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

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Abstract

The trade-off between efficiency gains and market power is central to antitrust analysis of mergers. However, direct empirical evidence on these gains remains limited. This paper uses transaction-level data from U.S. freight railroads from 1985 to 2005 and quantifies significant cost efficiencies resulting from mergers. These efficiency gains primarily arise from the elimination of interchange costs between railroad companies and the economies of scope achieved by operating a larger network. To understand the equilibrium effects of these mergers, I introduce and estimate a spatial equilibrium model featuring oligopolistic competition among railroad networks. Counterfactual analyses show that mergers led to a 12.9% reduction in costs and an 8.8% decrease in prices, while markups increased by 7.2% as non-merging firms reallocated investments away from regions where merged firms had achieved substantial cost reductions.

Keywords: Cost Efficiency, Oligopolistic Competition, Mergers, Market Power, Transportation

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1 Introduction

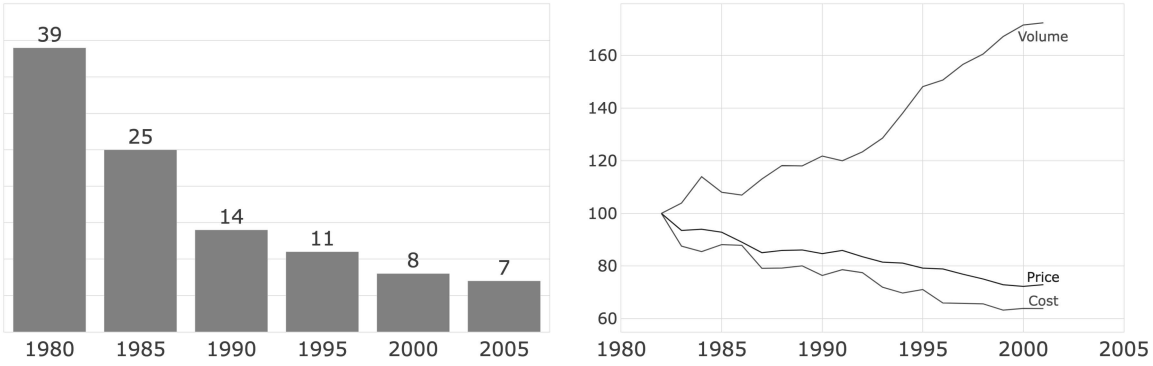
The transportation sector serves as the lifeblood of modern society, playing a vital role in facilitating commerce, trade, and social interactions. In many cases, the networks in this sector are owned by a few transportation companies that invest in their own infrastructure. These companies typically possess significant market power and hold substantial market shares. While existing research primarily focuses on the decisions made by social planners or atomistic players in creating transportation networks, the influence of market power in shaping transportation networks has yet to be explored.[1] This leaves important questions unanswered: how should mergers within these networks be analyzed, and what is their impact on transportation costs?

To shed light on these questions, this paper is the first to examine mergers in a network industry with oligopolistic competition. There are two main challenges in studying this issue. First, within a network, a decision made by a firm in one market can ripple across and influence its decisions in other markets where it operates. Second, in an oligopolistic competitive environment, firms must not only solve the complex optimization problem within their own networks but also consider the decisions of their competitors. This implies strong equilibrium effects of mergers, as non-merging firms will also re-adjust their operational decisions. Thus, to address both challenges, it is necessary to consider both the interdependence of markets within a single network and the interactions among networks owned by different firms. There is currently no model that does so in the literature. My paper aims to fill this gap by proposing a spatial equilibrium model of oligopolistic competition, where each firm decides where to invest in its own network infrastructure and makes routing and pricing decisions while considering the decisions of its competitors.

I apply the proposed model to the context of U.S. freight railroads, a network-based industry that has undergone significant changes in the competitive landscape over the past three decades. In addition to its historical significance for economic

[1]The transportation network can be designed by a social planner — an approach characterized by centralized decision-making. For instance, Fajgelbaum and Schaal (2020) studies the optimal highway network of a social planner. Alternatively, a transportation network can emerge from the actions of atomistic players in a decentralized manner, where individual entities like container ships independently choose their routes and ports, with the network forming from the cumulative decisions of these players. Current spatial models often analyze such cases by assuming the presence of numerous atomistic players. This approach has been used in Buchholz (2022) for taxis and in Brancaccio et al. (2020, 2023) for oceanic bulk shipping.

development, railroads continue to be one of the most crucial modes of transportation for freight, right up to the present day. According to the Association of American Railroads (AAR), railroads in 2016 transported about 40% of intercity ton-miles, more than any other mode of transportation. A series of mergers occurred in this industry between 1985 and 2005. The number of Class I railroads dropped from 39 to 7 over this period (Panel (a) of Figure 1), while the market share of the top four firms increased from 66% to 94%. Although concentration in this industry has increased, prices have steadily decreased. As illustrated in Panel (b) of Figure 1, prices per shipment fell by 20% in real terms between 1985 and 2005, while total shipment volume doubled. The price reduction suggests that there may have been efficiency gains following these railroad mergers, given the limited technological advancements observed within the industry during the study period.



(a) Number of Class I Railroads

(b) Shipment Price, Cost, and Volume

Figure 1: U.S. Freight Railroads

Notes: The data source used to construct the figures is the Class I Railroad Annual Report. Panel (a): Class I railroads are defined as those "having annual carrier operating revenues of $250 million or more in 1991 dollars." According to the Association of American Railroads, Class I railroads accounted for more than 95% of U.S. freight railroad industry revenues. Panel (b): Volume is measured in gross ton-miles carried, price is defined as freight revenue per ton-mile, and average cost is operating cost per ton-mile.

While economists have been aware of the trade-off between market power and efficiency gains at least since Williamson (1968), and this trade-off has been central to the antitrust analysis of horizontal mergers, there is still very little direct empirical evidence regarding the efficiency gains from mergers.[2] By applying the proposed model

[2]Notable exceptions include Ashenfelter et al. (2015) for the U.S. beer industry and Clark and Samano (2022) for the electricity distribution industry.

to the U.S. freight railroad industry, this paper uncovers and quantifies significant efficiency gains from railroad mergers.

I utilize four data sources in my analysis. First, I use the Carload Waybill Sample, a transaction-level dataset providing information on the shipment price, the types of commodities being transported, the total invoiced weight, equipment used, the railroads involved, and the specifics of origin, destination, and interchange points for every load.[3] Second, the Class I Railroad Annual Report provides yearly data on firm characteristics and aggregate operational statistics such as annual maintenance spending. Third, the Commodity Flow Survey contains information about shipment volumes across various transport modes for distinct origin–destination markets. Fourth, I obtain geographic data from the Department of Transportation regarding all U.S. rail lines and their affiliated railroad firms. This enables me to retrospectively map out the rail network of each railroad firm for any specified year. I have acquired all four datasets from 1985 to 2005.

I first provide suggestive evidence of efficiency gains by running a difference-in-differences analysis of shipment prices on merger dummies. The findings indicate that, on average, shipment prices have dropped by 9% after mergers. On routes where railroad companies engaged in an interchange prior to the merger, the price impact of the merger is 11%. For other route categories, the price effect is approximately 6%.

I then develop an empirical model that captures the annual decision-making process of railroad firms. In a railroad network, locations are arranged on a *graph*, and goods can only be shipped through connected locations. Each railroad firm possesses its own network, with the physical tracks being individually owned by each firm. In this network, the market locations are represented as nodes, while the physical tracks between them serve as arcs. The model needs to capture two important aspects of the environment noted previously: first, the interdependence of markets within a firm's network, and second, interactions among networks owned by separate firms. Taking these in turn, I incorporate market interdependence by permitting investments made on a particular arc to benefit all traffic from various origin–destination markets that pass through that arc. I observe the annual maintenance spending of each firm, which they can use to invest in routine maintenance activities and infrastructure upgrades

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

on tracks they own. Firms can abandon tracks by assigning no investment to them. Conditional on these investment choices, the routing for each origin–destination market is determined by identifying the connected nodes with the lowest transportation cost, which can be addressed as a linear programming problem. Concerning the second aspect, the interactions among firms, I allow them to compete in every origin–destination market. Firms compete on prices, and the resulting demand subsequently influences the firms' choices regarding investment and routing.

On the demand side, customers make discrete choices over which railroad company or an outside option (such as trucking) to use to transport goods from the origin to the destination. In equilibrium, the railroad firms choose the optimal pricing for every origin–destination market, decide on the routing for each shipment, and make investment decisions throughout their entire network.

I estimate demand for each origin–destination market using detailed waybill data. Regarding firms' decisions, there are three key cost parameters to be estimated. The first, the *impact of distance* parameter, determines how shipment costs vary with travel distance. The second, the *interchange cost* parameter, relates to costs incurred per interchange. Finally, the *investment efficiency* parameter evaluates how effectively investments in infrastructure reduce shipment costs. In my model, a positive *investment efficiency* parameter indicates that arcs with large investments will incur low marginal costs of shipment. This suggests an economy of scope within the model's framework, where consolidating multiple routes into a single path is more cost-effective than handling them separately. A zero value for the *investment efficiency* parameter indicates the absence of economies of scope, implying that all routes are of equal importance and offer no benefits from traffic consolidation.

These cost parameters are subsequently estimated using simulated method of moments. For the *impact of distance* parameter, I target the average shipping cost per mile in dollar terms. To estimate the *interchange cost* parameter, I use the average price difference between interchange and non-interchange routes. Lastly, in the ideal scenario for estimating the *investment efficiency* parameter, I would observe price differences resulting from varying levels of investment in different arcs. However, the actual investment amount for each arc is unobservable. To address this, I leverage the positive correlation between node connectedness and investment. If a station is physically located at a more central position within the network, it will likely receive greater investment. Therefore, in my analysis, I estimate the *investment efficiency*

parameter by analyzing the price differences across markets that result from varying degrees of node connectedness at their origins and destinations.

The estimated cost per mile of shipment amounts to \$1.20, comparable to the number published by the Association of American Railroads. The interchange cost is estimated to be \$217 for a single interchange, representing approximately 21% of the average shipment price. This finding underscores the significant expense associated with interchanges and highlights the potential for substantial cost efficiency gains by eliminating interchange costs following a merger. Finally, the estimated value of the *investment efficiency* parameter is significantly different from 0, indicating the presence of economies of scope. Moreover, the estimated *investment efficiency* parameter is less than 1, suggesting diminishing marginal returns in investment allocation for a specific arc.

Next, using the estimated parameters, I simulate the equilibrium outcomes before and after each merger among Class I railroads from 1985 to 2005. The results show that, on average, shipment cost falls by 12.9%, shipment price falls by 8.8%, and the markup increases by 7.2%. My counterfactual results closely align with the reduced-form evidence presented. Regarding the increased markup post-merger, my counterfactual analysis shows that reducing the number of firms in local markets is not the primary driving factor. Instead, the increased markup is primarily driven by non-merging firms reallocating resources away from regions where the merged firm achieves a significant cost reduction. As a consequence, this leads to additional growth in the merged firm's market share at the local market, resulting in greater markup increases in those regions. These results highlight the importance of considering equilibrium effects in merger analysis.

I investigate the key network characteristics that give rise to larger changes in shipping costs following mergers. I use two centrality measures to describe the nodes in a network: *degree centrality*, which captures the total number of links connected to the node within the network, and *betweenness centrality*, which evaluates the number of shortest paths that pass through the node. In both centrality measures, my findings show that markets with low centrality in the pre-merger network and high centrality in the post-merger network typically experience a greater reduction in shipping costs following a merger. Intuitively, when a node is positioned at the outer edges of the network before the merger and subsequently becomes more central in the post-merger network, it experiences a greater improvement in efficiency. Furthermore, the results

show that an increase in betweenness centrality leads to a larger reduction in shipment costs and a greater increase in markups after the merger when compared to a similar increase in degree centrality.

Lastly, to shed light on future merger policies, I investigate which types of mergers are more likely to improve welfare. I focus on the degree of overlap and complementarity between the two networks involved in the merger. The degree of overlap is measured by the overall percentage of markets that both merging firms were present in prior to the merger. As for complementarity, it is calculated as the overall percentage of interchanges carried out between the merging firms. The findings indicate that a high degree of overlap leads to significant cost reductions and substantial increases in markups. A high degree of complementarity also leads to significant cost reductions but only a modest increase in markups.

Related Literature

This paper contributes to four broad strands of literature, relating to: (i) horizontal mergers, especially efficiency gains of mergers; (ii) transportation networks; (iii) the railroad industry; and (iv) network competition in general.

First, this paper contributes to the literature examining the potential efficiency gains from mergers. 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. The price effects of mergers have been studied extensively in the literature. For example, the literature has looked at mergers in airlines (Borenstein, 1990; Kim and Singal, 1993; Peters, 2006), ready-mix concrete (Collard-Wexler, 2014), and hospitals (Dafny, 2009; Dafny, Ho and Lee, 2019). In contrast, few empirical studies focus on the efficiency gains of mergers. Notable exceptions are Ashenfelter et al. (2015); Jeziorski (2014); and Clark and Samano (2022). This paper contributes by providing direct empirical evidence of the efficiency gains from mergers in a network-based industry. Additionally, the results underscore the importance of considering equilibrium effects in merger analysis.

Second, this article contributes to the rapid growing literature on transportation. Fajgelbaum and Schaal (2020) study the optimal infrastructure investment decisions of a social planner. Frechette et al. (2019) look into the effects of entry restric-

tions and market thickness in taxi markets. Meanwhile, Buchholz (2022) investigates search frictions and regulations in taxi markets, and Brancaccio et al. (2020, 2023) analyze world oceanic shipping, with an emphasis on the influence of geography on shipment costs and on correcting inefficiencies stemming from the industry's decentralized nature. In general, the existing literature on transport markets typically takes one of two approaches, either looking at the decisions of a social planner or assuming the presence of numerous atomistic players, such as individual taxi drivers or container ships. While these approaches are effective for studying their respective sectors, in industries with a high degree of market concentration, such as railroads, it is necessary to further consider oligopolistic competition. Building on the groundwork established by these studies, my paper incorporates oligopolistic competition among transport firms. It allows each firm to make optimized decisions across the network while taking into account interactions with its rivals. This expands the scope of the literature in a relevant way and facilitates the analysis of mergers.

Third, my paper also contributes to the literature on the freight railroad industry — see Grimm and Winston (2000) and Gallamore and Meyer (2014) for excellent summaries. Most existing studies consider a change in some aggregate cost or price index, or examine merger effects by looking at individual markets independently.[4] Virtually no research has examined the effects of mergers by considering the interdependent nature of railroad networks through a structural model. This paper helps to fill this gap.

Last, this paper relates to the network competition literature. Ciliberto, Cook and Williams (2019) show the effect of consolidation on airline network connectivity using different measures of centrality, while Aguirregabiria and Ho (2012) examine factors contributing to the adoption of hub-and-spoke networks in the US airline industry. My model differs from these approaches by considering the interdependence of markets based on their geographical locations within a transport network.

Regarding monopolistic distribution networks, Holmes (2011) studies Wal-Mart's choice of locations and infers the magnitude of density economies, while Houde, New-

[4]Friebel et al. (2014) investigate the restructuring of the U.S. freight railroad after deregulation and document both network reductions (the abandonment of redundant rail lines) and labor downsizing following mergers. Prater et al. (2012) examine the sufficiency of rail freight competition and the effects of intramodal competition on rail rates. Event studies on specific merger cases in the literature also provide explanations for the origins of merger efficiency. Kwoka and White (1997) study the Union Pacific–Southern Pacific merger, and Pittman (2009) examines the Santa Fe and Southern Pacific merger proposal.

berry and Seim (2023) study the investment decisions leading to the expansion of Amazon's distribution network by considering the benefits of economies of density and vertical integration into package sortation. I contribute to this discussion by accounting for interactions among networks owned by different firms, specifically focusing on how these interactions affect overall welfare changes following mergers in equilibrium.

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

2 Industry Background

2.1 A Running Example: Train 9-698-21

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

The Santa Fe railway operates Train 9-698, which commences its journey from Los Angeles and terminates at Memphis.[5] The train commences its journey from Los Angeles promptly, proceeds without any delay and reaches Avard Oklahoma. Upon arrival at Avard Oklahoma, the train must be interchanged between Santa Fe railway and Burlington Northern railway. Initially, the train encountered a five-hour wait to exchange railcars with a tardy train from Richmond. Subsequently, the crew discovered that Burlington Northern had not dispatched a locomotive to retrieve the train.

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

Upon contacting Burlington Northern, the responsible party responded by stating that "you are not my first priority, so you'll have to wait." After additional delay, a locomotive eventually arrived and retrieved the train, which was subsequently transported by Burlington Northern until it finally reached its destination in Memphis.



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

The story of Train 9-698 serves to underscore three potential avenues for increasing efficiency through the merger between the Santa Fe railway and the Burlington Northern railway. First, the merger is expected to eliminate the interchange cost incurred at Avard. Second, the elimination of this cost would enable the merged entity to make better routing decisions by directing traffic towards the route between Los Angeles and Memphis. Third, by leveraging the newly re-optimized routing strategy, the merged firm can better allocate its resources, such as track maintenance spending. Specifically, if the route between Los Angeles and Memphis is made more efficient, other traffic from disparate origin–destination markets such as San Diego to Kansas City can also utilize this improved route. This concept is supported by industry professionals, for example, the Chief Operating Officer of CSXT stated that "An essential feature of the operating plan is to consolidate traffic over a smaller number of efficient, high-volume routes."[6]

Figure 2 is subsequently utilized to explain the definition of a "service" in the context of railroading. Notably, two distinct types of services can be identified, namely a single-line service and a joint-line service. A single-line service denotes a mode of transportation in which a single railroad company is responsible for the entire shipment from its origin to its destination. In contrast, a joint-line service is characterized by the involvement of two or more railroad companies, with each company

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

contributing to the transportation of a specific portion of the shipment. To exemplify:

- A shipment from **Los Angeles** to **Avard Oklahoma** is served by a single-line service offered by the Santa Fe railroad.
- A shipment from **Los Angeles** to **Claremore Oklahoma** is served by a joint-line service provided by the Santa Fe railroad and the Burlington Northern railroad. Specifically, the Santa Fe railroad carries the shipment from the origin Los Angeles to the interchange station Avard Oklahoma, following which the Burlington Northern railroad transports the shipment from Avard Oklahoma to Claremore Oklahoma.
- For a shipment from **Avard Oklahoma** to **Memphis**, both a single-line service and a joint-line service are available. The single-line service is provided by the Burlington Northern railway, while the joint-line service is offered by the Burlington Northern railway and the Union Pacific railroad.
- Finally, a shipment from **Claremore Oklahoma** to **Memphis** can be transported using two distinct single-line services. One such service is provided by the Burlington Northern railway, while the other is offered by the Union Pacific railway.

2.2 Two Salient Features of the Railroad Industry

Next, I discuss two salient features of the railroad industry.

First, decisions made by a railroad firm in a single origin–destination market can impact the decisions made in all other markets in which that firm operates. For instance, consider the case of train 9-698. The merger of the Burlington Northern railway and the Santa Fe resulted in an increase in efficiency along the route from Los Angeles to Memphis, which may have led to changes in routing decisions for adjacent areas to take advantage of the new, more efficient route. Additionally, investment decisions would be re-optimized for the entire network owned by the merged entity. I refer to this feature as the interdependence of markets within a railroad firm's network.

In this paper, investment decisions specifically refer to the allocation of funds for maintenance spending. There are two main reasons why annual investment decisions

are equivalent to annual maintenance spending for railroad firms. First, 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. As a result, there has been almost no investment in building new tracks. Second, the physical tracks for railroads today remain fundamentally similar in design and materials to those from 50 years ago. The core infrastructure has not undergone revolutionary changes; most improvements have focused on maintenance and incremental enhancements or replacements rather than significant upgrades in quality. Therefore, in this paper, I treat annual investment decisions as equivalent to the allocation of annual maintenance spending.

In addition to the merged entity re-solving the complex optimization problem for the entire network, all non-merging competitors will also adjust their pricing and operational decisions in equilibrium. I refer to this feature as the interaction among railroad firms, which underscores the importance of examining the equilibrium effects of mergers.

Figure 3 illustrates the network owned by the seven current Class I railroads. Each railroad firm retains ownership of its own physical tracks.[7]

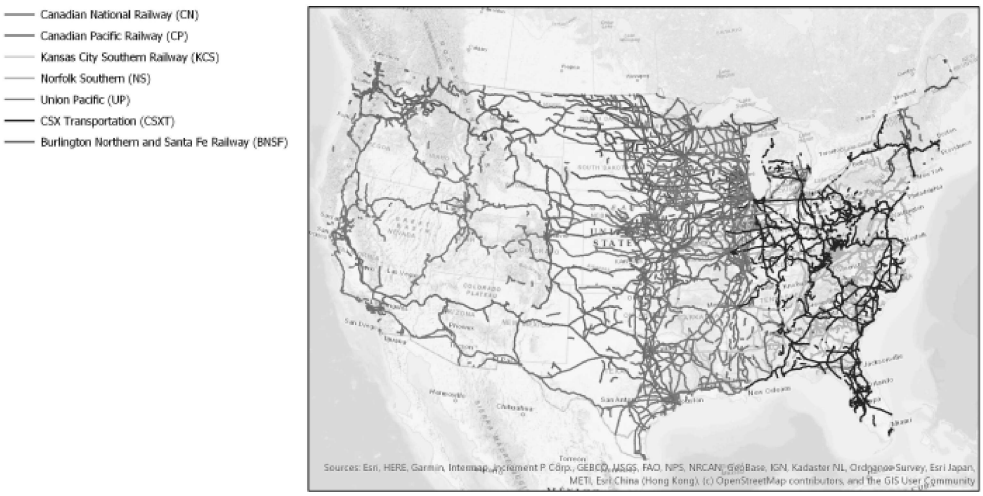


Figure 3: U.S. Class I Railroads

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

For additional information about this industry, I present a comprehensive history of US railroad mergers in Appendix A. Furthermore, I provide specifics on the freight transported by railroads and other modes of transportation in Appendix B.

3 Data

I utilize four datasets in my analysis. First, the Carload Waybill Sample, which contains detailed shipment information, including commodities carried, total billed weight, equipment used, participating railroads, and origin, destination, and interchange locations for each load. The Carload Waybill Sample accounts for approximately 2% of total freight railroad shipment transactions and includes detailed price information in its confidential version. It is designed to represent all U.S. rail traffic and is a stratified sample of waybills for carload shipments that move on U.S. railroads, collected annually by the Surface Transportation Board (STB). The stratification ensures that the sample adequately represents the diversity of rail traffic, including different types of commodities, shipment sizes, and routes.[8] I have roughly 12 million total observations for the past twenty years. Second, the Class I Railroad Annual Report R-1 dataset. This dataset contains yearly data on firm characteristics and aggregate operational statistics such as annual maintenance spending. Third, the Commodity Flow Survey. This dataset contains information on shipment volumes for different transportation modes, which I account for as share of outside options in my demand model.[9] Fourth, geographic information from the Department of Transportation. I utilize this dataset to obtain information on all U.S. rail lines and their associated railroad companies, allowing me to trace back through time and reconstruct the rail network of each railroad firm between 1985 and 2005. All four datasets cover the time span from 1985 to 2005.

Next, I provide summary statistics for the key variables from the waybill data. Table 1 shows the results. The shipment price per carload varies from \$384 to $\$1,266$ at the 25th and 75th percentiles, with a mean price of $\$1,034$. The shipment weight

[8] Waybill data have broad applications in, among other things, rate cases, exemption decisions, and analyses supporting regulations. Waybill data are also used by transportation practitioners, consultants, and law firms in preparing verified statements to be submitted in formal proceedings before the Board or other public agencies. For more details, see STB's official descriptions here.

[9] The U.S. Census Bureau conducts the Commodity Flow Survey every five years. I have access to data from the years 1993, 1997, 2002, 2007, and 2012.

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	

Source: The Surface Transportation Board, Carload Waybill Sample

per carload ranges from 16 tons to 102 tons at the 25th and 75th percentile, with an average weight of 54 tons. The average travel distance per shipment is 1,045 miles, with the 25th percentile at 404 miles and the 75th percentile at 1,647 miles. This indicates that railroad shipments are mainly long-distance. The median shipment price per ton-mile is 2.65 cents, a value that is similar to the industry-reported price per ton-mile.[10]

Table 2: Summary Statistics of Market Competition

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

Source: The Surface Transportation Board, Carload Waybill Sample

Next, I provide insight into the competitive landscape of the industry. In accordance with the Surface Transportation Board, a market is defined as an origin–destination pair where the origins and destinations correspond to the Bureau of Economic Analysis (BEA) economic areas. The contiguous United States comprises a total of 170 BEA areas.

Table 2 shows the number of markets and the percentage of interchange lines over the years. The number of Class I railroads decreased significantly from 39 to 7 due to the wave of mergers that occurred between 1985 and 2005. However, the

[10]According to the AAR, the mean price per ton-mile in the United States was 2.32 cents in 2001.

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

4 Reduced-form Evidence of Merger Gains

I first examine the changes in prices that occur after railroad mergers as a motivation to investigate the presence of efficiency gains. To do so, I use a regression model with the following specification:

$$\log P_{s,odt} = \gamma_{s(o)} + \gamma_{s(d)} + \gamma_{od} + \gamma_t + \delta_1 D_{s,odt} + X'_{s,odt}\beta + \epsilon_{s,odt},$$

In this equation, each service s corresponds to a specific combination of an origin railroad j_o and a destination railroad j_d, represented as $s = (j_o, j_d)$. If both the origin railroad j_o and the destination railroad j_d are equal to j, the service s is classified as a single-line service. An example of this is the shipment from Los Angeles to Avard, Oklahoma, as discussed in section 2, which is exclusively handled by the Santa Fe railroad. On the other hand, if j_o is not equal to j_d, the service s is classified as a joint-line service. For instance, the shipment from Los Angeles to Claremore, Oklahoma, involves both the Santa Fe railroad and the Burlington Northern railroad. In this scenario, j_o represents the Santa Fe railroad, and j_d represents the Burlington

[11] Appendix B.2 presents a year-by-year table with similar findings.

Northern railroad. $P_{s,odt}$ represents the price of service s from origin o to destination d at time t. The explanatory variables in the equation are as follows: γ_{od} controls for origin–destination fixed effect, $\gamma_{s(o)}$, $\gamma_{s(d)}$ control for firm fixed effect (origin and destination railroads), and γ_t controls for time fixed effect. $D_{s,odt}$ is an indicator of whether a merger has occurred to firms that provide service s from o to d before or at time t, and $X_{s,odt}$ represents shipment attributes, which includes the ownership of railcars and commodity dummies. $\epsilon_{s,odt}$ is an unobserved error.

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		-0.107^{***}
× Indicator of Interconnecting Route		(0.0178)
Indicator of Merger		-0.0690^{***}
× Indicator of Competing Route		(0.0180)
Indicator of Merger		-0.0641^{***}
× Non-interconnecting, Noncompeting Route		(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. *** $p < 0.001$

The estimation results are presented in Table 3. These results indicate that, on average, a railroad merger results in a 9.4% reduction in shipment price. Further examination of individual mergers reveals that the price effect is generally consistent across mergers.[12]

To examine the effects of railroad mergers on price changes for different route types, I interact the merger dummy variable with three route types: interconnecting route, competing route, and non-interconnecting, non-competing route. An interconnecting route refers to a route in which two firms conduct interchange and complete the shipment jointly. The results presented in column 2 of Table 3 indicate that interconnecting routes experience the largest reduction in price, with prices decreasing by 11% following mergers. In comparison, the other route types experience a price reduction of approximately 6.5% after mergers.

[12]See Table C.2 for robustness check results.

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

To examine whether the estimated price effects are the result of competition from other transportation modes like trucking, instead of the impact of railroad mergers, I investigate the price effects of mergers for different types of commodities. The rationale is that different types of commodities face varying levels of competition from other modes of transportation. Therefore, if the price effects are driven by changes in other transportation modes, the effects should be greater for commodities facing higher levels of competition from other modes of transport.

For instance, the Commodity Flow Survey (CFS) of 2012 indicates that coal is mainly shipped by railroads, with just 1.5% of coal being shipped by trucking, while 94.8% is shipped by rail. Conversely, food or kindred products are predominantly shipped by trucking, with 76.2% of such commodities being shipped by trucking and only 23.5% being shipped by rail. Therefore, if the decrease in prices results from competitive pressure from the trucking industry, we would expect to see a more significant reduction in the prices of transporting food products compared to the prices of shipping coal.

Table 4 displays the estimation results for the price effect of mergers on coal and food products. The findings demonstrate that railroad mergers have a significantly negative price effect for both these commodities, with the price effect being greater for coal. These results are not consistent with the hypothesis that the price effect is due to changes in other transport modes.

In Appendix C, I conduct a price regression for each commodity type to validate the findings. The outcomes indicate that the price reduction following railroad mergers is consistent across different commodities. Notably, commodities predominantly shipped by rail, such as coal, chemicals, and construction materials (clay, concrete, etc.), show a significant and substantial price reduction following railroad mergers.

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

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

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

5 Model

The findings above indicate a substantial reduction in prices after railroad mergers, especially on interconnecting routes. To further understand the equilibrium effects of mergers in the railroad sector, I introduce a spatial equilibrium model. The model has two salient features: it takes into account how decisions made in a particular origin–destination market can impact decisions in all other markets within a single network, and it considers oligopolistic competition among firms. These firms compete and simultaneously set prices, while also making routing and investment allocation decisions to minimize the overall operational expenses across the entire network.

In this section, I first present the demand functions. Following that, I explain my definition of a network, introduce the profit and cost functions, and detail the constraints each firm encounters in solving their optimization problem. Next, I present the Lagrangian for each firm and proceed to derive the solutions to the firm's problem. Finally, I discuss the concepts of equilibrium.

5.1 Demand

For each origin–destination market, customers choose a transportation service denoted as s to move their goods from the origin to the destination. There is an outside

option for shipping goods using modes of transportation other than railroads, which is denoted as $j_o = j_d = 0$. The utility that customer i derives from selecting service s to transport goods from origin o to destination d at time t is expressed as:

$$u_{is,odt} = \alpha \cdot p_{s,odt} + \beta \cdot \log TTM_{s,odt} + \gamma_{s(o)} + \gamma_{s(d)} + \gamma_m + \gamma_t + \xi_{s,odt} + \varepsilon_{is,odt} \quad (1)$$

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

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

$$h_{s,odt} = \frac{\exp(\alpha \cdot p_{s,odt} + \beta \cdot \log TTM_{s,odt} + \gamma_{s(o)} + \gamma_{s(d)} + \gamma_m + \gamma_t + \xi_{s,odt})}{1 + \sum_{s'} \exp(\alpha \cdot p_{s',odt} + \beta \cdot \log TTM_{s',odt} + \gamma_{s'(o)} + \gamma_{s'(d)} + \gamma_m + \gamma_t + \xi_{s',odt})}, \quad (2)$$

The demand for each service s at the o–d market is then derived as

$$Q_{s,odt} = M_{odt} \cdot h_{s,odt} \quad (3)$$

where M_{odt} denotes the market size of the o–d market at time t.

In my model, I assume that demand is independent of trip duration. Instead, railroad companies incur an interchange cost, which arises from the interconnections between different companies, as illustrated in the running example in Section 2.1. An alternative approach would model demand as dependent on trip duration, where interconnections increase trip duration rather than shipment costs. Given the data limitation—none of the transaction data records trip duration—I have opted to model demand without considering trip duration. I argue that while this choice may lead to different price predictions compared to a model that includes trip duration, in terms

of changes in consumer welfare, the two models are likely to be isomorphic.[13]

5.2 The Firm's Problem

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

Defining the Network. To construct a network $\mathcal{N}_j$ for a given railroad company j, a non-directed graph $(\mathcal{Z}_j, \mathcal{A}_j)$ is defined with nodes denoted by $\mathcal{Z}_j$ and arcs denoted by $\mathcal{A}_j$. The nodes in this network represent the centroids of the BEA regions, while the arcs correspond to the rail lines connecting each BEA economic area. The rail network of the Burlington Northern railway (BN) in 1994 is depicted in the left panel of Figure 4. A BEA area a is included in $\mathcal{Z}_j$ if BN has tracks in that region. Similarly, if two adjacent BEA areas are connected by tracks owned by BN, then $(a, b) \in \mathcal{A}_j$, as illustrated in the right panel of Figure 4. I follow the same process in constructing the network of each railroad firm for every year between 1985 and 2005, based on detailed geographic information for each rail line and information about the ancestry of rail lines obtained from the Federal Transit Administration.[14]

[13] In my model, a decrease in interconnection costs following a merger leads to lower shipment prices, thereby increasing consumer welfare. Conversely, in the alternative model that considers trip duration, the elimination of interconnection costs after a merger may not necessarily lead to lower prices; however, it will reduce trip duration, thereby enhancing consumer welfare. Therefore, although the two models may yield different predictions regarding price changes, they align more closely concerning their implications for consumer welfare.

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

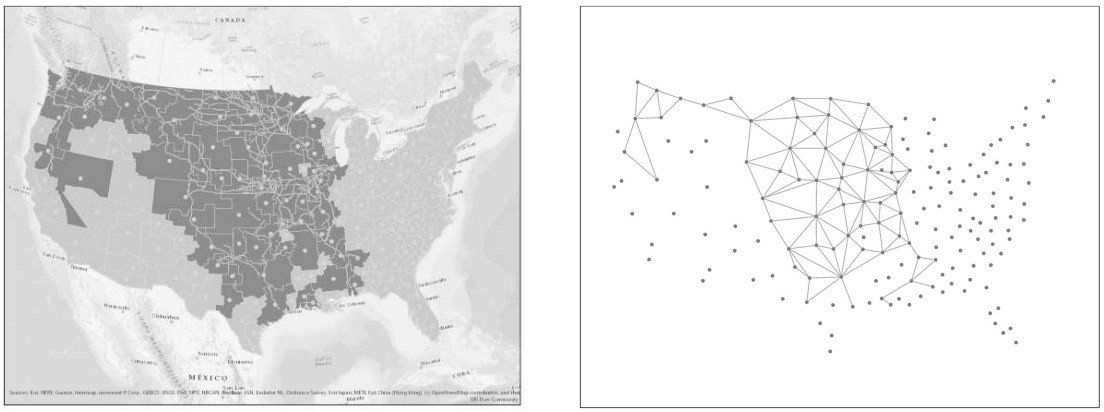


Figure 4: BN Rail Network

Profit Function. The profit function of firm j is defined as:

$$\begin{aligned}\pi_j(\boldsymbol{p_j}, \boldsymbol{\mathcal{R}_j}, \boldsymbol{I_j}) &= \sum_{s:s\in S(j)} p_{s,od} \cdot Q_{s,od}(p_{s,od}, \boldsymbol{p_{-s,od}}) - C(\boldsymbol{Q_j}, \boldsymbol{\mathcal{R}_j}, \boldsymbol{I_j}) \\ &= \sum_{s:s\in S(j)} (p_{s,od} - C_{s,od}(\boldsymbol{\mathcal{R}_j}, \boldsymbol{I_j})) \cdot Q_{s,od}(p_{s,od}, \boldsymbol{p_{-s,od}}). \qquad (4)\end{aligned}$$

The vector $\boldsymbol{p_j}$, $\boldsymbol{\mathcal{R}_j}$, and $\boldsymbol{I_j}$ represent the decisions of firm j for prices, routing, and investment allocation, respectively. I use bold symbols to represent vectors in my model. $S(j)$ represents the set of services that the railroad firm j offers.[15] $C_{s,od}$ is the marginal cost of transportation.

I assume that the originating railroad firm in the joint-line service determines the price, thereby avoiding any double marginalization.

Including double-marginalization will influence pricing decisions in each local market, thereby affecting the quantity that each railroad company needs to ship for each origin–destination market. However, it will not alter the approach to solving network optimization decisions, so the main insights of the model will remain unchanged. Quantitatively, this suggests that my results in the counterfactual analysis represent a lower bound for price reductions resulting from mergers. This is because eliminating double-marginalization would likely cause shipment prices to drop even further post-merger. I explain how double-marginalization can be incorporated into my model in the discussion of optimal pricing in equation (11).

[15]For all $s \in S(j)$, $j_o(s) = j$, $j_d(s) = j$, or $j_i(s) = j$, where o is the origin, d is the destination, and i is the interchange station. There can be multiple interchanges for a shipment. $S(j)$ is directly obtained from the data.

Interviews with railroad managers about how pricing decisions are made in the industry, documented in Appendix B.3, align with my current assumption. Additionally, the Department of Justice has examined the pricing decisions for joint-line services: Alexandrov, Pittman and Ukhaneva (2018) show that there is no double marginalization in the pricing of these services.

Furthermore, I assume that firms do not consider the cannibalization between their single-line and joint-line services offered in the same o–d market. In the data, it is rare for a railroad to provide both single- and joint-line services in the same o–d market, so relaxing this assumption has a minimal effect on the results.

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

$$C_{s,od} = \begin{cases} \sum_{(a,b)\in\mathcal{R}_{j,od}} c_{j,ab}(\boldsymbol{I}_j) & \text{if} \quad j_o = j_d \\ \sum_{j'\in J(s)} \sum_{(a,b)\in\mathcal{R}_{j',od_{j'}(s)}} c_{j',ab}(\boldsymbol{I}_{j'}) + \#_{interchanges} \cdot \eta & \text{if} \quad j_o \neq j_d \end{cases}. \tag{5}$$

In the case of a single-line service where the origin and destination railroads are the same ($j_o = j_d = j$), the marginal cost is obtained by adding up the costs of all arcs along the route from the origin to the destination for firm j. On the other hand, for a joint-line service where the origin and destination railroads are different ($j_o \neq j_d$), the marginal cost is calculated by summing the costs incurred by each participating railroad, in addition to the interchange costs. Here, $J(s)$ denotes the set of firms that provide service s, $\#_{interchanges}$ represents the total number of interchanges incurred, and η is the cost of a single interchange. There can be multiple interchanges for a shipment, involving firms as the origin railroad, interchange railroad 1, interchange railroad 2, ..., and the final destination railroad. In the data, 79.5% of trips that include interchanges incur one interchange. Among all trips, 95% have 0 or 1 interchange.

In my paper, interchanges specifically refer to the connections between different railroad companies. Within a firm, a shipment may travel through multiple stations, but these are not referred to as interchanges. However, my model does account for shipments traveling through multiple stations within a firm. Connections between multiple stations within a firm are captured by the summation of arc-level transportation costs, which vary for different stations. For a so-called *hub* within a firm, the arc-level cost can be particularly low, allowing traffic through that location to

benefit from the low transportation costs.

The arc-level transportation cost, $c_{j,ab}$, depends on the arc-specific geographic characteristics, $\delta_{j,ab}$, and the investment resources allocated by firm j to arc (a, b). The efficiency parameter γ reflects the effectiveness of resources and has a positive value. Therefore, if firm j allocates more investment resources to arc (a, b), the arc-level transportation cost $c_{j,ab}$ will be smaller.

Specifically, the arc-level transportation cost is defined as:

$$c_{j,ab} = \begin{cases} \delta_{j,ab}/(I_{j,ab}^{\gamma}) & \text{if} \quad I_{j,ab} > 0 \\ \infty & \text{if} \quad I_{j,ab} = 0 \end{cases}, \tag{6}$$

When $I_{j,ab} = 0$, the transportation on the arc (a, b) is assumed to be impossible, resulting in an infinite transportation cost.[16]

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

Typically, economies of scope refer to situations where producing one good reduces the cost of producing another related good. In this case, we can think of one good as the shipment for a particular origin–destination market, say from Los Angeles to Memphis, and the other related good as the shipment for another origin–destination market, say from San Diego to Kansas City.

In my current analysis, I do not consider economies of scale and congestion at the arc level due to computational constraints. Specifically, economies of scale and congestion refer to the effect of increased shipment quantity on marginal shipment cost for any given origin–destination market. We could modify equation (6) to express

[16] In my current model, I assume that $\delta_{j,ab} = \delta \cdot Dist_{j,ab}$, where $Dist_{j,ab}$ denotes the distance between nodes a and b for firm j, and the parameter δ measures the shipping cost per mile.

It is easy to enrich the model by adding other geographic characteristics to the cost function, such as

$$\delta_{j,ab} = \delta_1 \cdot (\text{Elevation}_{ab})^{\delta_2} \cdot \delta_3^{\text{CrossingRiver}_{ab}} \cdot Dist_{j,ab}.$$

the arc-level cost as:

$$c_{j,ab} = \frac{\delta Dist_{j,ab}}{I_{j,ab}^{\gamma}} \cdot Q_{j,ab}^{\tau}, \tag{7}$$

where $Q_{j,ab}$ is the quantity shipped through arc (a, b). If $\tau > 0$, then we have congestion; if $\tau < 0$, we have economies of scale. In my model, I set $\tau = 0$ to simplify the computation, which keeps the optimal routing problem as a linear programming problem. Including economies of scale or congestion would significantly increase computational complexity, particularly due to the need to solve the equilibrium multiple times during estimation.

While I have not implemented this in the current analysis, one could assess the importance of economies of scale by modifying the model post-estimation, incorporating both economies of scale and congestion as described in equation (7), to evaluate their impact on the results. In Appendix D.2, I discuss in more detail the alternative modeling approaches to incorporate these factors and their potential effects on optimal routing decisions.

It is also important to note that, although my model does not consider the economies of scale that affect the marginal cost of shipment at the arc level, it does incorporate economies of scale from fixed costs. Each railroad company has a fixed cost of operation, including administrative and general overheads; therefore, shipping a larger quantity does result in economies of scale at the aggregate level.

As documented in Section 2 and Appendix B.3, economy of scope appears to be a crucial source of synergy and presents significant challenges in operational decision-making in practice. Consequently, my baseline model prioritizes economy of scope due to its complexity and significance in strategic planning.

Constraints. The optimization problem of each firm j is subject to two constraints.

First, the investment allocation constraint:

$$\sum_{(a,b)\in\mathcal{A}_j} I_{j,ab} \leq K_j, \tag{8}$$

where K_j is the total annual maintenance spending.

One data limitation is that I only observe annual maintenance spending at the firm level, represented as K_j. Consequently, I rely on the model to predict how maintenance resources are distributed among different segments. To validate the model's

accuracy in predicting resource allocation, I take two steps. First, although I do not observe the actual allocation at the segment level, I do observe the abandonment of tracks (i.e., $I_{j,ab} = 0$) and the locations where these tracks were abandoned. Therefore, I verify whether the model's predicted track abandonment aligns with the actual observations after the mergers. Second, as we will see in the derivation of the optimal allocation decision in equation (14), the optimal allocation of maintenance resources in my model is proportional to track usage. To validate this, I first verify that, in practice, maintenance resources are indeed proportional to track usage.[17] Then, I examine the predicted shipment volumes and prices in each origin-destination market, for which I do have data. If the model's assumptions about investment allocation decisions are correct, this should be reflected in the observed changes in prices and shipment volumes for each market following mergers.

Despite the model's reliance on only three cost parameters and the complexity of the numerous markets involved in each merger, it achieves an accuracy rate of 63% in identifying the markets with the most significant price reductions. Moreover, the predictions of track abandonment following railroad mergers align well with the actual observed abandonment. This outcome underscores the model's ability to accurately predict the allocation of maintenance resources and effectively capture the underlying patterns in the data.

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

$$\sum_{a \in \mathcal{Z}_j(z)} Q_{s,od} \cdot \mathbb{1}\{(a,z) \in \mathcal{R}_{j,o_j(s),d_j(s)}\} + D_{j,z} = \sum_{b \in \mathcal{Z}_j(z)} Q_{s,od} \cdot \mathbb{1}\{(z,b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}. \tag{9}$$

Here, $\mathcal{Z}_j(z)$ denotes the set of neighbouring nodes of z, and $\mathbb{1}\{(a,z) \in \mathcal{R}_{j,od}\} = 1$ if the arc (a,z) is in the routing from o to d of firm j. Additionally, $D_{j,z}$ represents the

[17] The Surface Transportation Board (STB) and Federal Railroad Administration (FRA) provide regulatory oversight that reflects the correlation between usage and maintenance spending. For example, heavier traffic volumes and higher axle loads typically lead to increased maintenance requirements for tracks and bridges, which is reflected in the spending patterns of railroads. See more in the document regarding maintenance costs for mixed high speed passenger and freight rail corridors published by the FRA here.

net demand at node z and is defined as follows:

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

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

In this model, I do not account for the movement of empty railcars. When goods are transported from $a \to b$, I model the routing decision for that direction, but I do not consider the return trip of empty railcars from $b \to a$. A potential limitation of this approach is that in cases of unbalanced traffic flow, we might expect price discounts for return trips. For instance, if more commodities are shipped from the West Coast to the East Coast than in the reverse direction, there would likely be a discount for shipping from the East Coast to the West Coast—a phenomenon known in railroading as 'backhauling.' While this discount for aggregate traffic imbalance is partially addressed by origin–destination market fixed effects in the optimal pricing decision, I acknowledge that in the counterfactual analysis, the aggregate traffic flow may shift in equilibrium, thus altering the regions with imbalanced traffic flow. This aspect is not captured in the current model.

Furthermore, the balanced-flow constraint is specified at the origin–destination level rather than aggregated at the station level. An aggregate-level model would allow regions to choose their commodity sources more freely, which would require a general equilibrium model incorporating supply decisions for each region. Given the existing complexity of my model, I opted not to develop a full general equilibrium model. Moreover, many of my customers, such as power plants, have long-term contracts with coal providers, and manufacturing firms take time to relocate factories and facilities. Therefore, the results of my model should be interpreted as the implied welfare gains without reallocation of locations and re-optimization of import/export decisions. These gains represent a lower bound of the welfare implications if such adjustments were to be further allowed.

Lagrangian. Given the optimization problem, the lagrangian for firm j is

$$\mathcal{L}_j(\boldsymbol{p_j}, \boldsymbol{\mathcal{R}_j}, \boldsymbol{I_j}) = \sum_{s:s\in S(j)} \left(p_{s,od} - C_{s,od}(R_{j,o_j(s)d_j(s)}, \boldsymbol{I_j})\right) \cdot Q_{s,od} + \lambda_j \left(\sum_{(a,b)\in\mathcal{A}_j} I_{j,ab} - K_j \right) + \sum_{s:s\in S(j), z\in\mathcal{Z}_j} \lambda_{j,s,z} \tag{10}$$

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

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

5.3 Equilibrium

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

$$\frac{\partial \mathcal{L}_j}{\partial p_{s,od}} = Q_{s,od} + (p_{s,od} - C_{s,od}) \cdot \frac{\partial Q_{s,od}}{\partial p_{s,od}} - \frac{\partial Q_{s,od}}{\partial p_{s,od}} \cdot \left[\underbrace{\frac{\partial C_{s,od}}{\partial Q_{s,od}} Q_{s,od}}_{\text{own-cost effect}} + \underbrace{\sum_{s'\in S(j), s'\neq s} \frac{\partial C_{s',o'd'}}{\partial Q_{s,od}} Q_{s,o'd'}}_{\text{cross-cost effects}} \right] = 0. \tag{11}$$

Here is how the FOC for pricing is derived: The first part is the same as the FOC for a standard heterogeneous Bertrand competition model. For the second part inside the large bracket, we know that marginal cost is a function of investment and routing decisions; hence, $C = C(\mathcal{R}, I)$, as shown in equation (5). Because the optimal routing and investment decisions depend on the quantity shipped from each market, we redefine $C = C(\mathcal{R}(Q), I(Q))$. This dependency forms the basis for the term $\frac{\partial C}{\partial Q}$ in the first-order-condition with respect to price in equation (11).

I assume that when railroad firms set prices in local markets, they do not consider how changes in quantity would affect routing and investment allocation decisions. This assumption translates to setting the own-cost and cross-cost effects to zero. The

main reason for imposing this assumption is because solving for cross-cost effects can become computationally challenging as the number of markets increases. To investigate the impact of this assumption on equilibrium results, I derived analytical solutions for a simplified network by allowing for the own- and cross-cost effects in Appendix D. The numerical results indicate that the difference in equilibrium outcomes is minimal. This can be attributed to the fact that when one market dominates with a significant large shipment demand, the own- and cross-cost effects are essentially zero, whereas when none of the markets dominate (i.e., demand is evenly distributed), the own- and cross-cost effects tend to cancel each other out. Additionally, In Appendix B.3, I have documented interviews with local pricing managers who have stated that they do not strategically consider the impact of resulting demand from pricing quotes on operational decisions made by the operation department.

However, I want to emphasize that even after setting the own-cost and cross-cost effects to zero, there remains a strong interdependence of markets and interactions between firms. The interactions between firms are reflected in their oligopolistic pricing decisions, while the interdependence among markets arises from the firms' optimal choices regarding investment allocation and routing. For instance, if Firm 1 modifies its routing and allocation decisions in a specific area, this will affect its pricing decision in that origin–destination market. Consequently, these changes will influence the pricing decisions of its competitor, Firm 2, in the same market, thereby affecting the quantity shipped from that market, $Q_{2,od}$. This, in turn, impacts Firm 2's routing and investment decisions across all other markets, $I_2(\boldsymbol{Q}_2)$, and $\mathcal{R}_2(\boldsymbol{Q}_2)$.

In the counterfactual analysis of Section 7.1, I demonstrate how the equilibrium effects result in significant welfare implications post-merger. The re-optimization of network operations by the merged firm influences the investment decisions of all non-merging competitors. Specifically, my analysis shows that the reduction in the number of firms in local markets contributes only minimally to the increase in markup for the merged firm. Instead, the larger increase in markup primarily results from the resource reallocation by non-merging competitors.

Additionally, in my model, I assume there is no double-marginalization, and the originating railroad firm of the joint-line service determines the price. For instance, assume that a particular service s involves one interchange with two railroads, so the marginal cost is given by $C_{s,od} = C_{1,oi} + C_{2,id} + \eta$. The originating railroad firm 1 considers its own shipment cost $C_{1,oi}$ from the origin station to the interchange

station i, the shipment cost $C_{2,id}$ for firm 2 to ship from the interchange station i to the destination d, as well as the interchange cost η. It then chooses the optimal pricing $p_{s,od}$ based on the cost $C_{s,od}$.

Regarding the payment between companies, we can either assume that the originating railroad firm keeps all the profit and pays the destination railroad to break even on this particular shipment, or that both firms equally divide the profit, with each earning a positive profit for the shipment. Either approach will not affect the equilibrium outcome, because what matters is the quantity $Q_{s,od}$, which will influence the optimal investment and routing decisions as described in (12) and (15). Once the price $p_{s,od}$ is determined, $Q_{s,od}$ is correspondingly determined as well. The payment arrangement between companies will not affect $Q_{s,od}$.

Although I do not consider double marginalization in my current model, it is possible to incorporate it. We can assume a per-unit payment fee that is maximized by the upstream firm, as in the standard double-marginalization case. Specifically, using the example with one interchange and two railroad firms, the destination firm will choose the per-unit payment fee $\tau_{s,od}$, and its profit will be $(\tau_{s,od} - C_{2,id})Q_{s,od}$. For the originating railroad, the profit now becomes $(p_{s,od} - \tau_{s,od} - \eta - C_{1,oi})Q_{s,od}(p_{s,od})$. The originating railroad chooses $p_{s,od}$ to maximize its own profit, while the destination firm chooses $\tau_{s,od}$ to maximize its own profit. As a consequence, both $p^*_{s,od}$ and $Q^*_{s,od}$ will differ from those in my current model. However, this will not alter the approach to solving network optimization decisions, as the FOC for the investment decision and the LP for the routing decision will remain the same as in (12) and (15). Therefore, I argue that the main insights of the model will remain unchanged. Quantitatively, my results in the counterfactual analysis represent a lower bound for price reductions resulting from mergers without accounting for double-marginalization.

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

$$\frac{\partial \mathcal{L}_j}{\partial I_{j,ab}} = \gamma \cdot \delta_{j,ab} \cdot \frac{\sum_{s:s\in S(j)} Q_{s,od} \cdot \mathbb{1}\{(a,b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}}{I_{j,ab}^{\gamma+1}} + \lambda_j. \tag{12}$$

The numerator of this expression calculates the total quantity that travels through arc (a,b) by summing over all the origin and destination markets for which firm j

operates. The optimal allocation decision for each arc is then determined through the Kuhn-Tucker condition, which requires that for all $(a,b) \in \mathcal{A}_j$:

$$\frac{\partial \mathcal{L}_j}{\partial I_{j,ab}} \leq 0, \quad I_{j,ab} \geq 0, \quad \text{and } I_{j,ab} \frac{\partial \mathcal{L}_j}{\partial I_{j,ab}} = 0. \tag{13}$$

Here, I provide further intuition on the optimal allocation decisions. In equilibrium, for any non-zero $I^*_{j,ab}$ and $I^*_{j,a'b'}$, they satisfy

$$\begin{aligned} \frac{I^*_{j,ab}}{I^*_{j,a'b'}} &= \left[\frac{\delta_{j,ab} \cdot \sum_{s:s\in S(j)} Q^*_{s,od} \cdot \mathbb{1}\{(a,b) \in \mathcal{R}^*_{j,o_j(s),d_j(s)}\}}{\delta_{j,a'b'} \cdot \sum_{s:s\in S(j)} Q^*_{s,od} \cdot \mathbb{1}\{(a',b') \in \mathcal{R}^*_{j,o_j(s),d_j(s)}\}} \right]^{\frac{1}{\gamma+1}} \\ &= \left[\frac{\delta_{j,ab} \cdot q_{j,ab}(\boldsymbol{Q}^*_j, \boldsymbol{\mathcal{R}}^*_j)}{\delta_{j,a'b'} \cdot q_{j,a'b'}(\boldsymbol{Q}^*_j, \boldsymbol{\mathcal{R}}^*_j)} \right]^{\frac{1}{\gamma+1}} \end{aligned} \tag{14}$$

where $\delta_{j,ab}$ is the arc-specific geographic characteristics. $q_{j,ab}(Q, \mathcal{R})$ is the total shipment amount that runs through arc (a,b), which depends on the total quantity that needs to be shipped from each origin–destination market, $\boldsymbol{Q}_j$, and the routing decisions, $\boldsymbol{\mathcal{R}}_j$.

Equation (14) shows that the optimal allocation of maintenance resources is proportional to the usage of the track. The greater the quantity being shipped through a particular track, the more maintenance resources will be allocated to it. The exact ratio of allocation is influenced by the value of the *investment efficiency* parameter, γ, which affects the marginal returns of investment in a specific arc.

Optimal Routing Decisions. The optimal routing decision is equivalent to finding the least expensive route to travel from origin o to destination d for each o–d market. This can be formulated as a linear-programming problem:

$$\min_{\mathcal{R}_{j,od}} \sum_{(a,b)\in\mathcal{R}_{j,od}} \frac{\delta Dist_{j,ab}}{I^{\gamma}_{j,ab}} \tag{15}$$

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 constraint is binding in equilibrium, and the linear programming (LP) algo-

rithm used to determine the optimal routing decision enforces this constraint. LP algorithms, such as the Simplex method or Interior-Point methods, do not rely on setting derivatives to zero. Instead, they operate within the feasible region defined by the constraints, iteratively moving towards the optimal solution using linear algebra techniques. Consequently, the balanced-flow constraint appears in the LP but does not explicitly appear in the two FOCs for the pricing and allocation decisions as in equations (11) and (12).

As discussed earlier regarding the cost function, directly incorporating economies of scale or congestion parametrically as in equation (7), causes the optimal routing problem to no longer be a linear programming problem. However, we can address economies of scale or congestion through a layer-by-layer optimization approach. In Appendix D.2, I explain the alternative modeling approaches in detail, and equation (D.5) shows how the optimal routing decision will be affected. Nevertheless, I argue that the results from this layer-by-layer approach are unlikely to differ significantly from the current model.

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

Firstly, for each railroad firm j, the pricing decision for each service s in its set of services $S(j)$, $p^*_{s,od}$, must satisfy the first-order-condition in equation (11), taking into account the firm's own choice of routing and investment allocation decisions $\mathcal{R}^*_{j,od}$ and $I^*_{j,ab}$, as well as the pricing decisions $p^*_{-s,od}$, routing decisions $\mathcal{R}^*_{-j,od}$, and investment allocation decisions $I^*_{-j,ab}$ of all the other firms.

Secondly, the investment allocation decisions $I^*_{j,ab}$ must satisfy the Kuhn-Tucker condition in equation (13), given the pricing decisions $p^*_{s,od}$ and routing decisions $\mathcal{R}^*_{j,od}$.

Lastly, the routing decisions $\mathcal{R}^*_{j,od}$ must solve the linear programming problem in equation (15), given the pricing decisions $p^*_{s,od}$ and investment allocation decisions $I^*_{j,ab}$.

My approach for computing the equilibrium closely follows the definition presented above. In this paper, I constrain the equilibrium in such a way that the market share of a railroad firm is non-zero in a local o–d market if its observed market share is positive for that market in the data. This constraint eliminates equilibria where firms sort into local monopolies, such as one firm operating exclusively on the east coast

and the other on the west coast, which is inconsistent with the data.

Given a set of parameters, the steps to compute the equilibrium are as follows:

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

6 Estimation

I begin by presenting the argument for identification, followed by an explanation of how I estimate the parameters for both demand and cost. I estimate demand and cost parameters separately. The estimation of demand parameters is conducted using the two-stage least squares method, while the cost parameters are estimated through the simulated method of moments.

6.1 Demand Estimation

The demand model outlined in equation (3) shows that the difference between the logarithm of the observed market share for each service and the logarithm of the share for the outside good can be calculated as follows:

$$\log(h_{s,odt}) - \log(h_{0,odt}) = \alpha \cdot p_{s,odt} + \beta_1 \cdot \log TTM_{s,odt} + \zeta_{s,odt}. \tag{16}$$

In this equation, $h_{s,odt}$ represents the market share of a specific service s that serves the market route from origin o to destination d at a specific time t. The variable $h_{0,odt}$ represents the market share of the outside alternative. In my regression, the share of the outside good is constructed by calculating the shipment shares of other transportation modes, such as trucking and water shipping, using data from the Commodity Flow Survey.

The estimates of α and β_1 can be obtained from a linear instrumental variables regression of differences in log market shares on prices and service characteristics. The error term in equation (16) represents the unobserved market-specific demand shocks. Since I assume that railroads observe and account for this deviation, it will influence the market-specific markup and bias the estimate of price sensitivity. To address the issue of endogeneity, a series of steps are taken. Firstly, fixed effects for both origin and destination railroads, market fixed effects, and time fixed effects are incorporated. Furthermore, instrumental variables (IVs) are employed to mitigate the endogeneity problem.

The first set of instrumental variables used is commonly referred to as the "BLP Instruments." Much of the previous research treats the endogeneity problem by assuming the characteristics space is exogenous or predetermined.[18] Therefore, characteristics of other services will be correlated with price since the markup of each service will depend on the distance from the nearest neighbour. Here I use the average track miles and the distance to other railroads in the same *o–d* market as instruments.

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

[18] See Berry (1994), Berry, Levinsohn and Pakes (1995), and Bresnahan et al. (1997).

this approach.

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

Here, $TargetShare_{odt-1}$ represents the market share held by the target firm in the *o*–*d* market one year prior to the merger. Similarly, $AcquirorShare_{odt-1}$ indicates the market share of the acquiring firm in the *o*–*d* market before the merger took place.

Estimation Results. Table 5 presents the results. All standard errors are clustered at the market level (origin–destination). Columns (1)–(3) display the ordinary least squares results. The coefficient on price and the resulting own-price elasticities are relatively low, with absolute values less than 1. The logit demand structure does not impose a constant elasticity; therefore, the estimates imply a different elasticity for each service–market–year combination. Some statistics of the own-price elasticity distribution are shown at the bottom of each column. Two sets of instrument variables were explored to deal with the endogeneity problem. Column (4) uses BLP instruments described above as IVs in the same regression. Column (5) uses simulated changes in HHI as IVs. Finally, column (6) uses both sets of IVs. Columns (4)–(6) also include market, firm, and time fixed effects.

Several conclusions can be drawn from the results in Table 5. First, once IVs are used, the coefficient on price and the implied own-price elasticity both increase in absolute value. This is predicted by theory and holds in a wide variety of studies such as Nevo (2000) and Nevo (2001). Second, the "BLP instruments" seem to generate results almost identical to those produced by using the simulated change in HHI. The estimated price elasticity of demand, as shown in column (6), indicates an estimated price coefficient of approximately -0.72, resulting in an average price elasticity of demand of around -1.60. This estimated average price elasticity is comparable to estimates reported in the transportation literature. For instance, Wilson et al. (1988) estimated an own-price elasticity of demand for U.S. freight rail of -1.46. Beuthe et al. (2001) estimated a demand elasticity of -1.77 for total tonnes.

Table 5: Results of Demand Estimation

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

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

6.2 Estimation of Cost Parameters

There are three key cost parameters to be estimated. The first, the *impact of distance* parameter δ, determines how shipment costs vary with travel distance. The second, the *interchange cost* parameter η, relates to costs incurred per interchange. Finally, the *investment efficiency* parameter γ evaluates how effectively investments in infrastructure reduce shipment costs.

Estimation of the cost parameters $\theta = \{\delta, \eta, \gamma\}$ is implemented according to the following procedures. First, given a parameter value, the industry equilibrium is solved, resulting in optimal decisions for pricing, routing, and investment allocation, represented as $(\boldsymbol{p}(\theta), \boldsymbol{\mathcal{R}}(\theta), \boldsymbol{I}(\theta))$. After solving the equilibrium, I obtain the simulated moments as $\Gamma^S(\theta)$. Next, the estimate $\hat{\theta}$ is obtained through the simulated method of moments minimizes the weighted distance between the data moments and the simulated moments using the following objective function:

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

where W represents a positive-definite matrix.[19]

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

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

$$d_i(\mathcal{N}_j) = \sum_{k \in \mathcal{A}_j} \mathbb{1}\{a_{ik} = 1\} \tag{17}$$

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

$$b_i(\mathcal{N}_j) = \sum_{o,d \in \mathcal{Z}_j} \frac{\mathbb{1}\{i \in l(o,d)\}}{(Z_j - 1)(Z_j - 2)} \tag{18}$$

Here, Z_j refers to the total number of nodes in network $\mathcal{N}_j$, and $l(o,d)$ represents the shortest path from origin o to destination d. More specifically, the third and fourth data moments are obtained through regression analysis (represented by m_1 and m_2 in equation 19). In this analysis, the shipment price per mile for each origin-destination market is regressed on the degree centrality and betweenness centrality of the origin station:

$$P_{s,odt} = \gamma_{s(o)} + \gamma_{s(d)} + \gamma_m + \gamma_t + a_1 \cdot interchanges + m_1 \cdot d_o(\mathcal{N}_{j(s)}) + m_2 \cdot b_o(\mathcal{N}_{j(s)}) + \epsilon_{s,odt} \tag{19}$$

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

The rationale behind the identification argument is as follows: The first data

[19] I use the inverse of the variance–covariance matrix as the weighting matrix and estimate it using a bootstrap procedure.

moment focuses on quantifying the impact of travel distance on average shipping prices. As the value of δ increases, so does the average shipping cost per mile in dollar terms. Therefore, the first moment helps determine the value of the *impact of distance* parameter δ. The second moment compares the average price difference between interconnecting and non-interconnecting routes. When the interchange cost η increases, the price difference between these routes also increases. Therefore, conditional on the values of δ and γ, the second moment identifies the *interchange cost* parameter, η. Lastly, the value of γ represents the effectiveness of investment allocation resources and significantly influences the last two moments related to network measures. Intuitively, when $\gamma = 0$, resources have no impact on shipping costs, and only the travel distance between the origin and destination matters. As a result, there is no benefit in consolidating traffic, and the network structure does not affect shipping expenses, conditional on travel distance. Consequently, the values of m_1 and m_2 in equation (19) will be insignificantly different from 0. On the other hand, when $\gamma \neq 0$, the network structure plays a role in traffic consolidation, thereby affecting the effects of degree and betweenness centrality on prices. Therefore, the values of m_1 and m_2 are influenced by the value of the *investment efficiency* parameter, γ.

Table 6: Comparison of Data and Simulated Moments

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

Column (2) of Table 6 shows the data moments. The average shipping price per loaded car per mile is \$0.65, comparable to the number published by the Association of American Railroads. The average price difference between an interconnecting and a non-interconnecting route in the data is \$264.43 per loaded car. As a benchmark,

the average shipment price in the data is \$1034 per loaded car. Thus, the average price for joint-line service is about 26% higher than of average shipment price. The estimated impact of betweenness centrality on price is −\$0.30 in the data. Comparing a station at the 95th percentile of betweenness centrality to one at the 5th percentile, the price difference is approximately 14%.[20] Similarly, comparing a station at the 95th percentile to one at the 5th percentile in terms of degree centrality results in approximately a 2% difference in price.

Estimation Results. Table 7 reports the point estimates and their 95% confidence intervals. Following Andrews, Gentzkow and Shapiro (2017), I use finite differencing to calculate standard errors of the estimated parameters.[21] The estimated cost per efficient mile of shipment amounts to \$1.20. The interchange cost is estimated to be \$217, which represents approximately 21% of the average shipment price. This finding underscores the significant expense associated with interchange and highlights the potential for cost efficiency gains by eliminating interchange costs following a merger. Finally, the estimated value of γ is significantly different from 0, indicating that markets are truly interdependent. Moreover, with γ being less than 1, this suggests diminishing marginal returns in investment allocation for a specific arc.

Table 7: Estimation Results for Cost Parameters

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

Column (3) of Table 6 compares the simulated moments with the data moments. In general, the simulated moments match the data moments very well. To further

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

[21] Here is how I chose the step size for finite difference estimates of the standard errors: I started by setting the step size h to be a small percentage of each parameter's value (about 10^{-3}), and then I performed a convergence study. I gradually reduced h and looked for convergence in the derivative estimates. The estimates began to become noisy as h decreased to 10^{-6} of the parameter values, which I interpreted as an indication that h was too small, and the results were mainly affected by rounding errors. Therefore, after testing a range of step sizes and observing the stability of the derivative estimate, the step size was chosen to be 10^{-5} of each parameter's values.

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

7 Counterfactual Experiments

In my counterfactual analyses, I explore three key questions. First, I calculate the average gains from mergers between Class I railroads and analyze the sources of cost reductions and markup increases post-merger. Second, I examine the merger gains within a single merger, identifying which markets benefit and which suffer, and exploring the reasons behind this. Third, I compare the outcomes across various mergers, and assess the impact of different network structures of the merging parties on the extent of merger gains.

7.1 Efficiency Gains from Mergers

I calculate the average merger gains by comparing equilibrium results before and after the mergers. For each merger, I simulate the equilibrium outcomes both before and after the merger, and then calculate the changes in shipment prices, costs, and markups. In Appendix A, I provide a comprehensive account of railroad mergers. My analysis focuses on the 12 mergers between Class I railroads that occurred from 1985 to 2005. Figure A.2 illustrates the participating railroads and depicts the networks of the two parties involved in each of these twelve merger cases. The results of average

merger gains are then weighted according to the post-merger quantities and averaged across all individual origin-to-destination markets and all mergers.

In merger simulations, I assume that railroad firms do not make any entry or exit decisions in origin–destination markets. As shown in Table 2, the total number of *o–d* markets has been relatively stable at around 12,000 from 1985 to 2005, which is the period when most of the mergers occurred. Upon examining specific firms, I only observe a few instances of entry or exits in *o–d* markets post-merger. Hence, the data suggest that the extensive margin is not the primary driver post-merger.[22]

The results show that on average shipment cost reduces by 12.9%, shipment price reduces by 8.8%, and the markup increases by 7.2%. The simulated price reduction post merger in the baseline model is comparable to the price reduction observed in the data. On average, the merged firms become more profitable post merger. Although firms have a higher markup post merger, mergers create a large efficiency gain. As a result, consumers also benefit from the mergers and enjoy an 8.8% price reduction on average.

Unpacking the Black Box

The real strength of the proposed model is that it allows me to study the equilibrium effects of mergers and conduct counterfactual experiments to examine the sources of cost reductions and markup increases following a merger.

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

$$MG = f(NC_1, \theta_0) - f(NC_0, \theta_0). \tag{20}$$

Here, MG represents the merger gains obtained when the network structure of the merging firms changes from NC_0 to NC_1. In my analysis, I use three measures for

[22]Multiple equilibria in merger simulations: the estimation of cost parameters relies only on the necessary conditions of Nash equilibrium. Therefore, multiple equilibria do not affect the properties of the estimated parameters. However, multiple Nash equilibria would negatively affect the merger simulations. Although I cannot prove uniqueness, I perform a numerical search for multiple equilibria by altering the starting values while computing an equilibrium post-merger, and I do not find any multiple equilibria.

MG: price, cost, and markup. The function $f(\cdot, \theta)$ corresponds to the equilibrium model described in section 5. θ_0 represents the parameters estimated in section 6, which I refer to as the baseline parameters.

To examine the sources of merger gains, I conduct three counterfactual analyses by introducing different variations in θ. In the first counterfactual, denoted as $\theta_1 \equiv (\delta_0, 0, 0)$, I eliminate interchange costs and economies of scope. Here, the investigation focuses on merger gains given θ_1, calculated as:

$$MG = f(NC_1, \theta_1) - f(NC_0, \theta_1). \tag{21}$$

The intuition here is to envision a scenario with no interchange costs and no economies of scope initially. In this scenario, the benefit of the merger would come solely from shorter travel distances. We would then explore the extent of the merger gains after combining the two railroad networks.

In the second counterfactual, denoted as $\theta_2 \equiv (\delta_0, \eta_0, 0)$, I only turn off economies of scope. Finally, in the third counterfactual, denoted as $\theta_3 \equiv (\delta_0, 0, \gamma_0)$, I only turn off interchange costs. These counterfactual analyses allow for a comprehensive exploration of how changes in the structural parameters interact with the network structure to determine merger gains.

Table 8 shows how average merger gains change in the different counterfactuals.[23] Column (1) shows the baseline results using the estimated parameters $(\delta_0, \eta_0, \gamma_0)$.

Column (2) of Table 8 shows the results of the first counterfactual, in which I turn off both interchange cost and economies of scope $(\delta_0, 0, 0)$. The results show that when considering only travel distance as a factor, cost reduces by a small amount of 1.9% on average post merger. In local markets, the merged firm gains additional market power as both the acquiring and acquired firms operate in those markets, resulting in a reduction in the number of firms following the merger. However, the results show that merger-generated concentration in local markets only increases the markup slightly, by 0.7%. This outcome is not surprising given that, out of the twelve mergers examined, jointly owned markets typically represent only 3% to 6% (with a maximum of 12%) of the total markets owned by the two merging firms.

Column (3) of Table 8 shows the results of the second counterfactual, in which

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

Table 8: Average Merger Gains

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

I now allow for interchange cost but keep economies of scope turned off. Because merger eliminates interchange cost, the post-merger cost reduction is now larger, at 3.4% compared to the results for the first counterfactual. Meanwhile, there is no difference in increase of markup, which is still 0.7%. This means that reinstating interchange cost will increase efficiency gains after merger but will have no impact on firms' market power. Nevertheless, incorporating interchange cost alone is insufficient to explain all of the cost reduction in the results; it only explains 26% of the total cost reduction found in the baseline results.[24]

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

To further investigate what drives up the markup post-merger, I first examine how markup could be affected in the model. The markup for each firm j at market

[24]The baseline result shows a cost reduction of 12.9%. In the scenario where only interchange costs are considered, the cost reduction is 3.4%, amounting to 26% (calculated as 3.4/12.9) of the total cost reduction.

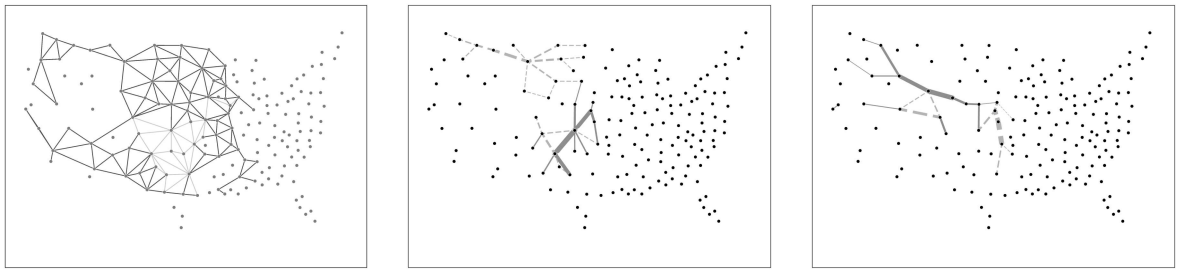
o–d is calculated from the first-order condition of the firm's optimization problem as

$$p_{j,od} - c_{j,od} = -\frac{1}{\alpha(1 - h_{j,od})} \tag{22}$$

where α is the price coefficient, and $h_{j,od}$ is the market share of firm j at market od. Equation (22) shows that the markup increases only when the local market share $h_{j,od}$ rises. One possible explanation is that the merger reduces the number of firms in local markets, thereby increasing a firm's market share in those markets. However, the first two counterfactuals show that merger-generated concentration in local markets only increases the markup slightly, by 0.7%.

I then investigate how the pricing and investment allocation decisions change for both merging and non-merging firms. The merger eliminates interchange costs and strengthens the connections of the merged firm, resulting in significant cost reductions, particularly in the interconnected areas of the two merging firms. I find that non-merging competitors reallocate their resources away from such regions in equilibrium. Assuming all other factors remain constant, when the merged firm's costs decrease in a given market, its market share in that market will increase. Consequently, the competitors' allocated resources to that market will have reduced utilization. This leads to a decrease in the competitors' marginal return on capital in that market, prompting them to reallocate their resources to other markets. When resources are moved away, the shipment cost of non-merging competitors will further increase in those markets. This results in further increases in the local market share of the merged firm. Hence, there will be a large increase in markup for the merged firm in the areas where the merged firm exhibits a large cost reduction post merger.

For example, Figure 5 shows that after the merger between Burlington Northern Railway (BN) and Santa Fe Railway (SF), the merged firm allocated more resources to improve the connectivity between the integrated sections of their network. In the west/eastbound direction, more resources were allocated to the arcs between Amarillo, TX and Omaha, NE. In the north/southbound direction, more was allocated to the arcs between South Dakota and Kansas. Panel (b) of Figure 5 shows the changes in allocation of resources for BNSF post merger. Meanwhile, in equilibrium, BNSF's primary competitor, Union Pacific Railway (UP), reallocates resources away from the South Dakota and Kansas areas and redirects them towards the Northwest corridor. Panel (c) of Figure 5 illustrates the resource allocation changes for UP subsequent



(a) BNSF Network (b) Changes of BNSF (c) Changes of UP

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

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

to the BN and ATSF merger. As a result of all these changes, the market share of BNSF in local areas near South Dakota and Kansas will further increase.

7.2 Within A Merger: Which Markets Benefit and Which Suffer?

Next, I investigate within a merger, how the extent of merger gain differs across different markets, taking into account the location of these markets in the network before and after the merger.

I derive the centrality measures for each node in the pre-merger network and in the post-merger network.[25] For instance, before the merger of the Burlington Northern railway and the Santa Fe railway, Kansas City was situated on the edge of Santa Fe's network, but afterwards, it found itself at the core of the combined network of Santa Fe and Burlington Northern. I will measure the degree centrality of Kansas City in both the pre-merger and post-merger networks, and then calculate the change in its

[25]I use two centrality measures in my analysis. Firstly, the *degree centrality* measures the total number of links a node has in a given network, as defined in equation (17). Secondly, the *betweenness centrality* measures the number of paths travelling through each node, as defined in equation (18).

network centrality resulting from the merger.

To summarize the findings, I perform a regression analysis where I examine the relationship between the simulated log-price changes and the changes in centrality measures after the merger.

$$\Delta \log P_{s,od} = \alpha_0 + \alpha_1 \cdot \mathbb{1}_{interchange} + \alpha_2 \cdot \Delta NC_o + \epsilon_{s,od} \tag{23}$$

Here, $\Delta \log P_{s,od}$ represents the simulated price changes before and after the merger. The term $\mathbb{1}_{\text{interchange}}$ is an indicator function that determines whether service s is a joint-line service provided by the two merging firms. ΔNC_o measures the changes in network centrality of the node before and after the merger. Intuitively, ΔNC_0 measures the change in centrality regarding the location of each station within a firm's network. In my analysis, ΔNC is either the changes in degree centrality ΔDC or changes in betweenness centrality ΔBC.

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 changes in degree centrality. The results 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 of changes in degree centrality. 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 of changes in betweenness centrality.

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

result, the Kansas City station enjoys a significantly larger efficiency gain following the merger of Burlington Northern Railway and Santa Fe Railway.

Unpacking the Black Box

Next, I investigate why the degree and betweenness centrality measures yield different results. To do so, I first conduct the same counterfactual experiments as described in equations (20) and (21). After obtaining the equilibrium outcomes from each of these counterfactual experiments, I re-run the regression as outlined in equation (23) and obtain the estimated results. To make the results easier to interpret, I report the difference of the merger gains between nodes at the 95th and 5th percentiles of changes in a centrality measure. For example, column (1) of Table 9 shows that 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 9 shows the results of these calculations.[26] Panel I of Table 9 shows how changes in centrality affect cost reduction post merger. The first counterfactual turns off interchange cost and economies of scope. Column (2) of Table 9 shows the results of this counterfactual: When only distance matters, increases in both degree and betweenness centrality result in higher cost reduction post merger. Furthermore, the degree and betweenness centrality measures produce similar results in this scenario. In the second counterfactual I reincorporate interchange cost. Column (3) shows no significant change regarding the effect of changes in centrality after doing so.[27]

The third counterfactual turns off 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 reduc-

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

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

Table 9: Merger Gains and Centralities

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

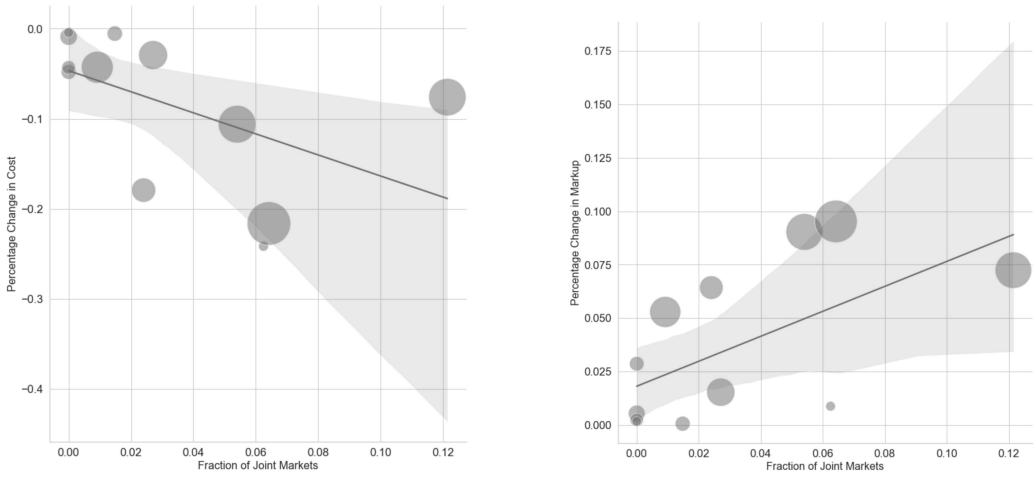
tion post merger. On the other hand, nodes with higher changes in degree centrality are likely to be located on the periphery of the pre-merger network. These nodes will have better routing options and hence shorter travel distances post merger. However, resources will not necessarily be reallocated to these nodes post merger.

Panel III of Table 9 shows how changes in centrality affect changes in markup post merger. 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. 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, turning off 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. This is because nodes with higher betweenness centrality benefit more from reallocation of resources and hence greater cost reduction post merger when economies of scope are present. As previously explained, non-merging competitors tend to move resources away from regions where the merged firm experiences a large efficiency gain. Therefore, nodes with greater increases in betweenness centrality post merger will have greater increases in local market share and hence in markup.

7.3 Across Mergers: What Kind of Mergers Are Better?

Last, I examine the impact of different network structures of the merging parties on the extent of merger gains, comparing the outcomes across various mergers. I focus on the extent of overlap and complementarity between the two networks involved in the merger. I measure the degree of overlap by calculating the overall percentage of markets operated by both merging firms prior to the merger. As for complementarity, I count the number of joint-line services (interlines) offered by the merging firms and calculate the proportion of interlines.

Figure 6 shows the relation between merger gains and degrees of overlap. The size of each circle in the figure corresponds to the total number of origin–destination markets involved in a specific merger. Panel (a) of the figure illustrates that higher degrees of overlap lead to more substantial cost reductions after the merger. In a merging network with a higher degree of overlap, the merged firm benefits more from economies of scope by eliminating redundant lines and consolidating traffic and resources. Panel (b) demonstrates that a higher degree of overlap also results in a larger increase in markup.

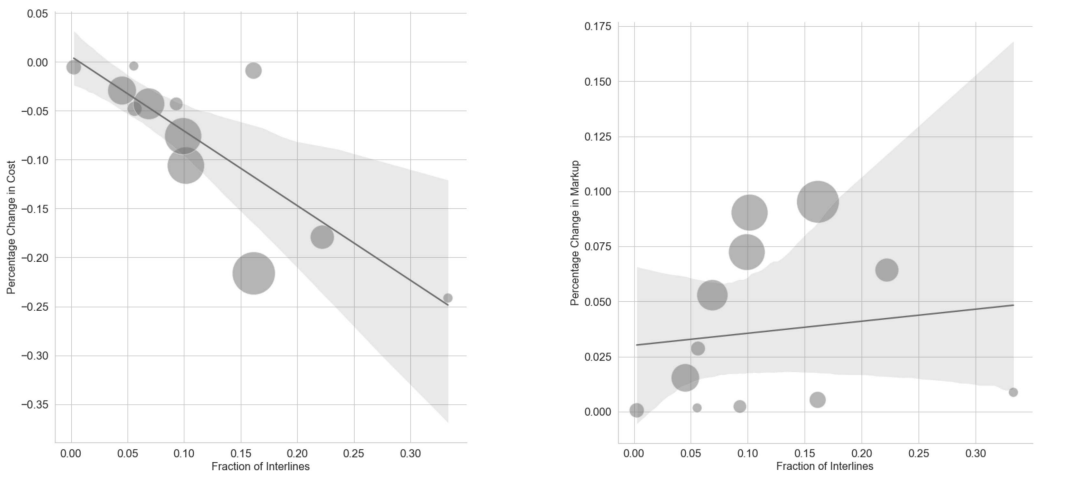


(a) Cost Changes and Degree of Overlap **(b)** Markup Changes and Degree of Overlap

Figure 6: Degree of Overlap and Average Merger Effects

Figure 7 shows the relationship between merger gains and degrees of complementarity. Panel (a) shows that higher degrees of complementarity lead to more significant cost reductions after the merger. When a merging network exhibits a higher degree

of complementarity, the merged firm benefits from a greater reduction in interchange costs.



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

Figure 7: Degree of Complementarity and Average Merger Effects

Comparing Panel (b) in Figure 7 with Panel (b) in Figure 6, we can observe that although a higher degree of complementarity also contributes to a larger increase in markup, the impact is comparatively less significant when compared to a higher degree of overlap.

Given the limited sample of twelve mergers, establishing causality is challenging. The results suggest that higher complementarity in merging networks often results in notable cost reductions and a modest increase in markup. Conversely, greater network overlap might lead to larger cost savings and a more substantial markup increase.

8 Conclusion

This paper quantifies significant cost efficiencies from mergers of U.S. freight railroads. The efficiency gains are primarily driven by the elimination of interchange costs between railroad companies and the economies of scope achieved by operating a larger network. To understand the equilibrium effects of these mergers, I propose a spatial equilibrium model of oligopolistic competition that considers two salient

features: the interdependence of markets within a network, and interactions between networks owned by different firms.

Applying this model to the U.S. railroad industry reveals that such mergers lead to significant cost reductions and a notable rise in markup. Counterfactual experiments show that the markup increase is not primarily due to a reduction in the number of firms in local markets. Instead, it results from non-merging competitors shifting resources away from areas where the merged firm achieves significant cost savings in equilibrium. Nonetheless, there is still pass-through to customers, leading to a reduction in shipment prices.

The findings of this paper also provide insights into future merger policies for network-based industries. It investigates which markets are likely to benefit or suffer from a merger and identifies the types of mergers that tend to be more advantageous. Nodes located on the edge of the network before the merger but at the center after the merger are more likely to experience significant cost reductions and an increase in markups, particularly when assessed using betweenness centrality. Across mergers, both a higher degree of overlap and complementarity between the networks being merged will result in substantial cost reductions. However, a higher degree of overlap is also associated with a notable increase in markup.

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Online Appendices: Not For Publication

A History of American Railroads

Figure A.1: Merger History of Railroads

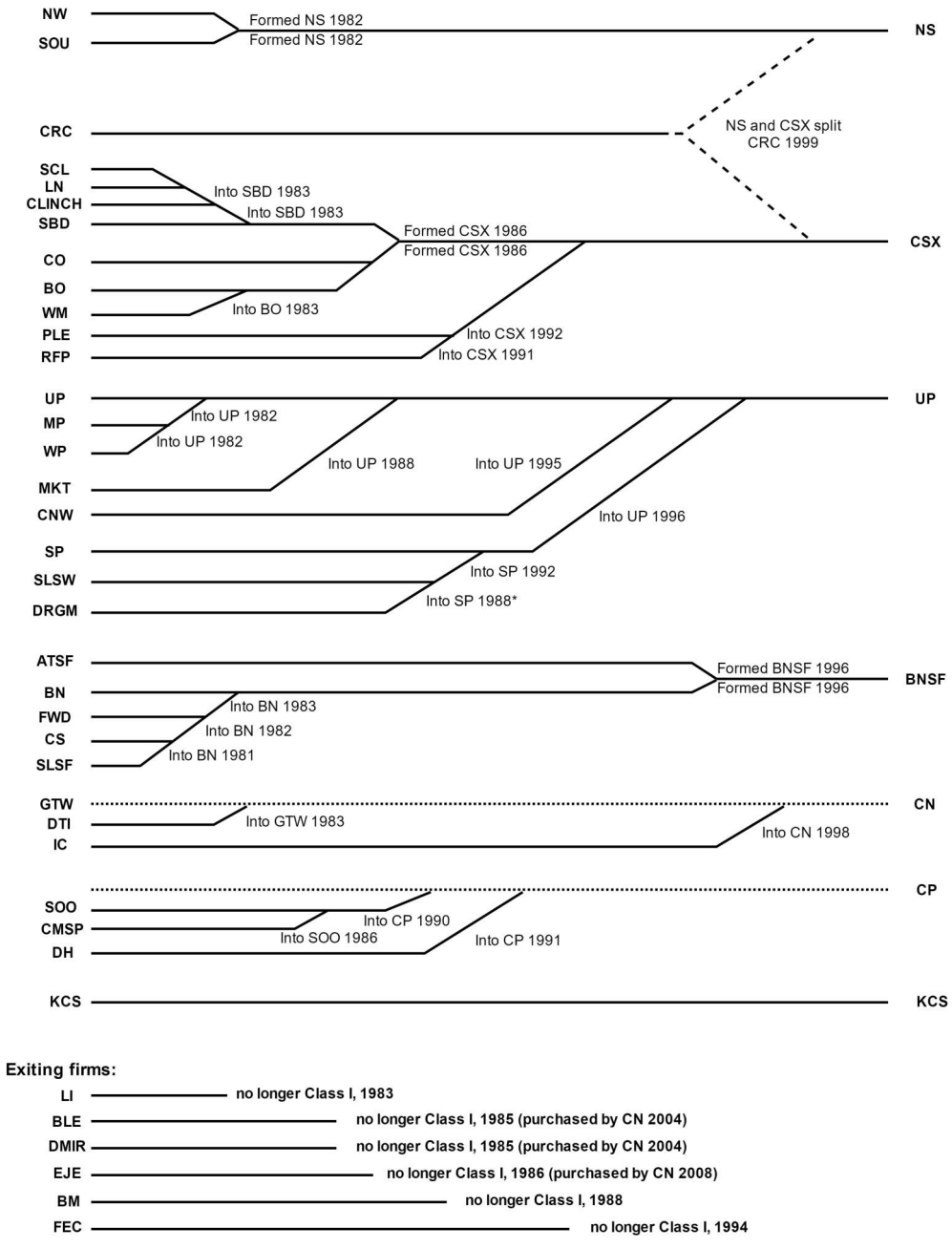
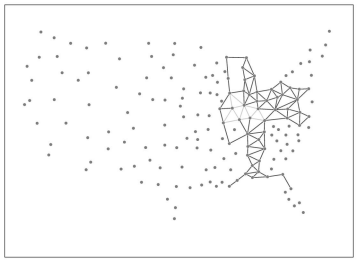
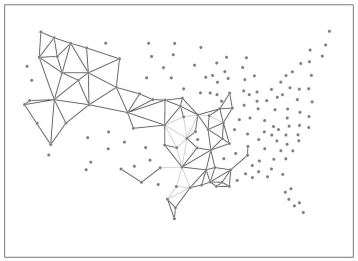


Figure A.2: Networks for Each Merger Case

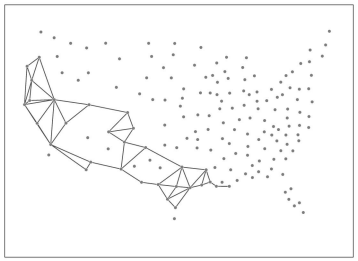
Note: Figure A.2 shows the networks of the two merging parties in each merger case between Class I railroads from 1985 to 2005. There were 12 mergers in total. Within each merger (firm1 + firm2), the network of firm1 is marked in green, that of firm2 is marked in purple, and the overlapping part is marked in yellow. For example, in panel (a) the network solely owned by COBO before the merger is marked in green, the network solely owned by SBD is marked in purple, and the overlapping region is marked in yellow.



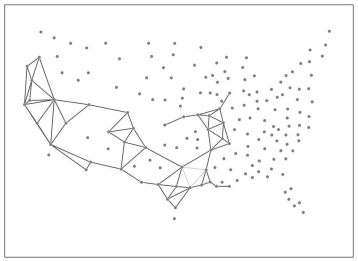
(a) 1986, COBO + SBD



(b) 1988, MKT + UP



(c) 1988, DRGW + SP



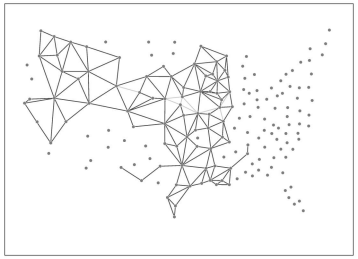
(d) 1992, SSW + SP



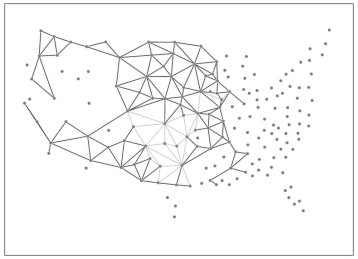
(e) 1992, LA + KCS



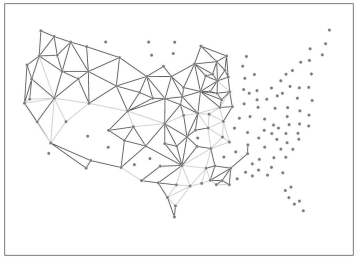
(f) 1993, MSRC + KCS



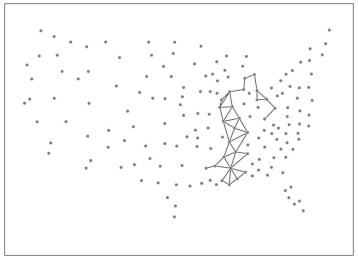
(g) 1995, CNW + UP



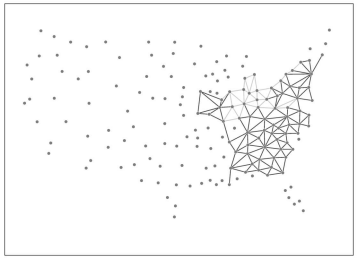
(h) 1996, ATSF + BN



(i) 1996, SP + UP



(j) 1998, CN + IC



(k) 1999, CR + NS



(l) 2004, WC + CN

B Details of U.S. Railroad Industry

B.1 Industry Statistics

Figures B.1 and B.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.

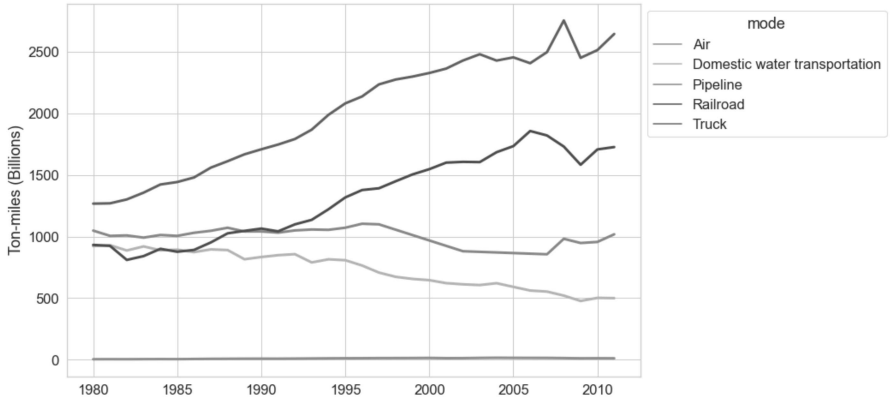


Figure B.1: U.S. total ton-miles of freight by mode

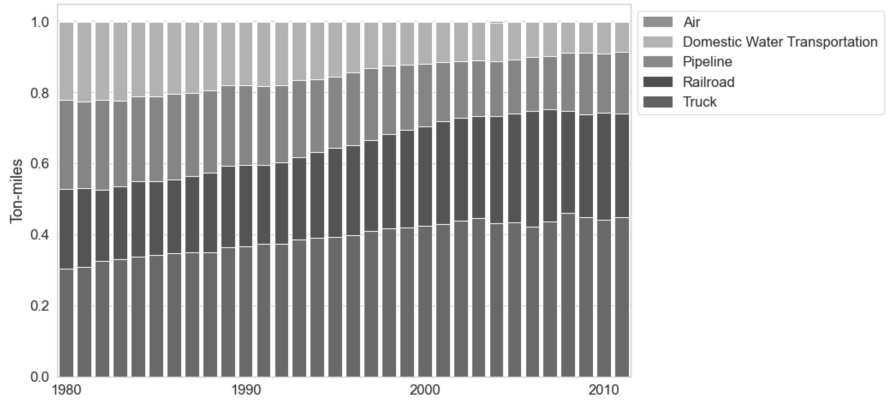


Figure B.2: U.S. total ton-miles of freight by mode (percentage)

B.2 More Summary Stats of Waybill Data

Table B.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	
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

Source: STB, Carload Waybill Sample

Table B.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 $611,033$ between 1985 and 2005. This shows that total volume of railroad shipment doubled from 1985 to 2005, consistent with the story in figure 1. Meanwhile, the percentage of interchange lines decreased from 41% to 11% while the total traffic volume doubled, showing that following the wave of mergers from 1985 to 2005, 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 2005, indicating that firms conduct oligopolistic competition in the local markets.

B.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.*

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

Table C.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 C.2 shows the estimation results for shipment price changes, which suggest that on average a railroad merger reduces the shipment price by 9.4%.

Table C.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

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.

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

Table C.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

D Discussion of the Model

D.1 Own and Cross-Cost Effects

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

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

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

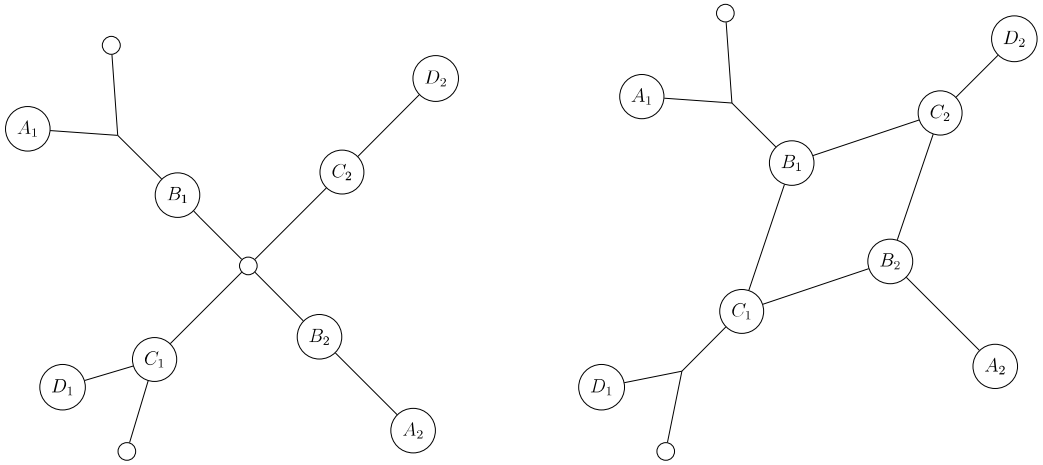
Below I compare the equilibrium results of the two models. There are three scenarios: no economy of scope ($\gamma = 0$), economy of scope ($\gamma \neq 0$) and the topology of the network is a tree, and economy of scope and non-tree network topology. The distinction between a tree and a non-tree network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

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

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

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

When $\gamma = 0$, maintenance allocation $\boldsymbol{I}$ no longer affects cost, and the optimal routing is to choose the shortest *o–d* path for each service s. Hence, the routing decision for each service s is independent. From equation D.1, we can see that the choice of



(a) Tree (b) Non-Tree

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

optimal routing depends only on the travel distance between each arc (a, b) and is irrelevant to the quantity being shipped. Therefore, $\frac{\partial C(\boldsymbol{Q},\boldsymbol{R},\boldsymbol{I})}{\partial Q_{s,od}} = \sum_{(a,b)\in\mathcal{R}^*_{j,od}} \delta_0 Dist_{j,ab} = C^{**}_{s,od}$. The second part of the equation holds because the optimal routing for firm j from o to d is the same in the two models when $\gamma = 0$. Therefore, both models' optimal strategies are equivalent when there is no economy of scope ($\gamma = 0$).

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

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

Proof: Equation D.1 shows that $C_{s,od}$ is inversely proportional to maintenance allocation $I_{j,ab}, (a, b) \in \mathcal{R}_{j,od}$. Therefore, the own- or cross-cost effect narrows down to how firms allocate the fixed amount of resources $I_{j,ab}$, where $\sum_{(a,b)\in\mathcal{A}_j} I_{j,ab} \leq K_j$. Based on the Kuhn-Tucker conditions in 13, we know that for any non-zero $I_{j,ab}$ and $I_{j,a'b'}$,

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

where $q_{j,ab}$ is the total amount of shipment running through arc (a, b), $q_{j,ab} = \sum_{s:s\in S(j)} Q_{s,od} \cdot \mathbb{1}\{(a, b) \in \mathcal{R}_{j,o_j(s),d_j(s)}\}$. Therefore, equation D.2 shows that the amount of allocation to arc (a, b) is proportional to the traffic going through arc (a, b). Therefore, when $Q_{s,od}$ increases, $\forall(a, b) \in \mathcal{R}_{j,od}, I_{j,ab}$ increases and hence $C_{s,od}$ decreases. That

is, the own-cost effect $\frac{\partial C_{s,od}}{\partial Q_{s,od}} < 0$. For market m to n, if m to n uses a totally different route than o to d (i.e. $\mathcal{R}_{j,od} \cap \mathcal{R}_{j,mn} = \emptyset$), then resources will be allocated away, yielding a higher shipment cost from m to n. Consequently, $\frac{\partial C_{s,mn}}{\partial Q_{s,od}} > 0$. However, if $\mathcal{R}_{j,od} \cap \mathcal{R}_{j,mn} \neq \emptyset$, m to n will partially benefit from the reallocation to arcs (a,b) where $(a,b) \in \mathcal{R}_{j,od} \cap \mathcal{R}_{j,mn}$. Hence, the net effect on $C_{s,mn}$ is ambiguous if $\mathcal{R}_{j,od} \cap \mathcal{R}_{j,mn} \neq \emptyset$.

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

Proof: From equation D.2, we know that

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

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

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

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

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

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

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

Proof: From Lemma 2, we know that when one market dominates, all the resources will be allocated to minimize the shipment cost for that dominant market in both

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

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

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

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

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

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

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

The last equality is obtained by subtracting the solutions of $I_{j,ab}$ into the equation.

Without loss of generality, we can assume that $Dist_{ab} = Dist_{a',b'}, \forall (a', b')$. Therefore, we have

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

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

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

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

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

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

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

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

Numerical Simulations: Topology of the Network is a Tree

In this numerical exercise, I assume that the topology of the network is the same as illustrated in panel (a) of Figure D.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 $D_1 \to D_2$.

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

Table D.1: Equilibrium Prices and Costs under Tree

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

Table D.2 shows the optimal allocation decisions I^*. There are three key findings of the numerical results. First, Panel I of Table D.2 shows the results when all four markets have equal amounts of demand ($M_{od} = 1, \forall od$). We can see that more resources are allocated to arcs (B_1, B_2) and (C_1, C_2) than the other arcs because more traffic goes through arcs (B_1, B_2) and (C_1, C_2) than the other arcs. For example, (B_1, B_2) is used by both market $A_1 \to A_2$ and $B_1 \to B_2$, while (A_1, B_1) is only used by market $A_1 \to A_2$. Second, when the importance of one market increases, more resources will be allocated to the routes used by that o–d market. In Panel II of Table D.2, the mass of demand of $M_{A_1A_2}$ is changed to 100 while the mass of demand is held at 1 for all the other markets. We can see that more resources are now allocated to the arcs $A_1 \to A_2$ go through (A_1, B_1), (B_1, B_2), and (B_2, A_2). Moreover, the allocation

amount for each arc approximately equals 2, which is consistent with Lemma 2. Third, there is no noticeable difference in the equilibrium allocation of resources between the benchmark model and the full model. Panel I shows the difference as 10^{-6}. Panel II 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 D.2: Equilibrium Allocation of Resources under Tree

Arc	Benchmark Model	Full Model	Difference
Panel I: $M_{od} = 1$ **for all four markets**			
(A_1, B_1)	0.80	0.80	−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

Numerical Simulations: Topology of the Network is Non-Tree

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

To investigate how routing and allocation decisions change in different cases, Table D.4 shows the optimal allocation decisions I^* and routing decisions $\mathcal{R}$. First, there

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

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

is no significant difference between the full model and the benchmark model in all cases. Second, we can observe that the routing from C_1 to C_2 is the same when we compare the results in Panel I with those in Panel III. The demand from A_2 to C_1 is higher in Panel III than in Panel I. Therefore, more resources are allotted to (A_2, B_2) and (B_2, C_1). Additionally, since both markets $A_2 \to C_1$ and $C_1 \to C_2$ use (B_2, C_1), allocation to (B_2, C_1) is also bigger than allocation to (A_2, B_2). Third, we can see that the routing from C_1 to C_2 changes when we compare the results in Panel I and II. As a result, allocation in Panel II is substantially higher than in Panel I for (A_1, B_1) and (B_1, C_1).

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

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

Arc	Benchmark Model	Full Model	Difference
Panel I: $M_{od} = 1$ **for all three markets**			
(A_1, B_1)	1.45	1.45	5E−05
(B_1, C_1)	1.45	1.45	5E−05
(D_1, C_1)	0.00	0.00	1E−07
(C_1, B_2)	2.11	2.11	−4E−05
(B_2, A_2)	1.49	1.49	1E−03
(B_2, C_2)	1.49	1.50	−1E−03
(C_2, D_2)	0.00	0.00	1E−07
(C_2, B_1)	0.00	0.00	1E−07
Routing of $C_1 \to C_2$		$C_1 \to B_2 \to C_2$	
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 $C_1 \to C_2$		$C_1 \to B_2 \to C_2$	

D.2 Economies of Scale and Congestion

In my model, the arc-level transportation cost is defined as:

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

When $I_{j,ab} = 0$, the transportation on the arc (a, b) is assumed to be impossible, resulting in an infinite transportation cost.

This specification is equivalent to setting $\tau = 0$ in equation (D.4):

$$c_{j,ab} = \frac{\delta Dist_{j,ab}}{I^{\gamma}_{j,ab}} \cdot Q^{\tau}_{j,ab}, \tag{D.4}$$

where $Q_{j,ab}$ is the quantity shipped through arc (a, b). If $\tau > 0$, we have congestion; if $\tau < 0$, we have economies of scale. As explained in Section 5.2, I set $\tau = 0$ to simplify computation, thereby keeping the optimal routing problem as a linear programming problem.

If incorporating economies of scale (or congestion) becomes necessary, I can use another method that does not impose the parametric form as in equation (D.4), thereby allowing me to continue framing the routing as linear programming problems. Interviews with practitioners suggest that they address congestion by solving optimization decisions layer by layer. For instance, they prioritize the main route from St. Louis to Chicago, determining the optimal routing for this key origin–destination first. Subsequently, they plan the next most important route, such as from New Orleans to Chicago, taking into account the congestion already introduced by the St. Louis to Chicago route. This process continues sequentially until all routes are optimized. I can replicate this layer-by-layer optimization approach in my model to incorporate economies of scale and congestion.

Specifically, in my current model the optimal routing decision is equivalent to finding the least expensive route to travel from origin o to destination d for each o–d market. This can be formulated as a linear-programming problem:

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

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

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

The optimal routing problem is then solved through LP algorithms, which operate within the feasible region defined by the constraints, iteratively moving towards the

optimal solution using linear algebra techniques.

Directly incorporating economies of scale or congestion parametrically as in equation (D.4), causes the optimal routing problem to no longer be a linear programming problem, because the marginal cost now varies with shipment quantity $Q_{j,ab}$ and is no longer constant. However, this challenge can be addressed by employing a layer-by-layer optimization approach. Specifically, for a target shipment from origin o to destination d, the quantity travelled through arc (a, b) is $Q_{j,ab}$, while the quantity already traveling trough arc (a, b) from previous layers is $Q'_{j,ab}$. Thus, the arc-level cost can be rewritten as

$$\begin{aligned} c_{j,ab} &= \frac{\delta Dist_{j,ab}}{I^{\gamma}_{j,ab}} \cdot \left(\sum_{(o',d') \neq (o,d)} q_{j,ab}(o', d') \right)^{\tau} \\ &= \frac{\delta Dist_{j,ab}}{I^{\gamma}_{j,ab}} \cdot (Q'_{j,ab})^{\tau} \end{aligned} \tag{D.5}$$

In this setup, changes in the routing decision for a specific shipment from o to d affect the quantity traveling through arc (a, b) for that particular shipment but not the quantities previously determined by earlier layers. This method allows us to maintain the optimal routing as a linear programming problem because, conditional on the quantities from previous layers, the arc-level cost of the shipment remains constant.

The main drawback of this approach lies in the subjective decisions regarding the sequence in which routes are optimized in the layer-by-layer process. In practice, operators typically prioritize routes based on shipment volume and customer needs. If I were to optimize based on the sequence of shipment quantities, my results are unlikely to differ significantly from the current model. This is because, for the heaviest traffic flows that are optimized first, the arc-level cost remains identical to that specified in my existing model. For subsequent layers optimized later, while there may be slight variations in routing options, their smaller quantities mean the overall impact on optimal decisions would be minimal.

E Counterfactual Results

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

Table E.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. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.