Network Structure and Efficiency Gains from Mergers: Evidence from U.S. Freight Railroads *

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Abstract

This paper examines competition among oligopolistic network firms and the influence of market power on the resulting equilibrium outcomes. I build a model of oligopolistic competition between transport firms, with each firm choosing its own network infrastructure endogenously to maximize profits. The model allows individual firms to optimize their decisions across the entire network, while also accounting for strategic interactions among competitors. I implement the proposed model in the context of U.S. freight railroads and present novel facts on merger gains using detailed waybill data. I use this framework to demonstrate (i) the strategic investment responses of non-merging firms are the main reasons behind the increase in markups after the merger wave and (ii) market outcomes are endogenously related to the structure of the network, as represented by degree and betweenness centrality. These mechanisms reveal a new role for market power in understanding competition within a network-based industry, which was previously concealed by looking only at the decisions of a social planner or atomistic players.

Keywords: Cost Efficiency, Transport Infrastructure, Oligopoly Competition, Mergers

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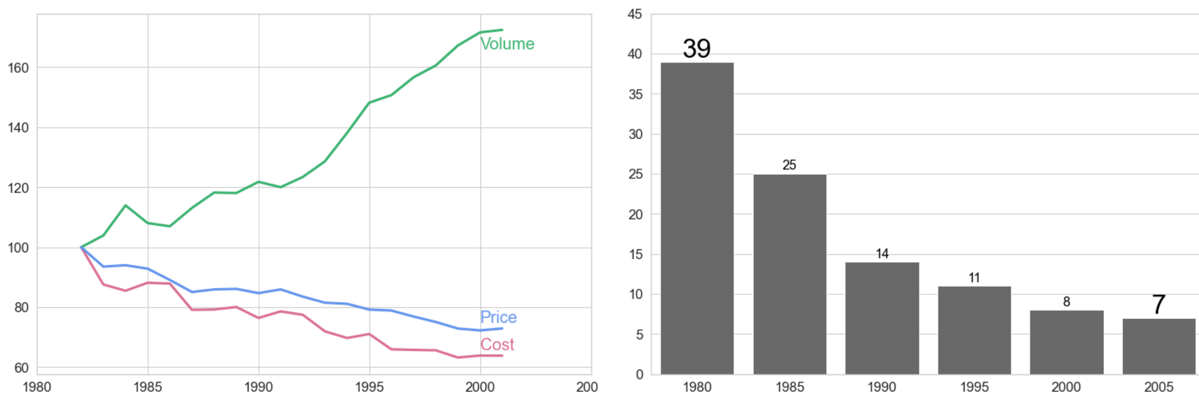
1 Introduction

Transportation infrastructure serves as the lifeblood of modern society, playing a vital role in facilitating commerce, trade, and social interaction. However, when conducting economic analysis, we typically consider the transportation network as externally predetermined. In recent studies, two contrasting approaches have been adopted: one emphasizes the decisions of a social planner (Fajgelbaum and Schaal, 2020), while the other focuses on the decisions of atomistic players (Brancaccio, Kalouptsidi and Papageorgiou, 2020). Nevertheless, in practice, the transportation sector exhibits significant concentration, with only a few dominant market players holding substantial market shares. Therefore, it is probable that the optimization decisions of one firm across the network will be influenced by the actions of other firms. How does competition among these oligopolistic transport network firms impact the equilibrium outcomes? Moreover, how are market outcomes endogenously related to the structure of the network itself? This paper aims to provide the first study that estimates a structural model of oligopolistic competition within transport networks. More specifically, I build a model of oligopolistic competition between transport firms where each firm chooses endogenously its own network infrastructure to maximize profits.

I apply the proposed model in the context of U.S. freight railroads, a network-based industry that has undergone significant changes in the competitive landscape over the past three decades. In addition to its historical significance for economic development, the railroad continues to be one of the most crucial modes of transportation for freight in the present day. According to the Association of American Railroads (AAR), in 2016 railroads transported about 40% of intercity ton-miles, more than any other mode of transportation. I consider a series of mergers in this industry from 1985 to 2005. The number of Class I railroads[1] dropped from 39 to 7 over this period, and the market share of the top four firms increased from 66% to 94%. Although concentration has increased in this industry, prices have decreased steadily. As illustrated in Panel (a) of Figure 1, prices per shipment decreased by 20% in real terms between 1985 and 2005, while the total shipment volume doubled. Given the limited technological advancements observed within the industry during the studied period, the price reduction indicates that there might be efficiency gains following these railroad mergers. However, understanding oligopolistic competition and mergers in a network-based industry is difficult. This is because, firstly, the decisions made by a railroad firm in a single origin–destination market can influence decisions in all other markets in which the firm operates. Secondly, following a merger, the merged entity needs to re-solve the complicated

[1] Class I railroads are defined as "having annual carrier operating revenues of $250 million or more in 1991 dollars." According to the AAR, Class I railroads accounted for more than 95% of U.S. freight railroad industry revenues in 2016.

optimization problem for the entire network, and competing firms will also strategically respond by altering their pricing and operational decisions. To account for these important factors, I construct a model of oligopolistic competition among transport firms in which each firm optimizes its pricing, routing, and maintenance allocation decisions endogenously to maximize profits.



(a) Shipment Price, Cost, and Volume

(b) Number of Class I Railroads

Figure 1: U.S. Freight Railroads

There is currently no existing model of this nature in the literature. The current literature on optimal transport network either considers a social planner as in Fajgelbaum and Schaal (2020), or assume a large number of ships and exporters where each individual ship decides on its search locations and exporters decide whether and where to export, as in Brancaccio et al. (2020). The social-planner approach enables optimization across the entire network, taking into account how infrastructure investment in one area impacts operational decisions in all other areas. However, this approach does not consider the strategic interaction among competitors, thereby constraining the scope for analyzing mergers. The alternative approach involving atomistic players does permit strategic interactions among different firms. However, since each individual firm is relatively small, it does not consider how infrastructure investment in one area influences operational decisions throughout the entire network. In contrast, my paper provides the opportunity for both individual firms to optimize their decisions over the entire network and for strategic interactions among competitors. The model I propose has the potential not only to analyze merger benefits within the freight railroad industry but also to address novel empirical questions that have yet to be explored in existing literature. For example, the market for electric vehicles has witnessed a ten-fold increase in annual unit sales over the past decade. However, an essential aspect to consider is how different electric vehicle companies make decisions regarding the charging infrastructure network.

To gain insights into this matter, it is imperative to understand oligopolistic competition within a transport network, which is precisely the focus of my model presented in this paper.

In conducting my analysis, I utilize three primary datasets: the confidential Carload Waybill Sample, the Class I Railroad Annual Report, and the Commodity Flow Survey. Among these sources, the Carload Waybill Sample provides extensive shipment-level information. The dataset includes details regarding shipment price, commodities transported, total billed weight, utilized equipment, participating railroads, as well as the origin, destination, and interchange locations for each load. By utilizing this detailed shipment data on 12 million waybills, I find that shipment prices have decreased by 9% post merger on average. I then examine the price effects for different route types. For routes where railroad companies conduct an interchange[2] before the merger, the price effect of mergers is 11%. For other types of routes, the price effect is around 6%.

Next, I present a static model that captures the annual decision-making process of railway firms. Specifically, I construct a model of oligopolistic competition among transport firms in which each firm optimizes its pricing, routing, and allocation decisions endogenously to maximize profits. In a network, locations are arranged on a graph, and goods can only be shipped through connected locations. Each railroad company possesses its own network, with the physical tracks being individually owned by each firm. In this network, the market locations are represented as nodes, while the physical tracks between them serve as arcs. The costs of transportation depend on the level of investment in infrastructure, such as the quality of tracks. Railroad firms can allocate maintenance resources to the tracks within their ownership to cover the costs of routine maintenance activities and infrastructure upgrades. These maintenance allocation decisions can be equal to or greater than zero in dollar amount. Overall, the railroad firms make decisions regarding the pricing for every origin–destination market, the routing for each shipment, and the allocation of maintenance resources within their networks.

Solving this problem is challenging for two reasons. Firstly dimensionality, because the space of all networks is large, and an investment in one link affects routing decisions, hence impacting the returns to investments across the network. Secondly, strategic interactions add complexity as firms strategically respond to the pricing and operational decisions made by other firms. In tackling these challenges, I exploit the fact that the subproblem of selecting the optimal routing can be framed as an optimal flow problem within a network. To address this, I leverage the insights from the operations research and optimal transport literature. I

[2] In railroading, an "interchange" refers to the location or facility where two or more different railroad companies meet to exchange cars and freight. At these points, one railroad's cars can be transferred to another railroad's tracks for continuing their journey. I present an actual instance of an interchange in section 2.1.

introduce a novel perspective by incorporating the element of imperfect competition among competing companies.

I then estimate the model using detailed waybill data. The demand parameters are estimated from a linear instrumental variables regression of differences in log market shares on prices and service characteristics. I employ two sets of instruments in my analysis. The first set involves the service characteristics of competing firms, commonly referred to as the "BLP instruments." Additionally, I utilize observed mergers between railroad firms as proxies to capture and measure changes in market power within local markets. Upon estimating the demand parameters, I employ the cross-sectional differences across various origin–destination markets to identify the cost parameters. These cost parameters are then estimated using the simulated method of moments. The cost parameter related to travel distance is identified by the average shipping cost per mile in dollar terms. Additionally, I employ the average price difference between interconnecting and non-interconnecting routes to identify the cost associated with a single interchange. To identify the cost parameter that governs the effectiveness of maintenance allocation resources, I focus on moments related to how network centrality impacts shipment prices. The underlying rationale is that this parameter influences the efficiency of traffic consolidation within a network, thereby affecting the effects of network centrality on shipment prices.

Using the estimated parameters, I simulate the equilibrium outcomes before and after each merger among Class I railroads from 1985 to 2005. The results show that on average, shipment cost reduces by 12.9%, shipment price reduces by 8.8%, and the additive markup increases by 7.2%. Per the increased markup post-merger, my analysis shows that reducing the number of firms in local markets is not the main driving factor. Instead, the increased markup is primarily driven by the strategic reaction of non-merging firms, who tend to reallocate resources away from regions where the merged firm gains significant cost reduction. As a consequence, this leads to additional growth in the merged firm's market share at the local level, resulting in greater markup increase in those regions. The findings confirm that looking only at changes at the individual route level is insufficient for understanding mergers in the network-based industry.

The results also demonstrate substantial heterogeneity in the gains from mergers when examined at the level of origin–destination markets. To investigate the relationship between merger gains and network structure, I first analyze the changes in centrality for each node following a merger. I then assess how these changes in centrality impact the magnitude of merger gains. I use two centrality measures in my analysis: degree centrality, which captures the total number of links connected to a specific node within the network, and betweenness centrality, which evaluates the number of paths that pass through each node. The results suggest that when a node is positioned at the outer edges of the network before the merger and subsequently becomes more central in the post-merger network, it experiences a greater improvement in efficiency. Additionally, an increase in betweenness centrality will lead to a larger reduction in shipment cost and a greater increase in markup after the merger when compared to a similar increase in degree centrality.

To further understand the impact of network centrality on merger gains, I perform counterfactual experiments by adjusting the structural parameters of the model. The results suggest that nodes experiencing increases in betweenness centrality not only enjoy improved routing options and shorter travel distances following the merger, but they also benefit more from resource reallocation. In comparison, nodes with increased degree centrality are more likely to benefit from better routing options, but not much from resource reallocation post merger.

Lastly, to shed light on future merger policies, I examine how the integration of networks affects the merger gains across different mergers. I analyze the relationship between merger gains and the extent of overlap and complementarity between the two networks involved in the merger. The degree of overlap is measured by the overall percentage of markets that both merging firms were present prior to the merger. As for complementarity, it is calculated as the overall percentage of interchanges carried out between the merging firms. The findings indicate that a high degree of overlap leads to significant cost reductions and substantial increases in markup. Conversely, a high degree of complementarity also leads to significant cost reductions but only a modest increase in markup.

Related Literature

This article relates to three broad strands of literature: (i) horizontal mergers, especially efficiency gains of mergers; (ii) network competition; and (iii) transportation infrastructure.

First, this article contributes to a growing literature that attempts to evaluate antitrust policy toward horizontal mergers. Economists have been aware of the trade-off between market power and efficiency gain at least since Williamson (1968), and the price effects of mergers are extensively studied in the literature. For example, the literature has looked at mergers in the airlines (Borenstein, 1990; Kim and Singal, 1993; Peters, 2006), hard-disk manufacture (Igami, 2017), ready-mix concrete (Collard-Wexler, 2014), and hospitals (Dafny, 2009; Dafny, Ho and Lee, 2019). However, there is very little direct empirical evidence for efficiency gains of mergers (a few exceptions are Ashenfelter et al., 2015; Jeziorski, 2014; Clark and Samano, 2022). Over and above the sparseness of the literature on the cost efficiency of mergers, even fewer studies have documented efficiency gains in network-based industries. This paper contributes to filling the gap in understanding efficiency gains in a network industry and to explore how network structure alters such merger gains.

This paper also contributes to the literature on the freight railroad industry. Grimm and Winston (2000) and Gallamore and Meyer (2014) provide an excellent summary of this literature. Most existing literature studies change in some aggregate cost or price index, or examines merger effects by looking at individual markets. Virtually no research has looked at merger effects by considering the interdependent nature of railroad networks. My paper contributes to filling this gap.

Second, this article relates to the network competition literature. Empirically, Ho (2009) studies the determinants of the insurer-provider networks with a focus on the vertical relationships between insurer plans and hospitals; Ciliberto, Cook and Williams (2019) show the effect of consolidation on airline network connectivity using different measures of centrality; Holmes (2011) studies Wal-Mart's choice of locations and infers the magnitude of density economies. From a theoretic perspective, Hendricks, Piccione and Tan (1999) investigates the conditions under which hub-spoke networks are equilibria when two large carriers compete. Aguirregabiria and Ho (2012) extend the static duopoly game of network competition to a dynamic framework by allowing local managers to decide whether or not to operate nonstop flights in their local markets. My model differs from those approaches by enabling every firm to have its own network and allowing each firm to endogenously choose its own network infrastructure. This feature enables me to introduce oligopolistic competition into transport networks. By doing that, we can generate much richer welfare implications, especially how network structure affects merger gains.

Last, this article is also related to the literature on the impact of transportation infrastructure and networks (e.g., Donaldson and Hornbeck, 2016; Donaldson, 2018; Allen and Arkolakis, 2014), and the proposed model in this article builds upon the recent literature on optimal transport network (Fajgelbaum and Schaal, 2020; Brancaccio et al., 2020). I differ from their papers by considering the imperfect competition conditions and allowing for markup for each railroad company. The analysis of the effects of network structure in this paper can be implemented both for merger gains and in any other relevant policy analysis.

The remainder of the paper is organized as follows. Section 2 describes the industry background. Section 3 outlines the three main datasets used in the paper, and Section 4 provides reduced-form evidence on merger gains after railroad mergers. Section 5 constructs the structural model of firm pricing, routing, and maintenance allocation decisions in a rail network. Section 6 presents the estimation results and assesses the validity of the model, while Section 7 presents the counterfactual experiments and results. Section 8 concludes.

2 Industry Background

2.1 A Running Example: Train 9-698-21

The story of Train 9-698-21 serves as a running example to explain the fundamental concepts of railroading that are used in this paper. To provide an overview of the simplified railway network, Figure 2 depicts the three principal railroad companies, namely the Santa Fe railway, the Burlington Northern railway, and the Union Pacific railway. The network is characterized by four nodes, namely, Los Angeles, Avard Oklahoma, Claremore Oklahoma, and Memphis, from which six eastbound markets can be identified, including trips between Los Angeles and Avard, Los Angeles and Claremore, Los Angeles and Memphis, Avard and Claremore, Avard and Memphis, and Claremore and Memphis.

The Santa Fe railway operates Train 9-698, which commences its journey from Los Angeles and terminates at Memphis.[3] On an average day, the train commences its journey from Los Angeles promptly, proceeds without any delay and reaches Avard Oklahoma ahead of schedule. Upon arrival at Avard Oklahoma, the train must be interchanged between Santa Fe railway and Burlington Northern railway. Initially, the train encountered a five-hour wait to exchange railcars with a tardy train from Richmond. Subsequently, the crew discovered that Burlington Northern had not dispatched a locomotive to retrieve the train. Upon contacting Burlington Northern, the responsible party responded by stating that "you are not my first priority, so you'll have to wait". After additional delay, a locomotive eventually arrived and retrieved the train, which was subsequently transported by Burlington Northern until it finally reached its destination in Memphis.

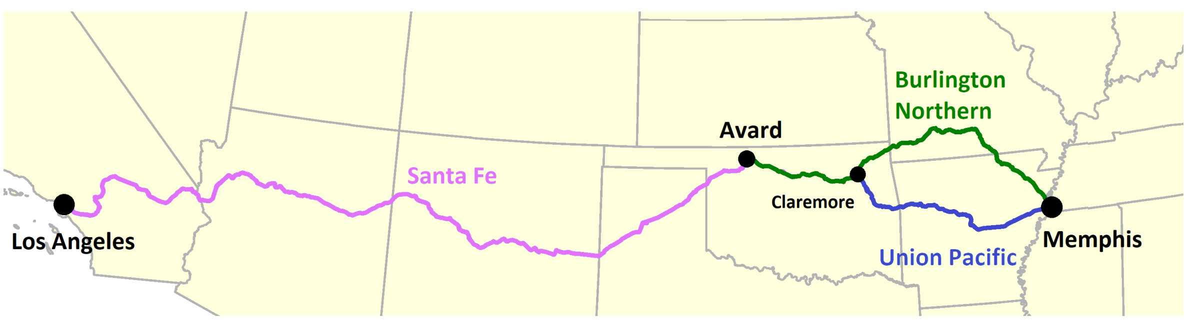


Figure 2: The Story of Train 9-698-21

The story of Train 9-698 serves to underscore three potential avenues for increasing efficiency through the proposed merger between the Santa Fe railway and the Burlington Northern railway. Firstly, the merger is expected to eliminate the interchange cost incurred at Avard. Secondly, the elimination of this cost would enable the merged entity to make

[3]Original story from *Trains* magazine "Twenty-four hours at Supai Summit".

better routing decisions by directing traffic towards the route between Los Angeles and Memphis. Thirdly, by leveraging the newly re-optimized routing strategy, the merged firm can better allocate its resources, such as track maintenance spending. Specifically, if the route between Los Angeles and Memphis is made more efficient, other traffic from disparate origin–destination markets such as San Diego to Kansas City can also utilize this improved route, thus enabling the merged firm to realize the benefits of *economy of scope*. This concept is supported by industry professionals, for example, the Chief Operating Officer of CSXT stated that "An essential feature of the operating plan is to consolidate traffic over a smaller number of efficient, high-volume routes."[4] In my model, I have incorporated all three sources of efficiency gain mentioned above, namely the elimination of interchange cost, optimal routing, and economy of scope through the efficient allocation of resources.

Figure 2 is subsequently utilized to explain the definition of a "product" in the context of railroading. Specifically, a product can be construed as a service-firm pair that pertains to a given origin–destination market. Notably, two distinct types of services can be identified, namely a single-line service and a joint-line service. A single-line service denotes a mode of transportation in which a single railroad company is responsible for the entire shipment from its origin to its destination. In contrast, a joint-line service is characterized by the involvement of two or more railroad companies, with each company contributing to the transportation of a specific portion of the shipment. To exemplify:

- A shipment from **Los Angeles** to **Avard Oklahoma** is served by a single-line service offered by the Santa Fe railroad.

- A shipment from **Los Angeles** to **Claremore Oklahoma** is served by a joint-line service provided by the Santa Fe railroad and the Burlington Northern railroad. Specifically, the Santa Fe railroad carries the shipment from the origin Los Angeles to the interchange station Avard Oklahoma, following which the Burlington Northern railroad transports the shipment from Avard Oklahoma to Claremore Oklahoma.

- For a shipment from **Avard Oklahoma** to **Memphis**, both a single-line service and a joint-line service are available. The single-line service is provided by the Burlington Northern railway, while the joint-line service is offered by the Burlington Northern railway and the Union Pacific railroad.

- Finally, a shipment from **Claremore Oklahoma** to **Memphis** can be transported using two distinct single-line services. One such service is provided by the Burlington

[4] Ex Parte No. 711 (Sub-No.1) Reciprocal Switching, Opening Comments, CSX Transportation Inc. The concept of achieving cost efficiency by consolidating traffic is also supported by the former CEOs of the Southern Pacific (Krebs, 2018) and Canadian National Railway (Harrison, 2005).

Northern railway, while the other is offered by the Union Pacific railway.

2.2 Defining the Network

In accordance with the Surface Transportation Board, a market is defined as an origin–destination pair where the origins and destinations correspond to the Bureau of Economic Analysis (BEA) economic areas. The contiguous United States comprises a total of 170 BEA areas. To construct a network $\mathcal{G}_j$ for a given railroad company j, a non-directed graph $(\mathcal{Z}_j, \mathcal{A}_j)$ is defined with nodes denoted by $\mathcal{Z}_j$ and arcs denoted by $\mathcal{A}_j$. The nodes in this network represent the centroids of the BEA regions, while the arcs correspond to the rail lines connecting each BEA economic area. The rail network of the Burlington Northern railway (BN) in 1994 is depicted in the left panel of Figure 3. A BEA area a is included in $\mathcal{Z}_j$ if BN has tracks in that region. Similarly, if two adjacent BEA areas are connected by tracks owned by BN, then $(a, b) \in \mathcal{A}_j$, as illustrated in the right panel of Figure 3. All available information of a network is recorded, including the total length of tracks owned by the firm in each BEA area, as well as the distance between connected nodes. I follow the same process in constructing the network of each railroad firm for every year between 1985 and 2005, based on detailed geographic information for each rail line and information about the ancestry of rail lines obtained from the Federal Transit Administration.[5]

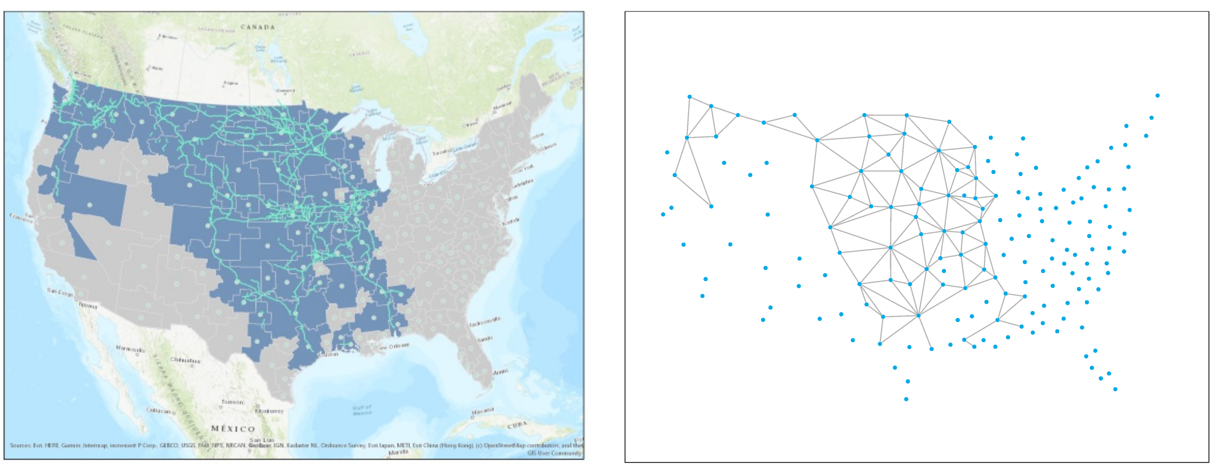


Figure 3: BN Rail Network

Here I discuss the challenges associated with analyzing the effects of mergers in the railroad industry. Firstly, decisions made by a railroad firm in a single origin–destination market can impact the decisions made in all other markets in which that firm operates.

[5]Historical information about railroad networks is obtained by comparing the shapefiles of U.S. rail lines available at http://osav-usdot.opendata.arcgis.com/datasets?keyword=Rail with information on merger history obtained from https://cta.ornl.gov/transnet.

For instance, consider the case of train 9-698. The merger of the Burlington Northern railway and the Santa Fe resulted in an increase in efficiency along the route from Los Angeles to Memphis, which may have led to changes in routing decisions for adjacent areas to take advantage of the new, more efficient route. Additionally, resource allocation decisions would be re-optimized for the entire network owned by the merged entity. Secondly, in addition to the merged entity having to re-solve the complex optimization problem for the entire network, all competing firms will strategically respond by altering their pricing and operational decisions. Figure 4 illustrates the network constituted by the seven current Class I railroads.[6] Each railroad firm retains ownership of its own physical tracks. The interdependence of markets within a railroad firm's network and the interaction of railroad firms in multiple markets adds to the complexity of understanding the behavior of merging firms and non-merging competitors after a railroad merger. To address this challenging issue, this paper proposes an equilibrium model of oligopolistic competition between railroad firms, in which each firm endogenously chooses its pricing, routing, and resource allocation decisions.

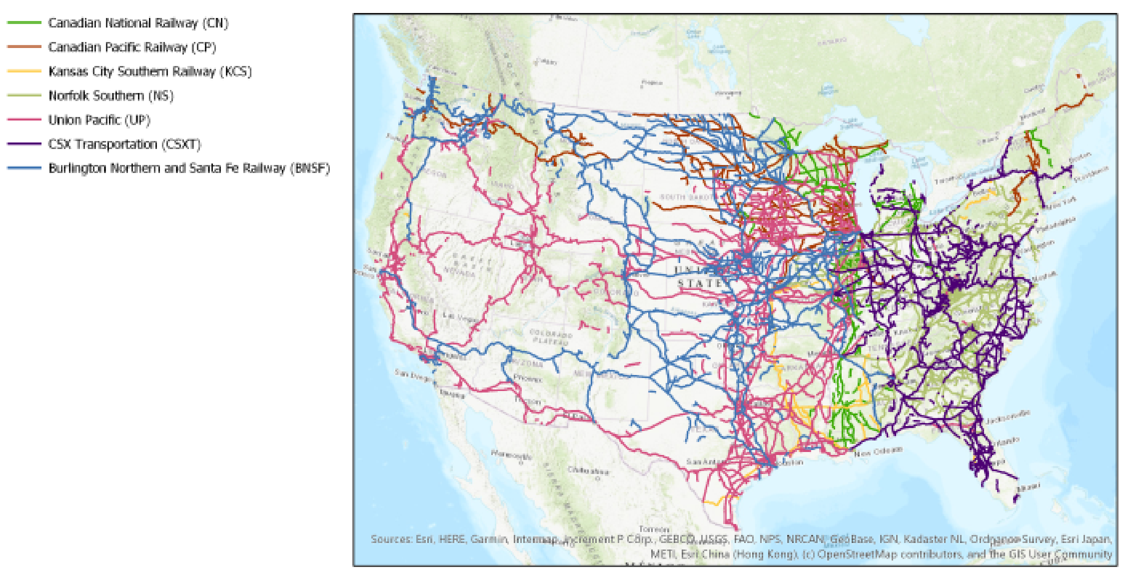


Figure 4: U.S. Class I Railroads

[6]Specifically, the Burlington Northern and Santa Fe Railway (BNSF) competes with the Union Pacific Railway (UP) in the western region, while the eastern region sees competition between CSX Transportation (CSXT) and the Norfolk Southern Railway (NS). In addition, two Canadian Class I railroads, namely the Canadian Pacific Railway (CP) and the Canadian National Railway (CN), facilitate the movement of freight shipments between Canada and the United States. The Kansas City Southern Railway (KCS) is located in the southern region and is responsible for connecting freight shipments between Mexico and the United States. See Appendix A for details on regulatory aspects and Appendix B for a comprehensive account of railroad mergers.

3 Data

My analysis relies on three main datasets: the confidential Carload Waybill Sample, the Class I Railroad Annual Report, and the Commodity Flow Survey. The Carload Waybill Sample, which is the most crucial of the three, provides me with comprehensive information on shipment price and related attributes. This dataset is derived from carload waybills for all freight rail traffic in the United States, submitted to the Surface Transportation Board by rail carriers that complete 4,500 or more revenue carloads annually. The dataset contains detailed shipment information, including commodities carried, total billed weight, equipment used, participating railroads, and origin, destination, and interchange locations for each load. The waybill sample accounts for approximately 2% of total waybills, and the confidential version also includes detailed price information. This dataset covers the period from 1984 to 2010. In addition to the Carload Waybill Sample, I also make use of the Class I Railroad Annual Report R-1 dataset, which includes information on firm attributes and aggregate operational statistics, and the Commodity Flow Survey, which provides information on shipment volumes for different transportation modes.[7] Finally, I utilize geographic information from the Department of Transportation to obtain data on all U.S. rail lines and their associated railroad companies, allowing me to trace back through time and reconstruct the rail network of each railroad firm between 1985 and 2005.

Table 1: Summary Statistics of Market Competition

Year	Number of Markets	Percentage of Interchange Lines	Number of Competitors in an o–d Market			Number of Waybills
			mean	25th percentile	75th percentile	
1985	12,088	41%	3	1	3	262,703
1990	11,835	35%	2	1	3	323,570
1995	11,632	26%	2	1	3	453,802
2000	11,732	14%	2	1	2	544,738
2005	11,611	11%	2	1	2	611,033

Source: The Surface Transportation Board, Carload Waybill Sample

Table 1 provides insight into the competitive landscape of the industry at the origin–destination level, where each market corresponds to a unique origin–destination pair, such as the Los Angeles to Memphis route. The number of Class I railroads decreased significantly from 39 to 7 due to the wave of mergers that occurred between 1985 and 2005, as shown in

[7]The U.S. Census Bureau conducts the CFS every five years. I have access to data from the years 1993, 1997, 2002, 2007, and 2012. The waybill data covers the period from 1985 to 2010. Hence, I utilize the data from 1993, 1997, 2002, and 2007 to estimate the demand.

Appendix B. However, the number of origin–destination markets remained relatively stable from 1990 to 2005, decreasing only slightly from 11,835 to 11,611. Thus, the impact of mergers on the extensive margin seems to be insignificant. Conversely, the percentage of interchange lines decreased from 41% to 11%, as firms eliminated a considerable number of them after the mergers. The average number of competitors in each origin–destination market also decreased slightly from 3 to 2 between 1985 and 2005, indicating that firms primarily engage in oligopolistic competition in most local markets. Appendix C.2 presents a year-by-year table with similar findings. Finally, the total number of waybills in the waybill sample increased from about 263,000 in 1985 to 611,000 in 2005, reflecting that the total volume of railroad shipment more than doubled during this period. Appendix C presents a graph that displays the total ton-miles of freight transported by each transportation mode between 1980 and 2011. Although the shipment volume also rose for other transportation modes, like trucking, the proportion of railroad shipment increased during the examined period.

Table 2: Summary Statistics of Variables

	Mean	Std. Dev.	25th Percentile	Median	75th Percentile
Price per Railcar ($)	1,034	1,399	384	703	1,266
Shipment Weight (Tons per Railcar)	54	46	16	26	102
Travel Distance (Miles)	1,045	773	404	854	1,647
Number of Waybills (Carrier-Origin-Destination-Date)				12,113,581	

Source: The Surface Transportation Board, Carload Waybill Sample

Table 2 presents a summary of the key variables from the waybill data. The shipment price per carload varies from $384 to $1,266 at the 25th and 75th percentiles, respectively, with a mean price of $1,034. The shipment weight per carload ranges from 16 tons to 102 tons at the 25th and 75th percentile, with an average weight of 54 tons. The mean travel distance for each shipment is 1,045 miles, and the 25th percentile of travel distance is 404 miles (650 km). This indicates that railroad shipments are mainly long-distance. The median shipment price per ton-mile for the data used in this analysis is 2.65 cents, a value that is similar to the industry-reported price per ton-mile. According to the AAR, the mean price per ton-mile in the United States was 2.32 cents in 2001.

4 Reduced-form Evidence

I examine the changes in prices that occur after railroad mergers in order to demonstrate efficiency gains. To do so, I use a regression model with the following specification:

$$\log P_{s,odt} = \mu_{od} + \gamma_s + \lambda_t + \delta_1 D_{s,odt} + X'_{s,odt}\beta + \epsilon_{s,odt},$$

In this equation, $P_{s,odt}$ represents the price of service s from origin o to destination d at time t. Service s can be either a single-line service or a joint-line service, as defined in section 2. If s is a single-line service, then it is carried by railroad firm j from the origin all the way to the destination. If s is a joint-line service, then shipment from o to d will be carried by firm j_o from origin o to the interchange station m, and then by firm j_d from station m to destination d. The explanatory variables in the equation are as follows: μ_{od} controls for origin–destination fixed effect, γ_s controls for service fixed effect, and λ_t controls for time fixed effect. $D_{s,odt}$ is an indicator of whether a merger has occurred to firms that provide service s from o to d before or at time t, and $X_{s,odt}$ represents shipment attributes. $\epsilon_{s,odt}$ is an unobserved error that is identically and independently distributed.

The estimation results are presented in Table 3. These results indicate that, on average, a railroad merger leads to a 9.4% reduction in shipment price. Further examination of individual mergers reveals that the price effect is generally consistent across mergers[8]. To examine the impact of railroad mergers on price changes for different route types, I interact the merger dummy variable with three route types: interconnecting route, competing route, and non-interconnecting, non-competing route. An interconnecting route refers to a route in which two firms conduct interchange and complete the shipment jointly.[9] The results presented in column 2 of Table 3 indicate that interconnecting routes experience the largest reduction in price, with prices decreasing by 11% following mergers. In comparison, the other route types experience a price reduction of approximately 6.5% after mergers.

The estimated price effect is consistent with other analyses of freight railroad mergers. The STB analysis of the Union Pacific–Southern Pacific merger showed a decrease in coal shipment prices by 11% and other commodity prices by 6% after the merger. Comparatively, the observed price effect of mergers in the U.S. freight railroad industry is more significant than in some other industries. For instance, Ashenfelter et al. (2015) found that the estimated price reduction resulting from merger efficiency in the brewing industry is only 2%. These

[8] See Table D.2 for robustness check results

[9] To illustrate, consider the route between Los Angeles and Claremore, Oklahoma, as described in Section 2. This is an interconnecting route because the shipment is served by a joint-line service provided by both the Santa Fe and Burlington Northern railroads. In contrast, the route between Claremore, Oklahoma and Memphis is a competing route because a shipment can be transported using two distinct single-line services.

findings suggest that cost efficiency following mergers is crucial in the railroad industry.

Table 3: Effect of Mergers on Price Change (by Route Types)

	(1) Log Price	(2) Log Price
Indicator of Merger	-0.093^{***}	
	(0.0142)	
Indicator of Merger × Indicator of Interconnecting Route		-0.107^{***}
		(0.0178)
Indicator of Merger × Indicator of Competing Route		-0.0690^{***}
		(0.0180)
Indicator of Merger × Non-interconnecting, Noncompeting Route		-0.0641^{***}
		(0.0171)
N	12,110,107	12,110,107
Firm FE	Yes	Yes
Year FE	Yes	Yes
o–d Route FE	Yes	Yes

Standard errors in parentheses. Clustered at route level. *** $p < 0.001$

It is possible to raise concerns that the observed price effects are due to competition from other transportation modes, such as trucking, rather than the impact of railroad mergers. To address this concern, I investigate the price effects of mergers for different types of commodities. The rationale is that different types of commodities face varying levels of competition from other modes of transportation. Therefore, if the price effects are driven by changes in other transportation modes, the effects should be greater for commodities facing higher levels of competition from other modes of transport. For instance, the Commodity Flow Survey (CFS) of 2012 indicates that coal is mainly shipped by railroads, with just 1.5% of coal being shipped by trucking, while 94.8% is shipped by rail. Conversely, food or kindred products are predominantly shipped by trucking, with 76.2% of such commodities being shipped by trucking and only 23.5% being shipped by rail.

Table 4 displays the estimation results for the price effect of mergers on coal and food products. The findings demonstrate that railroad mergers have a significantly negative price effect for both these commodities, with the price effect being greater for coal. These results contradict the hypothesis that the price effect is due to changes in other transport modes. In Appendix D, I conduct a price regression for each commodity type to validate the findings.

The outcomes indicate that the price reduction following railroad mergers is consistent across different commodities. Notably, commodities predominantly shipped by rail, such as coal, chemicals, and construction materials (clay, concrete, etc.), show a significant and substantial price reduction following railroad mergers.

Table 4: Effect of Merger on Price Change (by Commodities)

	(1) Log Price (Coal)	(2) Log Price (Food or Kindred Products)
Indicator of Merger	-0.179^{***}	-0.052^{***}
	(0.028)	(0.014)
Log Billed Weight	-0.030	-0.212^{***}
	(0.020)	(0.010)
Ownership of Railcar (Private)	-0.096^{***}	-0.132^{***}
	(0.027)	(0.008)
Ownership of Railcar (Trailer Train)	-0.021	-0.144^{***}
	(0.071)	(0.016)
N	1,002,552	882,066
Firm Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
o–d Route Fixed Effects	Yes	Yes

Standard errors in parentheses. Clustered at route level. *** $p < 0.001$

This section demonstrates that there is a significant decrease in prices following mergers, particularly for interconnecting routes. However, analyzing individual routes alone is insufficient for comprehending efficiency gains in this industry. This is because, firstly, the decisions made by a railroad firm in a single origin–destination market can influence decisions in all other markets in which the firm operates. Secondly, following a merger, the merged entity needs to re-solve the intricate optimization problem for the entire network, and competing firms will also strategically respond by altering their pricing and operational decisions. To account for these important factors, I construct a model of oligopolistic competition among transport firms in which each firm optimizes its pricing, routing, and allocation decisions endogenously to maximize profits.

5 Model

Motivated by the above findings, I propose a spatial model that centers on two things. Firstly, when selecting the most suitable routing and allocation choices, a railroad firm takes into consideration how decisions made in a particular origin–destination market can impact decisions in all other markets. Secondly, railroad firms react strategically to the pricing and operational decisions of their competitors. Customers in each origin–destination market make a discrete decision on whether to use a railway or alternative transportation modes for shipping. However, integrating the interdependence of multiple origin–destination markets is challenging due to the vast number of markets in a railway network. Additionally, I allow railroad firms to possess market power and make strategic decisions. To tackle this complex problem, I present a static model for railway firms' annual decisions. These firms compete and simultaneously set prices, while also making routing and allocation decisions to minimize the overall operational expenses across the entire network.

In this section, I will lay out the demand, supply, and equilibrium concepts. I close the section with a detailed discussion of the main assumptions.

5.1 Demand

For each origin–destination market, the customer selects a service (represented by s) to transport goods from the origin to the destination. s is a combination of a railroad firm and service type. For instance, s could refer to a Union Pacific railway's single-line service, or a joint-line service offered by both the Burlington Northern railway and the Santa Fe railway.

The utility that customer i derives from selecting service s to transport goods from origin o to destination d at time t is expressed as:

$$\begin{aligned} u_{is,odt} = {} & \alpha \cdot p_{s,odt} + \beta_1 \cdot \log TotalTrackMiles_{s,odt} + \alpha_o \cdot OrigRail_s + \alpha_d \cdot DestRail_s \\ & + \alpha_m \cdot Mkt_{od} + \alpha_t \cdot t + \varepsilon_{is,odt}. \end{aligned} \tag{1}$$

In the above equation, $p_{s,odt}$ denotes the shipping price, while $TotalTrackMiles_{s,odt}$ measures the total track mileage that the service provider(s) have in the origin and destination regions. Greater physical track mileage makes it easier to transfer goods from customers to railway companies, thus reducing loading and unloading time. To control for components of unobserved service quality, I include fixed effects for origin and destination railroads ($OrigRail_s$, $DestRail_s$), market fixed effects (Mkt_{od}), and time fixed effects. The market fixed effects also control for the distance between the origin and destination. Additionally, $\varepsilon_{is,odt}$ represents the customer-specific deviation from mean utility, which I assume follows an extreme-value type distribution.

Given the utility of customers, the demand for each service s at the o–d market is derived as

$$Q_{s,odt} = M_{odt} \cdot \frac{\exp(\alpha \cdot p_{s,odt} + \beta_1 \cdot \log TotalTrackMiles_{s,odt} + \xi_{s,odt})}{1 + \sum_{s'} \exp(\alpha \cdot p_{s',odt} + \beta_1 \cdot \log TotalTrackMiles_{s',odt} + \xi_{s',odt})}, \tag{2}$$

where M_{odt} denotes the market size of the o–d market at time t, while $\xi_{s,odt}$ represents the fixed effects discussed in equation 1.

5.2 The Firm's Problem

I analyze the annual decisions made by railroad firms in a static model and exclude the use of the subscript t in the following notation. At the beginning of each year, these firms choose the optimal pricing $\{p_{s,o_j,d_j}\}_{o_j \in \mathcal{Z}_j, d_j \in \mathcal{Z}_j}$, routing $\{\mathcal{R}_{j,o_j,d_j}\}_{o_j \in \mathcal{Z}_j, d_j \in \mathcal{Z}_j}$, and maintenance allocation decisions $\{I_{j,ab}\}_{(a,b) \in \mathcal{A}_j}$ in order to maximize their profits. The set $\mathcal{Z}_j$ represents the locations that the firm j serves, and $\mathcal{A}_j$ includes all the arcs where firm j can potentially allocate resources. The routing decision $\mathcal{R}_{j,od}$ refers to a series of connected arcs, such as $\mathcal{R}_{j,od} = \{(o, m_1), (m_1, m_2), (m_2, d)\}$, indicating that the route from o to d is $o \rightarrow m_1 \rightarrow m_2 \rightarrow d$. The maintenance allocation decisions $I_{j,ab} \geq 0$ represent the annual funds allocated to cover the costs of routine maintenance activities and infrastructure upgrades.

Let $S(j)$ be the set of services that the railroad firm j offers. The optimization problem can be defined as:

$$\pi_j := \max_{\{p_{s,od}\}, \{\mathcal{R}_{j,o_j(s),d_j(s)}\}, \{I_{j,ab}\}_{(a,b) \in \mathcal{A}_j}} \sum_{s: s \in S(j)} p_{s,od} \cdot Q_{s,od}(p_{s,od}, p_{-s,od}) - C(\overrightarrow{Q_j}, \overrightarrow{R_j}, \overrightarrow{I_j}) \tag{3}$$

subject to the resource allocation constraint:

$$\sum_{(a,b) \in \mathcal{A}_j} I_{j,ab} \leq K_j,$$

where K_j is the total annual maintenance spending taken from the data.

The optimization problem is also subject to the balanced-flow constraint, which requires that for any service s in any market o–d and for every node $z \in \mathcal{Z}_j$:

$$\sum_{a \in \mathcal{Z}_j(z)} Q_{s,od} \cdot \mathbb{1}\{(a, z) \in \mathcal{R}_{j,o_j(s),d_j(s)}\} + D_{j,z} = \sum_{b \in \mathcal{Z}_j(z)} Q_{s,od} \cdot \mathbb{1}\{(z, b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}.$$

Here, $\mathcal{Z}_j(z)$ denotes the set of neighboring nodes of z, and $\mathbb{1}\{(a, z) \in \mathcal{R}_{j,od}\} = 1$ if the arc

(a,z) is in the routing from o to d of firm j. Additionally, $D_{j,z}$ represents the net demand at node z and is defined as follows:

$$D_{j,z} = \begin{cases} Q_{s,od} & \text{if } z = o \\ -Q_{s,od} & \text{if } z = d \\ 0 & \text{otherwise.} \end{cases}$$

Intuitively, the balanced-flow constraint means that for any node z on railroad j's network, the inflow of goods from its neighboring nodes plus the net demand at that node must be equal to the outflow to its neighboring nodes.

Given the optimization problem, the Lagrange function for firm j is written as

$$\mathcal{L}_j(\boldsymbol{p_j}, \boldsymbol{\mathcal{R}_j}, \boldsymbol{I_j}) = \sum_{s:s\in S(j)} \big(p_{s,od} - C_{s,od}(R_{j,o_j(s)d_j(s)}, \boldsymbol{I_j})\big) \cdot Q_{s,od} + \lambda_j \left(\sum_{(a,b)\in\mathcal{A}_j} I_{j,ab} - K_j \right) \tag{4}$$
$$+ \sum_{s:s\in S(j), z\in\mathcal{Z}_j} \lambda_{j,s,z} \left(D_{j,z} + \sum_{a\in\mathcal{Z}_j(z)} Q_{s,od} \cdot \mathbb{1}\{(a,z)\in\mathcal{R}_{j,o_j(s),d_j(s)}\} - \sum_{b\in\mathcal{Z}_j(z)} Q_{s,od} \cdot \mathbb{1}\{(z,b)\in\mathcal{R}_{j,o_j(s),d_j(s)}\} \right).$$

The vector $\boldsymbol{p_j}$, $\boldsymbol{\mathcal{R}_j}$, and $\boldsymbol{I_j}$ represent the decisions of firm j for prices, routing, and maintenance allocation, respectively. $C_{s,od}$ is the marginal cost of transportation and λ's are Lagrangian multipliers.

The marginal cost of transportation $C_{s,od}$ is specified as

$$C_{s,od} = \begin{cases} \sum_{(a,b)\in\mathcal{R}_{j,od}} c_{j,ab}(\boldsymbol{I}_j) & \text{if} \quad j_o = j_d \\ \sum_{j'\in J(s)} \sum_{(a,b)\in\mathcal{R}_{j',od_{j'}(s)}} c_{j',ab}(\boldsymbol{I}_{j'}) + \#_{interchanges} \cdot \eta & \text{if} \quad j_o \neq j_d \end{cases}.$$

In the case of a single-line service where the origin and destination railroads are the same ($j_o = j_d = j$), the marginal cost is obtained by adding up the costs of all arcs along the route from the origin to the destination for firm j. On the other hand, for a joint-line service where the origin and destination railroads are different ($j_o \neq j_d$), the marginal cost is calculated by summing the costs incurred by each participating railroad, in addition to the interchange costs. Here, $J(s)$ denotes the set of firms that provide service s, $\#_{interchanges}$ represents the total number of interchanges incurred, and η is the cost of a single interchange.

The arc-level transportation cost $c_{j,ab}$ is dependent on the distance between a and b, as well as the amount of maintenance spending allocated by firm j to the arc (a,b). The efficiency parameter γ reflects the effectiveness of resources and has a positive value. Therefore, if firm j allocates more maintenance spending to arc (a,b), the arc-level transportation cost

$c_{j,ab}$ will be smaller. Specifically, the arc-level transportation cost is defined as:

$$c_{j,ab} = \begin{cases} \frac{\delta Dist_{j,ab}}{I_{j,ab}^{\gamma}} & \text{if} \quad I_{j,ab} > 0 \\ \infty & \text{if} \quad I_{j,ab} = 0 \end{cases}, \tag{5}$$

where $Dist_{j,ab}$ denotes the distance between nodes a and b for firm j, and the parameter δ is a scaling factor that ensures the units of $c_{j,ab}$ are consistent with the other terms in the optimization problem. When $I_{j,ab} = 0$, the transportation on the arc (a, b) is assumed to be impossible, resulting in an infinite transportation cost.

The efficiency parameter γ plays a crucial role in capturing *economy of scope* in my model. This is because when $\gamma \neq 0$, any maintenance spending allocated to the arc (a, b) leads to benefits for all the origin–destination markets that utilize that arc. For instance, in the case of Train 9-698, improving the route between Los Angeles and Memphis can also be advantageous for other traffic originating from different markets such as San Diego to Kansas City. Consequently, this highlights the benefits of economy of scope.

5.3 Equilibrium

Firm j is responsible for determining the price of each single-line service it provides and each joint-line service for which it is the origin railroad. The optimal pricing decision for each service $s \in S(j)$ is obtained by solving the first-order condition:

$$\frac{\partial \mathcal{L}_j}{\partial p_{s,od}} = Q_{s,od} + p_{s,od}\frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial Q_{s,od}}{\partial p_{s,od}}\left[C_{s,od} + \frac{\partial C_{s,od}}{\partial Q_{s,od}}Q_{s,od} + \sum_{s' \in S(j), s' \neq s} \frac{\partial C_{s',o'd'}}{\partial Q_{s,od}} Q_{s,o'd'}\right] = 0. \tag{6}$$

To obtain the optimal maintenance allocation decisions, we begin by taking the derivatives of the Lagrange function with respect to $I_{j,ab}$ for every arc $(a, b) \in \mathcal{A}_j$, yielding:

$$\frac{\partial \mathcal{L}_j}{\partial I_{j,ab}} = \gamma \cdot \delta Dist_{j,ab} \cdot \frac{\sum_{s:s \in S(j)} Q_{s,od} \cdot \mathbb{1}\{(a, b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}}{I_{j,ab}^{\gamma+1}} + \lambda_j.$$

The numerator of this expression calculates the total quantity that travels through arc (a, b) by summing over all the origin and destination markets for which firm j operates. The optimal allocation decision for each arc is then determined through the Kuhn-Tucker condition, which requires that for all $(a,b) \in \mathcal{A}_j$:

$$\frac{\partial \mathcal{L}_j}{\partial I_{j,ab}} \leq 0, \quad I_{j,ab} \geq 0, \quad \text{and } I_{j,ab}\frac{\partial \mathcal{L}_j}{\partial I_{j,ab}} = 0. \tag{7}$$

I assume that there is no congestion either within a market or between markets, hence the optimal routing decision is equivalent to finding the least expensive route to travel from origin o to destination d for each o–d market. This can be formulated as a linear-programming problem:

$$\min_{\mathcal{R}_{j,od}} \sum_{(a,b)\in\mathcal{R}_{j,od}} \frac{\delta Dist_{j,ab}}{I_{j,ab}^{\gamma}} \tag{8}$$

such that $\forall m' \in \mathcal{Z}_j$,

$$\mathbb{1}\{m' = o\} - \mathbb{1}\{m' = d\} + \sum_{a\in\mathcal{Z}_j(m')} \mathbb{1}\{(a,m') \in \mathcal{R}_{j,od}\} \leq \sum_{b\in\mathcal{Z}_j(m')} \mathbb{1}\{(m',b) \in \mathcal{R}_{j,od}\}.$$

A Nash equilibrium is a set of decisions, including pricing choices $p^*_{s,od}$, routing decisions $\mathcal{R}^*_{j,od}$, and maintenance allocation decisions $I^*_{j,ab}$, that satisfy the following conditions simultaneously:

Firstly, for each railroad firm j, the pricing decision for each service s in its set of services $S(j)$, $p^*_{s,od}$, must satisfy the first-order-condition in equation 6, taking into account the firm's own choice of routing and maintenance allocation decisions $\mathcal{R}^*_{j,od}$ and $I^*_{j,ab}$, as well as the pricing decisions $p^*_{-s,od}$, routing decisions $\mathcal{R}^*_{-j,od}$, and maintenance allocation decisions $I^*_{-j,ab}$ of all the other firms.

Secondly, the maintenance allocation decisions $I^*_{j,ab}$ must satisfy the Kuhn-Tucker condition in equation 7, given the pricing decisions $p^*_{s,od}$ and routing decisions $\mathcal{R}^*_{j,od}$.

Lastly, the routing decisions $\mathcal{R}^*_{j,od}$ must solve the linear programming problem in equation 8, given the pricing decisions $p^*_{s,od}$ and maintenance allocation decisions $I^*_{j,ab}$.

My approach for computing the equilibrium closely follows the definition presented above. Given a set of parameters, the steps to compute the equilibrium are as follows:

1. Initial guess of the optimal prices $p^0_{s,od}$.
2. Initial guess of the maintenance allocation decisions $I^0_{j,ab}$.
3. Use a linear-programming algorithm to compute the optimal routing decisions for each origin–destination pair.
4. Derive the maintenance allocation decisions, $I^1_{j,ab}$, from the Kuhn-Tucker condition.
5. If $|I^0 - I^1|$ is not close enough, return to step 2.
6. Derive the optimal prices, $p^1_{s,od}$, using the first-order condition.

7. If $|p^0 - p^1|$ is not close enough, return to step 1.

5.4 Discussion

I close this section with a discussion on several of my assumptions and some caveats.

Firstly, I assume that when railroad firms set prices in local markets, they do not consider how changes in quantity would affect routing and allocation decisions. This assumption translates to setting the own-cost and cross-cost effects to zero in the first-order-condition with respect to price in equation 6. The reason for imposing this assumption is because solving for cross-cost effects can become computationally challenging as the number of markets increases. As a result of this assumption, the interdependence between markets in the model primarily arises from railroad firms' optimal choices of maintenance allocation and routing. In making such decisions, railroad firms take into consideration that the efficiency of a single route would impact the cost of multiple markets across the entire network.

In Appendix C.3, I have documented interviews with local pricing managers who have stated that they do not strategically consider the impact of resulting demand from pricing quotes on operational decisions made by the operation department. To further investigate the impact of this assumption on equilibrium results, I derived solutions for a monopoly by allowing for the own- and cross-cost effects in Appendix E. The simulation results indicate that the difference in equilibrium outcomes is minimal. This can be attributed to the fact that when one market dominates with a significant large shipment demand, the own- and cross-cost effects are essentially zero, whereas when none of the markets dominate (i.e., demand is evenly distributed), the own- and cross-cost effects tend to cancel each other out.

Secondly, I assume that the originating firm of the joint-line service determines its price, thereby avoiding any double-marginalization of pricing. This assumption can be interpreted in two ways — either the originating railroad has all the bargaining power, or both railroad firms in the joint-line service jointly determine the price as one entity and divide the revenue between them meaningfully. Using Waybill data, Alexandrov, Pittman and Ukhaneva (2018) show that there is no issue with double marginalization in the pricing of the joint-line service. Interviews with railroad managers about how interchange works in the industry, documented in Appendix C.3, align with my assumption. Furthermore, I assume that firms do not consider the cannibalization between their single-line and joint-line services offered in the same *o*–*d* market. In reality, it is rare for a railroad to provide both single- and joint-line services in the same *o*–*d* market, so relaxing this assumption has a minimal effect on the results.

I do not have a uniqueness result for the Nash equilibria of this pricing, routing, and maintenance allocation game. In this paper, I constrain the equilibrium in such a way that the market share of a railroad firm is non-zero in a local o–d market if its observed market share is positive for that market in the data. This constraint eliminates equilibria where firms sort into local monopolies, such as one firm operating exclusively on the east coast and the other on the west coast. The estimation of cost parameters relies only on the necessary conditions of Nash equilibrium. Therefore, multiple equilibria do not affect the properties of the estimated parameters. However, multiple Nash equilibria would negatively affect the merger simulations. Although I cannot prove uniqueness, I perform a numerical search for multiple equilibria by altering the starting values while computing an equilibrium post-merger, and I do not find any multiple equilibria.

Finally, in merger simulations, I assume that railroad firms do not make any entry or exit decisions in origin-destination markets. As shown in Table 1, the total number of o–d markets has been relatively stable at around $12,000$ from 1986 to 2005, which is the period when most of the mergers occurred. Upon examining specific firms, I only observe a few instances of entry or exits in o–d markets post-merger. Hence, the data suggest that the extensive margin is not the primary driver post-merger. Additionally, in the United States, the difficulty of expropriating trackage rights has reached a point where virtually no new tracks have been laid in the last fifteen years. Consequently, entry into new markets where firms have no physical track is very difficult.

6 Estimation

6.1 Demand Estimation

The demand model outlined in equation 2 shows that the difference between the logarithm of the observed market share for each service and the logarithm of the share for the outside good can be calculated as follows:

$$\log(h_{s,odt}) - \log(h_{0,odt}) = \alpha \cdot p_{s,odt} + \beta_1 \cdot \log TotalTrackMiles_{s,odt} + \xi_{s,odt}. \tag{9}$$

In this equation, $h_{s,odt}$ represents the market share of a specific service s that serves the market route from origin o to destination d at a specific time t. The service s is defined as a combination of a railroad firm and a service type, which can be either single-line or joint-line service. On the other hand, the variable $h_{0,odt}$ represents the market share of the outside alternative. This refers to the percentage of all alternative transportation modes that operate within the same market, connecting the origin o to the destination d.

The estimates of α and β_1 can be obtained from a linear instrumental variables regression of differences in log market shares on prices and service characteristics. The error term in equation 9 represents the unobserved market-specific demand shocks. Since I assume that railroads observe and account for this deviation, it will influence the market-specific markup and bias the estimate of price sensitivity. To address the issue of endogeneity, a series of steps are taken. Firstly, fixed effects for both origin and destination railroads ($OrigRail_s$, $DestRail_s$), market fixed effects (Mkt_{od}), and time fixed effects are incorporated. The market fixed effects control for the distance between the origin and destination.

Furthermore, instrumental variables (IVs) are employed to mitigate the endogeneity problem. The first set of instrumental variables used is commonly referred to as the "BLP Instruments." Much of the previous research[10] treats the endogeneity problem by assuming the characteristics space is exogenous or predetermined. Therefore, characteristics of other services will be correlated with price since the markup of each service will depend on the distance from the nearest neighbor. Here I use the average track miles and the distance to other railroads in the same o–d market as instruments.

For my second set of IVs, I utilize mergers between railroad firms as proxies to capture changes in market power within local markets. Considering that railroad companies operate on a national scale, the decision to merge between two railroad companies is unlikely to be driven by local demand shocks in a single origin–destination market. Thus, I argue that the merger decision is orthogonal to local demand shocks. To examine the impact of mergers on market concentration, I analyze the changes in concentration following railroad mergers. To quantify these changes, I draw upon the methodologies presented in the works of Garmaise and Moskowitz (2006) and Dafny, Duggan and Ramanarayanan (2012) to construct a simulated change in the Herfindahl-Hirschman Index ($sim\Delta HHI$). The $sim\Delta HHI$ represents the projected change in the HHI that would have occurred after the merger if no other factors were to change. By utilizing the projected change instead of the actual change in the HHI, I aim to isolate the post-merger market share adjustments that may be influenced by local market conditions. The simulated change in the HHI is derived as a result of this approach.

$$\begin{aligned} sim\Delta HHI_{odt} &= (TargetShare_{odt-1} + AcquirorShare_{odt-1})^2 \\ &\qquad - (TargetShare^2_{odt-1} + AcquirorShare^2_{odt-1}) \\ &= 2 \times TargetShare_{odt-1} \times AcquirorShare_{odt-1}. \end{aligned}$$

Table 5 presents results obtained by regressing the difference of the log of each service's observed market share and the log of the share of the outside good on price, total miles of physical tracks, time, market, and firm dummy variables. Columns (1)–(3) display the

[10] See Berry (1994), Berry, Levinsohn and Pakes (1995), and Bresnahan, Stern and Trajtenberg (1997).

ordinary least squares results. The coefficient on price and the resulting own-price elasticities are relatively low, with absolute values less than 1. The logit demand structure does not impose a constant elasticity; therefore the estimates imply a different elasticity for each service–market–year combination. Some statistics of the own-price elasticity distribution are shown at the bottom of each column. Two sets of instrument variables were explored to deal with the endogeneity problem. Column (4) uses BLP instruments described above as IVs in the same regression. Column (5) uses simulated changes in HHI as IVs. Finally, column (6) uses both sets of IVs. Columns (4)–(6) also include market, firm, and time fixed effects.

Table 5: Results of Demand Estimation

		OLS			IV	
Variables	(1)	(2)	(3)	(4)	(5)	(6)
Price	0.240***	−0.280***	−0.281***	−0.708***	−0.681***	−0.720***
	(0.013)	(0.012)	(0.012)	(0.059)	(0.059)	(0.059)
Log Track Miles	0.485***	0.364***	0.334***	0.360***	0.358***	0.360***
	(0.016)	(0.015)	(0.016)	(0.016)	(0.016)	(0.016)
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
o–*d* Market Fixed Effect	–	Yes	Yes	Yes	Yes	Yes
Firm Fixed Effect	–	–	Yes	Yes	Yes	Yes
Instruments						
BLP instruments	–	–	–	Yes	–	Yes
Predicted ΔHHI	–	–	–	–	Yes	Yes
First-stage F-statistic	–	–	–	11.18	10.05	11.17
Own price elasticity						
Mean	0.53	–0.62	–0.62	–1.57	–1.51	–1.60
Standard errors	0.28	0.33	0.33	0.83	0.80	0.85
Median	0.51	−0.60	−0.60	−1.51	−1.45	−1.53

Note: Demand estimates are based on 30,058 market–service–year observations in 1993, 1997, 2002, 2007. Figures in parentheses are standard errors. *** p<0.01, ** p<0.05, * p<0.1

Several conclusions can be drawn from the results in Table 5. First, once IVs are used, the coefficient on price and the implied own-price elasticity both increase in absolute value. This is predicted by theory and holds in a wide variety of studies such as Nevo (2000) and Nevo (2001). Second, the "BLP instruments" seem to generate results almost identical to those produced by using the simulated change in HHI. The estimated price elasticity of demand, as shown in column (6), indicates an estimated price coefficient of approximately −0.72, resulting in an average price elasticity of demand of around −1.60. This estimated average price elasticity is comparable to estimates reported in the transportation literature.

For instance, Wilson et al. (1988) estimated an own-price elasticity of demand for U.S. freight rail of -1.46, while Beuthe et al. (2001) estimated a demand elasticity of -1.77 for total tonnes.

6.2 Estimation of Cost Parameters

There are three cost parameters to be estimated, $\Theta \equiv \{\eta, \delta, \gamma\}$. η represents the cost associated with a single interchange, while the parameter δ acts as a scaling factor to ensure the units of $c_{j,ab}$ align with the other components of the optimization problem. In my model, the efficiency parameter γ plays a vital role in capturing the concept of *economy of scope*. Consolidating maintenance allocation resources enables railroad firms to benefit from this economy of scope, and the magnitude of these benefits increases with higher values of γ.

Estimation of the cost parameters is implemented according to the following procedures. Firstly, I denote the set of data moments as Γ^d. Secondly, given a set of parameters θ, the industry equilibrium is solved, resulting in optimal decisions for pricing, routing, and maintenance allocation, represented as $(p^*_{s,od}, \mathcal{R}^*_{j,od}, I^*_{j,ab})$. Lastly, I define the simulated moments as Γ^S. The estimate $\hat{\theta}$ obtained through the simulated method of moments minimizes the weighted distance between the data moments and the simulated moments using the following objective function:

$$L(\theta) = \min_{\theta} [\Gamma^d - \Gamma^S(\theta)]' W [\Gamma^d - \Gamma^S(\theta)],$$

where W represents a positive-definite matrix. During the numerical analysis, I calculate $\widehat{W}$ using a bootstrap procedure. This involves randomly resampling the data and computing the moments of interest for each sample. Subsequently, I derive a variance–covariance matrix based on these bootstrap samples, and $\widehat{W}$ is obtained as the inverse of this variance–covariance matrix.

I target four data moments. The first moment captures the average price per mile for shipments. The second moment examines the average price difference between a route that has interconnections and one that does not. The third and fourth moments pertain to how the degree and betweenness centrality of a network impact shipment prices.

The degree centrality of a particular node i represents the total number of other nodes in the network $\mathcal{G}_j$ of firm j that have a direct connection to node i. Mathematically, the degree centrality of node i in network G_j can be expressed as:

$$d_i(\mathcal{G}_j) = \sum_{k \in A_j} \mathbb{1}\{a_{ik} = 1\} \tag{10}$$

On the other hand, betweenness centrality captures how frequently the node is found on the shortest path from an origin to a destination. Its calculation is as follows:

$$b_i(\mathcal{G}_j) = \sum_{o,d \in Z_j} \frac{\mathbb{1}\{i \in l(o,d)\}}{(Z_j - 1)(Z_j - 2)} \tag{11}$$

Here, Z_j refers to the total number of nodes in network $\mathcal{G}_j$, and $l(o,d)$ represents the shortest path from origin o to destination d. More specifically, the third and fourth moments (represented by m_1 and m_2 in Equation 12) are obtained through regression analysis. In this analysis, the shipment price per mile for each origin-destination market is regressed on the degree centrality and betweenness centrality of the origin station:

$$P_{s,odt} = \mu_{od} + \gamma_s + \lambda_t + a_1 \cdot interchanges + m_1 \cdot d_o(\mathcal{G}_{j(s)}) + m_2 \cdot B_o(\mathcal{G}_{j(s)}) + \epsilon_{s,odt} \tag{12}$$

In this equation, $P_{s,odt}$ represents the shipment price for a specific origin-destination market at a given time. The terms μ_{od}, γ_s, and λ_t account for the fixed effects related to railroads, origin-destination markets, and time periods, respectively. The variable *interchanges* captures the total number of interchanges. $d_o(\mathcal{G}_{j(s)})$ and $B_o(\mathcal{G}_{j(s)})$ represent the degree centrality and betweenness centrality of the origin station, respectively.

The rationale behind the identification argument is as follows: The first moment focuses on quantifying the impact of travel distance on average shipping prices. As the value of δ increases, so does the average shipping cost per mile in dollar terms. Therefore, the first moment helps determine the value of δ. The second moment compares the average price difference between interconnecting and non-interconnecting routes. When the interchange cost η increases, the price difference between these routes also increases. Therefore, conditional on the values of δ and γ, the second moment identifies the parameter of interchange cost, η. Lastly, the value of γ represents the effectiveness of maintenance allocation resources and significantly influences the last two moments related to network measures. Intuitively, when $\gamma = 0$, resources have no impact on shipping costs, and only the travel distance between the origin and destination matters. As a result, there is no benefit in consolidating traffic, and the network structure does not affect shipping expenses, conditional on travel distance. Consequently, the values of m_1 and m_2 in equation 12 will be insignificantly different from 0. On the other hand, when $\gamma \neq 0$, the network structure plays a role in traffic consolidation, thereby affecting the effects of degree and betweenness centrality on prices. Therefore, the values of m_1 and m_2 are influenced by the value of the parameter γ.

Column (2) of Table 6 shows the data moments. The average shipping price per loaded car per mile is \$0.65, comparable to the number published by the Association of American Railroads. The average price difference between an interconnecting and a non-interconnecting

Table 6: Comparison of Data and Simulated Moments

	(1) Identification	(2) Data Moments	(3) Simulated Moments
Average shipping price (per loaded car per mile)	pin down δ	\$0.65	\$0.65
Average difference of price between interconnecting route and non-interconnecting route (per loaded car per mile)	pin down η	\$0.26	\$0.24
Moments related to network measures			
m_1 (coefficient of degree centrality)	pin down γ, δ	$-$\$0.0014	$-$\$0.0016
		(0.0008)	(0.0000)
m_2 (coefficient of betweenness centrality)	pin down γ, δ	$-$\$0.2984	$-$\$0.3017
		(0.0094)	(0.0083)

route in the data is \$264.43 per loaded car. As a benchmark, the average shipment price in the data is \$1034 per loaded car. Thus, the average price for joint-line service is about 26% higher than of average shipment price. The estimated impact of betweenness centrality on price is $-$\$0.30 in the data. Comparing a station at the 95th percentile of betweenness centrality to one at the 5th percentile, the price difference is approximately 14%.[11] Similarly, comparing a station at the 95th percentile to one at the 5th percentile in terms of degree centrality results in approximately a 2% difference in price. Column (3) of Table 6 compares the simulated moments with the data moments. In general, the simulated moments match the data moments very well.

Table 7: Estimation Results for Cost Parameters

	Point Estimate	95% Confidence Interval
δ	1.2	$[1.10, 1.29]$
η	217	$[155, 279]$
γ	0.17	$[0.14, 0.20]$

Table 7 reports the point estimates and their 95% confidence intervals. Following Andrews, Gentzkow and Shapiro (2017), I use finite differencing to calculate standard errors of the estimated parameters. The estimated cost per efficient mile of shipment amounts to

[11]Betweenness centrality ranges from 0 to 1. In the data, the 95th percentile of betweenness centrality is 0.32, while the 5th percentile is 0.04. Consequently, the difference can be calculated as $-0.30\times(0.32-0.04) = -0.09$. Relative to the average shipping price of 0.65, this change amounts to approximately a 14% difference.

\$1.20. Additionally, the interchange cost is estimated to be \$217, which represents approximately 21% of the average shipment price. This finding underscores the significant expense associated with interchange and highlights the potential for substantial cost efficiency gains by eliminating interchange costs following a merger. Moreover, the estimated value of γ is found to be less than 1, indicating diminishing marginal returns in resource allocation for a specific arc.

To further validate my model, I conduct an evaluation of its out-of-sample performance. Specifically, I focus on comparing the observed and predicted price changes following a merger. In the data, the average price reduction after a merger is approximately 9.79%. In my model, the simulated average price reduction after a merger is 10.51%, which closely aligns with the observed change. Furthermore, I evaluate the predictive accuracy of my model in identifying the top 10% of markets with the greatest price reductions post-merger. Given the numerous markets involved in each merger, my model, despite having only three cost parameters, demonstrates an accuracy rate of 63% in identifying the markets with the highest price reductions. This outcome highlights the model's ability to effectively capture the underlying patterns in the data, despite its simplicity in terms of cost parameters. In conclusion, the out-of-sample evaluation demonstrates the strong performance of my model in accurately predicting price changes after mergers, both in terms of average reductions and identifying the markets with the highest reductions.

7 Counterfactual Experiments

I conduct two main counterfactual experiments. First, I calculate the average merger gains between Class I railroads from 1985 to 2005. Second, I investigate how network structure affects the level of merger gains.

7.1 Efficiency Gains from Mergers

I calculate the average merger gains by comparing equilibrium results before and after the mergers. These outcomes are weighted by post-merger quantity and averaged over all individual o–d markets and all mergers. For each merger, I simulate the equilibrium results both before and after the merger, and then calculate the changes in shipment prices, costs, and markup. The results show that on average shipment cost reduces by 12.9%, shipment price reduces by 8.8%, and the markup increases by 7.2%. The simulated price reduction post merger in the baseline model is comparable to the price reduction observed in the data. On average, the merged firms become more profitable post merger. Although firms have a higher markup post merger, mergers create a large efficiency gain. As a result, consumers also benefit from the mergers and enjoy an 8.8% price reduction on average.

There is a large heterogeneity of merger gains at the *o–d* market level. To summarize the heterogeneity of merger gains and their relationship to network structure, I derive the centrality changes for each node after a merger and calculate how they affect merger gains. Centrality is calculated within each firm's network. I use two centrality measures in my analysis. Firstly, the *degree centrality* measures the total number of links a node has in a given network, as defined in equation 10. Secondly, the *betweenness centrality* measures the number of paths traveling through each node, as defined in equation 11. To summarize the findings, I perform a regression analysis where I examine the relationship between the simulated log-price changes and the changes in centrality measures after the merger.

$$\Delta \log P_{s,od} = \alpha_0 + \alpha_1 \cdot \mathbb{1}_{interchange} + \alpha_2 \cdot \Delta NC_o + \epsilon_{s,od}$$

Here, $\Delta \log P_{s,od}$ represents the simulated price changes before and after the merger. The term $\mathbb{1}_{\text{interchange}}$ is an indicator function that determines whether service s is a joint-line service provided by the two merging firms. Additionally, ΔNC_o measures the changes in network centrality of the origin station before and after the merger.

The baseline results show that if post-merger degree centrality increases by one, shipment cost will further decrease by 0.53%. To better interpret the results, I calculate the difference of the merger gains between nodes in the 95th and 5th percentiles of ΔNC. The results show that a node at the 95th percentile of changes in degree centrality (ΔDC) has an extra 1.59 percent cost reduction and an extra 0.3 percent increase in markup post merger, compared to a node at the 5th percentile of ΔDC. By comparison, a node at the 95th percentile of changes in betweenness centrality (ΔBC) has an extra 5.17 percent cost reduction and an extra 1.17 percent increase in markup post merger compared to a node at the 5th percentile of ΔBC.

The results suggest that when a node is positioned at the outer edges of the network before the merger and subsequently becomes more central in the post-merger network, it experiences a greater improvement in efficiency. Additionally, the baseline findings indicate that, in comparison to degree centrality, nodes that demonstrate a greater increase in betweenness centrality benefit from a larger reduction in shipment cost and an increase in markup after the merger. For example, consider the case of Kansas City, which was initially located on the periphery of Santa Fe's network but served as a significant interchange point between Burlington Northern Railway and Santa Fe Railway. The merger amplifies the importance of Kansas City in the rail network, particularly when measured by the change in betweenness centrality. As a result, the Kansas City station enjoys a significantly larger efficiency gain following the merger of Burlington Northern Railway and Santa Fe Railway.

7.2 Unpacking the Black Box

To unpack the "black box" of why the network structure is related to the level of merger gains, I conduct the following analysis. Let MG be a measure of merger gains and NC a measure of network centrality. The structural parameters are represented by the vector $\boldsymbol{\theta}$. In the baseline experiment, I consider two network structures, NC_0 and NC_1 (pre- and post-merger), calculating the merger gains as

$$MG = f(NC_1, \boldsymbol{\theta}_0, \psi) - f(NC_0, \boldsymbol{\theta}_0, \psi).$$

Here, MG represents the merger gains obtained when the network structure of the merging firms changes from NC_0 to NC_1. The function $f(\cdot, \boldsymbol{\theta})$ corresponds to the equilibrium model described in section 5, where $\boldsymbol{\theta}_0$ represents the parameters estimated in section 6. Additionally, ψ includes all other relevant parameters in the model, such as the mass of demand and the networks of non-merging competitors.

There are three key cost parameters in the model: δ represents the per-mile travel costs, η quantifies the interchange cost, and γ measures the level of economies of scope. All three parameters $\boldsymbol{\theta}_0 \equiv (\delta_0, \eta_0, \gamma_0)$ in the baseline model are different from 0. To investigate how the network structure interacts with the structural parameters in determining merger gains, I conduct three counterfactual analyses by introducing different variations in $\boldsymbol{\theta}$. In the first counterfactual, denoted as $\boldsymbol{\theta}_1 \equiv (\delta_0, 0, 0)$, I eliminate interchange costs and economies of scope. Here, the investigation focuses on merger gains given $\boldsymbol{\theta}_1$, calculated as:

$$MG = f(NC_1, \boldsymbol{\theta}_1, \psi) - f(NC_0, \boldsymbol{\theta}_1, \psi).$$

In the second counterfactual, denoted as $\boldsymbol{\theta}_2 \equiv (\delta_0, \eta_0, 0)$, only economies of scope are eliminated. Finally, in the third counterfactual, denoted as $\boldsymbol{\theta}_3 \equiv (\delta_0, 0, \gamma_0)$, only interchange costs are eliminated. These counterfactual analyses allow for a comprehensive exploration of how changes in the structural parameters interact with the network structure to determine merger gains.

Table 8 shows how average merger gains change in the different counterfactuals.[12] Column (1) shows the baseline results using the estimated parameters $(\delta_0, \eta_0, \gamma_0)$. Column (2) of Table

[12] All numbers reported in Table 8 are weighted averages, weighting by post-merger quantity for each local o–d market.

8 shows the results of the first counterfactual, in which I turn off both interchange cost and economies of scope $(\delta_0, 0, 0)$. Without economies of scope, maintenance allocation decisions do not affect costs, and transportation costs are minimized by finding the shortest travel distance for each *o*–*d* market. As a result, the operational decisions for each market become independent. After also removing interchange cost, the benefit of merger comes solely from better routing and thus shorter travel distance for certain *o*–*d* markets. The results in column (2) show that when considering only travel distance as a factor, cost reduces by a small amount of 1.9% on average post merger. In local markets, the merged firm gains additional market power as both the acquiring and acquired firms operate in those markets, resulting in a reduction in the number of firms following the merger. However, the results show that merger-generated concentration in local markets only increases the markup slightly, by 0.7%. This outcome is not surprising given that, out of the twelve mergers examined, jointly owned markets typically represent only 3% to 6% (with a maximum of 12%) of the total markets owned by the two merging firms.

Table 8: Average Merger Gains

Percentage Change in:	Baseline (1) Distance + Interchange Cost + Economies of Scope $(\delta_0, \eta_0, \gamma_0)$	Unpacking the Black Box (2) Distance $(\delta_0, 0, 0)$	(3) Distance + Interchange Cost $(\delta_0, \eta_0, 0)$	(4) Distance + Economies of Scope $(\delta_0, 0, \gamma_0)$
Price	−8.8%	−1.4%	−2.8%	−3.8%
Cost	−12.9%	−1.9%	−3.4%	−7.2%
Markup	7.2%	0.7%	0.7%	6.9%

Column (3) of Table 8 shows the results of the second counterfactual, in which I now allow for interchange cost but keep economies of scope turned off. The operational decisions for each local market are still independent in this case, but it is now more costly to ship through interconnecting routes. Because merger eliminates interchange cost, the post-merger cost reduction is now larger, at 3.4% compared to the results for the first counterfactual. Meanwhile, there is no difference in increase of markup, which is still 0.7%. This means that reinstating interchange cost will increase efficiency gains after merger but will have no impact on firms' market power. Nevertheless, incorporating interchange cost alone is insufficient to explain all of the cost reduction in the results; it only explains 3.4% out of the 12.9% cost reduction found in the baseline results.

Column (4) of Table 8 shows the results of the third counterfactual, in which I turn off interchange cost but allow for economies of scope. The operational decisions for each local markets have become interdependent since any traffic passing through arc (a, b) can now make use of the allocated resources at that specific arc. After the merger, the merged firm can consolidate traffic and better utilize resources. Given economies of scope, we observe a higher cost reduction at 7.2% post merger. This shows that economies of scope are the major factor in driving down shipment cost after merger. Moreover, the inclusion of economies of scope leads to a significantly higher markup increase. Specifically, after the merger, the markup increase by 6.9%, in contrast to the mere 0.7% increase observed in the first two counterfactual scenarios.

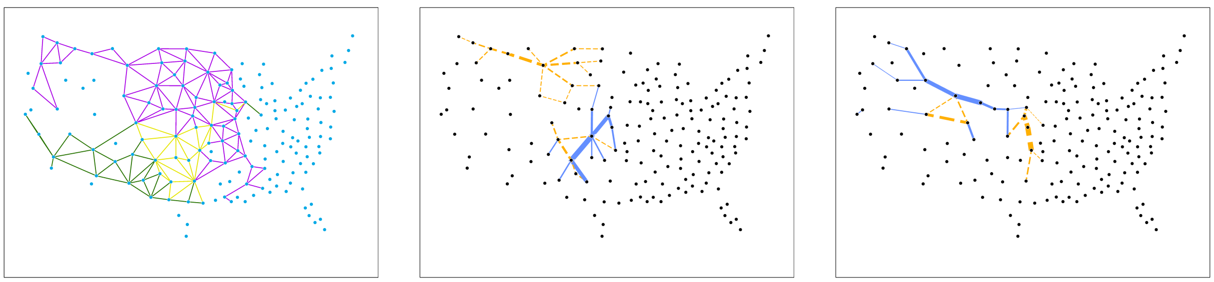
To further investigate what drives up the markup post-merger, I first examine how markup could be affected in the model. The markup for each firm j at market od is calculated from the first-order condition of the firm's optimization problem as

$$p_{j,od} - c_{j,od} = -\frac{1}{\alpha(1 - h_{j,od})} \tag{13}$$

where α is the price coefficient, and $h_{j,od}$ is the market share of firm j at market od. Equation 13 shows that the markup increases only when the local market share $h_{j,od}$ rises. One possible explanation is that the merger reduces the number of firms in local markets, thereby increasing a firm's market share in those markets. However, the first two counterfactuals show that merger-generated concentration in local markets only increases the markup slightly, by 0.7%.

I then investigate how the pricing and allocation decisions change for both merging and non-merging firms. The merger eliminates interchange costs and strengthens the connections of the merged firm, resulting in significant cost reductions, particularly in the interconnected areas of the two merging firms. I find that non-merging competitors strategically reallocate their resources away from such regions. Assuming all other factors remain constant, when the merged firm's costs decrease in a given market, its market share in that market will increase. Consequently, the competitors' allocated resources to that market will have reduced utilization. This leads to a decrease in the competitors' marginal return on capital in that market, prompting them to reallocate their resources to other markets.

When resources are moved away, the shipment cost of non-merging competitors will further increase in those markets. This results in further increases in the local market share of the merged firm. Hence, there will be a large increase in markup for the merged firm in the areas where the merged firm exhibits a large cost reduction post merger. For example, after the merger between Burlington Northern Railway (BN) and Santa Fe Railway (SF), the merged firm allocated more resources to improve the connectivity between the integrated sections of their network. In the west/eastbound direction, more resources were allocated to the arcs between Amarillo, TX and Omaha, NE. In the north/southbound direction, more was allocated to the arcs between South Dakota and Kansas. Panel (b) of Figure 5 shows the changes in allocation of resources for BNSF post merger. Meanwhile, in equilibrium, BNSF's primary competitor, Union Pacific Railway (UP), reallocates resources away from the South Dakota and Kansas areas and redirects them towards the Northwest corridor. Panel (c) of Figure 5 illustrates the resource allocation changes for UP subsequent to the BN and ATSF merger. As a result of all these changes, the market share of BNSF in local areas near South Dakota and Kansas will further increase.



(a) BNSF Network (b) Changes in Resources, BNSF (c) Changes in Resources, UP

Figure 5: Changes in Allocation of Resources After ATSF–BN Merger

Notes: Panel (a) shows the combined network of the two merging firms. The purple areas in the northwest represent the network solely owned by BN, while the green areas in the south represent the network solely owned by SP. The yellow areas indicate the overlapping region of the two networks. Panel (b) shows the changes in resource allocation for BNSF's network after the merger, while Panel (c) shows the changes in resource allocation for UP's network. In Panels (b) and (c), the solid blue line represents increased allocation after merger, while the dashed yellow line represents decreased allocation. The line thickness represents the magnitude of change. Changes in allocation are calculated by comparing the equilibrium allocation of resources post merger with that pre merger.

Degree and Betweenness Centrality Measures

Next, I investigate why the degree and betweenness centrality measures yield different results, as found in Section 7.1. To make the results easier to interpret, I calculate the difference of the merger gains between nodes at the 95th and 5th percentiles of ΔNC. Table 9 shows the results of these calculations.[13]

Panel I of Table 9 shows how changes in centrality affect cost reduction post merger. The first counterfactual eliminates interchange cost and economies of scope. Column (2) of Table

[13] Table G.1 in Appendix G shows the full regression results of merger gains on changes in network centrality.

9 shows the results of this counterfactual: When only distance matters, increases in both degree and betweenness centrality result in higher cost reduction post merger. Furthermore, the degree and betweenness centrality measures produce similar results in this scenario. A node at the 95th percentile of changes in degree centrality has an extra 3 percent cost reduction post merger than a node at the 5th percentile. Similarly, a node at the 95th percentile of changes in betweenness centrality has an extra 2.67 percent cost reduction post-merger compared to a node at the 5th percentile. In the second counterfactual I reincorporate interchange cost. Column (3) shows no significant change regarding the effect of changes in centrality after doing so.[14]

Table 9: Merger Gains and Centralities

	Baseline	Unpacking the Black Box		
	(1) Distance + Interchange Cost + Economies of Scope $(\delta_0, \eta_0, \gamma_0)$	(2) Distance $(\delta_0, 0, 0)$	(3) Distance + Interchange Cost $(\delta_0, \eta_0, 0)$	(4) Distance + Economies of Scope $(\delta_0, 0, \gamma_0)$
Panel I: Cost				
Δ Degree Centrality	−1.59%	−3.00%	−2.91%	−2.34%
Δ Betweenness Centrality	−5.17%	−2.67%	−2.86%	−4.73%
Panel II: Price				
Δ Degree Centrality	−2.28%	−3.36%	−3.24%	−2.85%
Δ Betweenness Centrality	−4.19%	−2.50%	−2.67%	−3.81%
Panel III: Markup				
Δ Degree Centrality	0.30%	0.03%	0.03%	0.33%
Δ Betweenness Centrality	1.17%	0.05%	0.05%	1.20%

The third counterfactual eliminates interchange cost but allows for economies of scope. Column (4) shows that under this counterfactual, changes in betweenness centrality have a greater effect on cost reduction compared to the first two counterfactuals, while changes in degree centrality have a smaller effect. Betweenness centrality measures the total number of paths that travel through each node. Therefore, with economies of scope present, firms will concentrate resources on nodes with high betweenness centrality, thus maximizing utilization of resources. As a result, nodes with higher changes in betweenness centrality will exhibit a greater cost reduction post merger. On the other hand, nodes with higher changes in degree centrality are likely to be located on the periphery of the pre-merger network. These nodes

[14] Regression results in Table G.1 show that the coefficient of indicator of interchange becomes much larger in the second counterfactual, meaning that the effect of interchange cost is mainly absorbed by the fixed effect of interlines, leaving the effect of changes in centrality unaffected.

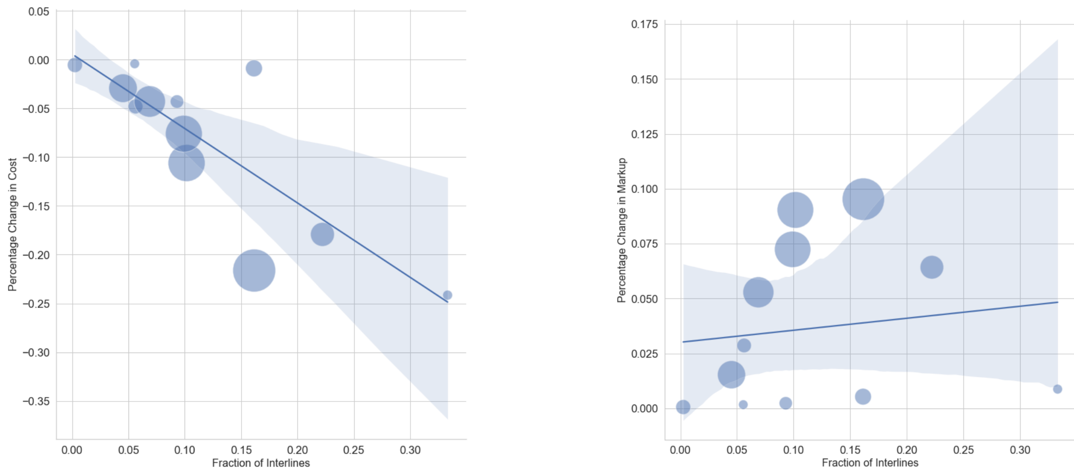
will have better routing options and hence shorter travel distances post merger. However, resources will not necessarily be reallocated to these nodes post merger.

Panel III of Table 9 shows how changes in centrality affect changes in markup post merger. Column (2) shows the results of the first counterfactual where both economies of scope and interchange cost are eliminated. Column (3) shows the results in the second counterfactual of eliminating only economies of scope. The results show that none of the changes in either degree or betweenness centrality have a strong impact on changes in markup in the absence of economies of scope. A node at the 95th percentile of change in degree centrality compared to a node at the 5th percentile has a slightly higher increase in markup at 0.03% post merger. This is consistent with our earlier finding that merger-induced concentration in local markets results in only a very small increase in markup. Column (4) shows the results of the third counterfactual, eliminating interchange cost while economies of scope remain present. We can see that changes in centrality have a much greater effect on changes in markup in this counterfactual. Moreover, changes in betweenness centrality have a greater effect on increase of markup than changes in degree centrality. A node at the 95th percentile of changes in betweenness centrality compared to a node at the 5th percentile exhibits a 1.2% higher increase in markup post merger. This is because nodes with higher betweenness centrality benefit more from reallocation of resources and hence greater cost reduction post merger when economies of scope are present. As previously explained, non-merging competitors tend to move resources away from regions where the merged firm experiences a large efficiency gain. Therefore, nodes with greater increases in betweenness centrality post merger will have greater increases in local market share and hence in markup.

Degree of Overlap and Complementarity

Last, I demonstrate the relationship between merger gains and the extent of overlap and complementarity between the two networks involved in the merger. I measure the degree of overlap by calculating the overall percentage of markets operated by both merging firms prior to the merger. As for complementarity, I count the number of joint-line services (interlines) offered by the merging firms and calculate the proportion of interlines.

Figure 6 shows the relationship between merger gains and degrees of complementarity. The size of each circle in the figure corresponds to the total number of origin–destination markets involved in a specific merger. Panel (a) shows that higher degrees of complementarity lead to more significant cost reductions after the merger. When a merging network exhibits a higher degree of complementarity, the merged firm benefits from a greater reduction in interchange costs. Panel (b) demonstrates that a higher degree of complementarity also results in a larger increase in markup.



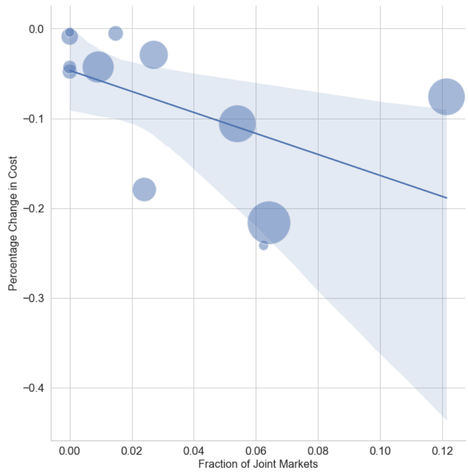
(a) Cost Changes and Degree of Complementarity (b) Markup Changes and Degree of Complementarity

Figure 6: Degree of Complementarity and Average Merger Effects

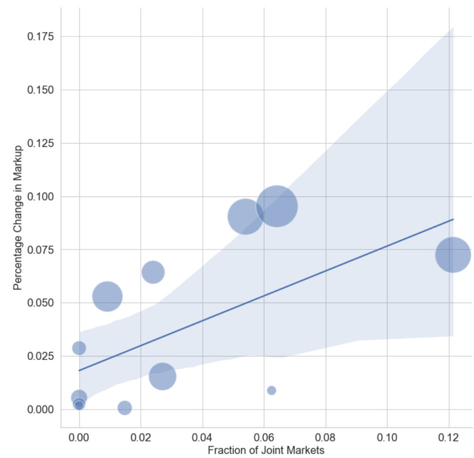
Figure 7 shows the relation between merger gains and degrees of overlap. Panel (a) of the figure illustrates that higher degrees of overlap lead to more substantial cost reductions after the merger. In a merging network with a higher degree of overlap, the merged firm benefits more from economies of scope by eliminating redundant lines and consolidating traffic and resources. Panel (b) demonstrates that a higher degree of overlap also results in a larger increase in markup. Comparing Panel (b) in Figure 6 with Panel (b) in Figure 7, we can observe that although a higher degree of complementarity also contributes to a larger increase in markup, the impact is comparatively less significant when compared to a higher degree of overlap.

8 Conclusion

I document evidence of improved cost efficiency following the wave of mergers in the U.S. railroad industry from 1985 to 2005. By conducting a reduced-form analysis with detailed route-level shipment data, I find that following the mergers, shipment prices decreased by 9.4% on average, and interconnecting routes had the largest price reduction, 11%, of all the route types. However, looking solely at the effect of individual routes is insufficient to understand efficiency gains in this industry due to the interdependency of the origin–destination markets in the network. To capture this important feature and examine how network structure affects the effect of mergers, I propose a model of oligopolistic competition among transport firms in which each firm optimizes its pricing, routing, and allocation decisions endogenously to maximize profits.



(a) (a) Cost Changes and Degree of Overlap



(b) (b) Markup Changes and Degree of Overlap

Figure 7: Degree of Overlap and Average Merger Effects

The counterfactual results show that reducing the number of firms in local markets is not the main reason behind increased markup post-merger. Instead, the increase in markup is driven mainly by the strategic reaction of non-merging competitors, which tend to move resources away from regions where the merged firm experiences a large efficiency gain. As a result, the merged firm's local market share grows even more, leading to a higher markup. Furthermore, I demonstrate that changes in betweenness centrality have a more substantial impact on reducing shipment costs and increasing markup post-merger compared to changes in degree centrality. This is because nodes with large increases in betweenness centrality benefit from better routing options and shorter travel distances post-merger; such nodes also benefit more from the reallocation of resources when economies of scope are present. In comparison, nodes with significant increases in degree centrality are more likely to benefit from improved routing options, but their gains from the reallocation of resources post-merger are relatively limited. Lastly, if the two merging networks exhibit higher levels of complementarity, there may be greater cost savings and a slight increase in markup. The extent of cost reduction and markup gains may be more substantial when there is a higher degree of overlap between the two merging networks.

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Online Appendices: Not For Publication

A Regulation Changes in the U.S. Railroad Industry

Here I document a brief history of regulation changes in the U.S. railroad industry. The information is collected from multiple sources by the Surface Transportation Board and other government resources.

History: 1887–1980

- 1887, the Interstate Commerce Act: Creation of ICC value of service pricing (VOS pricing)
- 1973, The Regional Rail Reorganization Act ("3R" act): Establishment of US Railway Association, abandoning designated portions of the Northeast system
- 1976, Railroad Revitalization and Regulatory Reform Act ("4R" act): Creation of Conrail, permitting a railroad to adjust its rates up or down within a "zone of reasonableness," initially within 8 percent of the existing ICC tariff but widened over time. Acceleration of the legal procedure dealing with abandoning unprofitable lines; processing of merger expedited
- 1980, The Staggers Act: The most important change is the removal of inefficient commodity rate regulation, enhancing the ability to abandon some lines and merge with others

Recent: 1980–current

- After the deregulation of 1980, ICC/STB no longer sets fixed prices for the railroad industry. Instead, it implements a constrained market pricing strategy, in which railroads are not allowed to set rates that are "too high." The STB does not have jurisdiction over the reasonableness of a rate for rail transportation unless the rail carrier providing the service has "market dominance." By statute, a necessary but not sufficient condition for a railroad to be considered to have market dominance is that the revenue produced by the rate is greater than 180% of its variable cost of providing the service as determined under the STB's Uniform Rail Costing System. When the rate goes beyond this 180% threshold, shippers are able to request STB to evaluate whether the service exhibits "market dominance." There are three methods that STB allow shippers to use to evaluate market dominance of rail carriers: Stand-alone cost constraint (the most frequently used tools in law suits, invented in 1985), the three-benchmark procedure (invented in 1996), and the simplified SAC (invented in 2007).
- 1985, ICC's Coal Rate Guidelines: ICC implements the requirement of constrained market pricing, in which the rate set by rail carriers needs to satisfy three constraints:
  - Revenue adequacy constraint: Intended to ensure that railroads earn enough revenue to make normal profits, but not more (three rate-law cases have invoked this principle since 1980 but all were settled between shipper and railroad company)

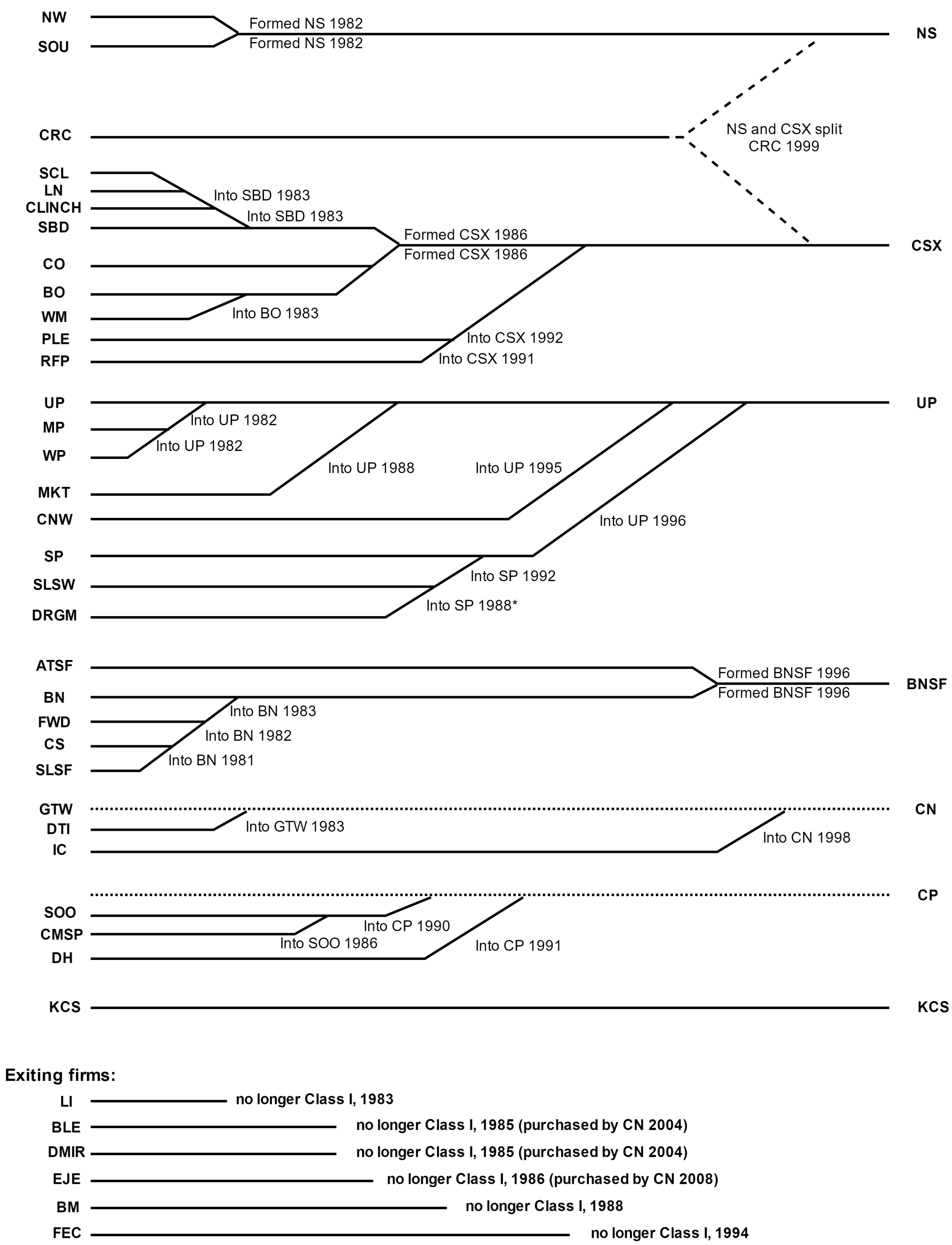
- Management efficiency constraint: Prevents the shippers from paying avoidable costs that result from the inefficiency of the railroad (zero cases have invoked this principle since 1980)
- Stand-alone cost constraint (SAC): Simulates the competitive rate that would exist in a contestable market by assuming a new highly efficient competitor railroad. The shipper must demonstrate that the "new" competitor would fully cover its costs, including a reasonable return on investment (full-SAC) (the most frequently used principle in rate cases. Fifty rate cases have invoked this principle since 1996, according to STB database)

- 1995, ICC Termination Act
- 1996, The Three-benchmark procedure (only applies to cases where the total revenue of service is under $1 million over five years)
  - Revenue shortfall allocation method: Determine the uniform mark-up above variable cost that would be needed from every shipper in the captive group ($R/VC > 180$) to cover the URCS fixed cost
  - R/VC for comparative traffic
  - $R/VC_{>180}$ average captive price: Calculate the average price of all the "captive" shippers

  Only three rate cases used three-benchmark from 1996 to 2007, while 25 rate cases used full-SAC in the same period.
- 2007, Simplified SAC (only applies to cases where the total revenue of service is under $5 million over five years): This allows shippers to use the existing infrastructure that serves the traffic, instead of coming up with a hypothetical stand-alone railroad to prove the market dominance of current service provider. Only two rate cases have used simplified-SAC since 2007, while 20 cases used full-SAC in the same period
- 2011, the National Industrial Transportation League filed a petition of reciprocal switching and urged regulatory change.
- 2013, Rate Regulations Reforms: Removed limit of simplified-SAC, raised limit of three-benchmark to $4 million (six rate cases after 2016, but all are using full-SAC method).
- 2016, Surface Transportation Board issued proposed rulemaking notice. In 2018, the Competitive Enterprise Institute issued a coalition letter and expressed concerns about network investment. Since the proposal in 2016, the STB has taken no further action.
- 2021, President Joe Biden signed an executive order to encourage the Surface Transportation Board to adopt rail regulatory reforms that shippers have long sought to promote competition.

B History of American Railroads

Figure B.1: Merger History of Railroads



C Details of U.S. Railroad Industry

C.1 Industry Statistics

Figures C.1 and C.2 plot the total ton-miles of freight carried by mode from 1980 to 2011, showing the importance of the railroad industry among all transportation modes. We can see that the U.S. railroad industry only accounts for a small proportion of total ton-miles of freight (around 20%), and accounts for an even smaller proportion than pipelines at the start of the 1980s. However, share increases continually after the deregulation of 1980 and reaches 33% before the financial crisis. According to the American Association of Railroads, if we only look at the intercity ton-miles, the railroad industry accounts for about 40% of the total shipping, more than any other transportation mode.

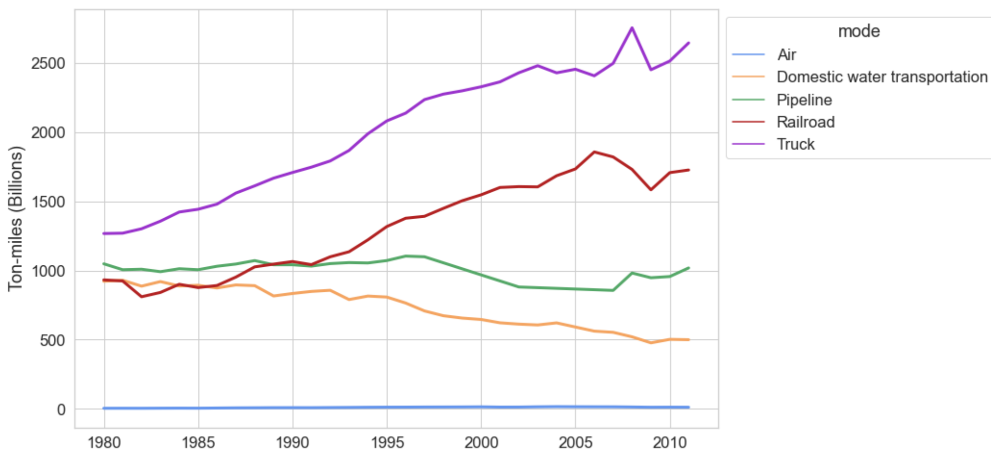


Figure C.1: U.S. total ton-miles of freight by mode

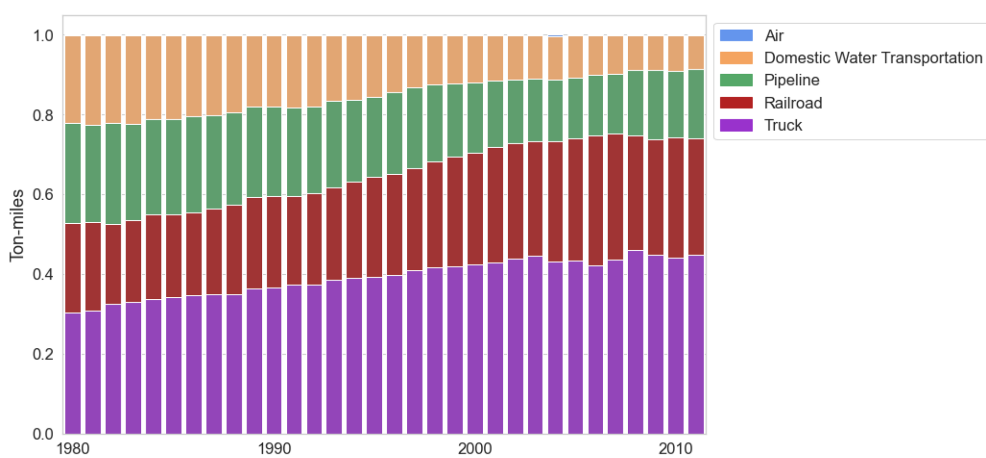


Figure C.2: U.S. total ton-miles of freight by mode (percentage)

C.2 More Summary Stats of Waybill Data

Table C.1: Summary Statistics of Market Competition (Annually)

Year	Number of Waybills	Percentage of Interchange Lines	Number of Competitors in an o–d Market			Number of o–d Markets (at BEA-to-BEA level)
			mean	25th percentile	75th percentile	
1984	262,626	41%	3	1	3	12,135
1985	262,703	41%	3	1	3	12,088
1986	276,177	38%	3	1	3	11,907
1987	300,324	35%	3	1	3	11,957
1988	322,257	35%	3	1	3	11,905
1989	324,936	36%	3	1	3	11,846
1990	323,570	35%	2	1	3	11,835
1991	314,705	32%	2	1	3	11,583
1992	346,632	31%	2	1	3	11,695
1993	373,868	29%	2	1	3	11,849
1994	426,092	27%	2	1	3	11,899
1995	453,802	26%	2	1	3	11,632
1996	457,505	25%	2	1	3	11,510
1997	473,070	23%	3	1	3	11,740
1998	496,856	20%	2	1	3	11,675
1999	524,856	15%	2	1	3	11,573
2000	544,738	14%	2	1	2	11,732
2001	522,927	14%	2	1	2	11,514
2002	535,722	13%	2	1	2	11,381
2003	554,967	13%	2	1	2	11,473
2004	580,572	12%	2	1	2	11,474
2005	611,033	11%	2	1	2	11,611
2006	632,748	11%	2	1	2	11,327
2007	611,421	10%	2	1	2	11,025
2008	568,584	10%	2	1	2	10,964
2009	477,526	10%	2	1	2	10,242
2010	533,364	10%	2	1	2	10,485

Source: STB, Carload Waybill Sample

Table C.1 shows that the pattern of year-on-year change tells the same story as in Table 1. First, total number of waybills in the waybill sample (the waybill sample is 2% of total waybills) changed from around $263,000$ to $533,000$ between 1985 and 2010. This shows that total volume of railroad shipment doubled from 1985 to 2010, consistent with the story in figure 1. Meanwhile, the percentage of interchange lines decreased from 41% to 10% while the total traffic volume doubled, showing that following the wave of mergers from 1985 to 2010, there was a significant decrease of interchanges. The number of o–d markets remained relatively stable over the years, with a small decrease from $11,835$ to $11,611$ from 1990 to 2005. Therefore, the change of extensive margin after the mergers does not seem to be a significant concern. Last, the average number of competitors in each o–d market slightly decreased from 3 to 2 from 1985 to 2010, indicating that firms conduct oligopolistic competition in the local markets.

C.3 Documentation of Interviews

1. Interview with business development manager of Canadian National:

   - How do firms make pricing decision?

     – The pricing department gets an estimate of operational cost from the costing department about how much money it costs to serve each origin–destination market. Then based on these cost estimates, the pricing department maximizes profits by charging a reasonable price margin as much as the market allows.

     – (The downward spiral) The service of a particular origin–destination market will be reduced if the operational cost outweighs the generated profits. However, sometimes this happens only because the operational cost is mismeasured. For example, the actual miles run by the train may not necessarily be fully related to the service it is providing. As a consequence, once a service is reduced, the volume of shipment decreases thus the operational cost further increases on a per-car basis, and more services get reduced.

   - How is interchange contract negotiated?

     – Usually the origin railroad has the bargaining power, but it depends. For example, there was a time when CN needed to make some shipment from Vancouver to New York, and they asked for a quote from the connecting railroad on shipment from Buffalo to New York. However, the Marketing representative from the other railroad only agreed to give a quote from Chicago to New York, rather than from Buffalo to New York, in order to maximize their revenue. "The hot stuff of one person is not the hot stuff of the other."

2. Interview with Train & Terminal Operations Manager at Lake State Railway Company (LSRC), about why interchange is costly and the incentive problem in exchanging equipment with another railroad.

   - As a short-line railroad, LSRC frequently interchanges railcars with Class I railroads. However, sometimes company C will park the train a few yards away from the designated interchange point, unplug their locomotives and leave the railcars there. So, LSRC has to use their own locomotives to pick up the railcars and move them into the station. The motive for that is because company C wants to make sure that their locomotives are returned in time and hence can be used for other hauling, especially in peak seasons when firms are generally short in power (locomotives), and they do not seem to care how much extra trouble this will cause LSRC.

3. The original story from *Trains* Magazine "Twenty-four hours at Supai Summit" provides details on why interchange is costly and coordination is a problem when two railroads are involved in a shipment.

   - The main customers of Train 9-698-21 were UPS and J.B. Hunt, and the train was an express freight train initiated to "reach downtown L.A. in time for UPS to deliver the next morning." The contract specified that Santa Fe be given haulage rights over BN to Memphis and Birmingham. These haulage rights meant that Santa Fe sold the service, then paid BN to run the trains east of Avard. However, according to Rollin Bredenberg, BNSF's vice president of transportation at that time, nothing went right with 9-698-21:

> *"It was very unreliable under the haulage agreement, pre-merger," reports Bredenberg, "BN's internal measurement of how well they ran trains did not include the performance of the Santa Fe haulage trains, so you can guess what happened." In an interview last year, Krebs (chairman of Santa Fe railway) said he finally had to tell key customers such as Hunt that they were free to go elsewhere until Santa Fe and BN could get their acts together.*

D Robustness Check for Reduced-form Analysis

First, as a robustness check of the price effect of mergers, I run the price regression for each type of commodity. Table D.1 shows a complete summary statistics of commodities shipped by rail from waybill data.

Table D.1: Descriptive Statistics of Commodity Types and Car Ownership Category

	Number of Waybills	Percentage
Commodities		
Field Crops	466,584	3.85%
Forest Products	5,361	0.04%
Marine Products	2,138	0.02%
Metallic Ores	93,371	0.77%
Coal	1,002,580	8.28%
Crude Petroleum	2,855	0.02%
Nonmetallic Minerals	371,109	3.06%
Ordnance or Accessories	1,838	0.02%
Food or Kindred Products	882,352	7.28%
Tobacco Products	1,222	0.01%
Textile Mill Products	9,533	0.08%
Apparel or Other Textile Products	46,414	0.38%
Lumber or Wood Products	487,386	4.02%
Furniture or Fixtures	34,101	0.28%
Pulp, Paper or Allied Products	483,980	4.00%
Newspapers and Books	15,933	0.13%
Chemicals	635,119	5.24%
Petroleum or Coal Products	158,794	1.31%
Rubber or Miscellaneous Plastics Products	62,202	0.51%
Leather Products	2,484	0.02%
Clay, Concrete, Glass or Stone Products	323,923	2.67%
Primary Metal Products	354,360	2.93%
Fabricated Metal Exc.	24,387	0.20%
Machinery Exc.	23,351	0.19%
Electrical Machinery	70,893	0.59%
Transportation Equipment	1,098,439	9.07%
Instruments, Optical Goods	3,192	0.03%
Miscellaneous Products	21,965	0.18%
Waste or Scrap Materials	342,374	2.83%
Miscellaneous Freight Shipments	60,474	0.50%
Containers	660,513	5.45%
Mail	43,970	0.36%
Freight Forwarder	3,689	0.03%
Shipper Association	48,529	0.40%
Miscellaneous Mixed Shipments	3,434,269	28.35%
Small Packaged Freight Shipments	62,495	0.52%
Waste Hazardous	7,329	0.06%
Other	762,855	6.30%
Car Ownership Category		
Privately Owned	5,349,791	44%
Railroad Owned	3,621,221	30%
Trailer Train	2,202,838	18%
Non-Categorized	939,731	8%
Waybills (Carrier-Origin-Destination-Date)	12,113,581	

Source: STB, Carload Waybill Sample

Then I study the effect of merger on price changes case by case. Table D.2 shows the estimation results for shipment price changes, which suggest that on average a railroad merger reduces the shipment price by 9.4%. If we look at the merger effect case by case, we find that most of the large mergers result in a price reduction of more than 10%, including the merger of the Burlington Northern and Santa Fe, the merger of the Southern Pacific and Union Pacific, and the merger of the Chicago and North Western Railway (CNW) and Union Pacific. The only exception is the merger of the Seaboard System Railroad (SBD), Chesapeake and Ohio Railway (CO), and Baltimore and Ohio Railroad (BO) which occurred in 1986. Mergers involving smaller railroad firms have an insignificant impact on shipment price, likely because these mergers affect only a small fraction of routes.

Table D.2: Effect of Merger on Price Change

	(1) Log Price	(2) Log Price
Indicator of Merger	−0.094***	
	(0.014)	
SBD		0.106***
		(0.021)
BNSF		−0.114***
		(0.023)
LA		−0.043
		(0.058)
MSRC		0.052
		(0.059)
IC		−0.025
		(0.041)
CNW		−0.162***
		(0.039)
MKT		0.009
		(0.044)
DRGW		0.018
		(0.043)
SP		−0.119***
		(0.021)
SSW		−0.227***
		(0.040)
WC		0.006
		(0.058)
Log Weight	−0.259***	−0.260***
	(0.015)	(0.015)
Private Railcars	−0.112***	−0.110***
	(0.009)	(0.009)
Trailer Train Railcars	−0.052***	−0.053***
	(0.009)	(0.009)
Observations	12,110,107	12,110,107
Number of marketID	22,510	22,510
Adjusted R-squared	0.361	0.363
Year FE	Y	Y
Firm FE	Y	Y
Commodity FE	Y	Y
O-D Route FE	Y	Y

Notes: Standard errors in parentheses, clustered at o–d route level
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: Surface Transportation Board, Carload Waybill Sample

As a robustness check, I run the price regression for each type of commodity (defined in STCC):

Table D.3: Effect of Merger on Price Change (by Commodities)

	(1) Field Crops	(2) Metallic Ores	(3) Coal	(4) Nonmetallic Minerals	(5) Food or Kindred Products	(6) Apparel or Textile Products	(7) Lumber or Wood Products	(8) Furniture or Fixtures	(9) Pulp, Paper	(10) Newspapers
Indicator of Merger	−0.009	0.048	−0.179***	−0.036	−0.052***	0.049	0.016	−0.023	−0.013	−0.057
	(0.014)	(0.062)	(0.028)	(0.029)	(0.014)	(0.047)	(0.013)	(0.036)	(0.015)	(0.042)
Observations	466,222	93,316	1,002,552	371,035	882,066	46,409	487,275	34,095	483,952	15,933
Number of marketID	6,982	1,086	1,360	3,697	10,766	1,210	8,145	1,694	8,441	780
Adjusted R-squared	0.178	0.144	0.251	0.234	0.266	0.767	0.274	0.829	0.299	0.667
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
o–d Route FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	(11) Chemicals	(12) Petroleum	(13) Plastics Products	(14) Clay, Concrete, Stone Products	(15) Primary Metal Products	(16) Fabricated Metal Exc.	(17) Machinery	(18) Electrical Machinery	(19) Transportation Equipment	(20) Miscellaneous Products
Indicator of Merger	−0.114***	−0.115***	−0.056**	−0.045***	−0.112***	−0.104***	−0.035	−0.146***	−0.022	0.022
	(0.031)	(0.024)	(0.028)	(0.015)	(0.027)	(0.035)	(0.037)	(0.038)	(0.035)	(0.035)
Observations	634,684	158,774	62,197	323,910	354,322	24,385	23,343	70,889	1,097,641	21,963
Number of marketID	10,462	4,175	2,087	6,670	6,639	2,009	2,072	1,996	7,177	1,163
Adjusted R-squared	0.157	0.210	0.730	0.262	0.163	0.558	0.413	0.569	0.321	0.765
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
o–d Route FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	(21) Waste or Scrap Materials	(22) Miscellaneous Freight Shipment	(23) Containers	(24) Mail	(25) Shipper Association	(26) Miscellaneous Mixed	(27) Small Packaged	(28) 49
Indicator of Merger	−0.000	−0.103*	0.049	0.036*	−0.179***	−0.170***	0.019	−0.072***
	(0.022)	(0.055)	(0.052)	(0.019)	(0.035)	(0.034)	(0.041)	(0.018)
Observations	341,973	60,443	660,061	43,965	48,523	3,434,108	62,487	762,745
Number of marketID	7,843	2,775	2,747	903	1,245	5,821	633	9,562
Adjusted R-squared	0.195	0.412	0.426	0.611	0.468	0.569	0.670	0.224
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y	Y	Y
o–d Route FE	Y	Y	Y	Y	Y	Y	Y	Y
o–d Route Cluter	Y	Y	Y	Y	Y	Y	Y	Y

The results show that price reduction following railroad mergers is consistent across different types of commodities. If we look particularly at commodities that are largely shipped by rail, such as coal, chemicals, and construction materials (clay, concrete, etc.), there is a large and significant price reduction following railroad mergers.

E Discussion of the Model

In the model, I assume that when railroad firms set prices in local markets, they do not consider how changes in quantity would affect routing and allocation decisions. This assumption translates to setting the own-cost and cross-cost effects to zero in the first-order-condition with respect to price:

$$Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial Q_{s,od}}{\partial p_{s,od}} \cdot \left[C_{s,od} + \underbrace{\frac{\partial C_{s,od}}{\partial Q_{s,od}} Q_{s,od}}_{\text{own-cost effect}} + \underbrace{\sum_{s' \in S(j), s' \neq s} \frac{\partial C_{s',o'd'}}{\partial Q_{s,od}} Q_{s,o'd'}}_{\text{cross-cost effects}} \right] = 0.$$

To investigate the impact of this assumption on equilibrium results, I derived solutions for a monopoly by incorporating the own- and cross-cost effects, which I refer to as the full model. In contrast, the benchmark model has the own- and cross-cost effects set to zero.

Below I compare the equilibrium results of the two models. There are three scenarios: no economy of scope ($\gamma = 0$), economy of scope ($\gamma \neq 0$) and the topology of the network is a tree, and economy of scope and non-tree network topology. The distinction between a tree and a non-tree network topology is illustrated in Figure E.1, where panel (a) depicts a tree topology, while panel (b) shows a non-tree topology in which $B_1 - C_1 - B_2 - C_2 - B_1$ forms a loop. The primary difference between the two is the number of routing options available. In a tree network topology, only one routing option exists for each o–d market.

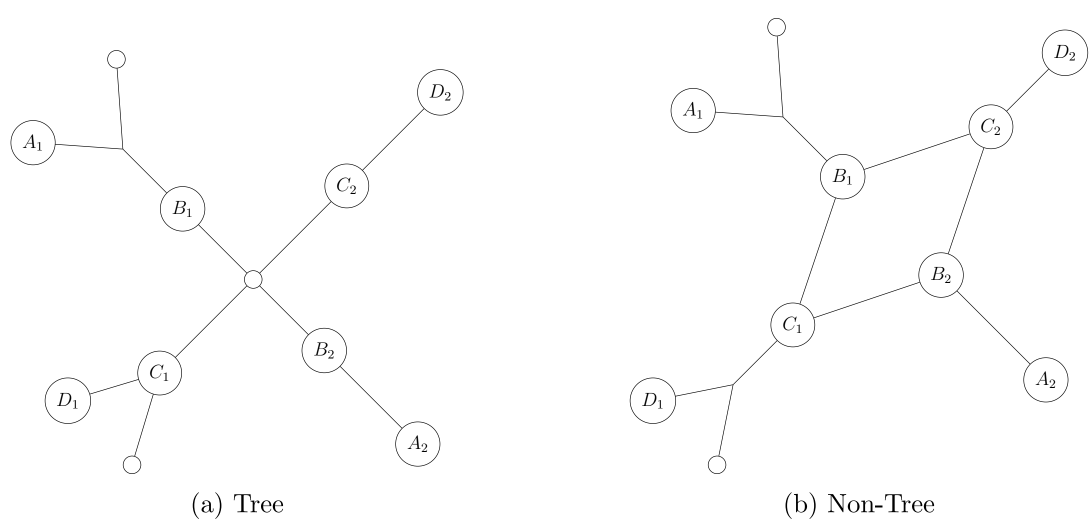


Figure E.1: Examples of Tree and Non-Tree Topologies

Proposition 1 *When there is no economy of scope ($\gamma = 0$), the optimal decision for each o–d market is independent, and the benchmark model is equivalent to the full model.*

Proof: The marginal cost of service s from o to d is specified as

$$\begin{aligned} C_{s,od}(\boldsymbol{I}_j, \mathcal{R}_{j,od}) &= \sum_{(a,b)\in\mathcal{R}_{j,od}} \frac{\delta_0 Dist_{j,ab}}{I_{j,ab}^{\gamma}} \\ &= \sum_{(a,b)\in\mathcal{R}_{j,od}} \delta_0 Dist_{j,ab} \qquad \text{if } \gamma = 0. \end{aligned} \tag{E.1}$$

When $\gamma = 0$, maintenance allocation $\boldsymbol{I}$ no longer affects cost, and the optimal routing is to choose the shortest o–d path for each service s. Hence, the routing decision for each service s is independent. From equation E.1, we can see that the choice of optimal routing depends only on the travel distance between each arc (a, b) and is irrelevant to the quantity being shipped. Therefore, $\frac{\partial C(\boldsymbol{Q},\boldsymbol{R},\boldsymbol{I})}{\partial Q_{s,od}} = \sum_{(a,b)\in\mathcal{R}^*_{j,od}} \delta_0 Dist_{j,ab} = C^{**}_{s,od}$. The second part of the equation holds because the optimal routing for firm j from o to d is the same in the two models when $\gamma = 0$. Therefore, both models' optimal strategies are equivalent when there is no economy of scope ($\gamma = 0$).

Next I discuss the case when $\gamma \neq 0$. When the topology of a network is a tree, there is only one routing option between each o–d market. Therefore, $R^*_{j,od}$ is irrelevant to the choice of prices and the allocation decision.

Lemma 1 *For any service s in market o–d, the own-cost effect $\frac{\partial C_{s,od}}{\partial Q_{s,od}} < 0$. The cross-cost effect for market m–n, $\frac{\partial C_{s,mn}}{\partial Q_{s,od}} > 0$ if $\mathcal{R}_{s,od} \cap \mathcal{R}_{s,mn} = \emptyset$. Otherwise the sign of the cross-cost effect is uncertain.*

Proof: Equation E.1 shows that $C_{s,od}$ is inversely proportional to maintenance allocation $I_{j,ab}, (a, b) \in \mathcal{R}_{j,od}$. Therefore, the own- or cross-cost effect narrows down to how firms allocate the fixed amount of resources $I_{j,ab}$, where $\sum_{(a,b)\in\mathcal{A}_j} I_{j,ab} \leq K_j$. Based on the Kuhn-Tucker conditions in 7, we know that for any non-zero $I_{j,ab}$ and $I_{j,a'b'}$,

$$\frac{I_{j,ab}}{I_{j,a'b'}} = \left[\frac{Dist_{j,ab} \cdot q_{j,ab}}{Dist_{j,a'b'} \cdot q_{j,a'b'}}\right]^{\frac{1}{1+\gamma}}. \tag{E.2}$$

where $q_{j,ab}$ is the total amount of shipment running through arc (a, b), $q_{j,ab} = \sum_{s:s\in S(j)} Q_{s,od} \cdot \mathbb{1}\{(a, b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}$. Therefore, equation E.2 shows that the amount of allocation to arc (a, b) is proportional to the traffic going through arc (a, b). Therefore, when $Q_{s,od}$ increases, $\forall(a, b) \in \mathcal{R}_{j,od}, I_{j,ab}$ increases and hence $C_{s,od}$ decreases. That is, the own-cost effect $\frac{\partial C_{s,od}}{\partial Q_{s,od}} < 0$. For market m to n, if m to n uses a totally different route than o to d (i.e. $\mathcal{R}_{j,od} \cap \mathcal{R}_{j,mn} = \emptyset$), then resources will be allocated away, yielding a higher shipment cost from m to n. Consequently, $\frac{\partial C_{s,mn}}{\partial Q_{s,od}} > 0$. However, if $\mathcal{R}_{j,od} \cap \mathcal{R}_{j,mn} \neq \emptyset$, m to n will partially benefit from the reallocation to arcs (a, b) where $(a, b) \in \mathcal{R}_{j,od} \cap \mathcal{R}_{j,mn}$. Hence, the net effect on $C_{s,mn}$ is ambiguous if $\mathcal{R}_{j,od} \cap \mathcal{R}_{j,mn} \neq \emptyset$.

Lemma 2 *When the demand of one single market dominates ($Q_{mn} \gg Q_{od}, \forall od \neq mn$), $I_{j,ab} \approx 0$ if $(a, b) \notin \mathcal{R}_{j,mn}$, and $I_{j,ab} \approx K_j \cdot \frac{Dist_{j,ab}^{\frac{1}{1+\gamma}}}{\sum_{(a',b')\in\mathcal{R}_{j,mn}} Dist_{j,a'b'}^{\frac{1}{1+\gamma}}}$ if $(a, b) \in \mathcal{R}_{j,mn}$.*

Proof: From equation E.2, we know that

$$\begin{aligned}\frac{I_{ab}}{I_{a'b'}} &= \left[\frac{Dist_{j,ab}\cdot q_{j,ab}}{Dist_{j,a'b'}\cdot q_{j,a'b'}}\right]^{\frac{1}{1+\gamma}}\\ &= \left[\frac{Dist_{j,ab}\cdot \sum_{s:s\in S(j)} Q_{s,od}\cdot \mathbb{1}\{(a,b)\in\mathcal{R}_{j,od}\}}{Dist_{j,a'b'}\cdot \sum_{s:s\in S(j)} Q_{s,od}\cdot \mathbb{1}\{(a',b')\in\mathcal{R}_{j,od}\}}\right]^{\frac{1}{1+\gamma}}.\end{aligned} \tag{E.3}$$

If $Q_{mn} \gg Q_{od}, \forall od \neq mn$, from equation E.3 we know that

$$\frac{I_{ab}}{I_{a'b'}} \approx 0$$

$\forall (a,b) \notin \mathcal{R}_{j,mn}$ and $(a',b') \in \mathcal{R}_{j,mn}$. Similarly, if $(a,b) \in \mathcal{R}_{j,mn}$ and $(a',b') \in \mathcal{R}_{j,mn}$, then $q_{ab} \approx q_{a'b'} \approx Q_{mn}$. Therefore,

$$\frac{I_{a'b'}}{I_{ab}} \approx \frac{Dist_{j,a'b'}^{\frac{1}{1+\gamma}}}{Dist_{j,ab}^{\frac{1}{1+\gamma}}}.$$

Because $\sum_{(a,b)} I_{ab} = K$, we have $I_{j,ab} \approx K \cdot \frac{Dist_{j,ab}^{\frac{1}{1+\gamma}}}{\sum_{(a',b')\in\mathcal{R}_{j,mn}} Dist_{j,a'b'}^{\frac{1}{1+\gamma}}}$ if $(a,b) \in \mathcal{R}_{j,mn}$ and $I_{j,ab} \approx 0$ if $(a,b) \notin \mathcal{R}_{j,mn}$.

Proposition 2 *When there is economy of scope ($\gamma \neq 0$) and the topology of the network is a tree, if the demand of a single market dominates, then the difference between the benchmark model and the full model is negligible. Otherwise, the direction of the bias of the benchmark model is ambiguous, and it depends on the level of demand in each origin–destination market.*

Proof: From Lemma 2, we know that when one market dominates, all the resources will be allocated to minimize the shipment cost for that dominant market in both models. Given that the network is a tree, the optimal routing decisions $\boldsymbol{R_j^*}$ are irrelevant to the choice of prices and allocation decisions. Therefore, the own- and cross-cost effect in the full model will be close to zero because the marginal change in quantities will have minimal effect on the routing and allocation decision. Hence, the optimal pricing decisions will essentially be identical in both models. Therefore, when a single market dominates, the difference between the benchmark model and the full model is negligible. From Lemma 1, we can see that the own-cost effect is negative while the cross-cost effect is mostly positive. Hence, the net effect and therefore the difference in pricing in the full and benchmark models are ambiguous.

Next, I discuss the case when $\gamma \neq 0$ and when the topology of a network is non-tree. In this scenario, the routing decision becomes non-trivial and has a significant impact on the allocation of resources. With a fixed set of routing decisions, we can determine the optimal allocation and pricing decisions. Since the set of origin-destination markets is finite, there is a limited number of possible routing options through those markets. Therefore, we can evaluate all possible routing decisions and identify the optimal solutions.

Lemma 3 *When the demand of one single market dominates ($Q_{mn} \gg Q_{od}, \forall od \neq mn$), $I_{j,ab} \approx 0$ if $(a,b) \notin \mathcal{R}_{j,mn}$, and $I_{j,ab} \approx K \cdot \frac{Dist_{j,ab}^{\frac{1}{1+\gamma}}}{\sum_{(a',b') \in \mathcal{R}_{j,mn}} Dist_{j,a'b'}^{\frac{1}{1+\gamma}}}$ if $(a,b) \in \mathcal{R}_{j,mn}$. The routing of m to n is obtained by solving the shortest travel distance between m and n in both models.*

Proof: We first show that Lemma 2 still holds when the topology of the network is non-tree. Given a set of routing decisions $\boldsymbol{\mathcal{R}}_{(\cdot)}$, the optimal allocation decisions in both models will be solved through

$$I_{j,ab} = \left[\frac{\gamma}{\lambda_j} \cdot \delta_0 Dist_{j,ab} \cdot q_{j,ab}\right]^{\frac{1}{1+\gamma}}$$

and, following the proof in Lemma 2, we can easily show that when the demand of one single market dominates ($Q_{mn} \gg Q_{od}, \forall od \neq mn$), $I_{j,ab} \approx 0$ if $(a,b) \notin \mathcal{R}_{j,mn}$, and $I_{j,ab} \approx K_j \cdot \left(Dist_{j,ab}^{\frac{1}{1+\gamma}} / \sum_{(a',b') \in \mathcal{R}_{j,mn}} Dist_{j,a'b'}^{\frac{1}{1+\gamma}} \right)$ if $(a,b) \in \mathcal{R}_{j,mn}$. Given the solutions to the optimal allocation decisions, the shipment cost can be rewritten as

$$\begin{aligned} C_{s,od}(\boldsymbol{I}_j) &= \sum_{(a,b) \in \mathcal{R}^*_{j,od}} \frac{\delta_0 Dist_{j,ab}}{I^{\gamma}_{j,ab}} \\ &= \sum_{(a,b) \in \mathcal{R}^*_{j,od}} \delta_0 Dist_{j,ab}^{\frac{1}{1+\gamma}} \sum_{(a',b') \in \mathcal{R}_{j,mn}} Dist_{j,a'b'}^{\frac{\gamma}{1+\gamma}}. \end{aligned}$$

The last equality is obtained by subtracting the solutions of $I_{j,ab}$ into the equation. Without loss of generality, we can assume that $Dist_{ab} = Dist_{a',b'}, \forall (a',b')$. Therefore, we have

$$C_{s,od}(\boldsymbol{I}_j) = \delta_0 Dist_{j,ab}^{\frac{1}{1+\gamma}} \cdot (\#\mathcal{R}_{od})^2$$

where $\#\mathcal{R}_{od}$ stands for the total number of arcs gone through by routing $\mathcal{R}_{od}$. Then to minimize shipment cost, the optimal routing decision is to find the shortest travel distance between o to d, which is irrelevant to the allocation and pricing decision.

Proposition 3 *When there is economy of scope ($\gamma \neq 0$) and the topology of the network is non-tree, if the demand of a single market dominates, then the difference between the benchmark model and the full model is negligible. Otherwise, the direction of the bias of the benchmark model is ambiguous and depends on the level of demand in each origin–destination market.*

Proof: Similar to the proof in Proposition 2, based on Lemmas 1 and 3 the equilibrium results of the full and benchmark models will be approximately the same when one market dominates. Otherwise, the direction of the bias is ambiguous.

Propositions 2 and 3 demonstrate that when there is an economy of scope ($\gamma \neq 0$) and no single market dominates, the difference between the benchmark model and the full model varies depending on the demand level in each origin-destination market, and the direction of the benchmark model's bias is uncertain. Therefore, I conduct numerical simulations to gain a better understanding of the magnitude of the difference in scenarios where no single market dominates.

In the numerical simulation, I assume a logit demand, the distance of all the arcs equals 1, and the parameter of the economy of scope $\gamma = 1$. Therefore, the shipment cost for each o–d market is

$$c_{s,od}(\boldsymbol{I}_j) = \sum_{(a,b)\in\mathcal{R}^*_{j,od}} \frac{1}{I_{j,ab}}.$$

I also assume that the total capital equals the number of edges in the numerical example. The constraint on allocation is that $\sum I_{j,ab} = K$. Appendix F displays the analytical solutions of the optimal strategies for the benchmark model and the full model for the tree and non-tree network topology cases. Based on the analytical solutions, I calculate the optimal strategies for the benchmark model and the full model in various situations. The main parameter I change in the simulation is the total mass of demand M_{od} for each o–d market.

Numerical Simulations: Topology of the Network is a Tree

In this numerical exercise, I assume that the topology of the network is the same as illustrated in panel (a) of Figure E.1. Assume that there are four origin–destination markets, $A_1 \to A_2$, $B_1 \to B_2$, $C_1 \to C_2$, and $D_1 \to D_2$. Online appendix F.1 shows the analytical solutions of the optimal strategies of the benchmark model and the full model.

Table E.1 compares the equilibrium price and cost results between the two models. In Panel I of Table E.1 when all four markets have an equal total mass of demand ($M_{od} = 1, \forall od$), the prices of $A_1 \to A_2$ and $D_1 \to D_2$ are higher than the prices of $B_1 \to B_2$ and $C_1 \to C_2$. This is because the former two markets have longer travel distances and more resources are allocated to (B_1, B_2) and (C_1, C_2), yielding lower cost for the latter two markets. In Panel II when the demand of $A_1 \to A_2$ dominates ($M_{A_1A_2} = 100$), we know that all resources are allocated to (A_1, B_1), (B_1, B_2), and (B_2, A_2). Hence, the cost of $C_1 \to C_2$ and $D_1 \to D_2$ is close to infinity and marked as NA. Equivalently, markets from $C_1 \to C_2$ and $D_1 \to D_2$ will not be served. Table E.1 shows that the difference in the equilibrium prices and costs between the benchmark model and the full model is very small.

Table E.2 shows the optimal allocation decisions I^*. There are three key findings of the numerical results. First, Panel I of Table E.2 shows the results when all four markets have equal amounts of demand ($M_{od} = 1, \forall od$). We can see that more resources are allocated to arcs (B_1, B_2) and (C_1, C_2) than the other arcs because more traffic goes through arcs (B_1, B_2) and (C_1, C_2) than the other arcs. For example, (B_1, B_2) is used by both market $A_1 \to A_2$ and $B_1 \to B_2$, while (A_1, B_1) is only used by market $A_1 \to A_2$. Second, when the importance of one market increases, more resources will be allocated to the routes used by that o–d market. In Panel II of Table E.2, the mass of demand of $M_{A_1A_2}$ is changed to 100 while the mass of demand is held at 1 for all the other markets. We can see that more resources are now allocated to the arcs $A_1 \to A_2$ go through (A_1, B_1), (B_1, B_2), and (B_2, A_2). Moreover, the allocation amount for each arc approximately equals 2, which is consistent with Lemma 2. Third, there is no noticeable difference in the equilibrium allocation of resources between the benchmark model and the full model. Panel I shows the difference as 10^{-6}. Panel II

Table E.1: Equilibrium Prices and Costs under Tree

Market	Prices			Costs		
	Benchmark Model	Full Model	Difference	Benchmark Model	Full Model	Difference
Panel I: $M_{od} = 1$ for all four markets						
$A_1 \to A_2$	5.56	5.56	1E-05	3.22	3.22	9E-06
$B_1 \to B_2$	3.61	3.61	-3E-06	0.71	0.71	-4E-06
$C_1 \to C_2$	3.61	3.61	-3E-06	0.71	0.71	-4E-06
$D_1 \to D_2$	5.56	5.56	1E-05	3.22	3.22	9E-06
Panel II: $M_{A_1A_2} = 100, M_{od} = 1$ for all the other markets						
$A_1 \to A_2$	4.17	4.17	3E-07	1.50	1.50	-4E-08
$B_1 \to B_2$	3.46	3.46	-9E-07	0.50	0.50	-1E-08
$C_1 \to C_2$	NA	NA	NA	NA	NA	NA
$D_1 \to D_2$	NA	NA	NA	NA	NA	NA

shows a smaller difference, of 10^{-8}. This also confirms Proposition 2: when the demand of a single market dominates, the difference between the two models is negligible.

Table E.2: Equilibrium Allocation of Resources under Tree

Arc	**Benchmark Model**	**Full Model**	**Difference**
Panel I: $M_{od} = 1$ for all four markets			
(A_1, B_1)	0.80	0.80	$-4\text{E}-06$
(B_1, B_2)	1.41	1.41	$8\text{E}-06$
(B_2, A_2)	0.80	0.80	$-4\text{E}-06$
(D_1, C_1)	0.80	0.80	$-4\text{E}-06$
(C_1, C_2)	1.41	1.41	$8\text{E}-06$
(C_2, D_2)	0.80	0.80	$-4\text{E}-06$
Panel II: $M_{A_1A_2} = 100, M_{od} = 1$ for all the other markets			
(A_1, B_1)	2.00	2.00	$5\text{E}-08$
(B_1, B_2)	2.01	2.01	$6\text{E}-08$
(B_2, A_2)	2.00	2.00	$5\text{E}-08$
(D_1, C_1)	0.00	0.00	$-6\text{E}-10$
(C_1, C_2)	0.00	0.00	$-2\text{E}-07$
(C_2, D_2)	0.00	0.00	$-6\text{E}-10$

Numerical Simulations: Topology of the Network is Non-Tree

Here I assume that the topology of the network is the same as illustrated in Panel (b) of Figure E.1. Assume that there are three origin–destination markets, $A_1 \to C_1$, $A_2 \to C_1$, and $C_1 \to C_2$. Online appendix F.2 shows the analytical solutions of the optimal strategies of the benchmark model and the full model. Table E.3 compares the results of equilibrium prices and costs between the two models. In Panel I, all three markets have an equal total mass of demand ($M_{od} = 1, \forall od$). In Panel II, the market from A_1 to C_1 dominates, and in Panel III, the market from A_2 to C_1 dominates. We can see that in all scenarios, the difference between the equilibrium prices and costs between the benchmark and the full model is very small.

Table E.3: Equilibrium Prices and Costs under Non-Tree

Market	Prices			Costs		
	Benchmark Model	Full Model	Difference	Benchmark Model	Full Model	Difference
Panel I: $M_{od} = 1$ **for all three markets**						
$A_1 \to C_1$	4.09	4.09	0.00	1.38	1.38	0.00
$A_2 \to C_1$	3.91	3.91	0.00	1.14	1.14	0.00
$C_1 \to C_2$	3.91	3.90	0.01	1.14	1.14	0.00
Panel II: $M_{A_1C_1} = 10, M_{od} = 1$ **for all the other markets**						
$A_1 \to C_1$	3.58	3.58	0.00	0.68	0.68	0.00
$A_2 \to C_1$	5.52	5.51	0.01	3.17	3.16	0.01
$C_1 \to C_2$	4.21	4.21	0.00	1.55	1.55	0.00
Panel II: $M_{A_2C_1} = 10, M_{od} = 1$ **for all the other markets**						
$A_1 \to C_1$	5.52	5.51	0.01	3.17	3.17	0.01
$A_2 \to C_1$	3.58	3.58	0.00	0.68	0.68	0.00
$C_1 \to C_2$	4.21	4.19	0.02	1.55	1.55	0.00

To investigate how routing and allocation decisions change in different cases, Table E.4 shows the optimal allocation decisions I^* and routing decisions $\mathcal{R}$. First, there is no significant difference between the full model and the benchmark model in all cases. Second, we can observe that the routing from C_1 to C_2 is the same when we compare the results in Panel I with those in Panel III. The demand from A_2 to C_1 is higher in Panel III than in Panel I. Therefore, more resources are allotted to (A_2, B_2) and (B_2, C_1). Additionally, since both markets $A_2 \to C_1$ and $C_1 \to C_2$ use (B_2, C_1), allocation to (B_2, C_1) is also bigger than allocation to (A_2, B_2). Third, we can see that the routing from C_1 to C_2 changes when we compare the results in Panel I and II. As a result, allocation in Panel II is substantially higher than in Panel I for (A_1, B_1) and (B_1, C_1).

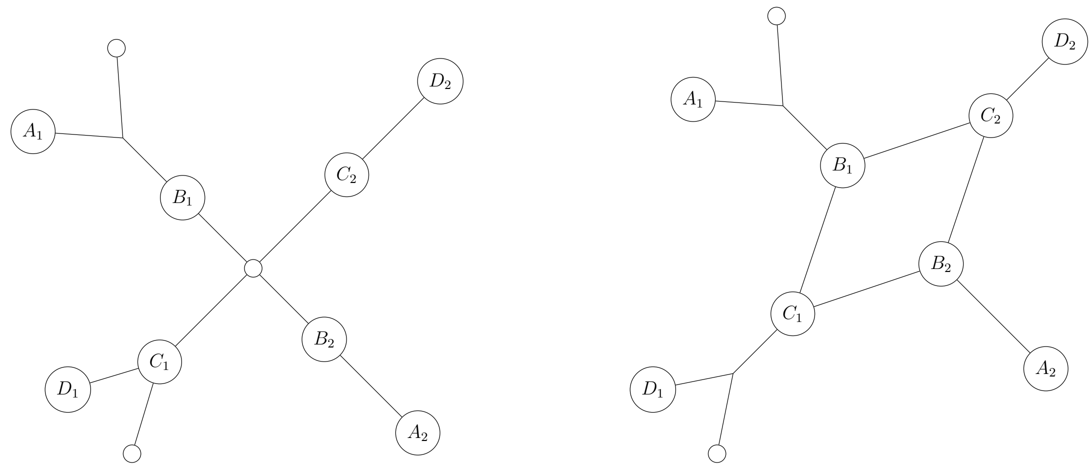
In conclusion, the results of the numerical simulations show that the difference in equilibrium outcomes between the full and benchmark models is minimal, regardless of whether the network topology is a tree or non-tree.

Table E.4: Equilibrium Allocation of Resources under Non-Tree

Arc	**Benchmark Model**	**Full Model**	**Difference**
Panel I: $M_{od} = 1$ **for all three markets**			
(A_1, B_1)	1.45	1.45	5E−05
(B_1, C_1)	1.45	1.45	5E−05
(D_1, C_1)	0.00	0.00	1E−07
(C_1, B_2)	2.11	2.11	−4E−05
(B_2, A_2)	1.49	1.49	1E−03
(B_2, C_2)	1.49	1.50	−1E−03
(C_2, D_2)	0.00	0.00	1E−07
(C_2, B_1)	0.00	0.00	1E−07
Routing of $C_1 \rightarrow C_2$	$C_1 \rightarrow B_2 \rightarrow C_2$		
Panel II: $M_{A_1C_1} = 10, M_{od} = 1$ **for all others**			
(A_1, B_1)	2.90	2.90	2E−03
(B_1, C_1)	3.02	3.02	2E−03
(D_1, C_1)	0.00	0.00	2E−16
(C_1, B_2)	0.63	0.63	−2E−03
(B_2, A_2)	0.63	0.63	−2E−03
(B_2, C_2)	0.00	0.00	2E−16
(C_2, D_2)	0.00	0.00	2E−16
(C_2, B_1)	0.82	0.82	6E−04
Routing of $C_1 \rightarrow C_2$	$C_1 \rightarrow B_1 \rightarrow C_2$		
Panel III: $M_{A_2C_1} = 10, M_{od} = 1$ **for all others**			
(A_1, B_1)	0.63	0.63	−1E−03
(B_1, C_1)	0.63	0.63	−1E−03
(D_1, C_1)	0.00	0.00	2E−16
(C_1, B_2)	3.02	3.01	2E−03
(B_2, A_2)	2.90	2.90	3E−03
(B_2, C_2)	0.82	0.82	−2E−03
(C_2, D_2)	0.00	0.00	2E−16
(C_2, B_1)	0.00	0.00	2E−16
Routing of $C_1 \rightarrow C_2$	$C_1 \rightarrow B_2 \rightarrow C_2$		

F Numerical Example

In the numerical example, I consider the two networks as in Figure E.1:



(a) Tree (b) Non-Tree

Panels (a) and (b) show a tree topologyand a non-tree topology respectively, where B_1 — C_1 — B_2 — C_2 — B_1 forms a loop. There are four shipment services, $A_1 \to A_2$, $B_1 \to B_2$, $C_1 \to C_2$, and $D_1 \to D_2$. Assume logit demand, then the demand for each o–d market is

$$Q_{od} = M_{od} \cdot \frac{\exp(\alpha p)}{1 + \exp(\alpha p)}.$$

Nested Model
Under the nested model, the profit function is

$$\pi := \sum_{od} [p_{od} - c_{od}] \cdot Q_{od}.$$

Therefore the FOC is derived as

$$\begin{aligned}
\frac{\partial \pi}{\partial p_{od}} &= \frac{\partial [p_{od} - c_{od}] \cdot Q_{od}}{\partial p_{od}} \\
&= Q_{od} + (p_{od} - c_{od}) \cdot \frac{\partial Q_{od}}{\partial p_{od}} \\
&= \frac{\exp(\alpha p)}{1 + \exp(\alpha p)} + (p - c) \cdot \frac{\alpha \exp(\alpha p)(1 + \exp(\alpha p)) - \alpha \exp(\alpha p)^2}{(1 + \exp(\alpha p))^2} \\
&= M_{od} \cdot h_{od} + (p - c) \cdot M_{od} \cdot \alpha h_{od}(1 - h_{od}) \\
\Rightarrow p_{od} &= c_{od} - \frac{1}{\alpha(1 - h_{od})}
\end{aligned}$$

where h_{od} is the market share of railroad in market o–d.

Full Model
Under the full model, the profit function is

$$\pi := \sum_{od} p_{od} \cdot Q_{od} - C(\boldsymbol{Q}).$$

The FOC is derived as

$$\frac{\partial \pi}{\partial p_{od}} = Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial C(\boldsymbol{Q}, \boldsymbol{R}, \boldsymbol{I})}{\partial Q_{s,od}} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}}.$$

In our numerical example, for the four markets, the FOCs are derived as

$$\begin{aligned}
& \frac{\partial \pi_{s,A_1A_2}}{p_{s,A_1A_2}} = 0 \\
\Rightarrow \quad & Q_{s,A_1A_2} + p_{s,A_1A_2} \cdot \frac{\partial Q_{s,A_1A_2}}{\partial p_{s,A_1A_2}} - \frac{\partial C(\boldsymbol{Q}, \boldsymbol{R}, \boldsymbol{I})}{\partial Q_{s,A_1A_2}} \cdot \frac{\partial Q_{s,A_1A_2}}{\partial p_{s,A_1A_2}} = 0 \\
\Rightarrow \quad & Q_{s,A_1A_2} + p_{s,A_1A_2} \cdot \frac{\partial Q_{s,A_1A_2}}{\partial p_{s,A_1A_2}} - \frac{\partial Q_{s,A_1A_2}}{\partial p_{s,A_1A_2}} \cdot \left[c_{s,A_1A_2} + \frac{\partial c_{s,A_1A_2}}{\partial Q_{s,A_1A_2}} Q_{s,A_1A_2} \right. \\
& \qquad \left. + \frac{\partial c_{s,B_1B_2}}{\partial Q_{s,A_1A_2}} Q_{s,B_1B_2} + \frac{\partial c_{s,C_1C_2}}{\partial Q_{s,A_1A_2}} Q_{s,C_1C_2} + \frac{\partial c_{s,D_1D_2}}{\partial Q_{s,A_1A_2}} Q_{s,D_1D_2} \right] = 0
\end{aligned}$$

$$\begin{aligned}
& \frac{\partial \pi_{s,B_1B_2}}{p_{s,B_1B_2}} = 0 \\
\Rightarrow \quad & Q_{s,B_1B_2} + p_{s,B_1B_2} \cdot \frac{\partial Q_{s,B_1B_2}}{\partial p_{s,B_1B_2}} - \frac{\partial Q_{s,B_1B_2}}{\partial p_{s,B_1B_2}} \cdot \left[c_{s,B_1B_2} + \frac{\partial c_{s,B_1B_2}}{\partial Q_{s,B_1B_2}} Q_{s,B_1B_2} \right. \\
& \qquad \left. + \frac{\partial c_{s,A_1A_2}}{\partial Q_{s,B_1B_2}} Q_{s,A_1A_2} + \frac{\partial c_{s,C_1C_2}}{\partial Q_{s,B_1B_2}} Q_{s,C_1C_2} + \frac{\partial c_{s,D_1D_2}}{\partial Q_{s,B_1B_2}} Q_{s,D_1D_2} \right] = 0
\end{aligned}$$

$$\begin{aligned}
& \frac{\partial \pi_{s,C_1C_2}}{p_{s,C_1C_2}} = 0 \\
\Rightarrow \quad & Q_{s,C_1C_2} + p_{s,C_1C_2} \cdot \frac{\partial Q_{s,C_1C_2}}{\partial p_{s,C_1C_2}} - \frac{\partial Q_{s,C_1C_2}}{\partial p_{s,C_1C_2}} \cdot \left[c_{s,C_1C_2} + \frac{\partial c_{s,C_1C_2}}{\partial Q_{s,C_1C_2}} Q_{s,C_1C_2} \right. \\
& \qquad \left. + \frac{\partial c_{s,A_1A_2}}{\partial Q_{s,C_1C_2}} Q_{s,A_1A_2} + \frac{\partial c_{s,B_1B_2}}{\partial Q_{s,C_1C_2}} Q_{s,B_1B_2} + \frac{\partial c_{s,D_1D_2}}{\partial Q_{s,C_1C_2}} Q_{s,D_1D_2} \right] = 0
\end{aligned}$$

$$\frac{\partial \pi_{s,D_1D_2}}{p_{s,D_1D_2}} = 0$$

$$\Rightarrow \quad Q_{s,D_1D_2} + p_{s,D_1D_2} \cdot \frac{\partial Q_{s,D_1D_2}}{\partial p_{s,D_1D_2}} - \frac{\partial Q_{s,D_1D_2}}{\partial p_{s,D_1D_2}} \cdot \Bigg[c_{s,D_1D_2} + \frac{\partial c_{s,D_1D_2}}{\partial Q_{s,D_1D_2}} Q_{s,D_1D_2}$$

$$+ \frac{\partial c_{s,A_1A_2}}{\partial Q_{s,D_1D_2}} Q_{s,A_1A_2} + \frac{\partial c_{s,B_1B_2}}{\partial Q_{s,D_1D_2}} Q_{s,B_1B_2} + \frac{\partial c_{s,C_1C_2}}{\partial Q_{s,D_1D_2}} Q_{s,C_1C_2} \Bigg] = 0$$

We know that the per-unit shipment cost is derived as

$$c_{od}(\boldsymbol{I}_j) = \sum_{(a,b)\in\mathcal{R}^*_{j,od}} \frac{\delta_0 Dist_{j,ab}}{I^{\gamma}_{j,ab}}.$$

F.1 Tree

Assume that $\gamma = 1$, $\delta_0 = 1$, and all adjacent nodes have distance 1; the cost function becomes

$$\begin{aligned} c_{A_1A_2} &= \frac{1}{I_{A_1B_1}} + \frac{1}{I_{B_1B_2}} + \frac{1}{I_{B_2A_2}} \\ c_{B_1B_2} &= \frac{1}{I_{B_1B_2}} \\ c_{C_1C_2} &= \frac{1}{I_{C_1C_2}} \\ c_{D_1D_2} &= \frac{1}{I_{D_1C_1}} + \frac{1}{I_{C_1C_2}} + \frac{1}{I_{C_2D_2}}. \end{aligned} \tag{F.1}$$

The optimal allocation is obtained through

$$\begin{aligned} I_{j,ab} &= \left[\frac{\gamma}{\lambda_j} \cdot \delta_0 Dist_{j,ab} \cdot q_{j,ab}\right]^{\frac{1}{1+\gamma}} \\ &= \left[\frac{q_{j,ab}}{\lambda_j}\right]^{\frac{1}{2}} \\ I_{A_1B_1} + I_{B_1B_2} &+ I_{B_2A_2} + I_{D_1C_1} + I_{C_1C_2} + I_{C_2D_2} = K_j. \end{aligned}$$

Assume that $K_j = 6$; then we have

$$\begin{aligned}
I_{A_1B_1} &= \frac{6q_{A_1B_1}^{1/2}}{q_{A_1B_1}^{1/2} + q_{B_1B_2}^{1/2} + q_{B_2A_2}^{1/2} + q_{D_1C_1}^{1/2} + q_{C_1C_2}^{1/2} + q_{C_2D_2}^{1/2}} \\
I_{B_1B_2} &= \frac{6q_{B_1B_2}^{1/2}}{q_{A_1B_1}^{1/2} + q_{B_1B_2}^{1/2} + q_{B_2A_2}^{1/2} + q_{D_1C_1}^{1/2} + q_{C_1C_2}^{1/2} + q_{C_2D_2}^{1/2}} \\
I_{B_2A_2} &= \frac{6q_{B_2A_2}^{1/2}}{q_{A_1B_1}^{1/2} + q_{B_1B_2}^{1/2} + q_{B_2A_2}^{1/2} + q_{D_1C_1}^{1/2} + q_{C_1C_2}^{1/2} + q_{C_2D_2}^{1/2}} \\
I_{D_1C_1} &= \frac{6q_{D_1C_1}^{1/2}}{q_{A_1B_1}^{1/2} + q_{B_1B_2}^{1/2} + q_{B_2A_2}^{1/2} + q_{D_1C_1}^{1/2} + q_{C_1C_2}^{1/2} + q_{C_2D_2}^{1/2}} \\
I_{C_1C_2} &= \frac{6q_{C_1C_2}^{1/2}}{q_{A_1B_1}^{1/2} + q_{B_1B_2}^{1/2} + q_{B_2A_2}^{1/2} + q_{D_1C_1}^{1/2} + q_{C_1C_2}^{1/2} + q_{C_2D_2}^{1/2}} \\
I_{C_2D_2} &= \frac{6q_{C_2D_2}^{1/2}}{q_{A_1B_1}^{1/2} + q_{B_1B_2}^{1/2} + q_{B_2A_2}^{1/2} + q_{D_1C_1}^{1/2} + q_{C_1C_2}^{1/2} + q_{C_2D_2}^{1/2}}.
\end{aligned} \tag{F.2}$$

Based on routing options, we know that

$$\begin{aligned}
q_{A_1B_1} &= Q_{A_1A_2} \\
q_{B_1B_2} &= Q_{A_1A_2} + Q_{B_1B_2} \\
q_{B_2A_2} &= Q_{A_1A_2} \\
q_{D_1C_1} &= Q_{D_1D_2} \\
q_{C_1C_2} &= Q_{D_1D_2} + Q_{C_1C_2} \\
q_{C_2D_2} &= Q_{D_1D_2}.
\end{aligned} \tag{F.3}$$

Substitute F.3 into F.2, we will then get

$$
\begin{aligned}
I_{A_1B_1} &= \frac{6Q_{A_1A_2}^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}} \\
I_{B_1B_2} &= \frac{6(Q_{A_1A_2} + Q_{B_1B_2})^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}} \\
I_{B_2A_2} &= \frac{6Q_{A_1A_2}^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}} \\
I_{D_1C_1} &= \frac{6Q_{D_1D_2}^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}} \\
I_{C_1C_2} &= \frac{6(Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}} \\
I_{C_2D_2} &= \frac{6Q_{D_1D_2}^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}.
\end{aligned}
$$

Then substitute the optimal allocation of infrastructure into F.1, we have

$$
\begin{aligned}
c_{A_1A_2} &= \frac{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}{3Q_{A_1A_2}^{1/2}} \\
&\quad + \frac{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}{6(Q_{A_1A_2} + Q_{B_1B_2})^{1/2}} \\
c_{B_1B_2} &= \frac{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}{6(Q_{A_1A_2} + Q_{B_1B_2})^{1/2}} \\
c_{C_1C_2} &= \frac{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}{6(Q_{D_1D_2} + Q_{C_1C_2})^{1/2}} \\
c_{D_1D_2} &= \frac{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}{3Q_{D_1D_2}^{1/2}} \\
&\quad + \frac{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}{6(Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}.
\end{aligned}
$$

Given the cost functions, we can derive the FOCs:

$$
\begin{aligned}
\frac{\partial c_{A_1A_2}}{\partial Q_{A_1A_2}} &= \frac{-2Q^2_{B_1B_2} - \left[2(Q_{A_1A_2}+Q_{B_1B_2})^{3/2} + Q^{3/2}_{A_1A_2}\right]\left[2Q^{1/2}_{D_1D_2} + (Q_{D_1D_2}+Q_{C_1C_2})^{1/2}\right]}{12Q^{3/2}_{A_1A_2}(Q_{A_1A_2}+Q_{B_1B_2})^{3/2}} \\
\frac{\partial c_{B_1B_2}}{\partial Q_{A_1A_2}} &= \frac{2Q_{B_1B_2} - Q^{1/2}_{A_1A_2}\left[2Q^{1/2}_{D_1D_2} + (Q_{D_1D_2}+Q_{C_1C_2})^{1/2}\right]}{12Q^{1/2}_{A_1A_2}(Q_{A_1A_2}+Q_{B_1B_2})^{3/2}} \\
\frac{\partial c_{C_1C_2}}{\partial Q_{A_1A_2}} &= \frac{2Q^{-1/2}_{A_1A_2} + (Q_{A_1A_2}+Q_{B_1B_2})^{-1/2}}{12(Q_{D_1D_2}+Q_{C_1C_2})^{1/2}} \\
\frac{\partial c_{D_1D_2}}{\partial Q_{A_1A_2}} &= \frac{2Q^{-1/2}_{A_1A_2} + (Q_{A_1A_2}+Q_{B_1B_2})^{-1/2}}{6Q^{1/2}_{D_1D_2}} + \frac{2Q^{-1/2}_{A_1A_2} + (Q_{A_1A_2}+Q_{B_1B_2})^{-1/2}}{12(Q_{D_1D_2}+Q_{C_1C_2})^{1/2}}.
\end{aligned}
\tag{F.4}
$$

Similarly, the FOCs w.r.t. $Q_{B_1B_2}$ are derived as

$$
\begin{aligned}
\frac{\partial c_{A_1A_2}}{\partial Q_{B_1B_2}} &= \frac{2Q_{B_1B_2} - Q^{1/2}_{A_1A_2}\left[2Q^{1/2}_{D_1D_2} + (Q_{D_1D_2}+Q_{C_1C_2})^{1/2}\right]}{12Q^{1/2}_{A_1A_2}(Q_{A_1A_2}+Q_{B_1B_2})^{3/2}} \\
\frac{\partial c_{B_1B_2}}{\partial Q_{B_1B_2}} &= \frac{-\left[2Q^{1/2}_{A_1A_2} + 2Q^{1/2}_{D_1D_2} + (Q_{D_1D_2}+Q_{C_1C_2})^{1/2}\right]}{12(Q_{A_1A_2}+Q_{B_1B_2})^{3/2}} \\
\frac{\partial c_{C_1C_2}}{\partial Q_{B_1B_2}} &= \frac{(Q_{A_1A_2}+Q_{B_1B_2})^{-1/2}}{12(Q_{D_1D_2}+Q_{C_1C_2})^{1/2}} \\
\frac{\partial c_{D_1D_2}}{\partial Q_{B_1B_2}} &= \frac{(Q_{A_1A_2}+Q_{B_1B_2})^{-1/2}}{6Q^{1/2}_{D_1D_2}} + \frac{(Q_{A_1A_2}+Q_{B_1B_2})^{-1/2}}{12(Q_{D_1D_2}+Q_{C_1C_2})^{1/2}}.
\end{aligned}
$$

The FOCs w.r.t. $Q_{C_1C_2}$ are derived as

$$
\begin{aligned}
\frac{\partial c_{A_1A_2}}{\partial Q_{C_1C_2}} &= \frac{(Q_{D_1D_2}+Q_{C_1C_2})^{-1/2}}{6Q^{1/2}_{A_1A_2}} + \frac{(Q_{D_1D_2}+Q_{C_1C_2})^{-1/2}}{12(Q_{A_1A_2}+Q_{B_1B_2})^{1/2}} \\
\frac{\partial c_{B_1B_2}}{\partial Q_{C_1C_2}} &= \frac{(Q_{D_1D_2}+Q_{C_1C_2})^{-1/2}}{12(Q_{A_1A_2}+Q_{B_1B_2})^{1/2}} \\
\frac{\partial c_{C_1C_2}}{\partial Q_{C_1C_2}} &= \frac{-\left[2Q^{1/2}_{A_1A_2} + 2Q^{1/2}_{D_1D_2} + (Q_{A_1A_2}+Q_{B_1B_2})^{1/2}\right]}{12(Q_{D_1D_2}+Q_{C_1C_2})^{3/2}} \\
\frac{\partial c_{D_1D_2}}{\partial Q_{C_1C_2}} &= \frac{2Q_{C_1C_2} - Q^{1/2}_{D_1D_2}\left[2Q^{1/2}_{A_1A_2} + (Q_{A_1A_2}+Q_{B_1B_2})^{1/2}\right]}{12Q^{1/2}_{D_1D_2}(Q_{D_1D_2}+Q_{C_1C_2})^{3/2}}.
\end{aligned}
$$

The FOCs w.r.t. $Q_{D_1D_2}$ are derived as

$$\frac{\partial c_{A_1A_2}}{\partial Q_{D_1D_2}} = \frac{2Q_{D_1D_2}^{-1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{-1/2}}{6Q_{A_1A_2}^{1/2}} + \frac{2Q_{D_1D_2}^{-1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{-1/2}}{12(Q_{A_1A_2} + Q_{B_1B_2})^{1/2}}$$

$$\frac{\partial c_{B_1B_2}}{\partial Q_{D_1D_2}} = \frac{2Q_{D_1D_2}^{-1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{-1/2}}{12(Q_{A_1A_2} + Q_{B_1B_2})^{1/2}}$$

$$\frac{\partial c_{C_1C_2}}{\partial Q_{D_1D_2}} = \frac{2Q_{C_1C_2} - Q_{D_1D_2}^{1/2}\left[2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2}\right]}{12Q_{D_1D_2}^{1/2}(Q_{D_1D_2} + Q_{C_1C_2})^{3/2}}$$

$$\frac{\partial c_{D_1D_2}}{\partial Q_{D_1D_2}} = \frac{-2Q_{C_1C_2}^2 - \left[Q_{D_1D_2}^{3/2} + 2(Q_{D_1D_2} + Q_{C_1C_2})^{3/2}\right]\left[2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2}\right]}{12Q_{D_1D_2}^{3/2}(Q_{D_1D_2} + Q_{C_1C_2})^{3/2}}.$$

F.2 Non-Tree

Assume that $\gamma = 1$, $\delta_0 = 1$, and all adjacent nodes have distance 1; the cost function becomes

$$\begin{aligned} c_{A_1C_1} &= \frac{1}{I_{A_1B_1}} + \frac{1}{I_{B_1C_1}} \\ c_{A_2C_1} &= \frac{1}{I_{A_2B_2}} + \frac{1}{I_{B_2C_1}} \\ c_{C_1C_2} &= \begin{cases} \frac{1}{I_{B_1C_1}} + \frac{1}{I_{B_1C_2}} & \text{if } C_1 \to B_1 \to C_2 \\ \frac{1}{I_{B_2C_1}} + \frac{1}{I_{B_2C_2}} & \text{if } C_1 \to B_2 \to C_2. \end{cases} \end{aligned} \tag{F.5}$$

The optimal allocation is obtained through

$$\begin{aligned} I_{j,ab} &= \left[\frac{\gamma}{\lambda_j} \cdot \delta_0 Dist_{j,ab} \cdot q_{j,ab}\right]^{\frac{1}{1+\gamma}} \\ &= \left[\frac{q_{j,ab}}{\lambda_j}\right]^{\frac{1}{2}} \end{aligned}$$
$$I_{A_1B_1} + I_{B_1C_1} + I_{C_1D_1} + I_{C_1B_2} + I_{B_2A_2} + I_{B_2C_2} + I_{C_2D_2} + I_{C_2B_1} = K_j.$$

Assume that $K_j = 8$; then we have

$$I_{ab} = \frac{8q_{ab}^{1/2}}{q_{A_1B_1}^{1/2} + q_{B_1C_1}^{1/2} + q_{C_1D_1}^{1/2} + q_{C_1B_2}^{1/2} + q_{B_2A_2}^{1/2} + q_{B_2C_2}^{1/2} + +q_{C_2D_2}^{1/2} + q_{C_2B_1}^{1/2}}. \tag{F.6}$$

Based on routing options, we know that

- If $C_1 \to B_1 \to C_2$

$$
\begin{aligned}
q_{A_1B_1} &= Q_{A_1C_1}, \quad q_{B_1C_1} = Q_{A_1C_1} + Q_{C_1C_2} \\
q_{C_1D_1} &= 0, \quad q_{C_1B_2} = Q_{A_2C_1} \\
q_{B_2A_2} &= Q_{A_2C_1} \\
q_{B_2C_2} &= 0, \quad q_{C_2D_2} = 0 \\
q_{C_2B_1} &= Q_{C_1C_2}
\end{aligned}
$$

- If $C_1 \to B_2 \to C_2$

$$
\begin{aligned}
q_{A_1B_1} &= Q_{A_1C_1} \\
q_{B_1C_1} &= Q_{A_1C_1} \\
q_{C_1D_1} &= 0 \\
q_{C_1B_2} &= Q_{A_2C_1} + Q_{C_1C_2} \\
q_{B_2A_2} &= Q_{A_2C_1} \\
q_{B_2C_2} &= Q_{C_1C_2} \\
q_{C_2D_2} &= 0 \\
q_{C_2B_1} &= 0
\end{aligned}
$$

Substitute the quantities into F.6, we will then get

- If $C_1 \to B_1 \to C_2$

$$
\begin{aligned}
I_{A_1B_1} &= \frac{8Q_{A_1C_1}^{1/2}}{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{B_1C_1} &= \frac{8(Q_{A_1C_1} + Q_{C_1C_2})^{1/2}}{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{C_1D_1} &= 0 \\
I_{C_1B_2} &= \frac{8Q_{A_2C_1}^{1/2}}{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{B_2A_2} &= \frac{8Q_{A_2C_1}^{1/2}}{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{B_2C_2} &= 0 \\
I_{C_2D_2} &= 0 \\
I_{C_2B_1} &= \frac{8Q_{C_1C_2}^{1/2}}{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}
\end{aligned}
$$

- If $C_1 \to B_2 \to C_2$

$$
\begin{aligned}
I_{A_1B_1} &= \frac{8Q_{A_1C_1}^{1/2}}{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{B_1C_1} &= \frac{8Q_{A_1C_1}^{1/2}}{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{C_1D_1} &= 0 \\
I_{C_1B_2} &= \frac{8(Q_{A_2C_1} + Q_{C_1C_2})^{1/2}}{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{B_2A_2} &= \frac{8Q_{A_2C_1}^{1/2}}{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{B_2C_2} &= \frac{8Q_{C_1C_2}^{1/2}}{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}} \\
I_{C_2D_2} &= 0 \\
I_{C_2B_1} &= 0
\end{aligned}
$$

Then substitute the optimal allocation of infrastructure into F.5; we have

- If $C_1 \to B_1 \to C_2$

$$
\begin{aligned}
c_{A_1C_1} &= \frac{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{8Q_{A_1C_1}^{1/2}} \\
&\quad + \frac{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{8(Q_{A_1C_1} + Q_{C_1C_2})^{1/2}} \\
c_{A_2C_1} &= \frac{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{4Q_{A_2C_1}^{1/2}} \\
c_{C_1C_2} &= \frac{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{8(Q_{A_1C_1} + Q_{C_1C_2})^{1/2}} \\
&\quad + \frac{Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{8Q_{C_1C_2}^{1/2}}
\end{aligned}
$$

- If $C_1 \to B_2 \to C_2$

$$\begin{aligned}
c_{A_1C_1} &= \frac{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{4Q_{A_1C_1}^{1/2}} \\
c_{A_2C_1} &= \frac{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{8Q_{A_2C_1}^{1/2}} \\
&\quad + \frac{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{8(Q_{A_2C_1} + Q_{C_1C_2})^{1/2}} \\
c_{C_1C_2} &= \frac{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{8(Q_{A_2C_1} + Q_{C_1C_2})^{1/2}} \\
&\quad + \frac{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{8Q_{C_1C_2}^{1/2}}
\end{aligned}$$

Given the cost functions, we can derive the FOCs:

- If $C_1 \to B_1 \to C_2$

$$\begin{aligned}
\frac{\partial c_{A_1C_1}}{\partial Q_{A_1C_1}} &= \frac{-Q_{C_1C_2}^2 - \left[Q_{A_1C_1}^{3/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{3/2}\right](2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2})}{16Q_{A_1C_1}^{3/2}(Q_{A_1C_1} + Q_{C_1C_2})^{3/2}} \\
\frac{\partial c_{A_2C_1}}{\partial Q_{A_1C_1}} &= \frac{Q_{A_1C_1}^{-1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{-1/2}}{8Q_{A_2C_1}^{1/2}} \\
\frac{\partial c_{C_1C_2}}{\partial Q_{A_1C_1}} &= \frac{Q_{A_1C_1}^{-1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{-1/2}}{16Q_{C_1C_2}^{1/2}} + \frac{Q_{A_1C_1}^{-1/2}(Q_{A_1C_1} + Q_{C_1C_2}) - (Q_{A_1C_1}^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2})}{16(Q_{A_1C_1} + Q_{C_1C_2})^{3/2}}
\end{aligned}$$

Similarly, the FOCs w.r.t. $Q_{A_2C_1}$ are derived as

$$\begin{aligned}
\frac{\partial c_{A_1C_1}}{\partial Q_{A_2C_1}} &= \frac{Q_{A_2C_1}^{-1/2}}{8Q_{A_1C_1}^{1/2}} + \frac{Q_{A_2C_1}^{-1/2}}{8(Q_{A_1C_1} + Q_{C_1C_2})^{1/2}} \\
\frac{\partial c_{A_2C_1}}{\partial Q_{A_2C_1}} &= \frac{-\left[Q_{A_1C_1}^{1/2} + (Q_{A_1C_1} + Q_{C_1C_2})^{1/2} + Q_{C_1C_2}^{1/2}\right]}{8Q_{A_2C_1}^{3/2}} \\
\frac{\partial c_{C_1C_2}}{\partial Q_{A_2C_1}} &= \frac{Q_{A_2C_1}^{-1/2}}{8(Q_{A_1C_1} + Q_{C_1C_2})^{1/2}} + \frac{Q_{A_2C_1}^{-1/2}}{8Q_{C_1C_2}^{1/2}}.
\end{aligned}$$

The FOCs w.r.t. $Q_{C_1C_2}$ are derived as

$$\frac{\partial c_{A_1C_1}}{\partial Q_{C_1C_2}} = \frac{(Q_{A_1C_1} + Q_{C_1C_2})^{-1/2} + Q_{C_1C_2}^{-1/2}}{16Q_{A_1C_1}^{1/2}} + \frac{Q_{C_1C_2}^{-1/2}(Q_{A_1C_1} + Q_{C_1C_2}) - \left[Q_{A_1C_1}^{1/2} + 2Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}\right]}{16(Q_{A_1C_1} + Q_{C_1C_2})^{3/2}}$$

$$
\begin{aligned}
\frac{\partial c_{A_2C_1}}{\partial Q_{C_1C_2}} &= \frac{(Q_{A_1C_1}+Q_{C_1C_2})^{-1/2}+Q_{C_1C_2}^{-1/2}}{8Q_{A_2C_1}^{1/2}} \\
\frac{\partial c_{C_1C_2}}{\partial Q_{C_1C_2}} &= \frac{-Q_{A_1C_1}^2-\left[Q_{C_1C_2}^{3/2}+(Q_{A_1C_1}+Q_{C_1C_2})^{3/2}\right](2Q_{A_2C_1}^{1/2}+Q_{A_1C_1}^{1/2})}{16Q_{C_1C_2}^{3/2}(Q_{A_1C_1}+Q_{C_1C_2})^{3/2}}
\end{aligned}
$$

- If $C_1 \to B_2 \to C_2$

$$
\begin{aligned}
\frac{\partial c_{A_1C_1}}{\partial Q_{A_1C_1}} &= \frac{-\left[(Q_{A_2C_1}+Q_{C_1C_2})^{1/2}+Q_{A_2C_1}^{1/2}+Q_{C_1C_2}^{1/2}\right]}{8Q_{A_1C_1}^{3/2}} \\
\frac{\partial c_{A_2C_1}}{\partial Q_{A_1C_1}} &= \frac{Q_{A_1C_1}^{-1/2}}{8Q_{A_2C_1}^{1/2}}+\frac{Q_{A_1C_1}^{-1/2}}{8(Q_{A_2C_1}+Q_{C_1C_2})^{1/2}}
\end{aligned}
$$

$$
\frac{\partial c_{C_1C_2}}{\partial Q_{A_1C_1}} = \frac{Q_{A_1C_1}^{-1/2}}{8(Q_{A_2C_1}+Q_{C_1C_2})^{1/2}}+\frac{Q_{A_1C_1}^{-1/2}}{8Q_{C_1C_2}^{1/2}}
$$

Similarly, the FOCs w.r.t. $Q_{A_2C_1}$ are derived as

$$
\begin{aligned}
\frac{\partial c_{A_1C_1}}{\partial Q_{A_2C_1}} &= \frac{(Q_{A_2C_1}+Q_{C_1C_2})^{-1/2}+Q_{A_2C_1}^{-1/2}}{8Q_{A_1C_1}^{1/2}} \\
\frac{\partial c_{A_2C_1}}{\partial Q_{A_2C_1}} &= \frac{-Q_{C_1C_2}^2-\left[Q_{A_2C_1}^{3/2}+(Q_{A_2C_1}+Q_{C_1C_2})^{3/2}\right](2Q_{A_1C_1}^{1/2}+Q_{C_1C_2}^{1/2})}{16Q_{A_2C_1}^{3/2}(Q_{A_2C_1}+Q_{C_1C_2})^{3/2}} \\
\frac{\partial c_{C_1C_2}}{\partial Q_{A_2C_1}} &= \frac{Q_{A_2C_1}^{-1/2}(Q_{A_2C_1}+Q_{C_1C_2})-(2Q_{A_1C_1}^{1/2}+Q_{A_2C_1}^{1/2}+Q_{C_1C_2}^{1/2})}{16(Q_{A_2C_1}+Q_{C_1C_2})^{3/2}}+\frac{(Q_{A_2C_1}+Q_{C_1C_2})^{-1/2}+Q_{A_2C_1}^{-1/2}}{16Q_{C_1C_2}^{1/2}}.
\end{aligned}
$$

The FOCs w.r.t. $Q_{C_1C_2}$ are derived as

$$
\begin{aligned}
\frac{\partial c_{A_1C_1}}{\partial Q_{C_1C_2}} &= \frac{(Q_{A_2C_1}+Q_{C_1C_2})^{-1/2}+Q_{C_1C_2}^{-1/2}}{8Q_{A_1C_1}^{1/2}} \\
\frac{\partial c_{A_2C_1}}{\partial Q_{C_1C_2}} &= \frac{(Q_{A_2C_1}+Q_{C_1C_2})^{-1/2}+Q_{C_1C_2}^{-1/2}}{16Q_{A_2C_1}^{1/2}}+\frac{Q_{C_1C_2}^{-1/2}(Q_{A_2C_1}+Q_{C_1C_2})-(2Q_{A_1C_1}^{1/2}+Q_{A_2C_1}^{1/2}+Q_{C_1C_2}^{1/2})}{16(Q_{A_2C_1}+Q_{C_1C_2})^{3/2}} \\
\frac{\partial c_{C_1C_2}}{\partial Q_{C_1C_2}} &= \frac{-Q_{A_2C_1}^2-\left[Q_{C_1C_2}^{3/2}+(Q_{A_2C_1}+Q_{C_1C_2})^{3/2}\right](2Q_{A_1C_1}^{1/2}+Q_{A_2C_1}^{1/2})}{16Q_{C_1C_2}^{3/2}(Q_{A_2C_1}+Q_{C_1C_2})^{3/2}}.
\end{aligned}
$$

G Counterfactual Results

Table G.1 shows the full regression results of merger gains on changes in network centrality.

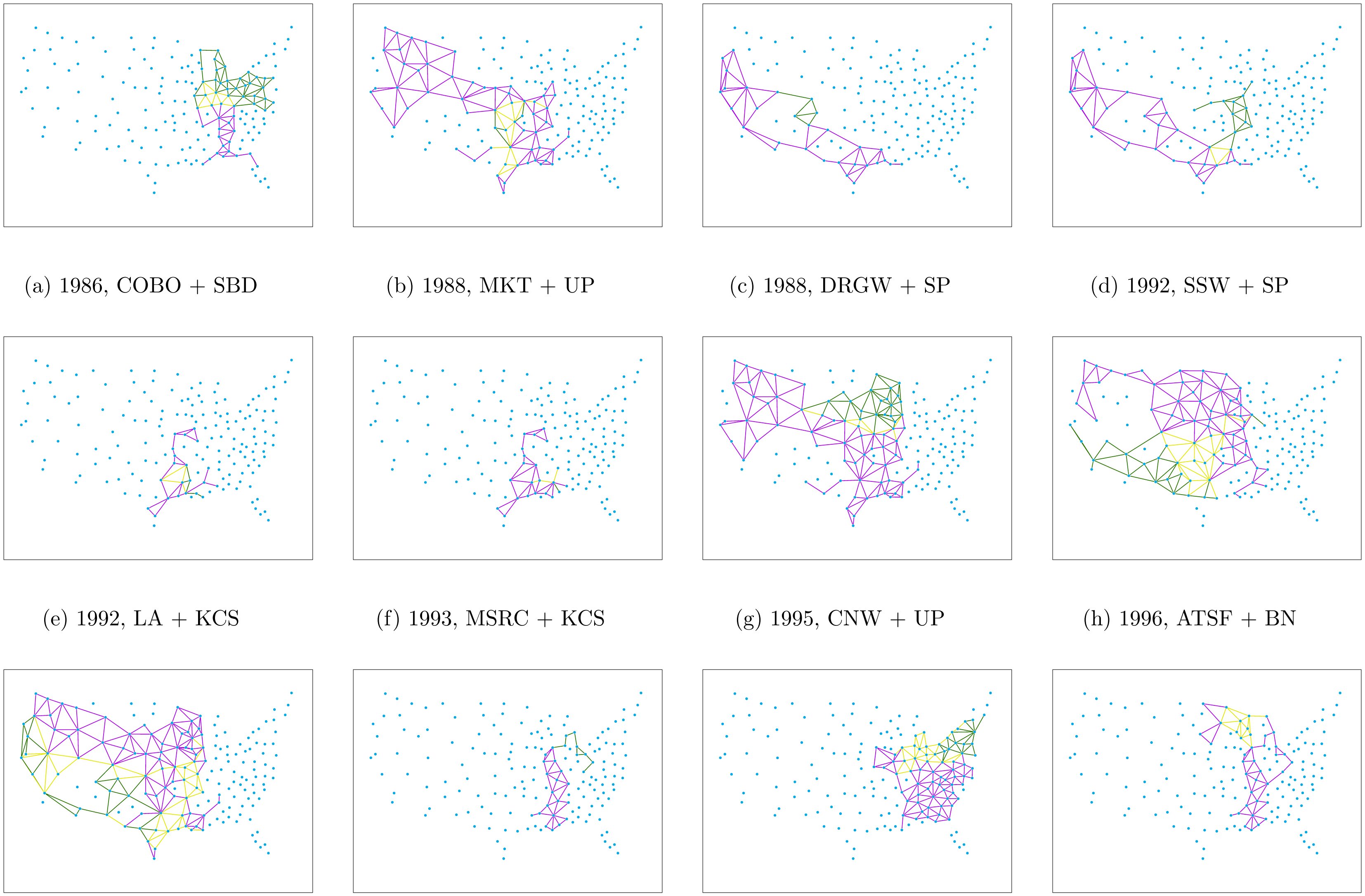
Table G.1: Merger Gains and Centralities (Regression Results)

	Baseline	Unpacking the Black Box		
	(1) Distance + Interchange Cost + Economies of Scope	(2) Distance	(3) Distance + Interchange Cost	(4) Distance + Economies of Scope
Panel I: $\Delta \log(\text{Price})$				
Δ Degree Centrality	−0.0076***	−0.0112***	−0.0108***	−0.0095***
	(0.0010)	(0.0005)	(0.0006)	(0.0009)
Δ Betweenness Centrality	−0.000154***	−0.000092***	−0.000098***	−0.000140***
	(0.000010)	(0.000007)	(0.000008)	(0.000009)
Indicator of Interchange	−0.3946***	−0.0572***	−0.2816***	−0.0481***
	(0.0033)	(0.0016)	(0.0019)	(0.0030)
Panel II: $\Delta \log(\text{Cost})$				
Δ Degree Centrality	−0.0053***	−0.0100***	−0.0097***	−0.0078***
	(0.0011)	(0.0005)	(0.0006)	(0.0010)
Δ Betweenness Centrality	−0.000190***	−0.000098***	−0.000105***	−0.000174***
	(0.000011)	(0.000008)	(0.000009)	(0.000010)
Indicator of Interchange	−0.4354***	−0.0621***	−0.2990***	−0.0581***
	(0.003385)	(0.001725)	(0.001997)	(0.003046)
Panel III: Δ log(Markup)				
Δ Degree Centrality	0.0010***	0.0001***	0.0001***	0.0011***
	(0.0003)	(0.0000)	(0.0000)	(0.0002)
Δ Betweenness Centrality	0.000043***	0.000002***	0.000002***	0.000044***
	(0.000003)	(0.000000)	(0.000000)	(0.000003)
Indicator of Interchange	0.0125***	0.0002***	0.0003***	0.0100***
	(0.0009)	(0.0001)	(0.0001)	(0.0008)

Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Figure G.1: Networks for Each Merger Case

Note: Figure G.1 shows the networks of the two merging parties in each merger case between Class I railroads from 1985 to 2005. There were 12 mergers in total. Within each merger (firm1 + firm2), the network of firm1 is marked in green, that of firm2 is marked in purple, and the overlapping part is marked in yellow. For example, in panel (a) the network solely owned by COBO before the merger is marked in green, the network solely owned by SBD is marked in purple, and the overlapping region is marked in yellow.



(a) 1986, COBO + SBD

(b) 1988, MKT + UP

(c) 1988, DRGW + SP

(d) 1992, SSW + SP

(e) 1992, LA + KCS

(f) 1993, MSRC + KCS

(g) 1995, CNW + UP

(h) 1996, ATSF + BN

(i) 1996, SP + UP

(j) 1998, CN + IC

(k) 1999, CR + NS

(l) 2004, WC + CN