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

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Abstract

In this paper, I study merger gains in a network-based industry and explore how network structure alters such efficiency gains. I build an optimal transport network model that considers imperfect network competition. Each firm owns a separate network, and locations in each network are arranged on a graph such that goods can only be shipped through connected locations. The model endogenizes the firm's pricing, routing, and maintenance allocation decisions. Using detailed waybill data on U.S. freight railroads, I document novel facts about merger gains; I then flexibly estimate the model. I use this setup to demonstrate (i) that reducing the number of firms in local markets is not the main reason behind increased markup post merger and (ii) the heterogeneity of merger gains and their relationship to network structure. These mechanisms reveal a new role for network structure in understanding merger gains of horizontal mergers that was previously concealed by looking only at individual market-level changes.

Keywords: Cost Efficiency, Transport Network, Network Competition, Horizontal Mergers

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1 Introduction

Following mergers and consolidations over the past thirty years, a small number of firms have gained a substantial market share in a range of sectors in the United States. For example, in the airline industry, a wave of consolidation happened during a short period in the late 1980s; in telecommunications, over six thousand acquisitions occurred between 1996 and 2006. However, an open question remains: are the efficiency gains of mergers small, large, or absent? In theory, a merger gives the combined firm greater market power, hence the ability to increase prices. But it may also generate efficiencies, reducing marginal costs and giving the combined firm an opportunity to lower prices. This trade-off has provided the economic framework for the antitrust analysis of horizontal mergers. Yet there is very little direct empirical evidence for efficiency gains of mergers, in particular whether they offset the incentive to raise prices. This is largely because it is difficult to measure and quantify whether mergers lower the marginal cost of production of the combined firm. Two valuable exceptions are Ashenfelter, Hosken and Weinberg (2015), in which the authors exploit panel scanner data and geographic variation to show efficiency gains in the U.S. beer industry, and Jeziorski (2014) who estimates the cost savings resulting from mergers in the U.S. radio industry through merger simulations. 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 aims to fill the gap in understanding efficiency gains in a network industry and to explore how network structure alters such merger gains.

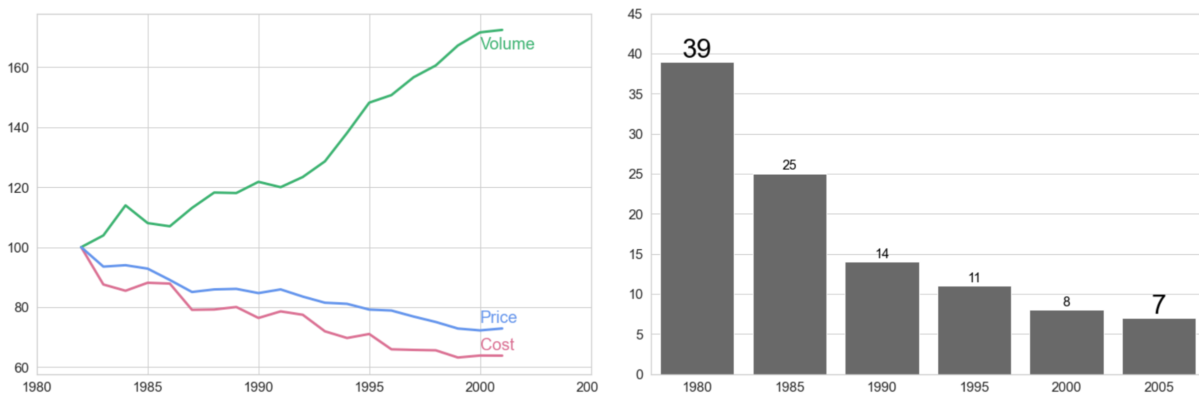
In a network, locations are arranged on a graph, and goods can only be shipped through connected locations. Transport costs depend on how much is invested in infrastructure such as the quality of the road, giving rise to an optimal transport problem in general equilibrium. Solving this problem is challenging for two reasons: dimensionality, because the space of all networks is large; and interactions, because an investment in one link affects routing decisions, hence impacting the returns to investments across the network. In tackling this challenging problem, I build upon the recent progress made by the literature that analyzes endogenous or optimal transport networks in economic models. I offer a twist to this literature by considering competing companies under imperfect competition. The current literature on optimal transport network either consider 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, Kalouptsidi and Papageorgiou (2020). Instead, my paper focuses on competing railroad companies that each solve an optimal network problem to minimize operation costs, while allowing for markups under oligopolistic competition.

The model I propose provides a new way to look at network competition. There are generally two ways of introducing a network into the conventional competition models. First, as in Aguirregabiria and Ho (2012), an airline's network is the set of city pairs that the airline connects via non-stop flights. Fixed and entry costs of providing new city-pair flights depend on the number of other non-stop connections the airline has in the two cities. This cost structure introduces hub size effects hence affect the adoption of hub-and-spoke networks. Second, as in Holmes (2011), the distribution cost of a Wal-Mart store is proportional to the distance between the store and the nearest distribution center. Therefore, this cost structure generates economies of density and endogenously determines the network formation decision, i.e. how many stores and distribution centers to have. Roughly speaking in both methods, what matters most regarding network effect is the total number of markets that each firm serves. My model differs from those approaches by considering the exact location of each market on a graph. Because goods can only be shipped through connected locations, the volume of shipment for each origin–destination market further affects how much is invested in infrastructure hence the efficiency of infrastructure that connects each market. This feature enables me to introduce both heterogeneity and interconnection of markets into the model. By doing that, we can generate much richer welfare implications, especially how network structure affects merger gains.

I apply the proposed model in the context of U.S. freight railroads, since these provide a good opportunity to study merger efficiency in a network-based industry. 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 change in the studied period, the price reduction indicates that there might be efficiency gains following these railroad mergers. The combined firm can abandon redundant rail lines that serve the same origin–destination market and eliminate interchange costs where before the merger, railcars would have needed to be switched between railroad companies. At the network level, the combined firm can consolidate traffic and choose shorter efficiency-weighted routes that were previously unavailable. In recent years, the U.S. government has

[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.

called for greater scrutiny of mergers, and the freight railroad sector is one of the main targets. Meanwhile, in 2021 the Canadian Pacific Railway and the Kansas City Southern Railway proposed a multi-billion-dollar merger. Therefore, in the particular context of this industry, it is important to understand whether railroad mergers result in efficiency gains and the key factors that impact merger effects.



(a) Shipment Price, Cost, and Volume

(b) Number of Class I Railroads

Figure 1: U.S. Freight Railroads

I begin my analysis by using detailed shipment data on 12 million waybills to quantify the efficiency gains of mergers. Railroad companies apply point-on-point pricing, and the waybill data contain price information at firm–origin–destination level. After controlling for observable characteristics and a rich set of fixed effects, I find that shipment prices have decreased by 9% post merger on average. I then open up the merger cases and examine the price effects for different route types. For routes where railroad companies exchanged railcars before the merger, the price effect of mergers is 11%. For other types of routes, the price effect is only 6%. The results suggest that merger efficiency gains vary by route type, eliminating railcar interchange costs being an important source of cost efficiency. One concern regarding these price effects is that they might be driven by competition from other transportation modes rather than mergers. I address this concern by showing that these price changes were much greater for commodities mostly transported by rail, such as coal, than for commodities significantly transported by other modes, such as food and kindred products. These results suggest that price effects are not driven by extrinsic competition.

I next construct and estimate an optimal transport network model with oligopolistic competition. One challenge in quantifying merger effects in the freight railroad industry is that origin–destination markets in a railroad network are interdependent. The shipment cost from an origin to a destination depends on the routing and maintenance allocation decision, which depends in turn on the location and demand of other markets in the railroad network. Therefore, looking only at changes at the individual route level is insufficient for understanding mergers in this industry. To capture this important interconnection feature, I propose an optimal transport network model by endogenizing the firm's pricing, routing, and maintenance allocation decisions. The full model of solving all the decisions simultaneously is computationally burdensome, and one key methodological innovation of this paper is to impose a nested structure on the model. In the nested model, firms first make routing and maintenance decisions to minimize operational costs and then compete in prices in each local market; I exploit the fact that the subproblem of choosing optimal routing is an optimal flow problem on a network, a well-understood problem in the operations research and optimal transport literature. I prove that when there is no economy of scope, or if the demand of a single market dominates, the nested model is equivalent to the full model. In other scenarios, I perform numerical simulations to show that the difference in the equilibrium outcomes between the two models is minimal. I then estimate the model using observed post-merger changes in the data.

I conduct two main counterfactual experiments using the estimated model. First, I calculate the average merger gains among Class I railroads from 1985 to 2005. For each merger, I simulate the equilibrium outcomes before and after. 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%. I further investigate the main driving forces of such changes and find that the economies of scope and eliminating interchange costs both contribute to cost reduction post merger. However, reducing the number of firms in local markets is not the main reason behind increased markup post merger. Instead, the increased markup is mainly driven by the strategic reaction of non-merging firms, which tend to move resources away from regions where the merged firm experiences a large efficiency gain because of changes in the marginal productivity of capital. This results in further increases in the merged firm's local market share and hence a larger increase in markup in those areas. This result confirms that looking only at changes at the individual route level is insufficient for understanding mergers in this industry.

Next, I demonstrate the heterogeneity of merger gains and clarify their relationship to network structure. I show that a node at the 95th percentile of changes in degree centrality 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. By comparison, a node at the 95th percentile of changes in betweenness centrality 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. To unpack the "black box" as to why the topology of the network is related to the level of merger gains, I examine how the measure of network centralities interacts with the key structural parameters. Results show that changes in betweenness centrality have a greater effect on both reductions of shipment cost and increase of markup post merger than changes in degree centrality. This is because nodes with large increases in betweenness centrality not only 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 large increases in degree centrality are more likely to benefit from better routing options, but not much from economies of scope post merger. Moreover, a higher degree of complementarity between the two merging networks will result in greater cost reductions and a mild increase in markup. A higher degree of overlap between the two merging networks will result in greater cost reduction and a greater 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) optimal transport network.

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). My paper contributes to the cost efficiency literature by providing reduced-form evidence and uncovering through a structural model the key efficiency gain mechanisms and how these change with network features specific to the merger.

This article 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 non-stop flights in their local markets. My paper adds to this literature by considering the exact locations of markets within the network, whereby the shipment on each origin–destination market depends on the efficiency of the infrastructure that connects that market. This new feature enables me to consider both the heterogeneity and the interconnection of markets.

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 Deregulation and Background

As explained in Section 1, the freight railroad industry plays a vital role in the U.S. economy. The railroad industry, however, has not always enjoyed financial success, and in recent decades it has undergone a remarkable evolution. Following a cycle of decline that began in the 1960s, many freight rail carriers came to face liquidation. At the start of the 1980s, the U.S. railroad industry accounted for only a small proportion of total ton-miles of freight, around 20%, carrying less than pipelines.

In response, a series of laws to deregulate the industry were enacted in the years 1973–1980.

Among them, the 1980 Staggers Act formally deregulated the industry by offering railroad companies much greater pricing and operating freedom. Deregulation sparked a wave of mergers of railroad companies: from 1980 to 2005, the number of Class I railroads decreased from 39 to 7. Figure 2 shows the network formed by the current seven Class I railroads: the Burlington Northern and Santa Fe Railway (BNSF) competes with the Union Pacific Railway (UP) in the west, while CSX Transportation (CSXT) and the Norfolk Southern Railway (NS) compete in the east. Two Canadian Class I railroads, the Canadian Pacific Railway (CP) and the Canadian National Railway (CN), connect freight shipments between Canada and the United States. The Kansas City Southern Railway (KCS) locates in the south, connecting freight shipments between Mexico and the United States.[2] Each railroad company owns its own physical tracks.

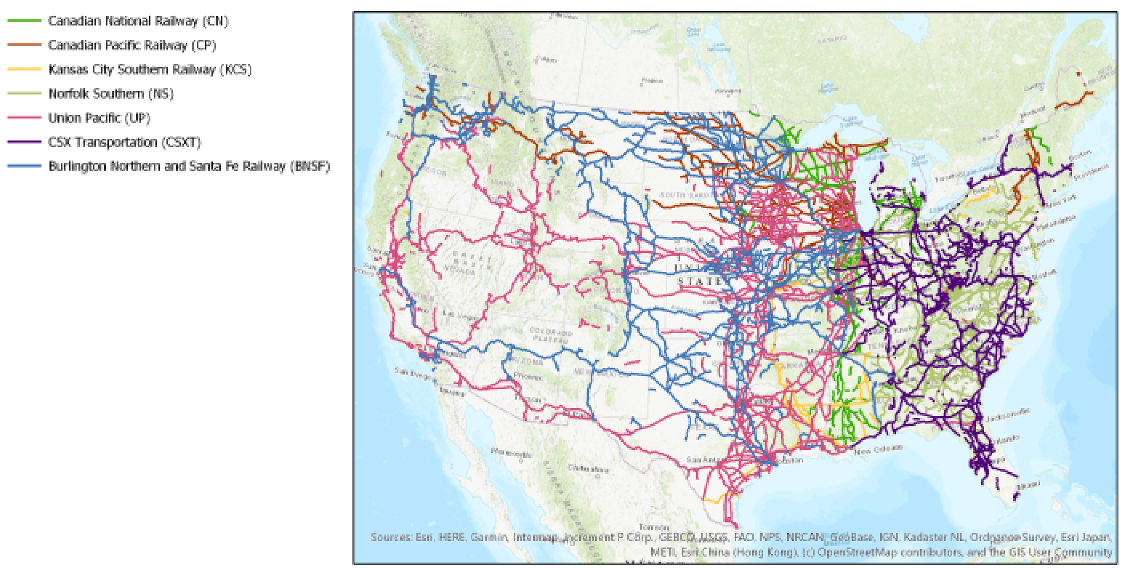


Figure 2: U.S. Class I Railroads

Since the mergers, the U.S. freight railroad industry has enjoyed a renaissance, becoming not only self-sustaining but one of the most efficient freight railroad systems in the world. The proportion of total ton-miles of U.S. freight carried by rail increased substantially after the deregulation of 1980. According to the Department of Transportation, in 2017 railroads were the second largest transport mode for freight service in the United States. Railroads carry 1,675 billion ton-miles of freight, accounting for 30% of total freight transportation. The majority of freight revenues in the U.S. freight railroad industry are generated by so-called Class I railroads. According to the AAR, in 2012 the seven Class I railroads generated $67.6 billion in freight revenues, accounting for around 95% of total freight revenues generated by railroad transport. In this paper, I focus on mergers of Class I railroads.

[2] Appendix A details a complete history of railroad mergers; Appendix D provides regulation details.

The U.S. railroad industry ships various commodities, but most carloads are generated by bulk shipments like coal, chemicals, and farm products. According to the AAR, in 2012 the top four commodities measured by the share of total tonnage were coal (37%), chemicals (10%), non-metallic minerals (9%), and farm products (8%). If we look at the share of revenues, these four commodities account for 17% (coal), 14% (chemicals), 5% (non-metallic minerals), and 8% (farm products) of total freight revenues. "King Coal" has been the most important commodity in the freight railroad industry, but the revenues it generates are in decline. Instead, carloads of intermodal shipping (miscellaneous mixed shipments such as containers) are nowadays increasing, accounting for 13% of total freight revenues in 2012.

2.2 The Story of Train 9-698-21

To better explain my model in the later sections, I introduce three core railroading concepts: interchange cost, interconnecting route versus competing route, and maintenance allocation decisions. I use the example of Train 9-698-21 to explain these three concepts. Train 9-698-21 went from Birmingham, Alabama to Los Angeles, beginning with Burlington Northern via the Avard gateway in the summer of 1994. This was before the Burlington Northern railway and the Atchison Topeka and Santa Fe railway discussed merging. I focus on the section between Los Angeles and Memphis, Tennessee.

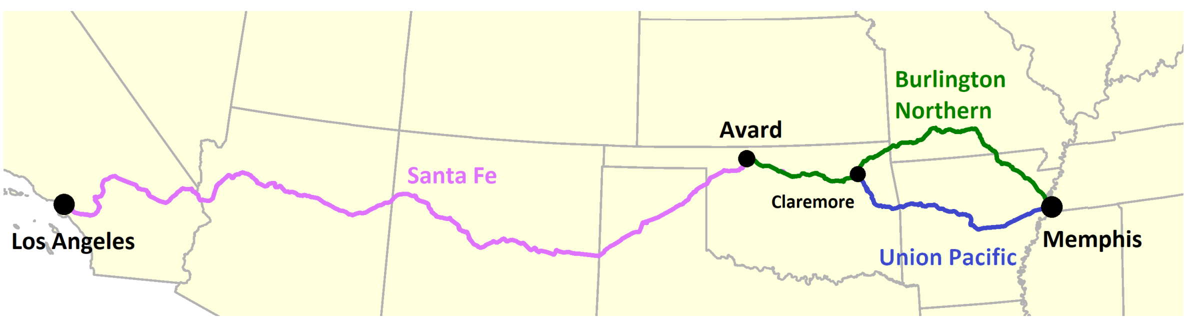


Figure 3: The Story of Train 9-698-21

First, the route from Los Angeles to Memphis is an example of an interconnecting route, because the train needs to ride both Santa Fe and Burlington Northern tracks. If a shipment originates in Claremore, Oklahoma and is bound for Memphis, the owner had a choice of riding the UP or the BN line, an example of competing routes. Second, this example shows the micro-level foundation of interchange cost. When Train 9-698-21 arrived at Avard gateway in Oklahoma, it needed to exchange crews and rolling stock (railcars and locomotives) between the BN and Santa Fe railways. However, because BN and Santa Fe prioritized this train differently, the usual result was delays in completing this process. Moreover, to check the condition of railcars and exchange rolling stocks took time and effort, further adding to the interchange cost. Appendix E.3 provides more details on why interchange is costly. Third, adequate and constant maintenance of tracks is essential for railroad operation. Regular track maintenance is costly,[3] and railroad companies decide on the frequency of track evaluation in each region. In the example of Train 9-698-21, if the railroad companies had invested more in the route from Los Angeles to Memphis by conducting more frequent track maintenance, the route efficiency from Los Angeles to Memphis would have increased.

Last, the economy of scope in my context means that, for instance, the marginal shipment cost will be lower if one railroad firm services both the markets from Los Angeles to Memphis and from San Diego to Kansas City than if two separate firms serve these markets. The reason is that traffic from different origin–destination pairs can utilize the same resources to make the shipment. The railroad firm can make the main route very efficient by allocating large track maintenance spending, and all traffic that travels through this route will benefit. According to CSXT's Chief Operating Officer, "An essential feature of the operating plan is to consolidate traffic over a smaller number of efficient, high-volume routes."[4] The idea of achieving greater cost efficiency by consolidating traffic is also supported by the former CEOs of the Southern Pacific (Krebs, 2018) and Canadian National Railway (Harrison, 2005).

In reality, in a much more complicated network a firm's pricing and routing decisions will significantly affect the degree of economy of scope that they achieve comparing before and after mergers. I capture this in my full model by considering the firm's pricing, routing, and maintenance allocation decisions based on their networks.

3 Data

I use three main datasets in my analysis: the confidential Carload Waybill Sample from the Surface Transportation Board (STB), the Class I Railroad Annual Report, and the Commodity Flow Survey. The confidential version of the Carload Waybill Sample provides detailed information on shipment price and corresponding shipment attributes; the Class I Railroad Annual Report R-1 dataset contains information on firm attributes and aggregate operational statistics; and the Commodity Flow Survey has information on shipment volumes for different transportation modes. I also make use of geographic information obtained from the Department of Transportation on all U.S. rail lines and their associated railroad companies. Based on the ancestry of each rail line, I trace back through time to reconstruct

[3]According to a Bloomberg report, a New Jersey Transit safety project costs more than $320 million, yet the agency still fell behind on rail maintenance, let its ranks of train engineers dwindle, and triggered a federal operations audit.

[4]Ex Parte No. 711 (Sub-No.1) Reciprocal Switching, Opening Comments, CSX Transportation Inc.

the rail network of each railroad firm between 1985 and 2005.

The Carload Waybill Sample is taken from carload waybills for all U.S. freight rail traffic submitted to the STB by those rail carriers completing 4,500 or more revenue carloads annually. The data contain detailed shipment information on such attributes as commodities carried, total billed weight, equipment used, participating railroads, and origin, destination, and interchange locations for each load. The waybill sample is about 2% of total waybills. The confidential Carload Waybill Sample to which I had access ranges from 1984 to 2010.

Table 1: 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	

Table 1 shows the summary statistics of key variables of the waybill data. Shipment price per carload ranges from \$384 to \$1,266 at the 25th and 75th percentiles respectively, with a mean price of \$1,034. Shipment weight per carload ranges from 16 tons to 102 tons at the 25th and 75th percentile, with a mean weight of 54 tons. Mean travel distance for each shipment is 1,045 miles, while the 25th percentile of travel distance is 404 miles (650 km). This shows that railroad shipments are mostly long-distance. For the data I use, the median shipment price per ton-mile is 2.65 cents. This value is comparable to the price per ton-mile reported in the industry. In the year 2001, the mean price per ton-mile in the United States was 2.32 cents according to the AAR.

Table 2: Summary Statistics of Market Competition

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

I next describe what the competition looks like in this industry. The market is defined at origin–destination level. Table 2 shows the total number of o–d markets, the average number of competitors serving each o–d market, and the percentage of interchange lines. First, the total number of waybills in the waybill sample went from around 263,000 in 1985 to 611,000 in 2005; that is, the total volume of railroad shipment more than doubled over this period. In Appendix E, I plot the total ton-miles of freight carried by each transportation mode from 1980 to 2011. The volume of shipment also increased for other transportation modes such as trucking, but the share of railroad shipment among all transportation modes increased in the studied period. In the reduced-form analysis, I provide evidence to show that competition from other transportation modes was not the main factor driving down the shipment price of freight railroad. Meanwhile, the percentage of interchange lines decreased from 41% to 11% while the total traffic volume doubled. Following the wave of mergers from 1985 to 2005, firms got rid of a large number of interchange lines. The number of o–d markets was relatively stable from 1990 to 2005, with a small decrease from 11,835 to 11,611. Therefore, the change of extensive margin after the mergers does not seem to be a significant concern here. Last, the average number of competitors in each o–d market slightly decreased from 3 to 2 from 1985 to 2005, showing that firms conduct oligopolistic competition in most of the local markets.[5]

4 Reduced-form Evidence

To provide evidence of efficiency gains, I examine how prices change following railroad mergers. The regression model is specified as

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

where the observation is defined at service-origin-destination-time level, and service s is either single-line service (carried by one railroad firm from origin to destination) or joint-line service (carried by at least two railroad firms with interchange involved). $D_{s,odt}$ is an indicator of whether a merger has happened to firms that provide service s from o to d before or equal to time t, and $X_{s,odt}$ are shipment attributes. I also control for firm, route, and year fixed effects in the regression.

Table 3 shows the estimation results. The results suggest that on average a railroad merger reduces the shipment price by 9.4%. By opening up the mergers and examining each individually, I found that the price effect is largely consistent across individual mergers.[6] To further decompose the effect of railroad mergers on price changes by different route types, I

[5]The year-by-year table is shown in Appendix E.2, which tells much the same story as in Table 2 here.

[6]Table F.2 shows the robustness check results obtained by looking at change of prices following each railroad merger.

interact the merger dummy with three route types: interconnecting route, competing route, and non-interconnecting, noncompeting route. As explained in Section 2, an interconnecting route is one in which two firms conduct interchange and complete the shipment jointly. Results in column 2 of Table 3 show that interconnecting routes have the largest price reduction among all route types, with price decreasing by 11% after mergers. By comparison, the other route types have a price reduction of about 6.5% following mergers.

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. *** $p < 0.001$

However, concerns might arise that these price effects are driven by competition from other transportation modes such as trucking, rather than by the effect of railroad mergers. Because comparable origin-destination-level shipment data for trucking is lacking, I cannot directly run the price regressions by controlling for competition of trucking. Instead, to address this concern, I examine the price effects of mergers for different types of commodities. The argument is that shipment of different types of commodities faces different levels of competition from other transportation modes. Therefore, if the price effects are driven by changes in other transportation modes, they should be greater for commodities facing higher competition from other modes of transport. Table 4 summarizes the two commodities used in this analysis. The Commodity Flow Survey (CFS) of 2012 shows that coal is mainly shipped by railroads. Only 1.5% of coal is shipped by trucking, while 94.8% is shipped by rail. By comparison, food or kindred products are largely shipped by trucking: 76.2% of food and kindred products are shipped by trucking, with only 23.5% shipped by rail.[7]

Table 4: Share of Coal and Food Shipment

	Coal (STCC 11)	Food or kindred products (STCC 20)
Total Ton-Miles in 2012 (Truck)	1.5%	76.2%
Total Ton-Miles in 2012 (Rail)	94.8%	23.5%

Table 5 shows the estimation results for price effect of mergers on coal and food products respectively. The results show that railroad mergers have a significantly negative price effect for both these categories. Moreover, the price effect of mergers is greater for coal.

Table 5: 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. *** $p < 0.001$

The pattern of results in Table 5 is contrary to the prediction of the hypothesis that the price effect is driven by changes in other transport modes. As a robustness check, I run the price regression for each type of commodity in Appendix F. The results show that price

[7] All weights are calculated by total ton-miles of shipment.

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.

The estimated price effect is comparable to other analysis of freight railroad mergers. In the STB analysis of the Union Pacific–Southern Pacific merger, the shipment price of coal was found to decrease by 11% and that of other commodities by 6% after the merger. The price effect of mergers found in the U.S. freight railroad industry is larger than in some other industries. For example, Ashenfelter et al. (2015) find that the estimated price reduction caused by merger efficiency is 2% in the brewing industry. In comparison, I find a 9.4% overall price reduction and a 17.9% average price reduction for coal shipments, which suggests that cost efficiency following mergers is important in the railroad industry.

In this section, I show that prices decrease after mergers and that the price effect is greater for interconnecting routes. However, looking solely at the effect of individual routes is insufficient to understand efficiency gain in this industry because the origin–destination markets in the network are interdependent. To capture this important feature and examine how network structure affects the effect of mergers, I propose an optimal transport network model by endogenizing the firm's pricing, routing, and allocation decisions.

5 Model

I define a market in the model as an origin–destination pair. On the demand side, I assume customers make discrete choices based on shipment price and shipment characteristics. Customers face an outside option: shipping by transportation modes other than railroads. Railroad firms do not make entry or exit decisions in each origin–destination market. The set of markets each firm serves is fixed and obtained from the data. Given the set of markets each firm serves, firms play a two-stage game. First, firms make routing and allocation decisions to minimize operational costs, conditional on the expected demand in each local market. Second, firms compete in local markets and choose prices simultaneously. In equilibrium, the expected demand in each local market is consistent with the outcome at the pricing stage. Firms provide either single- or joint-line service to serve a market. Single-line service is carried by one railroad firm from the origin to the destination. Joint-line service is carried by at least two railroad firms with interchange involved. I explain what firms do in my model in Section 5.2. Then in Section 5.3 I list the key assumptions in my model, explaining why I need them and how the equilibrium results will be affected if I relax those assumptions, and then discuss the possibility of multiple equilibria and how I select equilibrium.

5.1 Demand

In this paper I assume a logit demand for railroad shipment. The assumption of logit demand is widely used in estimating transportation demands, such as in Peters (2006). In each origin–destination market, consumer i chooses service s to ship from origin o to destination d. Service s is either a single- or joint-line service. For example, a shipment carried only by the Union Pacific railway from origin to destination is a single-line service. A shipment carried first by the Burlington Northern (BN) railway from origin to interchange station and then by the Santa Fe railway from interchange station to destination is a joint-line service.

The utility function of customer i choosing service s is

$$u_{is,odt} = \alpha \cdot p_{s,odt} + \beta_1 \cdot \log TotalTrackMiles_{s,odt} + \xi_{s,odt} + \varepsilon_{is,odt}.$$

where $\xi_{s,odt}$ is unobserved service quality and $\varepsilon_{is,odt}$ is the customer-specific deviation from mean utility. Customers care about shipment price $p_{s,odt}$ and travel time. Because I do not observe travel time in my data, I control for total track miles and origin–destination market dummies to approximate travel time. The market fixed effects control for the geographic distance between the origin and the destination. $TotalTrackMiles$ measures the total amount of physical track that the firm providing service s has in the origin and destination areas. The idea is that the more physical track there is, the easier it is to move things from the customer to the railroad company, thus shortening the travel time.[8] For example, say the o–d market is from LA to Houston, with a single-line service provided by the Union Pacific railway. Then $TotalTrackMiles_{s,odt}$ measures the total track miles that the Union Pacific railway owns in the LA and Houston areas. The total track miles for each firm are calculated from the detailed geographic information that I obtained. For example, panel (a) of Figure 5 shows the actual rail network of BN in 1994. Therefore, I can calculate the total track miles of each firm in each BEA area by aggregating the total physical track each firm owns in that particular area. In my counterfactual merger simulations, I construct the total track miles for the merged firm by summing up the total track owned by the acquiror and the target. To control for components of unobserved service quality that are constant within significant subsets of the data, I include fixed effects for railroads, o–d markets, and time periods:

$$\xi_{s,odt} = OrigRail_s \cdot \alpha_o + DestRail_s \cdot \alpha_d + Time_t \cdot \alpha_t + Mkt_{od} \cdot \alpha_m + v_{s,odt}$$

where $v_{s,odt}$ is the component of unobserved service quality that is not constant along these dimensions.

[8] Similar concepts such as airport presence are used in estimating airline demand; see Peters (2006).

5.2 The Firm's Problem

Each firm j owns a network $\mathcal{G}_j$ with corresponding nodes $\mathcal{Z}_j$ and arcs $\mathcal{A}_j$. In making pricing, routing, and maintenance allocation decisions, firms choose 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 $\{I_{j,ab}\}_{(a,b)\in\mathcal{A}_j}$ to maximize profit. Denote $S(j)$ as the set of services s in which j participates. Formulate the firm's optimization problem as

$$\pi_j := \max_{\{p_{s,od}\},\{\mathcal{R}_{j,o_j(s),d_j(s)}\},\{I_{j,ab}\}_{(a,b)\in\mathcal{A}_j}} \sum_{s\in S(j)} p_{s,od}\cdot Q_{s,od} - C(\boldsymbol{Q},\boldsymbol{R},\boldsymbol{I}) \tag{1}$$

with resource allocation constraint

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

and balanced-flow constraint: for any service s in any market o–d and $\forall$ nodes $z\in\mathcal{Z}_j$,

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

The resource allocation constraint means that each firm j has a fixed amount of resources K_j that can be allocated to the arcs $\mathcal{A}_j$ in its network. In the empirical analysis, K_j is the total annual maintenance spending exogenously obtained from the data. The balanced-flow constraint imposes that for any node z on railroad j's network $\mathcal{Z}_j$, the net demand $D_{j,z}$ plus the inflow of serviced goods (left-hand side) from its adjacent nodes $\mathcal{Z}_j(z)$ is equal to the outflow (right-hand side) to its adjacent nodes. Service s can be either single- or joint-line service; $s := [j_o, j_d]$ where j_o is the origin railroad and j_d is the destination railroad.

1. If $j_o = j_d = j$, s is a single-line service and carried by railroad firm j from the origin all the way to the destination.

2. If $j_o \neq j_d$, s is a joint-line service. Shipment from o to d will be carried by firm j_o from origin o to the interchange station m, then by firm j_d from station m to destination d. The location of the interchange station m is specific to each service–origin–destination triple and exogenously obtained from the data.[9]

[9] In the example of Train 9-698-21 in Section 2.2, the Burlington Northern and Santa Fe railways provide a joint-line service from LA to Memphis. The shipment is carried by the Santa Fe railway from LA to Avard, OK, interchanges with the Burlington Northern railway, and is then carried by the Burlington Northern railway from Avard to Memphis. In this case, Avard is the interchange station. In practice, the waybill data

The service set $S(j)$ is exogenous and obtained from the data. I impose a nested structure in my model, where firms first make routing and maintenance decisions to minimize operational costs, conditional on the expected demand in each local market. Then firms compete in local markets and choose prices simultaneously. I solve the model backward.

5.2.1 Stage Two: Local Market Competition

Once firms have made routing and allocation decisions in the first stage, the marginal cost of operation in each local market $C_{s,od}$ is determined. Firms then compete on price in local markets. Firm j chooses the price of each single-line service it provides and each joint-line service for which firm j is the origin railroad. The optimization problem for pricing is

$$\pi_{s,od} := \max_{p_{s,od}} [p_{s,od} - C_{s,od}] \cdot Q_{s,od}(p_{s,od}, p_{-s,od}).$$

The marginal cost $C_{s,od}$ of transportation of service s from o to d depends on the routing decision $\mathcal{R}_{s,od}$ and maintenance decision $\boldsymbol{I}_j$. Each element $I_{j,ab}$ of $\boldsymbol{I}_j$ measures the amount of resources that firm j allocates to arc (a,b). $C_{s,od}$ is parameterized as

$$C_{s,od} = \begin{cases} \sum_{(a,b)\in\mathcal{R}_{j,od}} c_{j,ab}(\boldsymbol{I}_j) & \text{if} \quad j_o = j_d \\ \sum_{(a,b)\in\mathcal{R}_{j_o,om}} c_{j_o,ab}(\boldsymbol{I}_{j_o}) + \sum_{(a',b')\in\mathcal{R}_{j_d,md}} c_{j_d,a'b'}(\boldsymbol{I}_{j_d}) + \eta & \text{if} \quad j_o \neq j_d \end{cases}, \tag{2}$$

where $c_{j,ab}$ is the arc-level cost to firm j, η is the interchange cost, and m is the interchange station. The routing $\mathcal{R}_{j,od} \in \mathcal{A}_j$ is a subset of connected arcs that routes firm j from origin o to destination d. Intuitively, equation 2 says that the per-unit transportation cost $C_{s,od}$ for single-line service ($j_o = j_d$) is the summation of arc-level costs over a firm j route from o to d. The per-unit cost for joint-line service ($j_o \neq j_d$) is the summation of cost for firm j_o from o to m and cost for firm j_d from m to d, plus the interchange cost η.

I follow Galichon (2016) and Fajgelbaum and Schaal (2020) in defining the per-unit cost of transportation at arc level $c_{j,ab} = \frac{\delta_0 Dist_{j,ab}}{I_{j,ab}^{\gamma}}$. The arc-level transportation cost $c_{j,ab}$ depends on the distance between a and b, and the amount of resources firm j allocates to arc (a,b). The efficiency parameter γ is expected to be positive. Therefore, if firm j allocates more resources to arc (a,b), the arc-level transportation cost $c_{j,ab}$ will be smaller. For any arc (a',b') such that $(a',b') \notin \mathcal{A}_j$, the arc-level cost of transportation $c_{j,a'b'}$ is ∞.

show that the location of the interchange station for each service–origin–destination triple is very stable and rarely changes.

5.2.2 Stage One: Operational Decision in the Network

In the first stage, firms form expectations over transportation demand in each local market $\widetilde{Q}_{s,od}$. Given the expected demand, firms choose the optimal routing and allocation decisions. In a single-line service from o to d, $o_j = o$ and $d_j = d$. In the case of joint-line service, $o_j = o, d_j = m$ for the origin railroad and $o_j = m, d_j = d$ for the destination railroad, where m is the interchange station. I use the notation $o_j(s)$ and $d_j(s)$ to summarize the above mapping from a service s to the required transportation origin and destination for the involved firm j.

Firms choose the optimal routing $\{\mathcal{R}_{j,o_j,d_j}\}_{o_j \in \mathcal{Z}_j, d_j \in \mathcal{Z}_j}$ and maintenance allocation decisions $\{I_{j,ab}\}_{(a,b)\in\mathcal{A}_j}$ to minimize total operational costs, subject to resource allocation and balanced-flow constraints. The cost minimization problem of firm j is written as

$$\min_{\{\mathcal{R}_{j,o_j(s),d_j(s)}\},\{I_{j,ab}\}_{(a,b)\in\mathcal{A}_j}} \sum_{s\in S(j)} C_{s,o_j(s),d_j(s)}(\boldsymbol{I}_j, \mathcal{R}_{j,o_j(s),d_j(s)}) \cdot \widetilde{Q}_{s,od} \tag{3}$$

with resource allocation constraint:

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

and balanced-flow constraint: for any service s in any market o–d and $\forall m' \in \mathcal{Z}_j$,

$$D_{j,m'} + \sum_{a\in\mathcal{Z}_j(m')} \widetilde{Q}_{s,od} \cdot \mathbb{1}\{(a,m') \in \mathcal{R}_{j,o_j(s),d_j(s)}\} \leq \sum_{b\in\mathcal{Z}_j(m')} \widetilde{Q}_{s,od} \cdot \mathbb{1}\{(m',b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}.$$

I show details of the solutions of my model in Appendix B. The intuition for the routing problem is that firm j chooses the shortest resource-weighted route in its own railroad network to travel from origin o_j to destination d_j. Firm j obtains the optimal routing for each market from o_j to d_j by solving a linear programming problem. The intuition for the optimal maintenance allocation decision is that firm j allocates more resources to arcs that carry a larger volume of traffic. For any non-zero $I_{j,ab}$ and $I_{j,a'b'}$, the optimal allocation decision satisfies

$$\frac{I_{j,ab}}{I_{j,a'b'}} = \left[\frac{Dist_{j,ab} \cdot q_{j,ab}}{Dist_{j,a'b'} \cdot q_{j,a'b'}}\right]^{\frac{1}{1+\gamma}}. \tag{4}$$

where $q_{j,ab}$ is the total amount of shipment running through arc (a,b).

To sum up, given the expected demand $\widetilde{Q}_{s,od}$ of each service in each origin–destination market, in the first stage firms choose routing and allocation decisions to minimize operational cost in equation 3, conditional on the expected shipment demand in each local market. The optimal routing of firm j is to choose the shortest resource-weighted route from origin o_j to destination d_j, and the optimal allocation is to allocate more resources to arcs with larger volumes of traffic. Then, given the operational cost, firms compete in local markets and choose prices simultaneously. In equilibrium, the expected shipment demand $\widetilde{Q}_{s,od}$ is consistent with the outcome determined at the pricing stage, $Q_{s,od}(p^*_{s,od}, p^*_{-s,od})$.

5.3 Discussion

Given the model setup, I now discuss the assumptions in my model. There are two key assumptions that I make. First, I assume that firms solve the maximization problem of equation 1 in a nested structure. Firms make the optimal routing and maintenance allocation decisions first and then make the pricing decisions. In the full model, firms simultaneously make pricing, routing, and maintenance allocation decisions. The main difference between the full model and the nested model is that in the nested one, when firms make pricing decisions, they do not consider how the changed quantity is going to affect the routing and allocation decisions. In the full model, the FOC with respect to price $p_{s,od}$ for each service s is derived as

$$Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial Q_{s,od}}{\partial p_{s,od}} \cdot \left[C_{s,od} + \underbrace{\frac{\partial C_{s,od}}{\partial Q_{s,od}} Q_{s,od}}_{\text{own-cost effect}} \quad + \underbrace{\sum_{s' \in S(j), s' \neq s} \frac{\partial C_{s',o'd'}}{\partial Q_{s,od}} Q_{s,o'd'}}_{\text{cross-cost effects}} \right] = 0, \tag{5}$$

while in the nested model, the FOC is derived as

$$Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial Q_{s,od}}{\partial p_{s,od}} \cdot C_{s,od} = 0. \tag{6}$$

In the nested model, the firms do not consider the own- and cross-cost effects when making pricing decisions. I impose the nested structure because solving the cross-cost effects becomes computationally burdensome as the number of markets increases. The problem worsens in estimating the model because we need to solve for equilibrium multiple times. By imposing the nested structure, the decision for each o–d market is now independent at the pricing stage, making the model more tractable and easier to solve. Then the question is, how far is the nested model from the full model? To shed some light on this question, in Appendix B

I derive the solutions corresponding to a monopoly for both the full and nested models and compare the equilibrium outcomes of the two models.

In Appendix B.3, I show that when there is no economy of scope ($\gamma = 0$), the nested model is equivalent to the full model (Proposition 1); and that when there is economy of scope ($\gamma \neq 0$), if the demand of a single market dominates, the difference between the nested model and the full model is negligible, regardless of whether the network is a tree or non-tree (Propositions 2 and 3). Otherwise, the direction of the difference between the nested model and the full model is ambiguous. To further study the direction and level of difference in the last case, I perform numerical simulations to compare the two models in Appendix B.4. The simulation results show that the difference in the equilibrium outcomes between the two models is small for each of various cases. The intuition is that when a single market dominates, there is no difference between the two models based on Propositions 2 and 3. When none of the markets dominate (i.e., the demand is more balanced), the own-cost and cross-cost effects are likely to cancel out. Hence the difference in the equilibrium outcomes between the full model and the nested model is minimal. Given this, and the fact that the nested model hugely reduces the computational burden, I choose to impose a nested structure in my model.

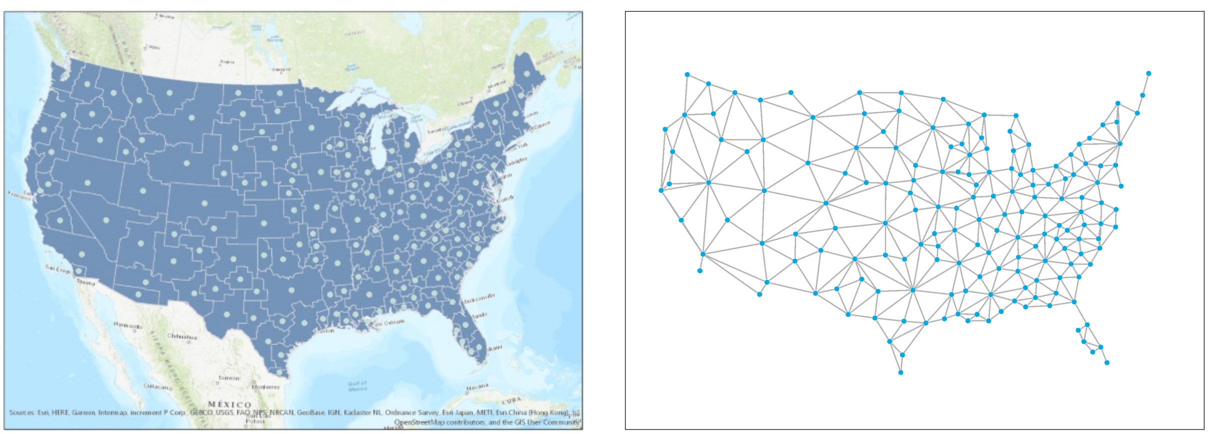
Second, I assume that railroad firms do not make entry or exit decisions in origin–destination markets. This assumption helps rule out some of the impractical equilibria. For example, two firms can sort into local monopolies, with one firm only operating on the east coast and the other only operating on the west coast. I select the equilibrium by restricting the simulated market share of a firm to be non-zero in equilibrium if the observed market share of that firm is positive in the data. This assumption is well-supported by the data. Figure E.1 shows that the total number of o–d markets was quite stable at the level of $11,500$ from 1986 to 2005, when most of the mergers happened. When I zoom into particular firms, I only observe a few entries or exits in o–d markets post-merger. Therefore, the data suggest that the extensive margin is not the main driver after the merger. Moreover, 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. Entry into new markets where firms have no physical track is very difficult.

However, even after imposing the assumption of no entry or exit, my model may still suffer from the problem of multiple equilibria. The uniqueness of equilibrium depends on the level of demand in each o–d market and the number and the location of o–d markets. Given the large number of markets in my empirical analysis, I am not able to analytically prove the uniqueness of equilibrium. Instead, I show in my counterfactual analysis that my equilibrium is numerically stable. One reason for this stability is that observed local monopoly markets help anchor the equilibrium.

Besides the two main assumptions, I also impose several other assumptions, including no double-marginalization of pricing and no cannibalization between own single-line service and joint-line service provided in the same o–d market. For interconnecting routes, I only consider joint-line service with one interchange, and I assume that the joint-line service's originating firm determines the service's price. The data support those assumptions, and relaxing them does not provide extra insight into the main results. Therefore, I make these simplification assumptions and focus mainly on the firms' pricing, routing, and maintenance allocation decisions. I explain and justify each of these assumptions in Appendix C.

5.4 Defining the Network

I define a network $\mathcal{G}$ as a directed graph $(\mathcal{Z}, \mathcal{A})$, where $\mathcal{Z}$ is a set of nodes and $\mathcal{A}$ is a set of arcs $\mathcal{A} \subseteq \mathcal{Z}^2$ which are pairs (x, y), where $x, y \in \mathcal{Z}$. In the model I define the nodes to be the centroids of BEA regions and the arcs as rail lines that connect each BEA economic area. Panel (a) of Figure 4 shows the 170 BEA regions in the contiguous United States and their centroids. Based on the locations and adjacencies of the BEA regions, I have constructed the virtual network in panel (b).

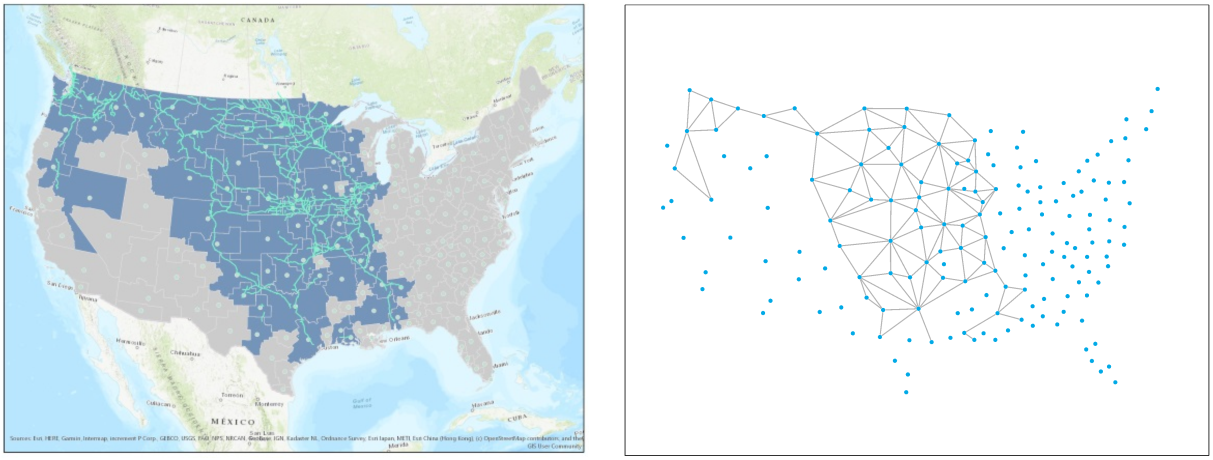


(a) BEA Regions and Their Centroids

(b) Virtual Network

Figure 4: U.S. Rail Network

I next obtain network information for each railroad firm. I denote the network of each firm j as $\mathcal{G}_j$, with arcs $\mathcal{A}_j$ and nodes $\mathcal{Z}_j$. Panel (a) of Figure 5 shows the actual rail network of BN in 1994, while panel (b) shows the virtual network for BN constructed from the actual information. For example, if two adjacent regions a and b are connected by rail lines owned by BN, then nodes $a, b \in \mathcal{Z}_j$ and arc $(a, b) \in \mathcal{A}_j$.



(a) Actual Rail Network of BN in 1994 (b) Virtual Network for BN

Figure 5: BN Rail Network

Following the same process, I construct the virtual network for every railroad firm in every year from 1985 to 2005, based on detailed geographic information for each rail line (coordinates) and information about the ancestry of rail lines obtained from the Federal Transit Administration. The geographic coordinates and historical information allow reconstruction of the rail network going back in time. Figure I.1 shows the virtual networks of the two merging parties in each merger case between Class I railroads from 1985 to 2005. There were 12 mergers in total in the studied period.

6 Estimation

6.1 Demand Estimation

In Section 5.1, the utility function of consumer i choosing service s is specified as

$$u_{is,odt} = \alpha \cdot p_{s,odt} + \beta_1 \cdot \log TotalTrackMiles_{s,odt} + \xi_{s,odt} + \varepsilon_{is,odt}.$$

Therefore, the difference of the logarithm of each service's observed market share and the logarithm of the share of the outside good can be derived as

$$\log(h_{s,odt}) - \log(h_{0,odt}) = \alpha \cdot p_{s,odt} + \beta_1 \cdot \log TotalTrackMiles_{s,odt} + \xi_{s,odt}. \tag{7}$$

Here, $h_{s,odt}$ is the market share of service s in serving the market from o to d at time t, while $h_{0,odt}$ is the market share of the outside option, which is the share of all other transportation modes serving the market from o–d. Usually, economists do not observe the share of the outside option when estimating demand. However, in this case I do observe it. The data on shipment by other transportation modes is obtained from the Commodity Flow Survey (CFS).[10]

The error term in equation 7 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 solve this endogeneity problem, I first control for a set of instrumental variables that attempts to proxy for the marginal costs directly. I control market fixed effects (origin–destination) and hence control for the geographic distance between the origin and destination. However, the actual travel distance between the same origin–destination market will be different across firms because different railroad firms have different track systems. The greater the travel distance, the higher the fuel and labor cost. Therefore, the actual travel distance is correlated with the actual marginal cost of shipment. I use the average travel distance obtained from data to proxy marginal cost. Another set of IVs I used is the so-called "BLP Instruments." Much of the previous research[11] 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 average travel distance of other railroads in the same o–d market as instruments.

Determining the plausibility of the instruments I described above is an empirical issue. Therefore, I examine another set of IVs, one which utilizes mergers between railroad firms to proxy for the change of market power in local markets. I compare the difference between the estimates implied by these different sets of IVs. Because the railroad companies have national networks, the merger decision between two railroad companies is unlikely to be in response to local demand shocks in one single origin–destination market. Therefore, I argue that the merger decision is orthogonal to local demand shocks. I look at the induced change in concentration following mergers of railroads. To measure the changes in concentration after mergers, I build on the works of Garmaise and Moskowitz (2006) and Dafny, Duggan and Ramanarayanan (2012) to construct the simulated change in the Herfindahl–Hirschman Index ($sim\Delta HHI$); $sim\Delta HHI$ measures the projected change in the HHI that would have occurred after the merger if nothing else changes. The purpose of using the projected change instead of the actual change in the HHI is to tease out post-merger market share adjustments

[10] The CFS is conducted every five years by the U.S. Census Bureau. The data I have available is for 1993, 1997, 2002, 2007, and 2012. The waybill data ranges from 1985 to 2010. Therefore, I use data from 1993, 1997, 2002, and 2007 to estimate the demand.

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

that may correlate with local market conditions. The simulated change in the HHI is derived

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

Because the demand estimation uses data from 1993, 1997, 2002, and 2007, I use the following mergers to construct $sim\Delta HHI$: the merger between the St. Louis Southwestern railway and the Southern Pacific railway in 1992, the merger between the Burlington Northern railway and the Atchison, Topeka and Santa Fe railway in 1995, the merger between the Union Pacific railway and the Southern Pacific railway in 1996, and the merger of Conrail in 1999.

Table 6: 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

Table 6 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 ordinary least squares results. The coefficient on price and the implied own-price elasticities are relatively low. 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 proxies for marginal costs and 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) include market, firm, and time fixed effects.

Several conclusions can be drawn from the results in Table 6. 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, even though there are reasons to doubt the validity of the first set of instruments, they seem to generate results almost identical to those produced by using the simulated change in HHI. The similarity between the coefficients does not guarantee that the two sets of IVs will produce identical coefficients in different models or that these are valid IVs. However, this finding does provide some support for the validity of the IVs used. The estimated price elasticity that I use is shown in column (6). Given an estimated price coefficient of around -0.72, the average price elasticity of demand in my data is -1.60. The estimated average price elasticity is comparable to estimates found in the transportation literature. For example, Wilson et al. (1988) estimated an own-price elasticity of demand for U.S. freight rail of –1.46 post-Staggers (after 1980), and Beuthe et al. (2001) estimated demand elasticity of -1.77 in total tonnes.

6.2 Estimation of Cost Parameters

In Section 5, the marginal cost of transportation of service s from o to d is parameterized as

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

and the arc-level transportation cost of firm j at arc (a, b) is

$$c_{j,ab} = \frac{\delta_0 Dist_{j,ab}}{I_{j,ab}^{\gamma}}.$$

Therefore, there are three cost parameters to be estimated, $\Theta_0 \equiv \{\delta_0, \gamma, \eta\}$. The parameter δ_0 captures the average shipment cost per efficient mile, γ captures the effectiveness of resources, and η captures interchange cost. Intuitively speaking, γ can also be interpreted as the parameter of economy of scope. The larger the value of γ, the more firms benefit from economy of scope by consolidating resources.

Estimation of the dynamic parameters Θ_0 is implemented according to the following procedures. First, denote the set of data moments as Γ^d. Second, for a given set of parameters Θ, the industry equilibrium is solved and optimal decisions for pricing, routing, and maintenance allocation $(\boldsymbol{p}^*, \boldsymbol{R}^*, \boldsymbol{I}^*)$ are generated. I define the simulated moments as Γ^S. The MSM estimate $\hat{\Theta}$ minimizes the weighted distance between the data moments and the simulated moments:

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

where W is a positive-definite matrix. In the numerical analysis, $\widehat{W}$ is calculated through a bootstrap procedure: I randomly resample the data and calculate the moments of interest for each sample; then, I obtain a variance–covariance matrix based on these bootstrap samples.

I target four data moments, listed in Table 7. The identification argument is as follows: The first moment measures travel distance's effect on average shipping price. Because δ_0 captures the average shipment cost per efficient mile, the larger the value of δ_0, the larger the value of average shipping expense per mile, whence the price. Therefore, the first moment helps pin down the value of δ_0. Conditional on the values of δ_0 and γ, the parameter of interchange cost η is identified by the second moment, the average price difference between an interconnecting route and a non-interconnecting route. When the value of interchange cost η increases, the price difference between an interconnecting route and a non-interconnecting route increases. Last, γ captures the effectiveness of resources, and the value of γ largely affects the value of the last two moments regarding network measures. To demonstrate how the value of γ affects routing and maintenance allocation decisions, I show comparative statistics of altering the value of γ in Appendix H. Intuitively, if $\gamma = 0$, resources do not matter for shipping cost, and only the travel distance between origin and destination is relevant. Therefore, there is no benefit from consolidating traffic, and network structure will not affect shipping expenses. If $\gamma \neq 0$, the network structure affects how traffic can be consolidated and hence the effect of degree and betweenness centrality on prices. Moment three is obtained by regressing shipment price per mile for each *o*–*d* market on the degree centrality of the origin station while controlling for the number of interchanges and fixed effects for railroads, *o*–*d* markets, and time period.[12] The unit of observations is the same as in equation 7. The fourth moment is obtained in a similar way by regressing the price per mile on the betweenness centrality of the origin station. Column (1) of Table 7 summarizes the identification arguments.

Column (2) of Table 7 shows the data moments. The average shipping price per loaded car

[12] I conducted robustness checks by regressing on centrality measures of the destination station or the average of the origin and the destination stations for each *o*–*d* market. The results are very similar.

Table 7: 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	\$0.65	\$0.65
Average difference of price between interconnecting route and other route (per loaded car per mile)	pin down η	\$0.26	\$0.24
Moments related to network measures			
Effect of degree centrality on price per loaded car per mile	pin down γ, δ_0	−\$0.0002	−\$0.0003
Effect of betweenness centrality on price per loaded car per mile	pin down γ, δ_0	−\$0.33	−\$0.32

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 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 effect of betweenness centrality on price is estimated as −\$0.30. If we compare a station with the highest betweenness centrality to a station with the lowest value, the price difference is −\$0.20, or about a 20% difference in price.

Table 8: Estimation Results for Cost Parameters

	Point Estimate	95% Confidence Interval
δ_0	1.2	$[1.10, 1.29]$
η	217	$[155, 279]$
γ	0.17	$[0.14, 0.20]$

Table 8 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. Shipment cost per efficient mile is estimated to be \$1.20. The estimated interchange cost is \$217, equivalent to 21% of the average shipment price. This confirms that interchange is very costly, so that eliminating interchange costs after a merger is a critical source of cost efficiency. The estimated value of γ is less than 1, indicating that the marginal return of allocating resources to a particular arc is decreasing. Therefore, railroad firms are more likely to allocate resources to multiple arcs rather than stacking them in only a few arcs. Column (3) of Table 7 compares the simulated moments with the data moments. In general, the simulated moments match the data moments very well. I then evaluate the out-of-sample performance to further validate my model. Specifically, I look at the discrepancy between the observed and predicted price changes post merger. On average, the price reduces by 9.79% post merger in the data. The simulated average price reduction post merger is 10.51% in my model, which is quite close to the observed change. Second, I rank the top 10% of markets for price reduction post merger in the data and assess the accuracy with which my model can predict. Averaged over all mergers, my model has an accuracy of 63% in predicting the top price-reduction markets. For each merger, there are thousands of markets, and although my model just has three cost parameters, it fits the data pattern quite well.

7 Counterfactual Experiments

I conduct two main counterfactual experiments. First, I calculate the average merger gains between Class I railroads from 1985 to 2005. For each merger, I simulate the equilibrium outcomes pre and post merger. Then I calculate the changes in shipment prices, costs, and additive markup. Second, I investigate how network structure affects the level of merger gains. I show how the measure of network centralities interacts with the structural parameters in determining merger gains, and I illustrate how the two merging networks' degrees of overlap and complementarity relate to such merger gains.

7.1 Efficiency Gains from Mergers

I calculate the average merger gains by comparing equilibrium results before and after the mergers. These are weighted by post-merger quantity and averaged over all individual *o–d* markets and all mergers. 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%. The simulated price reduction post merger in the baseline model is comparable to the price reduction observed in the data. On average, the merged firm becomes more profitable post merger. However, 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.

At the *o–d* market level, there is a large heterogeneity of merger gains. 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. The first notion I use is *degree centrality*, which measures the total number of links a node has in a given network. The second notion is *betweenness centrality*, which measures the number of paths traveling through each node. My model solves for the routing decision of each *o–d* pair in equilibrium. Based on the model-simulated routing, I calculate the total number of paths that travel through each node, defined as the betweenness centrality of that node in my analysis. 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, where ΔNC is the change in network centrality after a merger. 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. Therefore, the baseline results show that compared to degree centrality, nodes with a greater increase in betweenness centrality have a greater effect on both reductions of shipment cost and increase of markup post merger.

7.2 Unpacking the Black Box

To unpack the "black box" of why the topology of the network 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; also let $MG = \Delta f(NC, \boldsymbol{\theta})$ be the functional equation that relates these variables according to the equilibrium of my structural model. 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

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

That is, MG here captures the merger gains when the network structure changes from NC_0 to NC_1. There are three key parameters in the model: δ measures the per-mile travel costs, η measures the interchange cost, and γ measures the level of economies of scope. The baseline model uses estimated parameters from Section 6; all three parameters $\boldsymbol{\theta}_0 \equiv (\delta_0, \eta_0, \gamma_0)$ are different from 0. To investigate how the network structure interacts with the structural parameters in determining merger gains, I conduct three counterfactuals to incorporate various changes in $\boldsymbol{\theta}$. I eliminate interchange cost and economies of scope in the first counterfactual $\boldsymbol{\theta}_1 \equiv (\delta = \delta_0, \eta = 0, \gamma = 0)$ and investigate merger gains given $\boldsymbol{\theta}_1$,

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

I eliminate only economies of scope in the second counterfactual $\boldsymbol{\theta}_2 \equiv (\delta = \delta_0, \eta = \eta_0, \gamma = 0)$, and only interchange costs in the third counterfactual $\boldsymbol{\theta}_3 \equiv (\delta = \delta_0, \eta = 0, \gamma = \gamma_0)$.

Table 9 shows how average merger gains change in the different counterfactuals.[13] Column (2) of Table 9 shows the results of the first counterfactual, in which I turn off both interchange cost and economies of scope. Without economies of scope, all local *o*–*d* markets are 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.[14] When only travel distance matters, cost reduces by a small amount of 1.9% on average post merger. In local markets, the merged firm will still obtain extra market power. Because both the acquiror and acquiree are present in local markets, the number of firms reduces after merger. However, the results show that merger-generated concentration in local markets only increases the markup slightly, by 0.7%. This is not surprising, because across the twelve mergers I study, jointly owned markets typically only account for 3% to 6% (maximum 12%) of the total markets owned by the two merging firms.

Table 9: Average Merger Gains

Percentage Change in:	Baseline (1) Distance + Interchange Cost + Economies of Scope	Unpacking the Black Box (2) Distance	 (3) Distance + Interchange Cost	 (4) Distance + Economies of Scope
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 9 shows the results of the second counterfactual, in which I now allow for interchange cost but keep economies of scope turned off. Local markets are still independent in this case, but it is now more costly to ship through interlines. 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

[13] All numbers reported in Table 9 are weighted averages, weighting by post-merger quantity for each local *o*–*d* market.

[14] I assume that a firm can only choose the best routing within its own network. Therefore, even without any interchange cost, for single-line services firms cannot route through another firm's network. For joint-line services, I obtain the location of interchange stations from the data. When eliminating the interchange cost, firms cannot re-optimize routing by changing interchange stations pre merger.

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. However, 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.

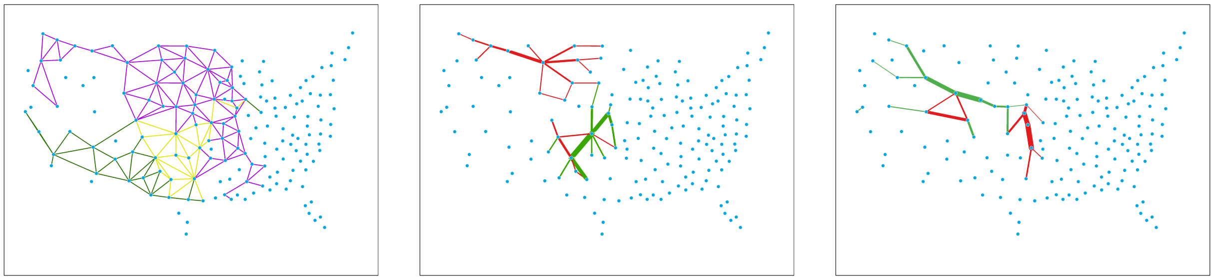
Column (4) of Table 9 shows the results of the third counterfactual, in which I turn off interchange cost but allow for economies of scope. Local markets are now interdependent, because any traffic going through arc (a, b) can utilize the resources allocated at that arc. After the merger, the merged firm can get rid of redundant lines, 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. More interestingly, we now observe a much higher increase in markup if we allow for economies of scope. Additive markup increases by 6.9% post merger compared to only 0.7% in the first two counterfactuals.

To further investigate what is happening here, I first check how markup could be affected in my model. Given a logit demand, the additive markup for each local market j at time t is calculated from the FOC of the firm's optimization problem as

$$\eta_{jt} \equiv p_{jt} - c_{jt} = -\frac{1}{\alpha(1 - s_{jt})} \tag{8}$$

where α is the price coefficient. From equation 8, we can see that markup increases only when local market share s_{jt} increases. When local markets are independent, reduction of price driven by lower cost and increased concentration of market power driven by merger will both increase a firm's market share in a local market. However, the first two counterfactuals show that these are not likely to be the main factors driving up markup, because the implied markup increase is only 0.7%. Therefore, the increase in markup has to be driven by the interdependence of the o–d markets.

I then investigate how the pricing and allocation decision changes for merging and non-merging firms. Because merger eliminates interchange cost and enhances the merged firm's connections, the connected areas of the two merging firms in particular will exhibit a large cost reduction. I find that non-merging firms strategically shift their resources away from such regions. Everything else held constant, when the merged firm's cost reduces in a market, the market share of the merged firm will increase in that market. Therefore, non-merging firms will serve lower shipment quantities in the same market, and hence the resources allocated to that market by the non-merging firms will be utilized by less shipment. As a result, the marginal return of capital for the non-merging firms decreases in that market, leading them to re-allocate resources to other markets.



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

Figure 6: Changes in Allocation of Resources After ATSF–BN Merger

Notes: Panel (a) shows the combined network of the two merging firms. Green, purple, and yellow arcs show the network owned only by BN, the network owned only by SF, and the overlapping region of the two networks, respectively. Panels (b) and (c) show the change in allocation of resources. Green represents increased allocation after merger, while red 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.

This can be seen from equation 4 in the model section of this article. Resources allocated to arc (a, b) are proportional to the quantity of shipment going through arc (a, b). When resources are moved away, the shipment cost of non-merging firms 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 of BN and ATSF, the merged firm allocated more resources to enhance connections between the two parts of the merged 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 6 shows the changes in allocation of resources for BNSF post merger. Meanwhile, in equilibrium BNSF's main competitor, Union Pacific railway (UP), moves resources away from those areas around South Dakota and Kansas. Panel (c) of Figure 6 shows the changes in allocation of resources for UP after the merger of BN and ATSF. As a result of all these changes, the market share of BNSF in local areas near South Dakota and Kansas will further increase.

In summary, results in Table 9 show that elimination of interchange cost and economies of scope both contribute to cost reduction post merger. However, reduction of the number of firms in local markets is not the main reason behind increased markup post merger, which instead is mainly driven by the strategic reaction of non-merging firms. The non-merging firms tend to move resources away from regions where the merged firm experiences a large efficiency gain because of changes in marginal productivity of capital. This results in further increases in the local market share of the merged firm and hence larger increase in markup in those areas.

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 10 shows the results of these calculations.[15] For example, in the baseline model, a node at the 95th percentile of changes in degree centrality has an extra 1.59 percent cost reduction post merger compared to a node at the 5th percentile of changes in degree centrality.

Table 10: Merger Gains and Centralities

	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: 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%

Panel I of Table 10 shows how changes in centrality affect cost reduction post merger. The first counterfactual eliminates interchange cost and economies of scope. Column (2) of Table 10 shows the results of this counterfactual: When only distance matters, increases in both degree and betweenness centrality result in higher cost reduction post merger. 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. In the second counterfactual I reincorporate interchange cost. Column (3) shows no significant change regarding the effect of changes in centrality after doing so.[16]

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

[16] Regression results in Table I.1 show that the coefficient of indicator of interchange becomes much larger

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 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 10 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. When there are no economies of scope, as in the first two counterfactuals, each *o*–*d* market is independent. 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 firms 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.

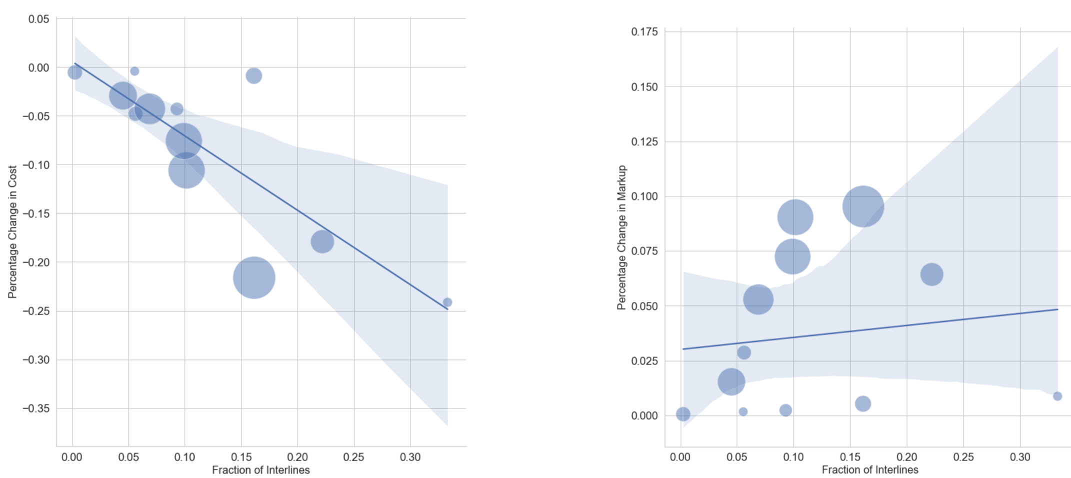
In summary, the results in Table 10 show that changes in betweenness centrality have a greater effect on both reduction of shipment cost and increase of markup post merger

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.

than changes in degree centrality. This is because nodes with large increases in betweenness centrality benefit not only from better routing options and shorter travel distance post merger, but also more from reallocation of resources when economies of scope are present. In comparison, nodes with large increases in degree centrality are more likely to benefit from better routing options, but not much from economies of scope post merger.

Degree of Overlap and Complementarity

Last, I show how merger gains vary with the degree of overlap and complementarity of the two merging networks. Specifically, I illustrate how merger gains vary across different mergers. I measure the degree of overlap by the total fraction of markets operated by both merging firms before the merger. Regarding the degree of complementarity, for each merger I count the number of interlines that are operated by the two merging firms and then obtain the proportion of interlines.



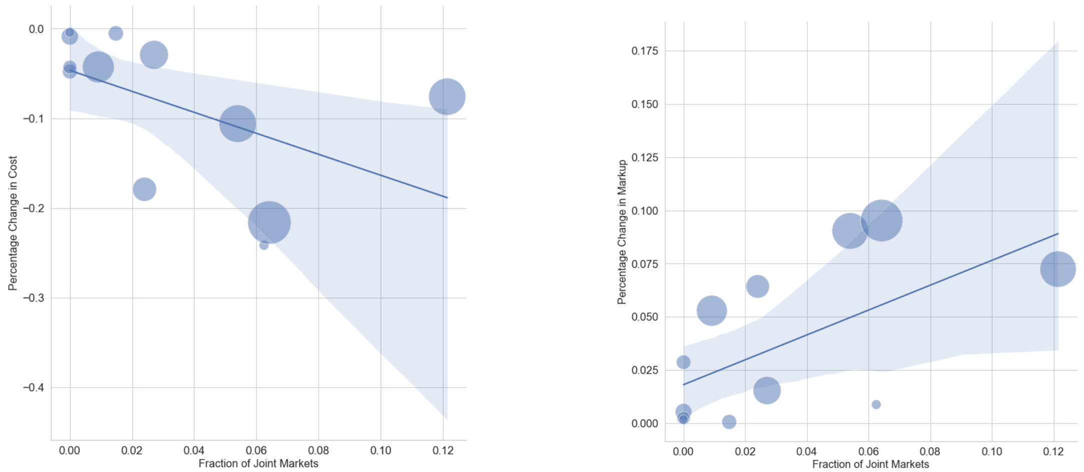
(a) Cost Changes and Degree of Complementarity

(b) Markup Changes and Degree of Complementarity

Figure 7: Degree of Complementarity and Average Merger Effects

Figure 7 shows the relationship between merger gains and degrees of complementarity. Size of circle represents the total number of origin–destination markets in the particular merger. Panel (a) shows that higher degrees of complementarity result in greater cost reduction post merger. For a merging network with a higher degree of complementarity, the merged firm benefits more from eliminating interchange costs. Panel (b) shows that a higher degree of complementarity also results in a greater increase in markup.

Figure 8 shows the relation between merger gains and degrees of overlap. Panel (a) shows that higher degrees of overlap result in greater cost reduction post merger. For a merging



(a) (a) Cost Changes and Degree of Overlap **(b)** (b) Markup Changes and Degree of Overlap

Figure 8: Degree of Overlap and Average Merger Effects

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) shows that a higher degree of overlap results in a greater increase in markup. If we compare Panel (b) in Figure 7 with Panel (b) in Figure 8, we can see that although a higher degree of complementarity also results in a greater increase in markup, the effect is much flatter.

Given the limited number of observations (only twelve mergers), I cannot draw any causal relation here. The results may indicate that a higher degree of complementarity between the two merging networks will result in greater cost reductions and a mild increase in markup, while a higher degree of overlap between the two merging networks will result in greater cost reductions and a greater increase in markup.

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 an optimal transport network model by endogenizing the firm's pricing, routing, and allocation decisions.

The counterfactual results show that averaged over all mergers, shipment cost was reduced by 12.9%, shipment price was reduced by 8.8%, and the additive markup increased by 7.2% after the wave of mergers. Moreover, network structure or topology matters in the freight network industry because it affects how much firms benefit from economy of scope. The counterfactual results show that within a merger, an increase in the degree centrality of a node by 1 unit results in a 0.53 percent extra reduction in cost. I then unpack the "black box," investigating how network structure affects the level of merger gains. I derive three main findings. First, 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 firms, which tend to move resources away from regions where the merged firm experiences a large efficiency gain. As a result, the combined company's local market share grows even more, leading to a higher markup. The first finding demonstrates the importance of considering market interdependence when estimating merger gains. Second, I show that changes in betweenness centrality have a greater effect on the reduction of shipment cost and the increase of markup post-merger than 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 large increases in degree centrality are more likely to benefit from better routing options but only a little from economies of scope post-merger. Third, if the two merging networks are more complementary, there may be greater cost savings and a slight increase in markup. The cost reduction and markup gain may be bigger if there is more overlap between the two merging networks.

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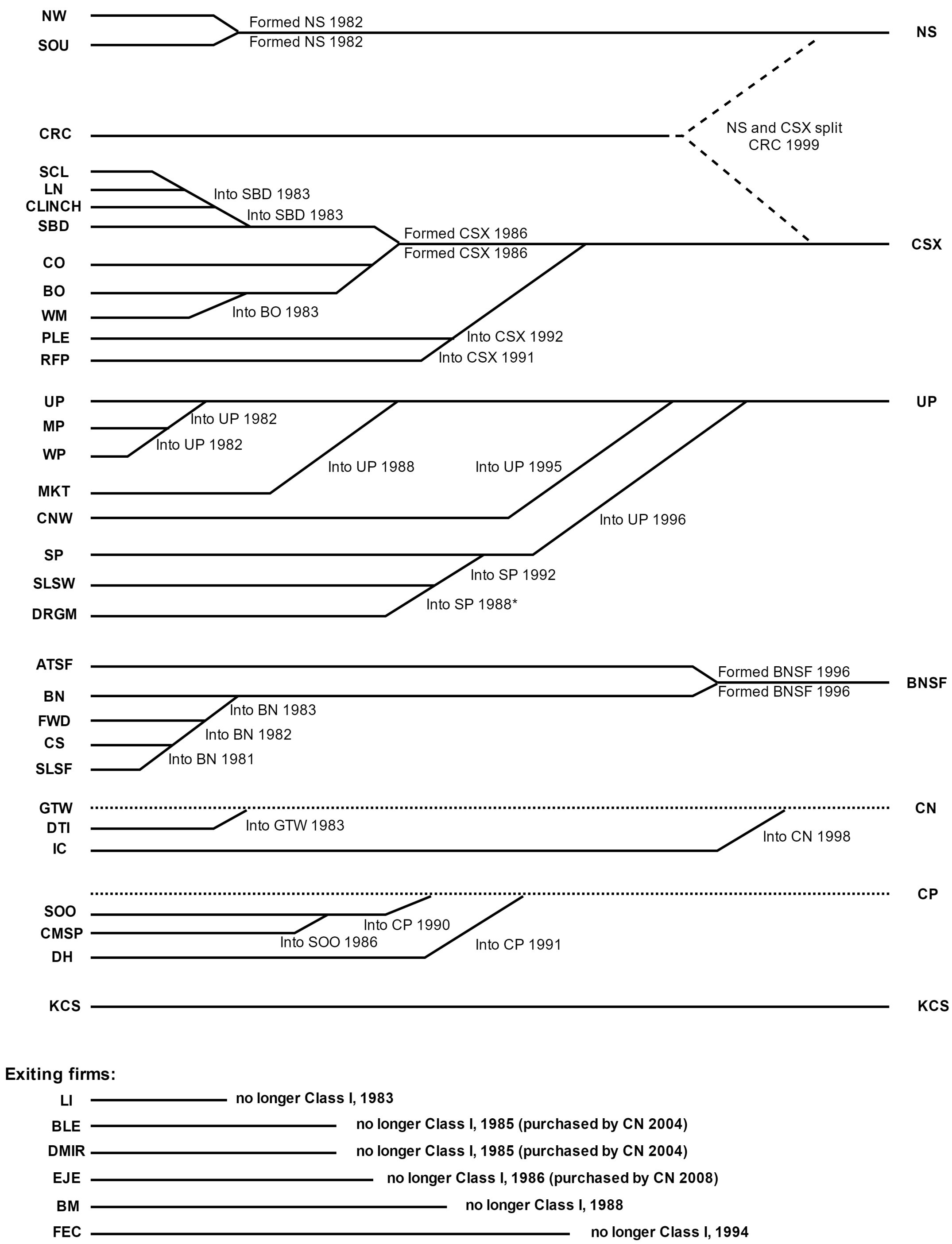
Online Appendices: Not For Publication

A History of American Railroads

Figure A.1: Merger History of Railroads



B Discussion of the Model

In this section, I explain the solutions of the model and explore the difference between the full model and the nested model. I solve the optimization problem of the full and nested models for a monopoly in Sections B.1 and B.2 respectively. Then I compare the equilibrium results of the two models in Sections B.3 and B.4.

B.1 The Full Model

Each firm j owns a network $\mathcal{G}_j$ with corresponding nodes $\mathcal{Z}_j$ and arcs $\mathcal{A}_j$. Firms make pricing, routing, and maintenance decisions, choosing 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 decisions $\{I_{j,ab}\}_{(a,b)\in\mathcal{A}_j}$ to maximize profit. Denote $S(j)$ as the set of services s in which j participates. The optimization problem is defined as

$$\pi_j := \max_{\{p_{s,od}\},\{\mathcal{R}_{j,o_j(s),d_j(s)}\},\{I_{j,ab}\}_{(a,b)\in\mathcal{A}_j}} \sum_{s:s\in S(j)} p_{s,od} \cdot Q_{s,od} - C(\boldsymbol{Q}, \boldsymbol{R}, \boldsymbol{I}) \tag{B.1}$$

$$\Rightarrow \max_{\boldsymbol{p},\boldsymbol{R},\boldsymbol{I}} \sum_{s:s\in S(j)} p_{s,o_j(s)d_j(s)} \cdot Q_{s,o_j(s)d_j(s)} - c_{s,o_j(s),d_j(s)}\big(\boldsymbol{I}_j, \mathcal{R}_{j,o_j(s),d_j(s)}\big) \cdot Q_{s,o_j(s)d_j(s)}$$

with resource allocation constraint:

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

and balanced-flow constraint: for any service s in any market o–d and $\forall$ node $z \in \mathcal{Z}_j$,

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

The balanced-flow constraint imposes that for any node z on railroad j's network $\mathcal{Z}_j$, the net demand $D_{j,z}$ plus the inflow of serviced goods (left-hand side) from its adjacent nodes $\mathcal{Z}_j(z)$ is equal to the outflow (right-hand side) to its adjacent nodes.[17] The resource allocation constraint shows that each firm j has a fixed amount of resources K_j that it

[17]The details of the balanced-flow constraint are:

- $\mathbb{1}(\cdot)$ is an indicator function, with $\mathbb{1}\{(a,m') \in \mathcal{R}_{j,od_j(s)}\} = 1$ if arc (a,m') is in the routing from o_j to d_j of firm j.
- $a \in \mathcal{Z}_j(m)$ means that a is a neighbor of node m. The total inflow of traffic into node m' is the summation of traffic from all the arcs (a,m') of firm j such that $a \in \mathcal{Z}_j(m)$.
- $D_{j,m'}$ is the net demand at node m'; $D_{j,m'} = \begin{cases} Q_{s,od} & \text{if } m' = o \\ -Q_{s,od} & \text{if } m' = d \\ 0 & \text{otherwise.} \end{cases}$

can allocate to the arcs $\mathcal{A}_j$ in its network. Given the optimization problem, the Lagrange function of firm j is written as

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

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

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

where $c_{j,ab}$ is the arc-level cost of firm j:

$$c_{j,ab} = \frac{\delta_0 Dist_{j,ab}}{I_{j,ab}^{\gamma}}.$$

For each service $s \in S(j)$ that firm j provides, the optimal pricing decision is solved through the FOC:

$$\begin{aligned} & \frac{\partial \mathcal{L}_j}{p_{s,od}} = 0 \\ \Rightarrow \quad & Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial C(\boldsymbol{Q}, \boldsymbol{R}, \boldsymbol{I})}{\partial Q_{s,od}} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} = 0 \\ \Rightarrow \quad & Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial Q_{s,od}}{\partial p_{s,od}} \cdot \left[C_{s,od} + \underbrace{\frac{\partial C_{s,od}}{\partial Q_{s,od}} Q_{s,od}}_{\text{own-cost effect}} + \underbrace{\sum_{s'\in S(j), s'\neq s} \frac{\partial C_{s',o'd'}}{\partial Q_{s,od}} Q_{s,o'd'}}_{\text{cross-cost effects}} \right] = 0. \end{aligned} \tag{B.2}$$

By taking the derivatives with respect to $I_{j,ab}$ for every arc $(a,b) \in \mathcal{A}_j$, we can calculate

$$\frac{\partial \mathcal{L}_j}{I_{j,ab}} = \sum_{s:s\in S(j)} \frac{\gamma \cdot \delta_0 Dist_{j,ab} \cdot Q_{s,od} \cdot \mathbb{1}\{(a,b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}}{I_{j,ab}^{\gamma+1}} + \lambda_j.$$

Given the resource allocation constraint, the optimal allocation decision is obtained through the Kuhn–Tucker condition such that $\forall (a,b) \in \mathcal{A}_j$,

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

Therefore, for any non-zero $I_{j,ab}$ and $I_{j,a'b'}$, we know that

$$\frac{I_{j,ab}}{I_{j,a'b'}} = \left[\frac{Dist_{j,ab} \cdot q_{j,ab}}{Dist_{j,a'b'} \cdot q_{j,a'b'}}\right]^{\frac{1}{1+\gamma}} \tag{B.3}$$

where $q_{j,ab}$ is the total amount of shipment running through arc (a, b), $q_{j,ab} = \sum_{s:s\in S(j)} Q_{s,od} \cdot \mathbb{1}\{(a, b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}$. The resource allocation constraint binds at the maxima, hence

$$\sum_{(a,b)\in\mathcal{A}_j} I_{j,ab} = K_j. \tag{B.4}$$

Because I assume that there is no congestion within a market or across markets, 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, which is represented by solving $\forall s \in S(j)$:

$$\min_{\mathcal{R}_{j,od}} \sum_{(a,b)\in\mathcal{R}_{j,od}} c_{j,ab}$$

$$\Rightarrow \min_{\mathcal{R}_{j,od}} \sum_{(a,b)\in\mathcal{R}_{j,od}} \frac{\delta_0 Dist_{j,ab}}{I^{\gamma}_{j,ab}}$$

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

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

This is a linear-programming problem, and can be written vectorially as

$$\min_{\boldsymbol{q}} \boldsymbol{c} \times \boldsymbol{q} \quad \text{such that } \nabla\boldsymbol{q} = \begin{bmatrix} \cdots \\ -1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ \cdots \end{bmatrix}_{J\times 1} . \tag{B.5}$$

where J is the number of nodes owned by firm j. $\nabla q = -1$ at the origin o and 1 at the destination d. This minimization problem is solved using linear-programming algorithms. Combining the solutions to equation B.5 with the system of equations of B.2, B.3 and B.4, we can obtain the maxima $\boldsymbol{p}^*, \boldsymbol{R}^*$, and $\boldsymbol{I}^*$ of the full model.

B.2 The Nested Model

In the nested model, firms make their pricing, routing, and maintenance decisions in two stages. In the first stage, firms form expectations over transportation demand in each local market $\widetilde{Q}_{s,od}$. Given the expected demand, firms choose the optimal routing and allocation decisions. In the second stage, firms compete in local markets and choose prices simultaneously. In equilibrium, the expected demand in each local market is consistent with the outcome at the pricing stage.

Stage Two: Local Market Competition

$$\pi_{s,od} := \max_{p_{s,od}} [p_{s,od} - C_{s,od}] \cdot Q_{s,od} \tag{B.6}$$

Stage One: Operational Decision in the Network

$$\min_{\{\mathcal{R}_{j,o_j(s),d_j(s)}\},\{I_{j,ab}\}_{(a,b)\in\mathcal{A}_j}} \sum_{s:s\in S(j)} C_{s,o_j(s),d_j(s)}(\boldsymbol{I}_j, \mathcal{R}_{j,o_j(s),d_j(s)}) \cdot \widetilde{Q}_{s,od} \tag{B.7}$$

given resource allocation constraint:

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

and balanced-flow constraint: for any service s in any market o–d and $\forall$ nodes $z \in \mathcal{Z}_j$,

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

I solve the model backward. In the second stage, for each service s that firm j provides, $s \in S(j)$, the optimal pricing decision is solved through the FOC:

$$\begin{aligned} &\frac{\partial \pi_{s,od}}{p_{s,od}} = 0 \\ \Rightarrow \quad & Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial Q_{s,od}}{\partial p_{s,od}} \cdot C_{s,od} = 0. \end{aligned} \tag{B.8}$$

In the first stage, given the expected demand in each local market $\widetilde{Q}_{s,od}$, firm j solves the cost minimization problem in equation B.7. The Lagrange function of firm j is written as

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

Similarly to the full model, by taking the derivatives with respect to $I_{j,ab}$ for every arc $(a,b) \in \mathcal{A}_j$ we can obtain the optimal allocation decision via the Kuhn–Tucker condition.

For any non-zero $I_{j,ab}$ and $I_{j,a'b'}$, we have

$$\frac{I_{j,ab}}{I_{j,a'b'}} = \left[\frac{Dist_{j,ab} \cdot q_{j,ab}}{Dist_{j,a'b'} \cdot q_{j,a'b'}}\right]^{\frac{1}{1+\gamma}} \tag{B.9}$$

where $q_{j,ab}$ is the total amount of shipment running through arc (a,b), $q_{j,ab} = \sum_{s:s\in S(j)} \widetilde{Q}_{s,od} \cdot \mathbb{1}\{(a,b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}$. The resource allocation constraint binds at the maxima, hence

$$\sum_{(a,b)\in\mathcal{A}_j} I_{j,ab} = K_j. \tag{B.10}$$

The optimal routing decision for each $s \in S(j)$ is obtained by solving the linear-programming problem

$$\min_{\boldsymbol{q}} \boldsymbol{c} \times \boldsymbol{q} \quad \text{such that } \nabla \boldsymbol{q} = \begin{bmatrix} \cdots \\ -1 \\ 0 \\ 1 \\ 0 \\ \cdots \end{bmatrix}_{J\times 1}. \tag{B.11}$$

where $\nabla q = -1$ at the origin o and 1 at the destination d.

In equilibrium, $\widetilde{\boldsymbol{Q}} = \boldsymbol{Q}(\boldsymbol{p}^*)$. Combining the solutions to equation B.11 with the system of equations of B.8, B.9 and B.10, we can obtain the maxima $\boldsymbol{p}^*, \boldsymbol{R}^*, \boldsymbol{I}^*$ of the nested model. In the next section, I compare the full and nested models' equilibrium results.

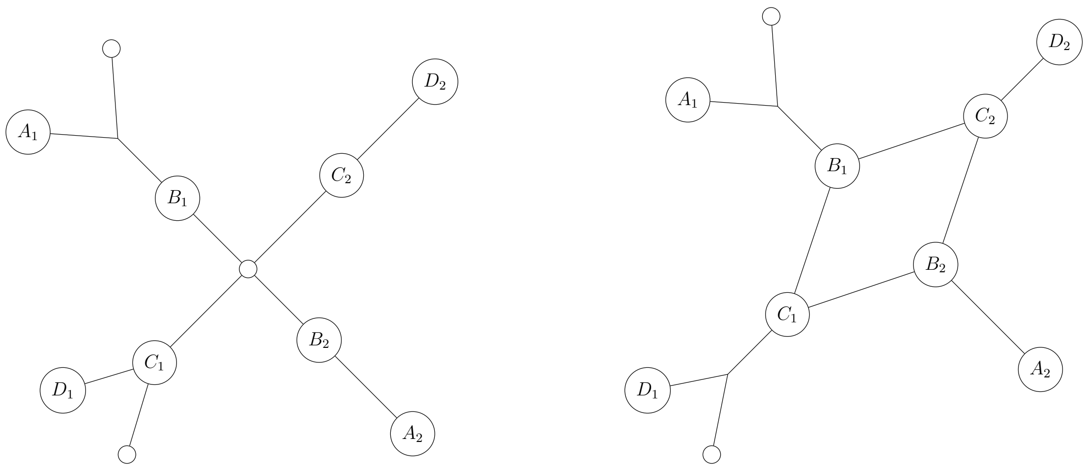
B.3 Comparing Equilibrium Results in the Two Models

Table B.1 compares the solutions for pricing, routing, and allocation decisions between the full model and the nested model. The key difference between the two models is that when solving the optimal pricing for each service $p_{s,od}$, in the full model the firm considers how the changed quantity will further affect the routing and allocation decisions, affecting in turn the shipment cost of all the relevant markets ($\frac{\partial C(\boldsymbol{Q},\boldsymbol{R},\boldsymbol{I})}{\partial Q_{s,od}}$). In the nested model, in solving the optimal pricing the firm takes the shipment cost as given ($C^{**}_{s,od}$).

Table B.1: Optimal Strategies in Full Model versus Nested Model

	Full Model	Nested Model
Pricing	$\frac{\partial \pi_{s,od}}{p_{s,od}} = 0$ $\Rightarrow Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial C(\boldsymbol{Q},\boldsymbol{R},\boldsymbol{I})}{\partial Q_{s,od}} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} = 0$	$\frac{\partial \pi_{s,od}}{p_{s,od}} = 0$ $\Rightarrow Q_{s,od} + p_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - C^{**}_{s,od} \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} = 0$
Maintenance Allocation	$I^*_{j,ab} = \left[\frac{\gamma}{\lambda_j} \cdot \delta_0 Dist_{j,ab} \cdot q^*_{j,ab}\right]^{\frac{1}{1+\gamma}}$	$I^{**}_{j,ab} = \left[\frac{\gamma}{\lambda_j} \cdot \delta_0 Dist_{j,ab} \cdot q^{**}_{j,ab}\right]^{\frac{1}{1+\gamma}}$
Routing	$\min_{\boldsymbol{q}} \boldsymbol{c}(\boldsymbol{I}^*) \times \boldsymbol{q} \quad \text{such that } \nabla \boldsymbol{q} = \boldsymbol{Q}^*_{\boldsymbol{s}}$	$\min_{\boldsymbol{q}} \boldsymbol{c}(\boldsymbol{I}^{**}) \times \boldsymbol{q} \quad \text{such that } \nabla \boldsymbol{q} = \boldsymbol{Q}^{**}_{\boldsymbol{s}}$

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. Figure B.1 illustrates when the topology of a network is a tree and when it is non-tree. Panel (a) shows a topology that is a tree, and panel (b) shows a non-tree where $B_1 — C_1 — B_2 — C_2 — B_1$ forms a loop. The key difference between a tree and a non-tree is the variety of routing options. For a tree networked topology, there is only one routing option for each o–d market.



(a) Tree

(b) Non-Tree

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

B.3.1 Without Economy of Scope ($\gamma = 0$)

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

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

$$C_{s,od}(\boldsymbol{I}_j, \mathcal{R}_{j,od}) = \sum_{(a,b)\in\mathcal{R}_{j,od}} \frac{\delta_0 Dist_{j,ab}}{I^{\gamma}_{j,ab}}$$
$$= \sum_{(a,b)\in\mathcal{R}_{j,od}} \delta_0 Dist_{j,ab} \qquad \text{if } \gamma = 0. \tag{B.12}$$

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 B.12, 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 ($\gamma = 0$).

B.3.2 With Economy of Scope ($\gamma \neq 0$) and Tree Network Topology

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 B.12 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 $\sum_{(a,b)\in\mathcal{A}_j} I_{j,ab} \leq K_j$. Equations B.3 and B.9 show 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 equations B.3 and B.9, we know that

$$\begin{aligned}\frac{I_{ab}}{I_{a'b'}} &= \left[\frac{Dist_{j,ab} \cdot q_{j,ab}}{Dist_{j,a'b'} \cdot q_{j,a'b'}}\right]^{\frac{1}{1+\gamma}} \\ &= \left[\frac{Dist_{j,ab} \cdot \sum_{s:s\in S(j)} Q_{s,od} \cdot \mathbb{1}\{(a,b) \in \mathcal{R}_{j,od}\}}{Dist_{j,a'b'} \cdot \sum_{s:s\in S(j)} Q_{s,od} \cdot \mathbb{1}\{(a',b') \in \mathcal{R}_{j,od}\}}\right]^{\frac{1}{1+\gamma}}. \end{aligned} \tag{B.13}$$

If $Q_{mn} \gg Q_{od}, \forall od \neq mn$, from equation B.13 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 nested model and the full model is negligible. Otherwise, the direction of the bias of the nested 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 $\boldsymbol{R}_{\boldsymbol{j}}^{*}$ 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 nested 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 nested models are ambiguous.

B.3.3 With Economy of Scope ($\gamma \neq 0$) and Non-Tree Network Topology

In this case we compare the equilibrium results between the full and nested models when the network is non-tree. With a non-tree topology, the optimal allocation decision is still solved via equations B.3 and B.9, while the optimal pricing decisions are solved via equations B.2 and B.8. However, with the non-tree topology the routing decision is non-trivial and changes in terms of the allocation of resources. Given one set of routing decisions, we can solve the optimal allocation and pricing decisions. Because the set of origin–destination markets is finite, we have finite possibilities of routing through those markets. So we can exhaust the possibilities of routing decisions and find 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

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

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

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

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 nested model and the full model is negligible. Otherwise, the direction of the bias of the nested 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 nested models will be approximately the same when one market dominates. Otherwise, the direction of the bias is ambiguous.

If it is not the case that one market dominates, then the comparison in a non-tree network is more complicated than in a tree network. The routing decisions might differ in the two models when the network is non-tree. Propositions 2 and 3 show that when there is an economy of scope ($\gamma \neq 0$) and none of the single markets dominates, the difference between the nested model and the full model depends on the level of demand in each origin–destination market and the direction of the bias of the nested model is ambiguous. To provide some insight into the size of the difference, I provide results from numerical simulations in Section B.4.

B.4 Comparing Results in the Two Models: Numerical Simulation

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 G displays the analytical solutions of the optimal strategies for the nested 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 nested 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.

B.4.1 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 B.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 G.1 shows the analytical solutions of the optimal strategies of the nested model and the full model.

Table B.2 compares the equilibrium price and cost results between the two models. In Panel I of Table B.2 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 B.2 shows that the difference in the equilibrium prices and costs between the nested model and the full model is very small.

Table B.2: Equilibrium Prices and Costs under Tree

Market	**Prices**			**Costs**		
	Nested Model	Full Model	Difference	Nested 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

Table B.3 shows the optimal allocation decisions I^*. There are three key findings of the numerical results. First, Panel I of Table B.3 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 B.3, 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 nested model and the full model. Panel I shows the difference as 10^{-6}. Panel II 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 B.3: Equilibrium Allocation of Resources under Tree

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

B.4.2 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 B.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 G.2 shows the analytical solutions of the optimal strategies of the nested model and the full model. First, to investigate how routing and allocation decisions change in different cases, Table B.3 shows the optimal allocation decisions I^* and routing decisions $\mathcal{R}$. First, there is no significant difference between the full model and the nested 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).

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

Arc	Nested 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 $C_1 \to C_2$		$C_1 \to B_2 \to C_2$	
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 $C_1 \to C_2$		$C_1 \to B_1 \to C_2$	
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 $C_1 \to C_2$		$C_1 \to B_2 \to C_2$	

Table B.5 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 nested and the full model is very small.

Table B.5: Equilibrium Prices and Costs under Non-Tree

Market	**Prices**			**Costs**		
	Nested Model	Full Model	Difference	Nested 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

In summary, the simulation results in Section B.4 show that regardless of whether the network's topology is a tree or non-tree, the difference in the equilibrium outcomes between the full and nested models is minimal.

C Discussion of the Assumptions

Besides the two main assumptions I discuss in Section 5, here I list the other assumptions I impose in the model.

1. For interconnecting routes, I assume that the originating firm of the joint-line service determines the price of the service and there is no double-marginalization of pricing. One way to interpret this assumption is that the originating railroad has all the bargaining power. Another is to think of the two railroad firms in the joint-line service as jointly determining the price as one entity and then dividing the revenue between them in a meaningful way. Using Waybill data, Alexandrov, Pittman and Ukhaneva (2018) show that there is no issue with double marginalization in the pricing of the interconnecting route. I document interviews with railroad managers about how interchange works in this industry in Appendix E.3, which coincides with my assumption here. In the interviews, the managers also mentioned that when the pricing department gives quotes to the customers, they do not strategically consider how the resulting demand affects the subsequent operational decision. Therefore, my nested model approximates the underlying data-generating process well.

2. I assume that firms do not consider the cannibalization between their single-line and joint-line services provided in the same o–d market. This assumption means that each service is priced independently, even if a firm may participate in a single- and a joint-line service in the same market. For example, imagine three services serving the market from LA to Memphis: a single-line service provided by the Burlington Northern railway, a single-line service provided by the Union Pacific railway, and a joint-line service provided by the two railways. I assume that the Burlington Northern railway prices the single-line and joint-line services independently. In reality, the case of a railroad offering both a single- and a joint-line service in the same o–d market is very rare, so I made this assumption to simplify computation. Relaxing this assumption has barely any effect on the results.

3. In my model, I consider joint-line service with only one interchange. In the data, more than 90% of joint-line services involve only one interchange. This assumption can easily be relaxed. For example, if there is more than one interchange, say service s from o to d is $s = [j_1, j_2, \cdots, j_n]$, the general form of transportation cost of service s from origin o to destination d is written as

$$C_{s,od} = \sum_{j \in J(s)} \sum_{(a,b) \in \mathcal{R}_{j,od_j(s)}} c_{j,ab} + \#_{interchanges} \cdot \eta$$
$$= \sum_{j \in J(s)} \sum_{(a,b) \in \mathcal{R}_{j,od_j(s)}} \left[\frac{\delta_0 Dist_{j,ab}}{I^{\gamma}_{j,ab}} \right] + \#_{interchanges} \cdot \eta$$

   where $J(s)$ is the set of firms that provide service s, and $\#_{interchanges}$ is the total number of interchanges incurred in providing service s.

D 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.

E Details of U.S. Railroad Industry

E.1 Industry Statistics

Figures E.1 and E.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.

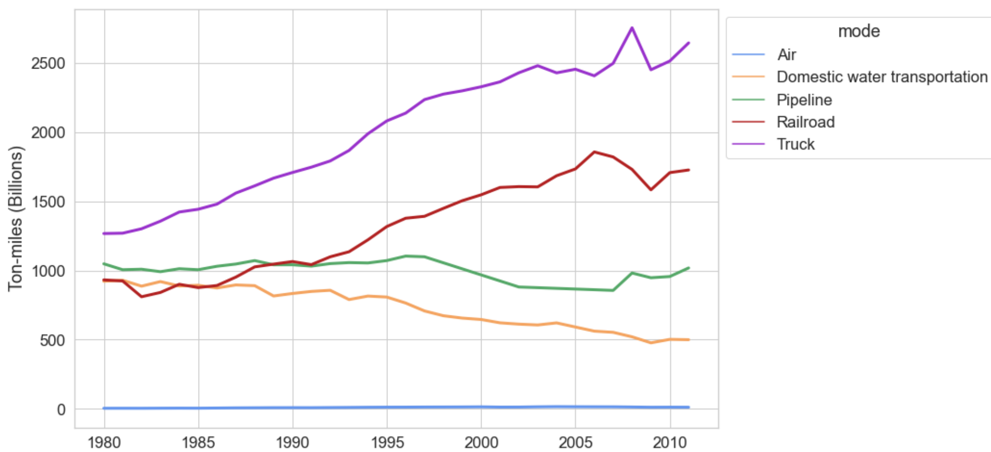


Figure E.1: U.S. total ton-miles of freight by mode

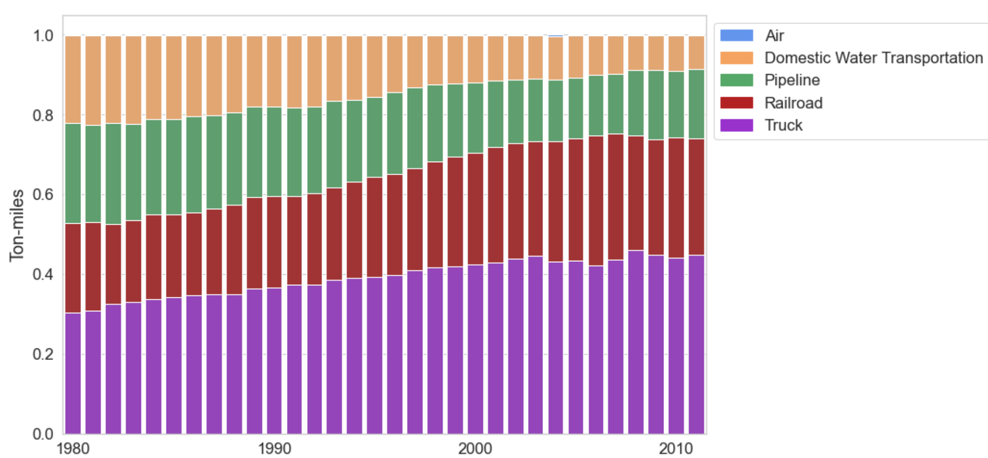


Figure E.2: U.S. total ton-miles of freight by mode (percentage)

E.2 More Summary Stats of Waybill Data

Table E.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 E.1 shows that the pattern of year-on-year change tells the same story as in Table 2. 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.

E.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.*

4. I also interviewed Terminal Superintendent at Conrail about how interchange works and why it is costly. Consult the author for more details.

F 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 F.1 shows a complete summary statistics of commodities shipped by rail from waybill data.

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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Field Crops	Metallic Ores	Coal	Nonmetallic Minerals	Food or Kindred Products	Apparel or Textile Products	Lumber or Wood Products	Furniture or Fixtures	Pulp, Paper	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

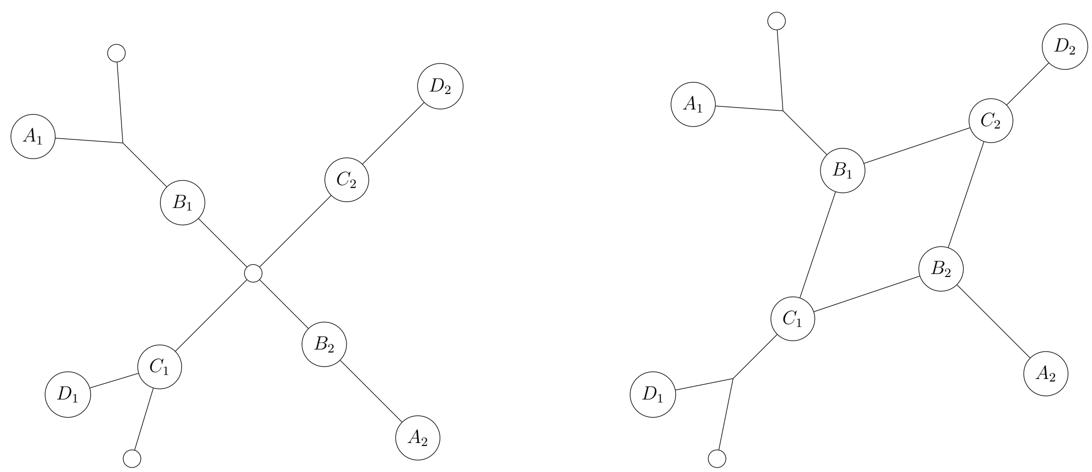
	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
	Chemicals	Petroleum	Plastics Products	Clay, Concrete, Stone Products	Primary Metal Products	Fabricated Metal Exc.	Machinery	Electrical Machinery	Transportation Equipment	Miscellaneous Products
Indicator of Merger	−0.114***	−0.115***	−0.056**	−0.045***	−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)	(22)	(23)	(24)	(25)	(26)	(27)	(28)
	Waste or Scrap Materials	Miscellaneous Freight Shipment	Containers	Mail	Shipper Association	Miscellaneous Mixed	Small Packaged	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.

G Numerical Example

In the numerical example, I consider the two networks as in Figure B.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

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

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

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

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

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

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

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

G.1 Tree

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

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

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

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

Based on routing options, we know that

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

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

$$I_{A_1B_1} = \frac{6Q_{A_1A_2}^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}$$

$$I_{B_1B_2} = \frac{6(Q_{A_1A_2} + Q_{B_1B_2})^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}$$

$$I_{B_2A_2} = \frac{6Q_{A_1A_2}^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}$$

$$I_{D_1C_1} = \frac{6Q_{D_1D_2}^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}$$

$$I_{C_1C_2} = \frac{6(Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}$$

$$I_{C_2D_2} = \frac{6Q_{D_1D_2}^{1/2}}{2Q_{A_1A_2}^{1/2} + (Q_{A_1A_2} + Q_{B_1B_2})^{1/2} + 2Q_{D_1D_2}^{1/2} + (Q_{D_1D_2} + Q_{C_1C_2})^{1/2}}.$$

Then substitute the optimal allocation of infrastructure into G.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:

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

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

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

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

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

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

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

G.2 Non-Tree

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

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

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

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

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 G.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 G.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 $C_1 \to B_2 \to C_2$

$$c_{A_1C_1} = \frac{2Q_{A_1C_1}^{1/2} + (Q_{A_2C_1} + Q_{C_1C_2})^{1/2} + Q_{A_2C_1}^{1/2} + Q_{C_1C_2}^{1/2}}{4Q_{A_1C_1}^{1/2}}$$

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

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

Given the cost functions, we can derive the FOCs:

- If $C_1 \to B_1 \to C_2$

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

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

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

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

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

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

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

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

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

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

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

- If $C_1 \to B_2 \to C_2$

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

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

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

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

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

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

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

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

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

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

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

H Comparative Statistics

(a) Allocation of Resources, $\gamma = 0$

(b) Routing of $3 \to 7$, $\gamma = 0$

(c) Allocation of Resources, $\gamma = 0.5$

(d) Routing of $3 \to 7$, $\gamma = 0.5$

(e) Allocation of Resources, $\gamma = 0.85$

(f) Routing of $3 \to 7$, $\gamma = 0.85$

Figure H.1: How Value of γ Affects Allocation and Routing Decisions

Figure H.1 shows how Conrail's routing and allocation decisions change when the value of γ changes. Panels (a), (c), and (e) show the maintenance allocation decision; line thickness shows the number of resources allocated. Panels (b), (d), and (f) show the routing decision for origin 3 and destination 7 when the value of γ changes.

I show the comparative statistics of three scenarios when $\gamma = 0, 0.5$, and 0.85, respectively. When $\gamma = 0$, resources do not matter. Hence each market is independent. Resources are evenly allocated to all arcs owned by Conrail in Panel (a), routing from 3 to 7 adopts the shortest distance $3 \to 10 \to 7$ in Panel (b). When γ is non-negative, there is economy of scope, so it is more cost-efficient to consolidate traffic and allocate more resources to routes with larger traffic volume. Comparing Panel (c) to (a) or Panel (e) to (c), we see that when γ increases, the allocation is more consolidated within "major" routes. Regarding routing, as γ increases the optimal routing no longer follows the shortest distance because the routing now takes advantage of the lower cost of going through "major" routes (like "highway" vs. "country road"). The optimal routing changes from $3 \to 10 \to 7$ in Panel (b) to $3 \to 10 \to 8 \to 7$ in Panel (d) and $3 \to 10 \to 9 \to 8 \to 7$ in Panel (f). In summary, the comparative statistics show that the value of γ affects the effectiveness of resources and hence routing and allocation decisions.

I Counterfactual Results

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

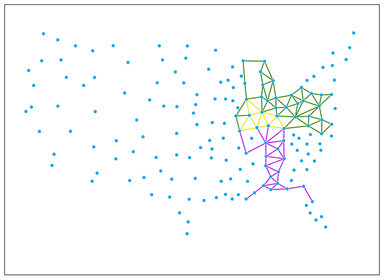
Table I.1: Merger Gains and Centralities (Regression Results)

	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: Δ log(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: Δ log(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)

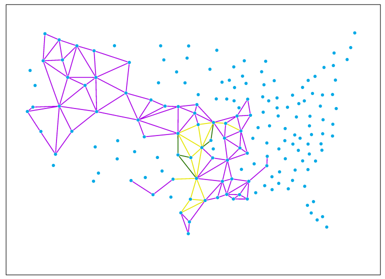
Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Figure I.1: Networks for Each Merger Case

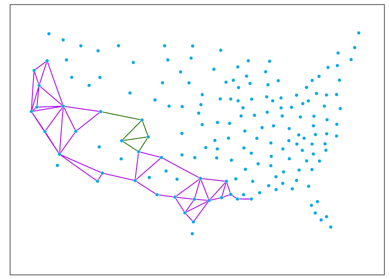
Note: Figure I.1 shows the virtual networks of the two merging parties in each merger case between Class I railroads from 1985 to 2005. There were 12 mergers in total. Within each merger (firm1 + firm2), the network of firm1 is marked in green, that of firm2 is marked in purple, and the overlapping part 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.



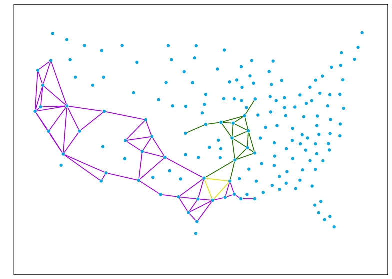
(a) 1986, COBO + SBD



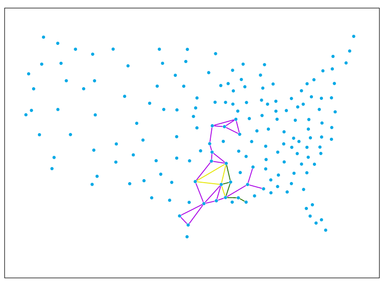
(b) 1988, MKT + UP



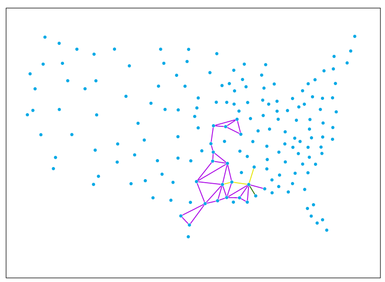
(c) 1988, DRGW + SP



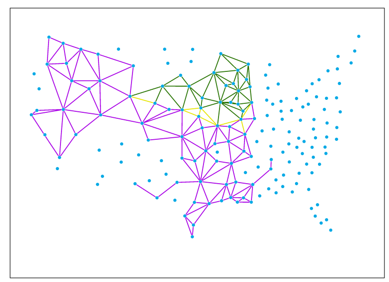
(d) 1992, SSW + SP



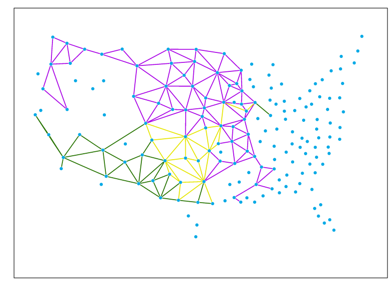
(e) 1992, LA + KCS



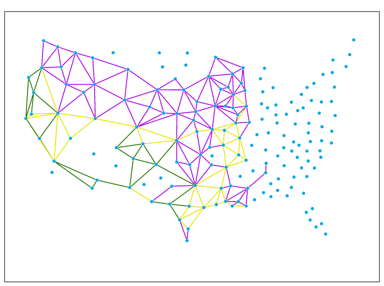
(f) 1993, MSRC + KCS



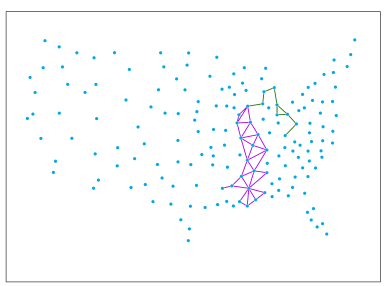
(g) 1995, CNW + UP



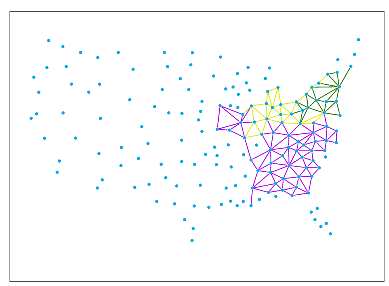
(h) 1996, ATSF + BN



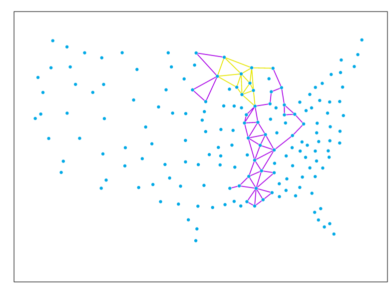
(i) 1996, SP + UP



(j) 1998, CN + IC



(k) 1999, CR + NS



(l) 2004, WC + CN