to endogenous changes in internal

[29] Allen and Arkolakis (2014) estimate that eliminating the IHS would reduce U.S. welfare by 1.1–1.4%. Their model and our Iceberg Limit are not directly comparable due to differences in modeling choices and calibration, including land expenditure shares, trade elasticities, spatial granularity, and construction of the counterfactual shock. For example, the expenditure share on goods traded on the IHS (i.e. tradable goods) is 75% in Allen and Arkolakis (2014) and 15% in our calibration.

[30] See Appendix B.3 for details on the counterfactual data construction.

[31] Table 9 in Appendix C provides the full breakdown of travel time and distance changes by market type, and Figure 2 displays the changes in iceberg costs by market type and by origin.

Figure 5: Eliminating the Interstate Highway System: Equilibrium Effects and Welfare Decomposition



Note: See Section 5 for panel descriptions. In panels (a)–(c), dot color indicates market type and diamond markers indicate the medoid route of each type; panels (a) and (b) are trimmed to exclude extreme low-density tails. Panel (d) bubble area is proportional to $L_n/\bar{L}_{\text{US}}$; the U.S. aggregate bubble matches the values in Table 5.

iceberg costs. Canada (orange) sits at $(0.05, 0.38)$, with a sharper welfare decline than the U.S. average on the trade-share axis. The U.S. shock propagates to Canada's domestic transportation prices, accounting for 12% of Canada's welfare decline—a channel absent under iceberg costs.

5.2 Harmonizing Interstate Trucking Regulations

Commercial trucking in the U.S. is subject to a body of regulations we group under the umbrella term *interstate trucking regulations*, with two sources of cost wedges between cross-state and within-state shipments. The first is *heterogeneity* of state-level rules—weight limits, trailer configurations, oversize/overweight permitting, and commercial-vehicle registration fees apportioned across operating jurisdictions—forcing an interstate carrier to comply with the most restrictive standard or highest-fee schedule on any traversed route. The second is *regime activation*: federal regulations and federally-mandated multi-state compacts on fuel-tax apportionment, federal insurance minima, and motor-carrier safety[32] come into force the moment a carrier crosses a state line, even when state rules are uniform, and intrastate-only carriers avoid them altogether.

Crossing a state line therefore imposes compliance burdens absent on intrastate markets of identical distance and travel time. For instance, Michigan allows gross vehicle weights up to 164,000 lbs on certain state highways, but a carrier crossing into Ohio must comply with the federal 80,000 lb Interstate limit—forcing it to reduce its payload by more than half or obtain an overweight permit; 27 U.S. states prohibit longer combination vehicles that are permitted in the other 23; oversize loads require separate permits from each state traversed, with fees, escort rules, and operating-hour restrictions that vary widely; and any cross-state operation activates federal hours-of-service rules, fuel-tax apportionment, vehicle-registration apportionment, and minimum-insurance regulations that intrastate-only operations can avoid. Appendix C.2 documents these regulations in detail.

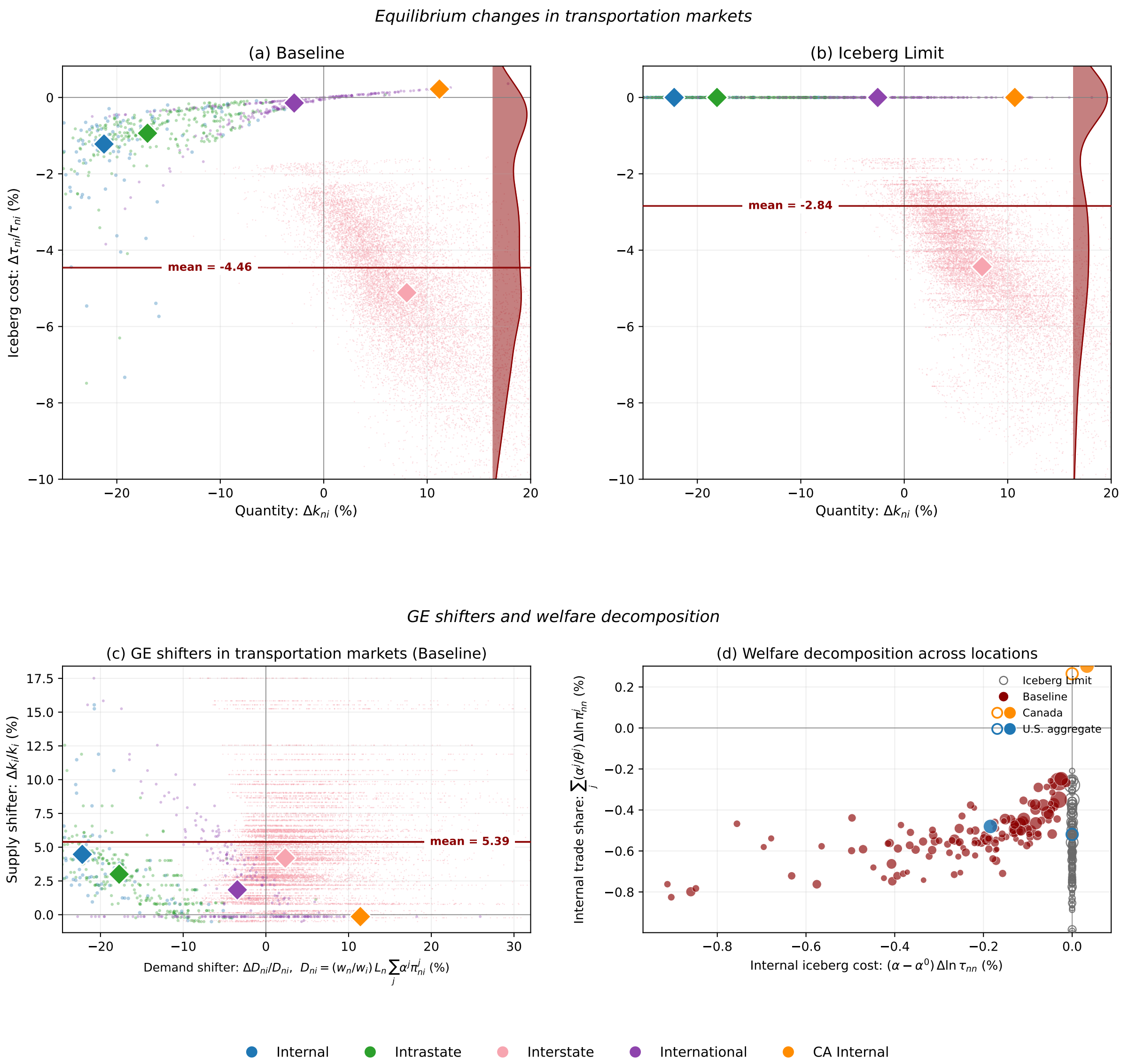
The Shock. We evaluate the benefits of harmonizing these regulations by eliminating the state border effect from the estimated fundamental cost $\tilde{c}_{ni}$ in equation (20). This shock to fundamental costs is identical across the baseline and the Iceberg Limit. In the Iceberg Limit, the implied exogenous change in iceberg costs is

$$\left.\frac{\Delta\tau_{ni}}{\tau_{ni}}\right|_{\mathrm{IL}} = \frac{-\hat{\delta}_{\mathrm{STATE\_border}} \cdot \mathrm{STATE\_border}_{ni}}{\tilde{c}_{ni} + f_i + \varphi_i}, \tag{22}$$

[32] The four channels documented in Appendix C.2 are the International Fuel Tax Agreement (IFTA), the International Registration Plan (IRP), federal financial-responsibility regulations (49 CFR 387), and the FMCSA safety regime (49 CFR Parts 380–399).

where $\hat{\delta}_{\text{STATE\_border}}$ is the state border effect from column 4 of Table 3, and f_i and φ_i are calibrated as described in Section 4.4. Because $\hat{\delta}_{\text{STATE\_border}}$ is common to all interstate markets, the proportional change is larger for routes of relatively short length across states, where the border friction is a larger share of fundamental costs. Central states like Nebraska, Iowa, and Missouri experience the largest reductions in exogenous iceberg costs, ranging from −9.5% to −10.0%.[33]

Figure 6: Harmonizing Interstate Trucking Regulations: Equilibrium Effects and Welfare Decomposition



Note: See note to Figure 5.

Propagation through Transportation Markets. On average across all transportation markets, iceberg costs fall by 4.46% in the baseline, compared to 2.84% in the Iceberg

[33]Figure 3 in Appendix C displays the shock by market type and by origin.

Limit—an amplification factor of 1.57. The shock hits only interstate markets, leaving internal, intrastate, Canada-internal, and international fundamental costs unchanged. Panels (a) and (b) of Figure 6 show the resulting propagation. In the Iceberg Limit, iceberg costs decline only on interstate markets, with $\Delta\tau_{ni}/\tau_{ni} = 0$ for other market types. In the baseline, general equilibrium effects propagate the shock to every transportation market. Iceberg costs fall by 1.2% at the internal medoid and 2.4% on average across internal markets. Panel (c) shows the underlying baseline mechanism: the aggregate stock of trucks in the U.S. expands by 5.4% (versus 2.6% in the Iceberg Limit) as interstate markets become more profitable, and transportation demand reallocates away from short-distance markets.

Welfare. U.S. welfare increases by 0.67% in the baseline compared to 0.52% in the Iceberg Limit—an amplification factor of 1.29 (Table 5). Panel (d) shows the welfare decomposition by location: in the Iceberg Limit, all 128 U.S. locations sit on the vertical axis; in the baseline, the cloud spreads to the left and the U.S. aggregate at $(-0.18, -0.48)$ attributes more than a quarter of the welfare gain to the internal-iceberg-cost channel.

Panel (d) also reflects a terms-of-trade deterioration for Canada. Because the shock acts only on U.S. domestic fundamental costs, Canadian import prices barely change, while U.S. labor demand pulls Canadian relative wages down. Canada substitutes toward internal sources—its internal trade share rises by 11%—resulting in a welfare loss in the Iceberg Limit. In the baseline, panel (c) shows that transportation demand on Canada's internal market rises, raising the internal iceberg cost endogenously and amplifying the loss.

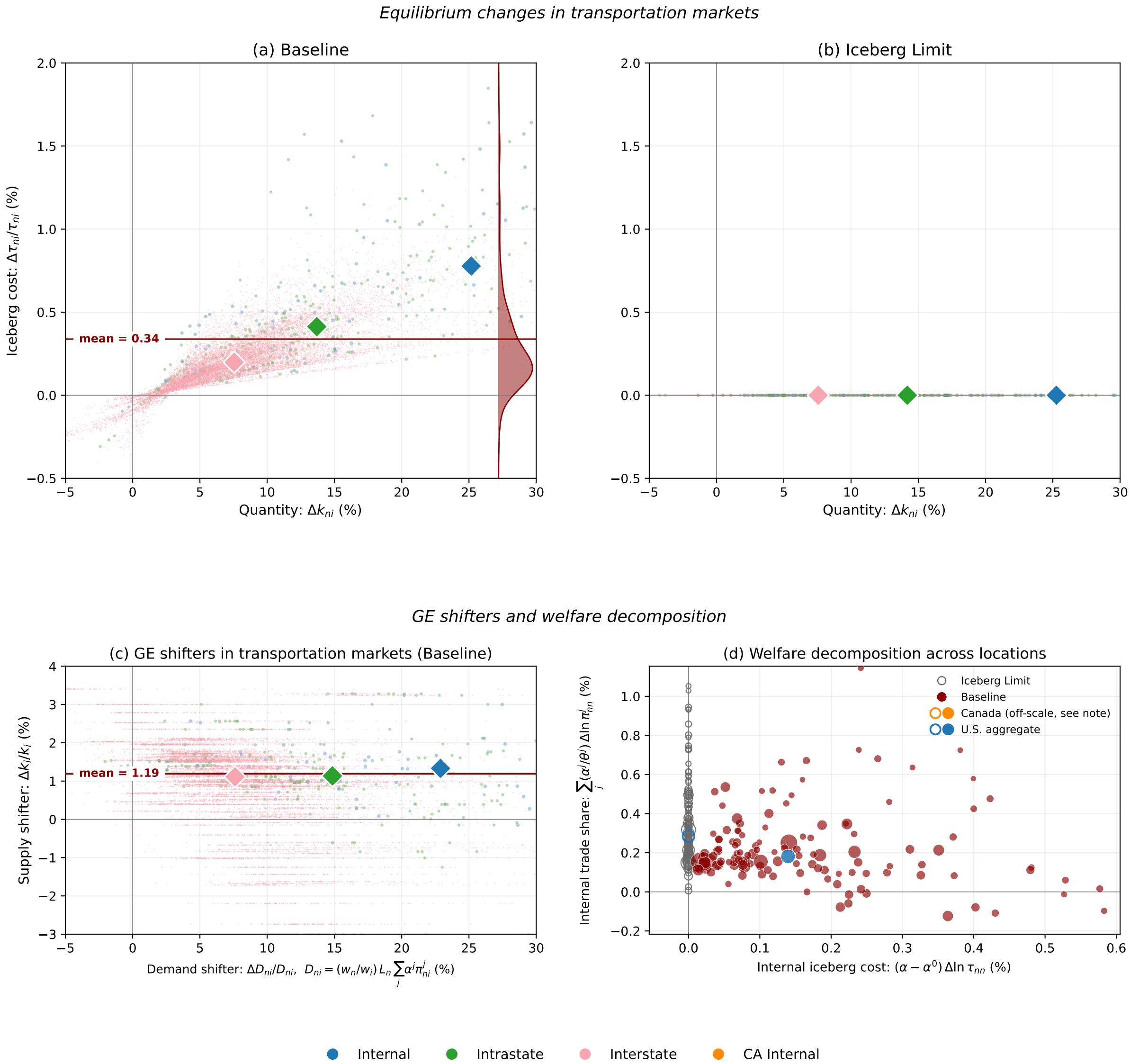
5.3 Shutting Down the U.S.–Canada Border

We explore the counterfactual autarky equilibrium, shutting down the U.S.–Canada border to quantify the gains from trade. Trucking is the dominant mode of freight transportation between the U.S. and Canada, accounting for 58% of bilateral trade by value in 2017 (Bureau of Transportation Statistics, 2018), with 11 million trucks crossing the border in 2017 (Maoh et al., 2021). Brown (2012) provides reduced-form estimates of an 18% to 31% premium for cross-border shipments relative to comparable domestic shipments, depending on the direction of crossing. The premium reflects customs brokerage and documentation fees incurred on every shipment, cabotage restrictions that prevent truckers from picking up domestic return loads (forcing empty backhauls), and hours-of-service rules that are not mutually recognized, forcing drivers on cross-border routes to comply with the more restrictive regime. Appendix C.3 documents these regulatory differences in detail.[34]

[34] Brown (2015) further shows that this cross-border cost premium rose after 9/11, consistent with the tightening of customs and security requirements at the border.

The Shock. We simulate the closure of the U.S.–Canada border by setting route-specific fundamental costs c_{ni} to infinity for all transportation markets that cross the U.S.–Canada border. This forces both countries to rely exclusively on their domestic transportation networks.

Figure 7: U.S.–Canada Border Closure: Equilibrium Effects and Welfare Decomposition



Note: See note to Figure 5. Panels (a), (b), and (c) restrict the sample to U.S. transportation markets: international markets are closed under the counterfactual and the Canada-internal market is off-axis. In panel (d), the Canada bubble is off-scale: its coordinates are (+0.75, +16.15) in the baseline and (0.00, +16.16) in the Iceberg Limit.

Propagation through Transportation Markets. On average across U.S. transportation markets, iceberg costs rise by 0.34% in the baseline while remaining unchanged in the Iceberg Limit. This experiment highlights a mechanism typically absent in studies on border effects and international integration: internal transportation prices adjust endogenously to the border shock. The shock is the most geographically asymmetric of the four experiments; in panel (b) of Figure 7, $\Delta\tau_{ni}/\tau_{ni} = 0$ exactly in every domestic market in the Iceberg Limit, since no domestic fundamental cost is shocked. In panel (a), the baseline breaks this degeneracy: transportation demand reallocates toward domestic transportation markets (the internal medoid shows a 25% equilibrium quantity increase), domestic transportation prices rise endogenously, and the welfare cost of the border shock is amplified relative to the iceberg benchmark. Panel (c) reveals a feature unique to this experiment, driven by the shock's geographical asymmetry: the baseline supply shifter $\Delta k_i/k_i$ is heterogeneous in sign across U.S. locations and correlated with the distance to Canada (Pearson $\rho = +0.36$). The nearest-quartile U.S. locations see no net expansion (+0.0% on average) while the farthest-quartile locations expand by +1.3%; in Canada, the stock of trucks decreases by 10.7% as the loss of international markets reduces entry incentives.

Welfare. Transportation markets amplify the U.S. gains from trade with Canada from 0.28% in the Iceberg Limit to 0.32% in the baseline—an amplification factor of 1.13 (Table 5). Panel (d) of Figure 7 shows the welfare decomposition by location: in the Iceberg Limit, all 128 U.S. locations sit on the vertical axis; in the baseline, the cloud spreads to the right, and the U.S. aggregate at $(0.14, 0.18)$ attributes 44% of the welfare gains from trade to the internal-iceberg-cost channel. Canada's gains from trade with the U.S. are, not unexpectedly, an order of magnitude larger (16.16% in the Iceberg Limit) and are also amplified by transportation markets (16.90% in the baseline). Canada's bubble is off-scale in panel (d); its values are reported in the figure note.

5.4 The Advent of Autonomous Trucks

Autonomous trucking technology has advanced rapidly: Aurora launched the first commercial driverless freight service in Texas in 2025 and plans to scale to over 200 trucks by 2026. Industry estimates suggest full autonomy could reduce total operating costs by 45%, generating savings of $85 to $125 billion for the U.S. for-hire trucking industry (Chottani et al., 2018).[35]

The Shock. We decrease fundamental costs by 45% uniformly across transportation markets, in both the baseline and the Iceberg Limit. In the Iceberg Limit, the implied

[35] The savings stem from three main channels. First, driver compensation accounts for 40% of trucking operating costs and is largely eliminated under full autonomy. Second, autonomous trucks can operate near-continuously, doubling daily range from 600 to 1,200 miles by eliminating mandatory rest periods, which raises asset utilization without increasing fleet size (Deloitte, 2024). Third, AI-optimized driving patterns reduce fuel consumption by an estimated 11–32% (Aurora Innovation, 2025).

exogenous change in iceberg costs is

$$\left.\frac{\Delta\tau_{ni}}{\tau_{ni}}\right|_{\mathrm{IL}} = \frac{-0.45\,\tilde{c}_{ni}}{\tilde{c}_{ni} + f_i + \varphi_i},$$

where $\tilde{c}_{ni}$ is estimated from (20) and f_i and φ_i are calibrated as described in Section 4.4.[36] Central states see the largest reductions (−22% to −28%), while California and New York see smaller decreases (−6% to −11%).[37]

Propagation through Transportation Markets. On average across all transportation markets, iceberg costs fall by 13.06% in the baseline, compared to 9.26% in the Iceberg Limit—an amplification factor of 1.41. A comparison of panels (a) and (b) of Figure 8 reveals a pattern of *asymmetric amplification* in the baseline model: general-equilibrium propagation amplifies the cost shocks relatively more on short-distance markets. In panel (b), the shock is uneven across market types in the Iceberg Limit: although uniform in fundamental costs, $\tilde{c}_{ni}$ is a larger share of τ_{ni} on long routes than on short ones, so iceberg costs decline more on interstate than on internal markets.[38] In panel (a), general-equilibrium reallocations of transportation demand amplify the asymmetry. On average across markets, the baseline-to-Iceberg Limit gap in iceberg cost changes is monotonically larger in absolute value for shorter-distance market types: 5.9 percentage points on internal markets, 4.2 on intrastate, and 3.2 on interstate.[39] Panel (c) unpacks the underlying mechanism: the aggregate stock of trucks in the U.S. rises by 16.0% and transportation demand reallocates away from internal and intrastate markets (demand shifter −46% and −31% on average) toward interstate and international ones (+11%).

Welfare. U.S. welfare increases by 2.03% in the baseline compared to 1.57% in the Iceberg Limit—an amplification factor of 1.29 (Table 5). Panel (d) shows the welfare decomposition by location. This is the only experiment where the Iceberg Limit cluster is also off the vertical axis, because internal transportation markets are directly shocked. Still, the baseline cluster sits systematically further from the origin, with the U.S. aggregate at $(-0.65, -1.35)$, against $(-0.15, -1.42)$ in the Iceberg Limit. The internal iceberg cost channel accounts for 33% of the welfare gains in the baseline, against 10% in the Iceberg Limit.

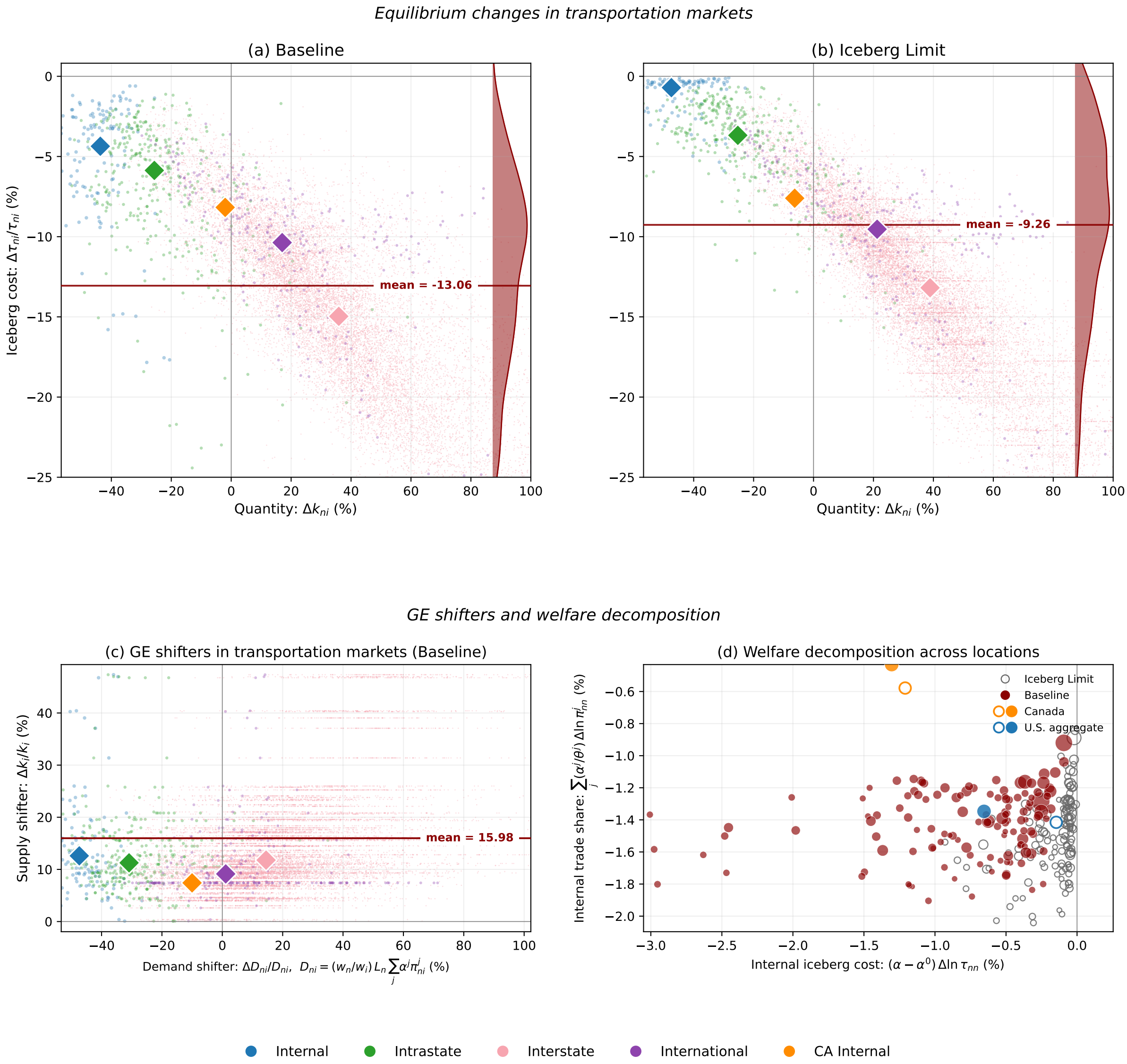
[36] Since $\tilde{c}_{ni}$ is a linear combination of estimated regression coefficients and route-level observables (equation (20)), the 45% reduction is equivalent to scaling down each estimated coefficient—the marginal cost per mile, per hour, and per border crossing—by 45%. The shock thus captures the impact of autonomy on reducing the distance, time, and border gradients of fundamental costs. See Appendix B.9 for a formal discussion.

[37] Figure 4 in Appendix C displays the shock by market type and by origin.

[38] At the medoid: −44% quantity and −4.4% iceberg cost for internal markets; +36% quantity and −15% iceberg cost for interstate markets.

[39] The cross-market Spearman correlation between the demand shifter $\Delta D_{ni}/D_{ni}$ and the baseline-to-Iceberg Limit gap in iceberg cost changes is −0.33.

Figure 8: Autonomous Trucks: Equilibrium Effects and Welfare Decomposition



Note: See note to Figure 5.

6 Conclusion

The implications of endogenous transportation costs for the spatial distribution of economic activity remain an open question (Allen and Arkolakis, 2025); our paper aims to narrow this gap. We develop a quantitative spatial trade model in which transportation costs are equilibrium prices, determined in competitive transportation markets defined over directional origin-destination pairs. By nesting the standard iceberg cost formulation as a limiting case, our framework isolates a propagation channel absent from workhorse trade models: local shocks to fundamental shipping costs—driven by infrastructure, regulation, borders, or technology—propagate to the entire distribution of transportation prices through general equilibrium reallocations of supply and demand. We derive a welfare decomposition that separates the effects of these shocks into changes in internal trade shares, familiar from the ACR tradition, and changes in endogenous internal iceberg costs, unique to our framework.

Across four counterfactual exercises calibrated to 129 North American regions, transportation markets amplify equilibrium transportation cost changes by 30–57% and aggregate welfare effects by 13–29% relative to the iceberg benchmark. The new channel accounts for a quarter to nearly half of the total welfare effect across experiments. These results are disciplined by an estimated transportation supply elasticity of 7.9, identified using an original dataset of trucking prices and an instrument grounded in the gravity structure of transportation demand.

Our analysis has a practical implication for policy evaluation: cost-benefit analyses of infrastructure investment, regulatory harmonization, border policy, and technology adoption based on models with exogenous trade costs may understate welfare effects by missing the endogenous propagation of shocks through transportation markets.

Several limitations point to directions for future research. We model a single transportation mode (trucking) and abstract from intermodal substitution; extending the framework to rail, air, and maritime shipping would enable a richer set of counterfactuals. Our static framework does not capture the dynamic adjustment of transportation networks or the entry and exit of truckers over time. Finally, treating Canada as a single region limits the analysis of cross-border effects. We view these as opportunities to build on the framework developed here.

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