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The Impact of Reduced Coal Consumption on the Southeastern Railroad Network

By:
Dr. Mark L. Burton
Research Associate Professor, Department of Economics
Director, Transportation Economics, Center for Transportation Research
University of Tennessee, Knoxville
E-mail: mburton3@utk.edu

Dr. David B. Clarke, P.E.
Executive Director, Center for Transportation Research
University of Tennessee, Knoxville
E-mail: dclarke@utk.edu

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TECHNICAL SUMMARY

Title

<u>The Impact of Reduced Coal Consumption on the Southeastern Railroad Network</u>

Introduction

In the post-World War II era, coal's use in electricity generation and steel production soared, both domestically and internationally. Consequently, transporting coal became the railroad industry's greatest source of both revenue and freight traffic. The virtual collapse of America's integrated steel producers during the last two decades of the 20th century greatly reduced domestic metallurgical coal consumption, though U.S. coal remained competitive in offshore markets. Fortunately, producers offset at least a portion of this decline through increased sales to electric utilities.

Now, given abundant new supplies of low cost natural gas, environmental concerns, and increasing regulatory requirements, electric utilities are retiring coal fired generating capacity. This decreasing reliance on coal as a fuel will have pronounced effects on America's railroads. While the decoupling of electricity generation and coal transportation is taking place throughout the United States, the effects are greatest in the east. There, the rapid decline in coal-fired generating capacity and an equally pronounced reduction in the mining of Appalachian coal bode significant change for eastern railroads.

Approach and Methodology

The study had three goals:

1. to document historical coal production, consumption, and transportation patterns in the eastern U.S. east of the Mississippi River and to describe changes to those patterns over the past two decades
2. to catalogue and analyze the "early" railroad industry responses to reduced coal transportation demands
3. to develop an analytical platform capable of predicting specific railroad network locations affected by coal-related changes, providing a tool for both private sector and public sector decision-makers who wish to test the impacts of various coal production scenarios and public-sector responses.

This analytical platform, using the RAILNET model, incorporates:

- a highly specialized GIS depiction of the domestic railroad network;
- a complex routing algorithm that optimizes traffic routings, while simultaneously reflecting exogenous influences such as carrier sovereignty, institutional restrictions on interchange; and carrier-specific operating plans that include elements like directional running; and
- cost parameters that capture route-specific cost differences under varying levels of link use.

The study team collected data on forecasted coal production and coal fired utility plant closures. The data were used to derive coal flows for a base year (2011) and a future year (2036). The Carload Waybill Sample (CWS) provided nationwide traffic from other commodities.

The team upgraded the RAILNET model and network to determine flow patterns. Comparison of the flows for the two cases identified affected network elements and carriers.

Findings

The modeling determined that the decline in utility coal consumption could reduce annual rail transportation by 72.8 billion ton-miles. The two major eastern carriers, Norfolk Southern and CSX Transportation would experience the greatest losses, at 23.4 and 30.7 billion ton-miles respectively. Affected lines link coal producing locations in Appalachia with consumers in southeastern states and with Atlantic coast export terminals. Several important Appalachian mainlines would experience significant traffic losses. During the course of the study, line and facility downgrading or closure in the region followed patterns predicted by the analysis.

Conclusions

The study findings, while needing further refinement, hint at possible policy challenges and opportunities. First, much of the forecasted uniform Appalachian coal production decline over 2011-2036 appears to have already occurred. This is consistent with utility strategies to retire obsolete coal-fired generating capacity as quickly as possible. Thus, the majority of the potential impact on rail traffic may have occurred.

Second, ongoing and future traffic impacts attributable to reduced coal reliance are (and will continue to be) largely constrained to Appalachia. The coal routes in this region exist in relative isolation from other railroad network activities. While diminished coal volumes threaten freight rail access in Appalachia's coal producing regions, this threat is not likely to spread to other segments of the eastern U.S. Any railroad problems associated with declining coal are likely to be localized and any policy responses to the challenges associated with reduced rail network access will need to originate at the same local levels.

Finally, the extent of predicted reduced coal traffic between Appalachia and eastern deep draft ports depends almost exclusively on the demands for coal exports. While many factors can influence these volumes, coal exports certainly can be influenced by to changes in U.S. trade policies. Any modification of trade policy that diminishes the competitiveness of Appalachian coal in global markets, is also likely to further threaten rail corridors linking Appalachia with East Coast ports.

Recommendations

The research revealed several areas for future work. First, the linkage between network displays and the underlying data, especially to permit GIS based editing, would significantly expedite network modifications and validation. Second, data is needed on terminal-specific cost and performance attributes which were unavailable for this study. The RAILNET platform is capable of incorporating these parameters. Finally, link-specific functions relating traffic density to unit costs could enhance the mathematical program. It is worth exploring this possibility. General work on the current set of network cost parameters is needed to differentiate between carriers and individual network elements.

Primary Contact Principal Investigator

Dr. Mark L. Burton
Research Associate Professor
Department of Economics
University of Tennessee, Knoxville
E-mail: mburton3@utk.edu

Other Faculty and Students Involved

Dr. David B. Clarke, P.E.
Executive Director
Center for Transportation Research
University of Tennessee, Knoxville
E-mail: dclarke@utk.edu

M.S. Student: Pankaj Dahal

NURail Center

217-244-4444
nurail@illinois.edu http://www.nurailcenter.org/

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Mark L. Burton
David B. Clarke

Center for Transportation Research

THE UNIVERSITY OF TENNESSEE KNOXVILLE

NURail Center

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1. INTRODUCTION

For nearly 200 years, economic self-interest has bound coal and American railroads in a symbiotic partnership. For more than half of that period, coal was the dominant fuel for railroad locomotives and railroads were among the coal industry's largest customers. Even when coal faded as a transportation fuel, the commercial codependence between railroads and coal producers continued. The steel industry, both domestic and off shore, remained a steady consumer of metallurgical coal from U.S. mines. In an energy-hungry, post-World War II era, coal's use in electricity generation soared, both domestically and internationally.[1] Consequently, the transportation of coal to utilities, mills, and export terminals became the railroad industry's greatest source of both revenue and freight traffic.[2] The virtual collapse of America's integrated steel producers during the last two decades of the 20th century greatly reduced domestic metallurgical coal consumption, though U.S. coal remained competitive in the export market. Through the first decade of the 21st century, increases in steam coal demand more than offset the decline in domestic metallurgical coal.

The economic bonds that link coal producers, freight railroads, and electricity producers are fundamental, though not immutable. Consequently, changes to any one of these industries quickly affect all three. Given abundant new supplies of low cost natural gas, environmental concerns, and increasing regulatory requirements, electric utilities are sharply curtailing coal fired generation. It follows, then, that the electric utility industry's decreasing reliance on coal as a fuel is having pronounced effects on America's railroads. Moreover, while the decoupling of electricity generation and coal transportation is taking place throughout the United States, the effects are greatest in the east. There, the rapid retirement of coal-fired generating capacity and an equally pronounced reduction in the mining of Appalachian coal bode significant change for eastern railroads.[3]

Within this context, the current study has three goals. First, we attempt to document historical coal production, consumption, and transportation patterns in the U.S. in the region east of the Mississippi River and to describe changes to those patterns over the past two decades. In doing so, it is important to segregate lasting, long run trends from the volatile cyclical influences that are typical in energy markets.

Our second goal is to catalogue and analyze the "early" railroad industry responses to reduced coal transportation demands. Beginning in 2015, both eastern Class I railroads and the region's short-line railroads have made infrastructure and operating adjustments in response to changing coal volumes.[4] Some of these changes, like the coal industry changes that precipitated them, are probably transient responses to cyclical traffic disruptions. However, these initial railroad

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[1] See U.S. Department of Energy, Energy Information Administration Annual Energy Review, 2012, Table 7.3 https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb0703

[2] See Association of American Railroads, *Statistics of Class I Railroads*, 1978-2015.

[3] See Sections 2.4 and 2.5 for more detail.

[4] The first announced coal-related Class I railroad adjustment involved the CSX closure of shop facilities at Erwin, Tennessee and the discontinuance of service along much of its trackage between Kingsport, Tennessee, and Russell, Kentucky.

industry responses, even if temporary, may inform expectations about the more lasting rail industry changes expected in response to long-run declines in coal traffic.

The third goal of the current research is to develop an analytical platform capable of predicting specific railroad network locations affected by coal-related changes. Such an analytical instrument could provide a powerful tool for private and public sector decision-makers who wish to test the impacts of various coal production scenarios and public-sector responses.

We organize the remainder of the current report as follows: Section 2 provides a sketch of coal market mechanics, descriptions of eastern coal production, consumption, and movement of (primarily Appalachian) coal, with specific attention to how reduced coal reliance is affecting transportation demands. In Section 3, we catalogue the changes in railroad operations and infrastructure already observed as a response to reduced coal demands. This section concludes with a summary of the options available to the region's railroads as they consider further, long-run adjustments. Sections 4 and 5 describe our rail network analysis platform that identifies the specific locations of likely long-run changes in rail network configuration and availability. Finally, Section 6 presents analytical findings and provide some recommendations for further work.

2. PRODUCING, CONSUMING, AND TRANSPORTING EASTERN COAL

Energy markets are global, complicated, and erratic. Understanding the long-run outlook for the movement of Appalachian coal requires a careful focus on market basics and insensitivity to short-run disturbances. It is, therefore, useful to summarize the long-run basics that will continue to define the markets for Eastern coal. It is then easier to consider the market disruptions that have further perturbed production and transportation activities.

2.1 A summary of coal market mechanics

Distilling complex international fuel and energy markets to arrive at a few market basics requires many simplifications. For those who are more familiar with these markets, the explanations provided here might seem mundane. Our intent, however, is to provide more casual readers with a workable foundation for understanding current and foreseeable trends in the transportation of Appalachian coal.

BASIC NO. 1 *For two or more generations, the majority of coal consumed in the U.S. has been "steam coal" used to generate electricity.*

Historically, the U.S. has used coal for a variety of industrial purposes, including but not limited to electricity generation.[5] As recently as 1965, power generation accounted for barely half of U.S. coal consumption. However, since then, the electric utility share of domestic coal consumption has climbed consistently. By 1980, the utility share had reached 81 percent nationally; by 2000, this share was 91 percent; and in 2009, at the same time that coal's contribution to electricity generation peaked, nearly 94 percent of all coal consumed in the U.S. was burned to produce electricity.[6] Of all the major coal-producing regions, Appalachia is the least dependent on domestic utility consumption, but this consumption still accounts for roughly 70 percent of Appalachian coal output.[7]

BASIC NO. 2 *Both the absolute quantity of coal used in electricity production and coal-fired generation's share of total production continue to fall. For the most part, natural gas fueled capacity has replaced retired coal-fired generating plants, though some new facilities use energy sources such as wind, solar, and biomass fuel.*

From 2001 forward, coal's share of total domestic electricity production has fallen from 51 percent in that year to 33 percent in 2015. The actual amount of electricity produced from coal peaked in 2007 at just over 2 billion megawatts.

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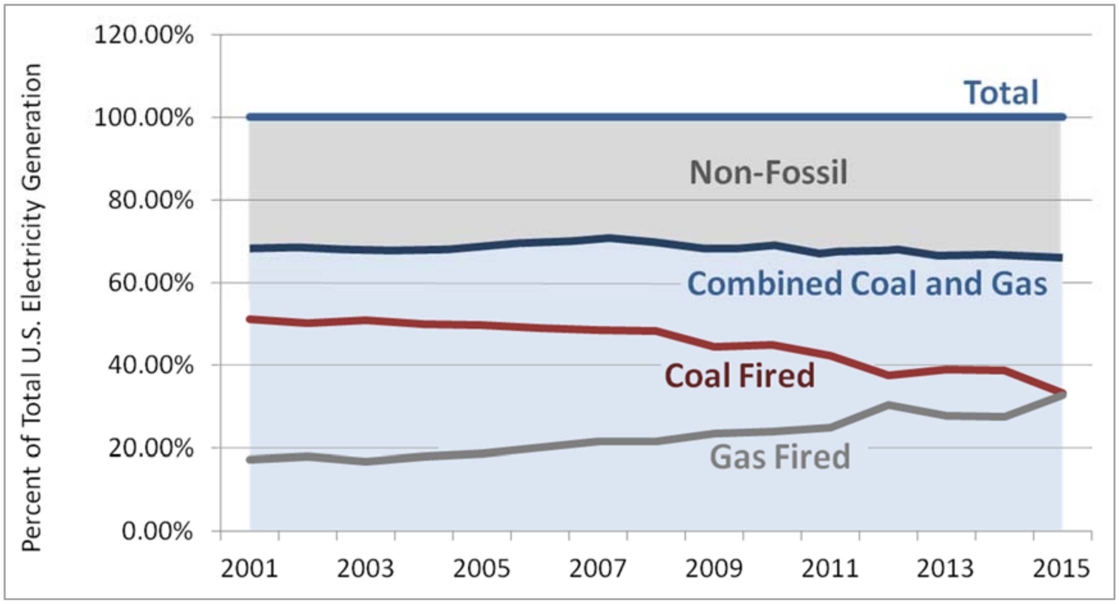
[5] In 1949, the year in which the EIA series begins, nearly 15 percent of all U.S. coal consumption was by the transportation sector, presumably as fuel for steam locomotives and water vessels.

[6] While the numbers reported in the text are national in nature, similar values emerge when the analysis included only those states that are most likely to burn Appalachian coal. For 2014, the national utility share of coal was roughly 93 percent. In those regions most likely to consume Appalachian coal, the utility total represented 91 percent of total consumption. The U.S. Energy Information Administration provided all data. See http://www.eia.gov/coal/data.php#consumption

[7] Twenty-three states recorded, at least, some coal production during 2016. However, within the current context, coal produced in the Illinois basin (Illinois, Indiana, and western Kentucky) and coal produced in the Powder River basin (Montana and Wyoming) competes effectively in Appalachian coal markets. See, U.S. Energy Information Administration | Quarterly Coal Report, January - March 2017, Table 2.

During this same period, the natural gas share of domestic electricity production has nearly doubled from 17.1 percent in 2001 to 32.7 percent in 2015. Indeed early estimates suggest that natural gas has overtaken coal as a source of electricity generation. The contribution from other fuel sources (both renewable and non-renewable) has grown only slightly from 32 percent in 2001 to 34 percent in 2015. Figure 1 depicts fuel shares.



Source: Energy Information Administration

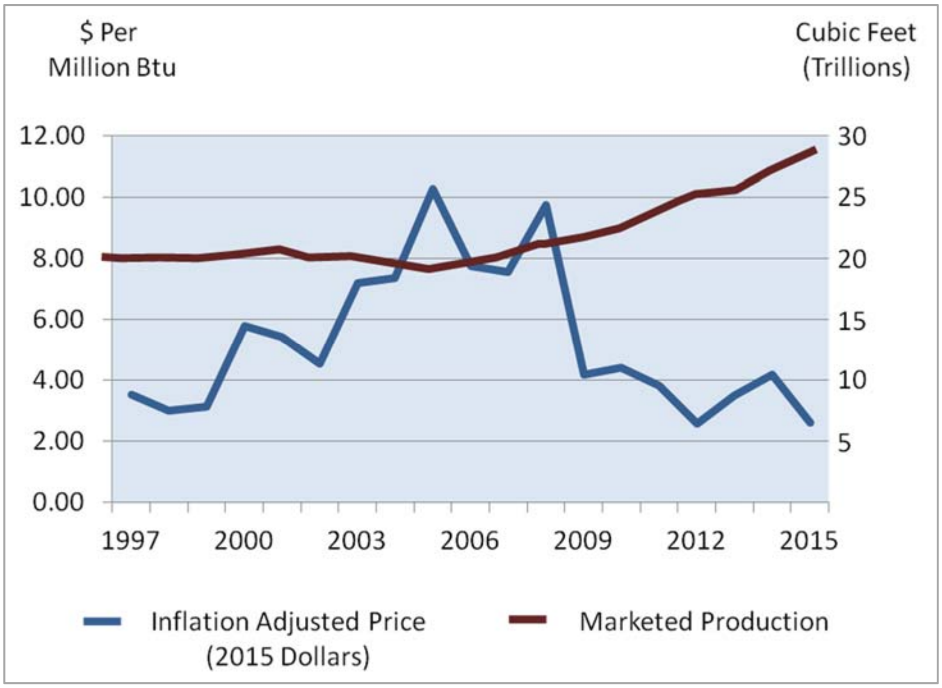
Figure 1. Shares of Coal and Natural Gas in Electricity Generation

BASIC NO. 3 *Among other factors, increased domestic natural gas production has driven down gas prices, facilitating the transition from coal-fired to gas-fired electricity generation while keeping down-stream electricity prices stable.*

Perhaps the single biggest energy story of the new century is the emergence of hydraulic fracturing (fracking) as a prominent means of extracting natural gas and petroleum from reserves previously deemed unrecoverable.[8] In the northern prairie states and in western Canada, producers use fracking to unlock crude petroleum reserves. However, in the southwest and eastern U.S., fracking primarily produces natural gas. In combination, these additional supplies have created what some are calling an *energy renaissance*.

Within the current context, increased (and still expandable) supplies of natural gas have allowed electricity producers to move quickly toward the replacement of coal without causing a lasting increase in natural gas prices or in the downstream price of electricity. Figure 2 depicts domestic natural gas prices and output between 1997 and 2015.

[8] U.S. producers have practiced hydraulic fracturing for more than a century. However, the combination of "slick water" fracking and horizontal drilling emerged in West Texas in the late 1990s.



Source: Energy Information Administration. Price=Average Henry Hub Spot Price

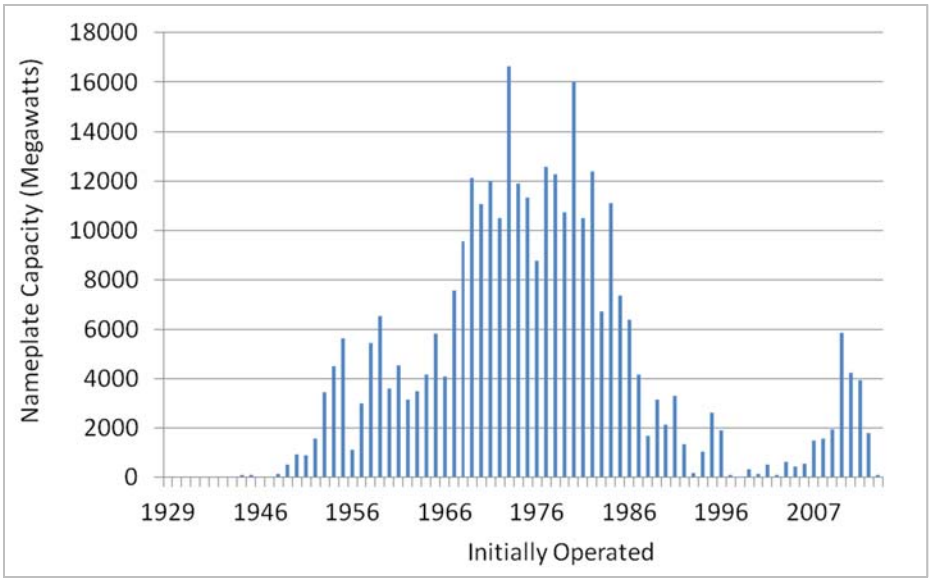
Figure 2. Inflation Adjusted Natural Gas Prices and Marketed Annual Gas Production

BASIC NO. 4 *The asset lives of existing coal-fired facilities, how quickly these facilities can be affordably retired, and public policies that encourage reductions in pollutant emissions largely dictate the pace of the ongoing transition from coal-fired electricity generation.*

Coal-fired generating plants represent billions of dollars of utility company investments. Accordingly, utility managers are reluctant to retire these plants prematurely. Thus, information describing the design lives of the existing coal-fired facilities could, to some degree, predict the timing, location, and quantity of coal demand in coming decades.

Figure 3 depicts the startup dates of the coal-fired generating capacity currently available for operation. Almost exactly two-thirds of this capacity entered service between 1965 and 1984, so that it is between 30 and 50 years old. Simple calculations that assume an average 50-70 year facility life (without substantial reinvestment), assume coal consumption rates that mirror electricity outputs, and assume no new coal-fired facilities will be built, then these data suggest that steam coal could account for as little as 17 percent of electricity production by 2036.[9]

[9] This is, by every measure, a gross calculation. It does not consider past or potential investments that may extend the lives or improve the efficiency of existing facilities; it does not consider adjustments to the frequency or extent of coal-fired facility dispatch; and it ignores the effects of future regulation or changing input prices on potential retirements.



Source: Energy Information Administration

Figure 3. Vintage of Operational Coal-Fired Generating Capacity

BASIC NO. 5 *Eastern coal is less dependent on domestic electricity production and more dependent on export markets than coal produced elsewhere in the U.S. This export dependence is expected to increase with or without implantation of the EPA's Clean Power Plan (CPP).*

The characteristics of the high-grade, bituminous coal produced in central Appalachia make it suitable for both electricity generation and for metallurgical applications. This versatility, combined with proximity to eastern deep-draft ports has allowed Appalachian producers to substitute export opportunities for declining domestic demands. Analysts expect this pattern to grow in its importance to regional production. Indeed, within its forecasts, the most recent release of the U.S. Department of Energy's *Annual Energy Outlook* suggests:

> Production of coal in the Appalachian region declined sharply before 2015 as domestic coal buyers shifted from Appalachian steam coal toward other coal sources or to other fuels for economic reasons. The Appalachian region remains a major source of metallurgical coal, whose markets are not directly affected by the CPP. With or without the CPP, Appalachia's producers depend on sales of both metallurgical and steam coal in international markets.[10]

As discussed below, this dependence on international markets affects coal-related vulnerabilities for Appalachia.

2.2 Recent cyclical disturbances

In 2015, domestic coal production suddenly seemed to collapse into a depressed state that extended through much of 2016. In reality, the roots of this downturn lie in the long-run trends

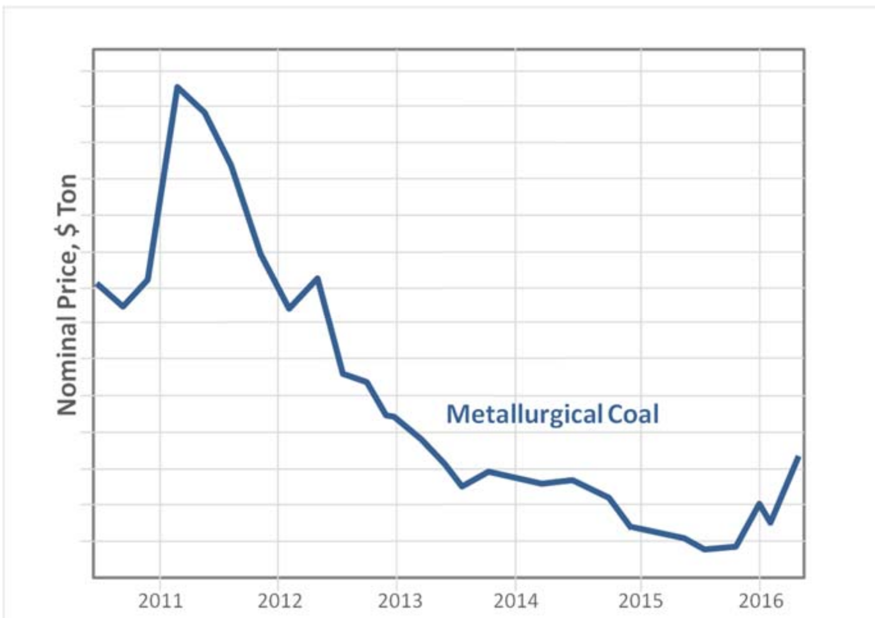
[10] See, U.S. Department of Energy, *Annual Energy Outlook: 2016*, Released August 2015, p. ES-3.

described above. However, a coincident turn in international markets and failed strategies by U.S. producers made it more challenging.

The recovery of the U.S. economy post the 2008 Great Recession did not produce a rebound in steam coal volumes. At the same time, however, the international market for metallurgical coal showed significant potential. In response to this perceived opportunity, large U.S. coal producers leveraged existing assets to invest heavily in additional metallurgical coal capacity.[11]

Unfortunately, these investments were ill timed. The international price for metallurgical coal peaked in 2011 – the same year as many of the U.S. firm investments – and began the precipitous and prolonged five-year slide depicted in Figure 4. While not quite so dramatic, the decline in U.S. export coal followed essentially the same pattern.

By 2015, the heavy debt incurred to acquire new metallurgical coal capacity, combined with falling met coal prices, and the steady, ongoing decline in domestic steam coal markets, placed nearly every major U.S. coal producer in an untenable financial position.



Source: Bloomberg

Figure 4. Nominal Benchmark Prices for Metallurgical Coal

Alpha Natural Resources filed for Chapter 11 bankruptcy protection in August of 2015; Arch Coal filed for similar protection in January of 2016; and finally, Peabody Energy – the world's largest coal producer – filed for bankruptcy protection in April of 2016. In total, the aggregate share value of U.S. coal producers fell from a 2011 high of $78 billion to a 2016 total of just over $12 billion.[12]

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[11] In 2011, Alpha Natural Resources spent $7 billion to acquire Massey Energy, Arch Coal purchased the International Coal Group for $3.4 billion, and Peabody Energy acquired Australian producer MacArthur Coal for $5.2 billion.

[12] To review the recent financial troubles of domestic coal producers, see: "Coal Miner Alpha Natural Resources Files for Bankruptcy," *Bloomberg*, August 3, 2015,

2.3 Traditional production and consumption of eastern coal

Again, markets for fuel and energy are global. Thus, constructing and relying on limited geographic boundaries for the sake of simplicity comes with some risk. Nonetheless, the current review of coal production and consumption focuses on the United States east of the Mississippi River. Even so, it will sometimes be necessary to include descriptions of other domestic and international influences. Table 1 summarizes 2014 coal production in 11 eastern states. Figure 5 depicts active coal mines and the more general coal producing areas.

Table 1. 2014 Coal Production in the Eastern U.S.

PRODUCTION					
Geographic unit	**2014 coal production (KTons)**	**2014 share of U.S. production**	**2014 export volume (KTons)**	**Share of total 2014 U.S. exports**	**Export share of 2014 state total**
Alabama	16,363	1.6%	12,049	12.4%	73.6%
Georgia	-	-	-	-	-
Kentucky	77,335	7.7%	3,293	3.4%	4.3%
Maryland	1,978	0.2%		0.0%	0.0%
Mississippi	2,625	0.3%	-	-	-
North Carolina	-	-	-	-	-
New York	-	-	-	-	-
Ohio	22,252	2.2%	101	0.1%	0.5%
Pennsylvania	60,910	6.1%	5,323	5.5%	8.7%
South Carolina	-	-	-	-	-
Tennessee	839	0.1%	-	-	0.0%
Virginia	15,059	1.5%	6,748	6.9%	44.8%
West Virginia	112,187	11.2%	29,250	30.1%	26.1%
Appalachian states	**309,548**	**30.7%**	**56,764**	**58.4%**	**18.5%**
Delaware	-	-	-	-	-
Florida	-	-	-	-	-
Illinois	*57,969*	*5.8%*	*10,170*	*10.5%*	*17.5%*
Indiana	*39,267*	*3.9%*	*85*	*0.1%*	*0.2%*
Michigan	-	-	-	-	-
New Jersey	-	-	-	-	-
Region total	**406,784**	**40.4%**	**67,019**	**68.9%**	**16.6%**
U.S. Total	**1,000,049**	**100.0%**	**97,257**	**100.0%**	**9.7%**

Source: Energy Information Administration

Within the region considered here, mines in West Virginia, Kentucky, Pennsylvania, Illinois, Indiana, and Ohio dominate coal production. All of the West Virginia and Pennsylvania output and most of the coal produced in Kentucky is associated with the Appalachian region, while Illinois, Indiana, and western Kentucky coal is from the Illinois basin. In total, the coal depicted here represented roughly 40 percent of all domestic U.S. production in 2014.

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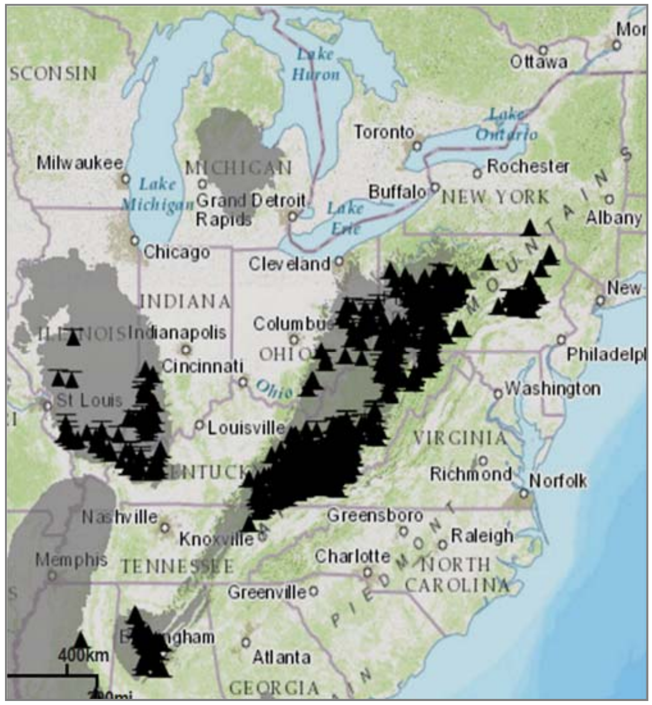
http://www.bloomberg.com/news/articles/20150803/coalmineralphanaturalresourcesfilesforbankruptcy; Arch Coal Files for Bankruptcy in Latest Blow to U.S. Miners *Bloomberg*, January 16, 2016, http://www.bloomberg.com/news/articles/20160111/archcoalfilesforbankruptcyreaches45billiondebtdeal; and Coal Slump Sends Mining Giant Peabody Energy Into Bankruptcy, Bloomberg, April 13, 2016, http://www.bloomberg.com/news/articles/20160413/peabodymajorityofitsusentitiesfileforchapter11



Source: Energy Information Administration

Figure 5. Eastern Coal Production

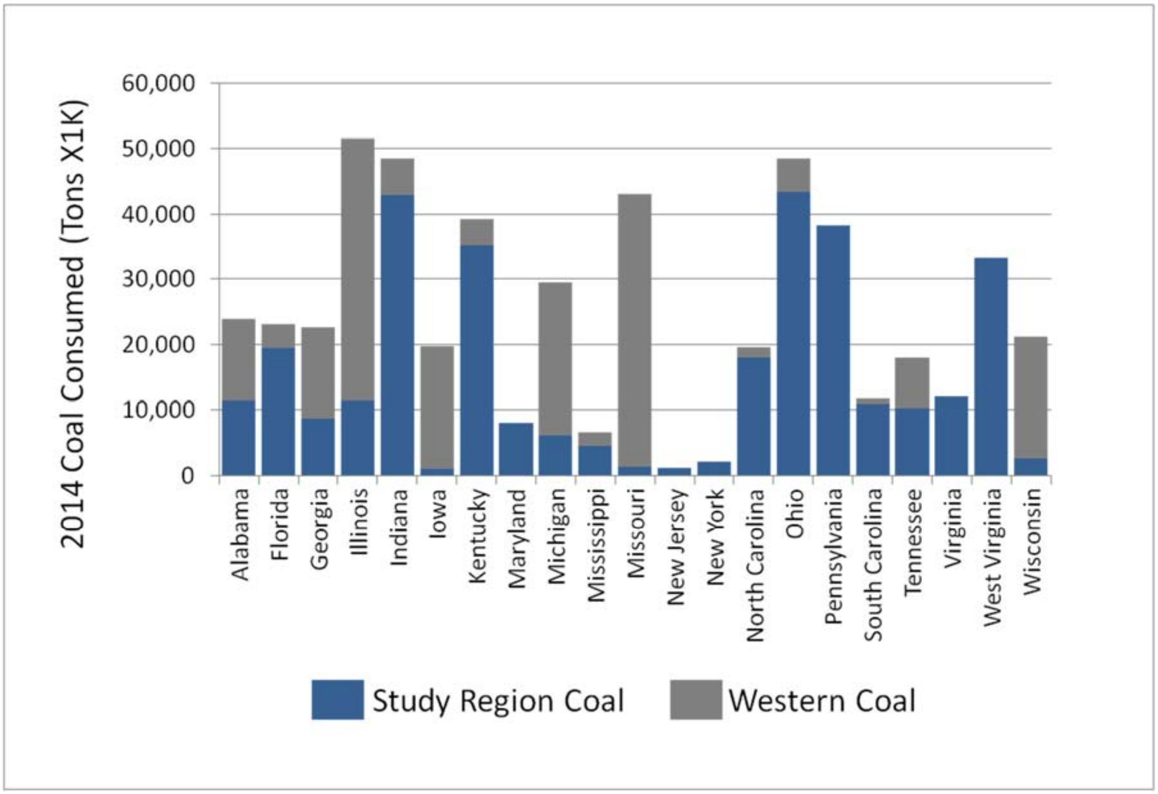
On average, the U.S. consumes roughly 90 percent of domestically produced coal, mostly in the production of electricity. However, for Appalachian coal, exports play a more important role. Approximately 25 percent of all output from the study region moves to international markets, much of it as metallurgical coal. High-quality central Appalachian bituminous coal that moves primarily across Virginia ports and Alabama coal shipped via Mobile dominate these exports.

Producers ship the remainder of the study region coal to consumers who are generally located in or relatively near the producing states. Figure 6 summarizes coal shipments from study region states. It also includes the volume of western coal consumed by the receiving states.

Together, these patterns of production and domestic consumption, export volumes, and port locations define the movement of coal throughout Appalachia and the eastern U.S. The next task is to explore specific routes that carry coal between production and consumption points.

2.4 The ongoing transition and its effects

Figure 1 (Section 2) illustrates the decline in coal's share of total U.S. electricity generation and the corresponding increase in the share of electricity produced with natural gas. Table 2 provides similar data for total electricity output, along with estimates of the U.S. population. These data show that, not only did coal's share of production decline, but the total amount of electricity produced through coal also fell. While to some degree, this reflects the reduced use of operable coal-fired plants, it more generally represents the full retirement of coal-fired facilities.



Source: Energy Information Administration

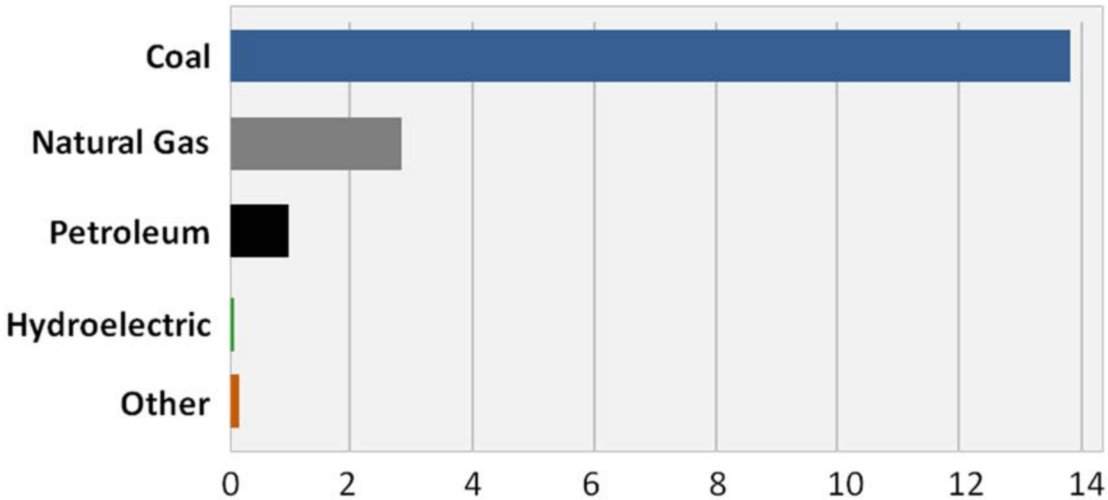
Figure 6. 2014 Consumption of Eastern Coal

Table 2. U.S. Electricity Generation
(Thousands of Megawatts for Utility Scale Facilities)

YEAR	Coal-fired	Natural gas fired	All other sources	Total (utility-scale generation)	Estimated U.S. population
2006	1,990,511	816,441	1,257,750	4,064,702	298,360,000
2007	2,016,456	896,590	1,243,700	4,156,746	301,230,000
2008	1,985,801	882,981	1,250,605	4,119,387	304,090,000
2009	1,755,904	920,979	1,273,448	3,950,331	306,770,000
2010	1,847,290	987,697	1,290,072	4,125,059	309,410,000
2011	1,733,430	1,013,689	1,353,021	4,100,140	311,770,000
2012	1,514,043	1,225,894	1,307,829	4,047,766	314,140,000
2013	1,581,115	1,124,836	1,360,013	4,065,964	316,540,000
2014	1,581,710	1,126,609	1,385,286	4,093,605	319,070,000
2015	1,356,057	1,335,068	1,396,255	4,087,380	321,560,000

Source: Energy Information Administration

Nationwide, utilities retired nearly 21 gigawatts (GW) of coal-fired electricity generation between 2009 and 2014, representing six percent of U.S. coal-fired capacity. This trend continues, unabated.[13] In 2015, 94 coal-fired power plants closed, with the combined net summer capacity of 13,556 megawatts. Utilities scheduled another 41 coal plants, with a combined net summer capacity of 5,326.5 megawatts, to close in 2016. However, this study has not verified the actual closures.[14] Figure 7 depicts 2015 generating facility retirements across generating sources.



Source: Energy Information Administration

Figure 7. 2015 Generating Capacity Retirements, (Gigawatts)

2.5 Predicting future eastern coal production

Beginning with the Clean Air Act of 1970, Americans have shown a tireless preference for air quality improvements. There is no reason to believe this will change. Moreover, to the extent that burgeoning natural gas production makes it possible to reduce reliance on coal-fired energy production without facing measurably higher electricity prices, the movement away from coal is almost sure to be a component of U.S. environmental policy.

Figure 8 illustrates a sample of announced coal-fired facility retirements between now and 2036. For each coal, this tells much of (but not all) the foreseeable future story. The missing component is the volatile international demand for high quality, bituminous metallurgical coal that, in the recent past, has consumed roughly 20 percent of Appalachian production.

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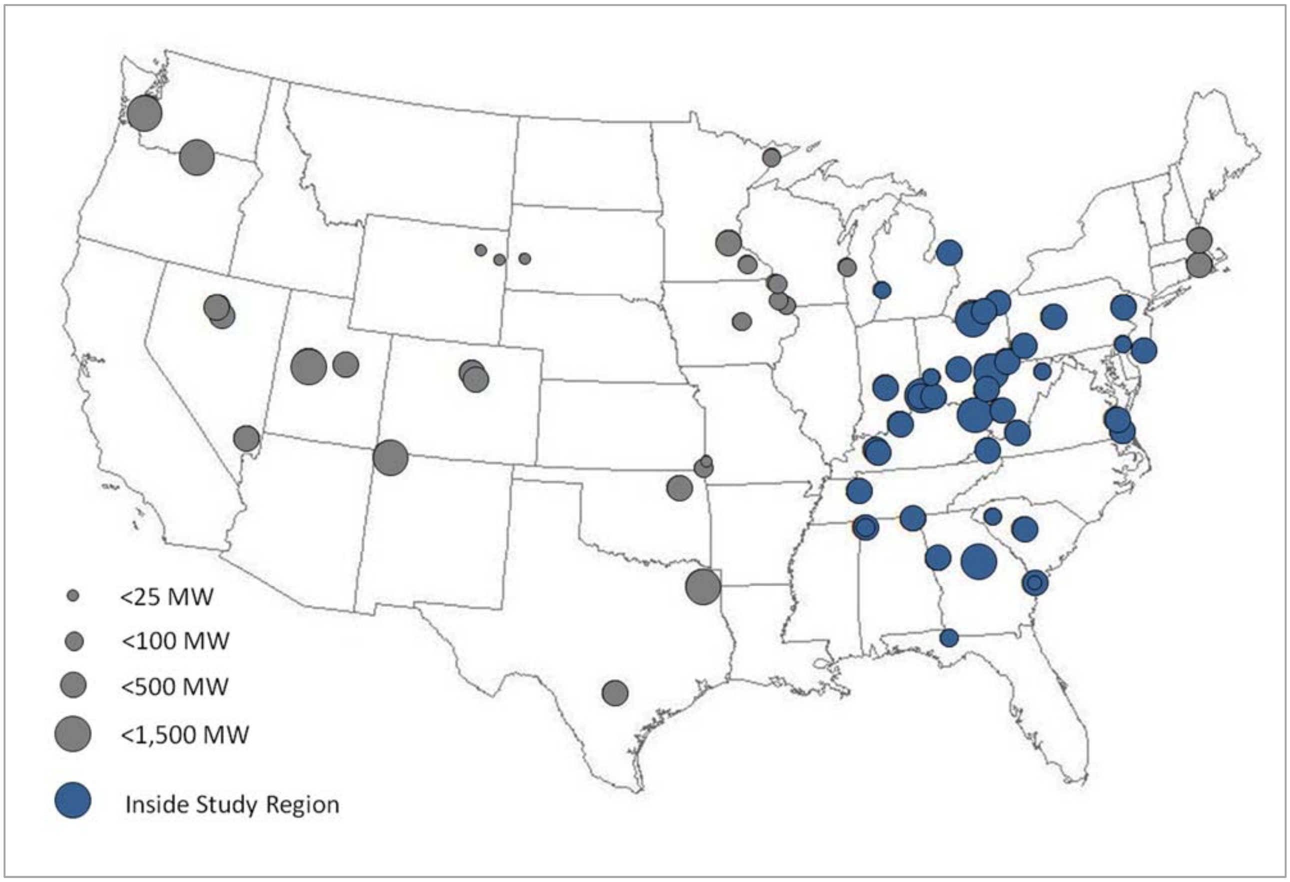
[13] See *Union of Concerned Scientists*, "TVA Pulls the Plug on More Coal Plants; Others Will Surely Follow," November 18, 2013, http://blog.ucsusa.org/jeffdeyette/tvapullstheplugonmorecoalplantsotherswillsurelyfollow306

[14] See Morning Consult, "Coal Plants Are Shutting Down, With or Without Clean Power Plan," May 3, 2016, https://morningconsult.com/author/jack/



Source: Energy Information Administration

Figure 8. Announced Coal-Fired Plant Retirements (As of 2014)

Ultimately, the next two decades are likely to see a continuation of the trend in evidence since 2008 whereby domestic coal volumes fall by roughly five percent annually. In any given year, the effects of international demands may reinforce or offset this trend. State-specific coal production forecasts produced by West Virginia University support this future course.[15] Table 3 summarizes these forecasts.

2.6 Traditional freight volumes and mode choice

Throughout the nation's history, coal consumption has been an important generator of freight transportation. In America's colonial period, coal imports and exports often moved as ballast aboard sailing vessels. By the early 19th century, a desire to move coal and grain motivated the development of canal systems throughout the northeast and old Midwest. Later, particularly in

[15] See West Virginia University, Bureau for Business and Economic Research, *Coal Production in West Virginia: 2017:2040*, 2017. http://business.wvu.edu/files/d/cbeb6e87-6e4a-4f7a-a781-3cc1b31326c5/coal-production-forecast-2017-2040.pdf

eastern Pennsylvania and other parts of the Mid-Atlantic region, the growing industrial use of coal and its value as an export fed the development of the earliest U.S. railroads.[16]

Table 3. Forecasted Coal Production
(All Grades, Tons in Millions)

Year / State	AL	Eastern KY	MD	OH	PA	TN	VA	Northern WV	Southern WV
2011	19.1	67.9	2.9	28.2	59.2	1.5	22.5	41.8	92.8
2016	9.1	16.9	1.6	12.6	45.9	0.7	12.8	43.5	36.5
% Change	-52.2%	-75.1%	-46.4%	-55.3%	-22.5%	-56.9%	-43.2%	4.0%	-60.7%
2021	10.5	16.8	1.7	12.6	52.9	0.7	15.4	49.1	40.5
% Change	15.7%	-0.3%	8.2%	0.0%	15.3%	6.9%	20.7%	12.8%	10.8%
2026	12.2	15.0	1.8	12.2	50.1	0.7	13.8	49.4	36.2
% Change	15.5%	-10.6%	3.7%	-3.4%	-5.2%	5.0%	-10.6%	0.7%	-10.6%
2031	13.7	13.6	1.7	11.4	46.9	0.8	12.5	48.8	32.7
% Change	12.5%	-9.6%	-6.3%	-6.3%	-6.3%	4.6%	-9.6%	-1.2%	-9.6%
2036	14.8	13.1	1.6	11.3	46.6	0.8	12.0	48.4	31.4
% Change	7.9%	-3.9%	-0.8%	-0.8%	-0.8%	3.6%	-3.9%	-0.9%	-3.9%
25-Year	**-4.3**	**-54.9**	**-1.3**	**-16.9**	**-12.6**	**-0.7**	**-10.5**	**6.5**	**-61.4**
% Change	**-22.5%**	**-80.8%**	**-44.1%**	**-59.9%**	**-21.3%**	**-47.6%**	**-46.8%**	**15.6%**	**-66.2%**

The commercial codependence of coal and freight transport survived throughout the 20th century and, until very recently, seemed destined to endure indefinitely. Indeed, as recently as 2014, coal accounted for 39 percent of all U.S. railroad tonnage and 19 percent of Class I railroad freight revenues.[17] Similarly, in 2014, coal constituted roughly 32 percent of all inland waterway traffic and on the Ohio River represented nearly half (47 percent) of all commercial 2014 traffic passing through system locks.[18]

However, based on the long-run trends described in the previous section, the nature and extent of the commercial relationship between coal and freight transportation is almost certain to change. These changes will affect the freight carriers' operations in every region of the U.S. and, in turn, affect the availability and pricing of freight services for non-coal freight customers. In the remainder of the current section, we focus on freight in Appalachia, beginning with a description of the status quo.

Users close to production points in the Appalachian region consume much coal; nearly all (domestic) consumption is east of the Mississippi River. When distances are sufficiently short

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[16] For a thorough discussion of early freight traffic in the U.S., see Albert J. Churella, *The Pennsylvania Railroad, Volume 1: Building an Empire, 1846-1917 (American Business, Politics, and Society)*, University of Pennsylvania Press, 2012.

[17] See Association of American Railroads, *Analysis of Class I Railroads* (various years).

[18] For system tonnage, see, U.S. Army Corps of Engineers, *Waterborne Commerce of the United States 2014*, Part 2, p. 223. For lock statistics see, U.S. Army Corps of Engineers, *Lock Use Performance and Characteristics,* Public Lock Commodity Report (Calendar Years 1999-2015).

(less than 100 miles) and volumes are small, coal moves by truck. When volumes are large and inland navigation is feasible, coal moves by barge. Most often, however, coal moves by rail in unit trains that often operate directly between preparation plants and electric generating facilities or, in the case of exports, deep-draft ports.

Both Kentucky and West Virginia have state designated coal-haul roadway systems designed to accommodate loaded coal trucks. In addition to these systems, the consensus is that coal truck travel is both possible and evident throughout the coal-producing region wherever there are adequate roadways. Both barge and railroad transport are different.

Private sector barge owners and towing companies operate on navigable waterways as determined by the U.S. Coast Guard. The U.S. Army Corps of Engineers (Corps) designs, constructs, and maintains the waterway system. On most waterway reaches, dams create pools of the required depth for navigation. Navigation locks at the dams allow for vessel movement between pools.[19]

With very few exceptions, railroad infrastructure is under private ownership. Railroad companies create, maintain, and operate the infrastructure for rail freight transportation. Without an adequate source of traffic, companies will rationalize or remove railroad infrastructure

Figure 9 illustrates mainline railroad lines and main-stem waterway system components. Table 4 summarizes the extent of these systems within the region.

Table 5 provides a summary of the freight transportation modes used to deliver 2014 coal to final destination states. Table 6 reverses the analytical lens and depicts the importance of coal traffic as a share of overall freight activity for both rail and barge. Together, these data make clear the rigid interdependence that has historically existed between coal production and freight transportation. Focusing on West Virginia, Kentucky, Pennsylvania, and Ohio, rail or barge carriers delivered 87.3 percent of all regional coal shipments in 2014. At the same time, coal traffic accounted for 47.3 percent of all locked tonnage on the Ohio River main stem and 68.3 of all rail shipments originating in these four states. At least historically, without the ability to transport coal to distant users, the region's coal reserves would have been of far less value; without the need to move coal, much of the region's transportation infrastructure would have been unnecessary.

[19] Only two major waterway segments are devoid of locks and dams. These are the Missouri River below the head of navigation near Council Bluffs, Iowa to its confluence with the Mississippi and the lower Mississippi River for its entirety below St. Louis.

Source: Center for Transportation Research

Figure 9. Simplified Regional Waterway and Railroad Networks

Table 4. Summary of Regional Waterway and Railroad Infrastructure

Railroad network		Waterway network	
Primary Class I carriers*	CSXT, NS	Mainstem Ohio River miles***	436
Total freight RR miles**	16,970	Navigable tributary miles***	768
Number of short line carriers	83	Mainstem Ohio River locks***	12
Total regional short line miles	5,459	Navigable tributary locks***	33
Holding co. short lines	35		
Holding co. short line miles	3,475		

Source: Center for Transportation Research

*CSX and Norfolk Southern are the primary Class I carriers in the region. However, BNSF, Canadian Pacific, and the Canadian National also operate limited regional trackage.

**Totals only include waterway mileages and the number of locks for operating portions of the inland navigation system within the region. Specifically, the tributary total excludes upper portions of the Alleghany River where locks are in “care-taker” status.

Table 5. Modes Used for 2014 Regional Coal Delivery

	DOMESTIC					EXPORT	TOTAL
STATE	Other, tons (000)	Rail, tons (000)	Barge, tons (000)	Truck, tons (000)	Domestic total (000)	Export total (000)	Grand total 000)
Alabama	-	1,603	2,514	2,088	6,205	12,049	18,254
Illinois	5,011	17,657	21,382	3,749	47,799	10,170	57,969
Indiana	-	28,828	4,592	5,762	39,182	85	39,267
Kentucky	165	41,111	22,291	10,474	74,042	3,293	77,335
Maryland	-	-	-	1,921	1,921	-	1,921
Mississippi	-	-	-	2,625	2,625	-	2,625
Ohio	-	3,515	16,527	3,997	24,039	101	24,140
Pennsylvania	1,676	35,147	8,952	9,813	55,587	5,323	60,910
Tennessee	-	757	63	19	839	-	839
Virginia	1,041	5,777	1,701	2,697	11,216	6,748	17,964
West Virginia	5,222	39,812	35,426	2,476	82,937	29,250	112,187
Regional total	**13,115**	**174,206**	**113,449**	**45,622**	**346,392**	**67,019**	**413,411**
U.S. (all states)	**67,156**	**609,567**	**113,453**	**99,232**	**889,976**	**97,257**	**1,000,049**

Source: Energy Information Administration

Table 6. Coal's 2014 Share of Regional Waterway and Rail Traffic

Railroad origin state	Loaded coal tons (000)	Total loaded tons (000)	Coal percentage of total
Alabama	10,750	38,160	28.2%
Kentucky	49,292	59,157	83.3%
Ohio	15,571	66,191	23.5%
Pennsylvania	32,961	51,551	63.9%
Virginia	19,485	32,232	60.5%
West Virginia	86,139	92,328	93.3%
Appalachian Total	214,198	430,583	49.7%
Illinois	21,322	115,899	18.4%
Indiana	22,618	54,154	41.8%
Regional total	**258,138**	**678,863**	**38.0%**
U.S. total	**750,200**	**1,764,100**	**42.5%**

Ohio River lock and dam	2014 coal traffic Tons (000)	2014 total traffic, tons (000)	Coal percentage of total
Ohio 52	21,513	87,930	24.5%
Ohio 53	11,694	76,478	15.3%
Belleville	27,890	44,813	62.2%
Cannelton	36,545	69,895	52.3%
Meldahl	20,797	46,182	45.0%
Dashields	14,591	20,309	71.8%
Emsworth	14,294	18,616	76.8%
Greenup	16,391	41,703	39.3%
Hanibal	29,809	44,240	67.4%
Myers	23,083	64,174	36.0%
Markland	22,742	52,754	43.1%
McAlpine	35,847	69,930	51.3%
Mongomery	14,512	20,966	69.2%
Newburgh	40,845	77,995	52.4%
New Cumberland	20,540	31,208	65.8%
Pike Island	20,315	32,238	63.0%
Racine	29,022	46,287	62.7%
Robert Byrd	19,944	40,833	48.8%
Smithland	25,075	71,041	35.3%
Willow Island	26,814	41,660	64.4%
Ohio River total	**472,265**	**999,253**	**47.3%**

Source: Association of American Railroads / U.S. Army Corps of Engineers

3. THE SHORT-RUN RAIL INDUSTRY RESPONSE AND LIKELY FUTURE ACTIONS

Transportation equipment is long-lived but mobile. Carriers can generally move coal related equipment to other U.S. regions and can often use it for moving commodities other than coal. Consequently, the impacts of diminished coal traffic on equipment investments are less pronounced and of less concern here. The impacts of diminished coal volumes on the infrastructure that forms line-haul route segments and terminal facilities is far more important to long-run mobility.

Further, as noted above, the public sector largely provides roadways and inland navigation infrastructure, where no financial return is immediately required. In this environment, policy-makers can more easily resist decisions to downgrade or abandon facilities regardless of commercial inactivity.

Almost exclusively, private sector companies own railroad infrastructure. Railroad companies build, maintain, and operate both line-haul track and terminal facilities. These private investments must earn revenues for investors. This fundamental distinction makes railroads more sensitive to both ongoing costs and prospects for future traffic. Therefore, it is not surprising that the first evidence of diminished coal volumes emerged within the rail sector.

3.1 Initial rail industry responses

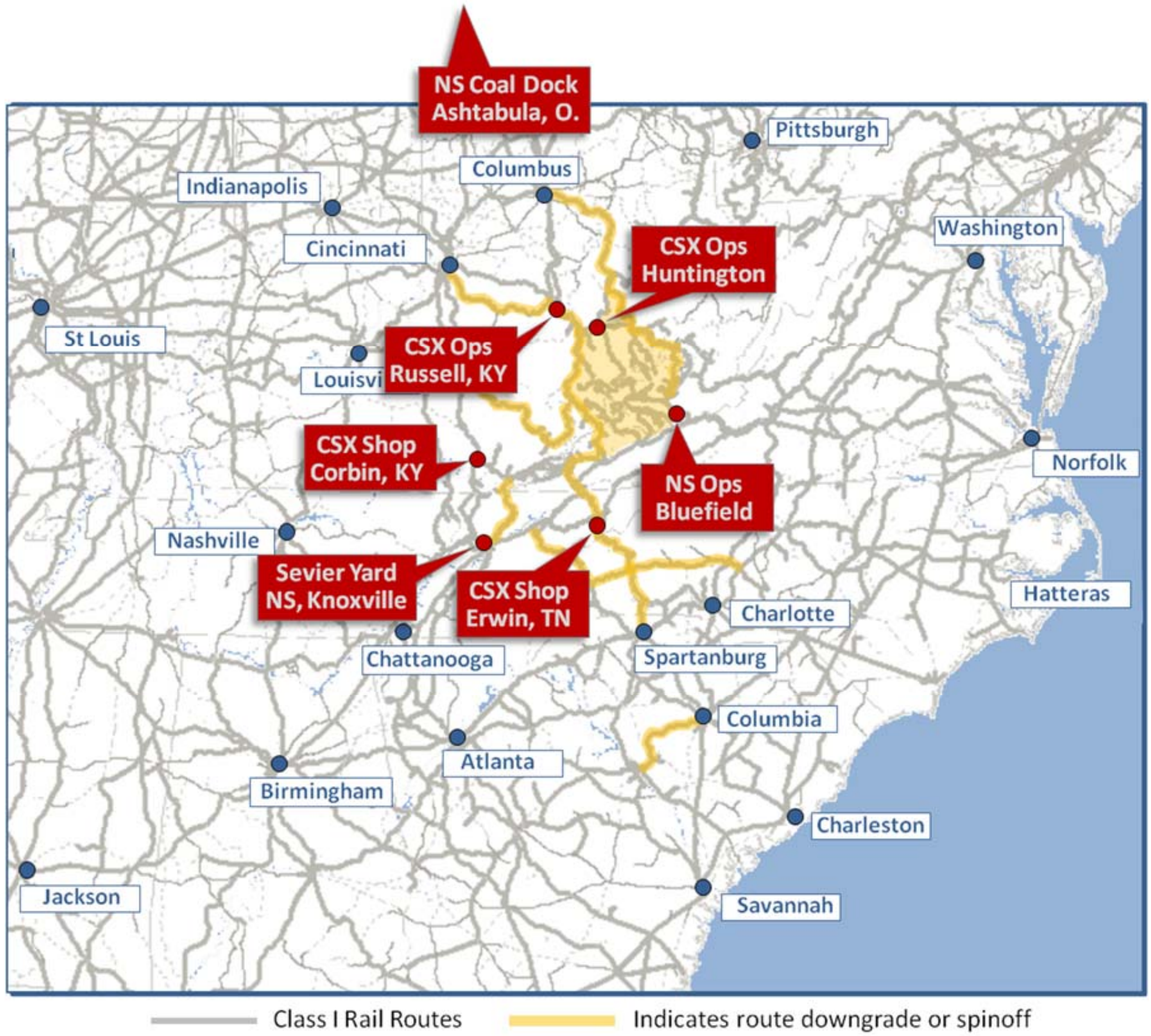
In the fall of 2015, seemingly without warning, both Norfolk Southern and CSX – the region's dominant Class I railroads – began announcing a sequence of both operating and infrastructure changes in response to declining coal volumes. These actions included closing terminal and yard facilities in Ashtabula, Ohio; Bluefield, West Virginia; Corbin, Kentucky; Erwin, Tennessee; Huntington, West Virginia; Knoxville, Tennessee, and Russell, Kentucky. Additionally, many route segments throughout the region were downgraded, services were curtailed, and in one case (NS from Columbus to southern West Virginia), a secondary mainline route was leased to a short-line operator. Figure 10 graphically depicts these actions. It underscores that the focus of first-round cuts was in Appalachia along routes handling Appalachian coal production. In total, these changes led to the elimination or relocation of approximately 1,500 full-time positions.

Even ignoring further reductions in coal traffic, both CSX and NS may undertake additional force reductions, route downgrades, and facility closures. As an example, in 2016, NS announced its intentions to "dispose of" an additional 1,500 route miles by 2020.[20] More recently, a new management cohort at CSX has engaged in a variety of system-wide cuts and closures to reduce costs and bolster shareholder returns.

While the cuts depicted in Figure 1 imposed observable hardships on specific Appalachian communities, there is one highlight. Norfolk Southern and CSX have not to-date engaged in any irreversible action. More specifically, neither has undertaken the abandonment of any major track segment within the study region nor have they removed terminal facilities. This is an

[20] See *Norfolk Southern*, "Norfolk Southern announces further details of its strategic plan to reduce costs, drive profitability, and accelerate growth," press release, January 27, 2016, http://www.nscorp.com/content/nscorp/en/news/norfolksouthernannouncesfurtherdetailsofitsstrategicplantoreduc.html

observable contrast to the wholesale route abandonments evidenced in the mid-1980s in response to regulatory reforms.



Source: Center for Transportation Research

Figure 10. Class I Railroad Response to Diminished Coal Traffic

3.2 Long-run implications for regional freight mobility

Because railroads build, maintain, and pay property taxes on the route segments over which they operate and because they are subject to ongoing financial scrutiny, they constantly monitor forecasted traffic volumes and revenues. Route segments are routinely improved or downgraded based on their roles in generating economic returns. Over an intermediate time frame, segments that do not contribute to earnings may be taken out of service to avoid maintenance costs. However, in the long run, under-performing lines are eventually disposed of, either through sales or leases to other railroads or through abandonment.

Railroad economics embody a number of unique characteristics, but economies of density is a most important one. Economies of density suggest that unit costs – the cost per carload, car-mile, or ton-mile – decrease as larger amounts of freight traffic are concentrated onto a particular route segment. In railroading, these economies are seemingly inexhaustible.

Historically, robust coal volumes provided many eastern rail routes with a great deal of traffic density, so that *all* traffic traveling these routes could move at relatively low unit costs. The loss of coal traffic and the desire to rebuild traffic densities is leading railroads to consolidate remaining traffic onto fewer routes where possible. For those routes where diverted traffic restores density, service quality and pricing may change very little. However, when carriers divert network traffic *away* from routes, remaining customers are likely to observe less frequent service, diminished reliability, and (potentially) higher freight rates. Consolidation has prompted the system changes thus far. A desire for further consolidation may motivate further changes as coal traffic declines continue.

3.3 Incentives for and methods of network rationalization

"Network Rationalization" is a euphemism used for a freight provider's decisions to downgrade, sell, lease, or abandon unprofitable route segments, facilities, or operations. To evaluate possible "rationalizations", carriers must simultaneously consider large volumes of information describing the freight traffic generated locally along each candidate route segment or facility and the role that each smaller network part plays in accommodating the whole of system-wide traffic. Generally, the ideal freight network exactly balances the benefits gained by reaching more customers in more places against the economies that result from densely packing as much traffic as possible onto as few route-miles as possible.[21]

Network rationalizations are essential to the management of all freight modes. However, again, because railroads own the networks over which they operate, both the incentives for and scope of possible actions are greatest for this mode. Moreover, railroad capital is long-lived. In making decisions about what to keep and what to relinquish, railroad managers must evaluate current conditions *and* predict the *future* value of each candidate route segment or facility. The overall process is full of uncertainty. Thus, carriers have learned that there is often value in postponing decisions on route disposition or in considering alternatives that are reversible if conditions change.[22]

Among the possible carrier actions there are, at least four choices. Faced with a need for change, a Class I railroad can (1) continue service along a route, but downgrade the capacity of that route; (2) leave the route in place, but discontinue service; (3) relinquish all interest in the route through abandonment; or (4) voluntarily sell or lease the route to another Class I railroad or to a short-line. Moreover, in the event the railroad seeks to abandon a railroad line, the law provides

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[21] Not surprisingly, economists term these *Economies of Density,* the spatial analogue of the more commonly known Economies of Scale.

[22] In the world of economics and finance, integrating the value of retained flexibility into decision-making processes is rooted in Real-Options theory. For an application of this construct in a railroad setting see, Mark Burton and Charles Sims, "Understanding Railroad Investment Behaviors, Regulatory Processes, and Related Implications for Efficient Industry Oversight," *Review of Industrial Organization*, September 2016.

ways for affected jurisdictions to intervene in the disposition of the abandoned route even if regulatory agencies approve the owning railroad's application for abandonment.

Three of these four actions are generally reversible by the owning railroad. With investment and over time, a railroad can restore capacity on a downgraded route. Traffic can return to routes taken out of service. If control over a route is ceded to another railroad through lease or sale, the lease can be terminated or the line (at least, potentially) can be repurchased. Each of these reversals entails varying degrees of expense. The fourth option – route abandonment – is difficult to reverse, particularly after infrastructure removal and right-of-way disposal.

3.3.1 Downgrading a rail route

Railroads can appreciably reduce maintenance costs by downgrading the level of performance expected from lesser-used routes. At least as an interim measure, this strategy can be an effective way trimming costs without sacrificing long-run alternatives.

A rail route's physical characteristics – the number, alignment, and quality of mainline tracks; the length and spacing of sidings; the severity and frequencies of curves and grades; and the signal system(s) used to control train operations – determine its capacity. In addition to designing and constructing track that will support a specific level of intended use, railroads must also maintain route segments based on prescribed federal standards that are (partially, at least) correlated to that planned use.

Specifically, the Federal Railroad Administration divides rail track into five classes.[23] When a railroad designates an intended class for a particular piece of track, it becomes responsible for ensuring the track and supporting structures meet the FRA standards associated with that designated class. It follows that, if a railroad wants to reduce maintenance-of-way spending for a route segment, it can reclassify that segment to reflect a reduced level of performance. Here, the most likely reclassification is from Class 3, where the maximum freight train speed is 40 m.p.h., to Class 2, where the maximum freight train speed is 25 m.p.h. As an example of this approach, Norfolk Southern has recently downgraded its route between Asheville and Salisbury, North Carolina from Class 3 to Class 2.

3.3.2 Service discontinuance or line abandonment

From a legal standpoint, any shipper located along an active rail line operated by a railroad common carrier can demand transportation services from that carrier. A railroad has only two ways to avoid this obligation. It can completely abandon the rail route in question or, as an alternative, it can apply for a regulatory *service discontinuance*. While the administrative processes for these paths are similar, the outcomes are quite different. In the case of a service discontinuance, the railroad retains ownership, must leave the infrastructure in place, and is obligated to restore service if conditions warrant doing so. If the railroad abandons the subject line, it relinquishes all claims to the right of way and opportunities for service restoration.[24]

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[23] FRA actually defines nine track classes, plus a category known as "excepted" track. Almost all U.S. freight track falls into Classes 1-5. For a full description see, *Track and Rail and Infrastructure Integrity Compliance Manual*, Volume II Track Safety Standards, Chapter 1: Track Safety Standards Classes 1 through 5, Federal Railroad Administration, January 2014.

[24] For a detailed description of the abandonment or service discontinuance process see, Surface Transportation Board, *OVERVIEW: Abandonments & Alternatives to Abandonments*, April 1997. For a more community oriented description of the same processes, see Duane J. Rosa, "Economic Impact of "Railroad Line Abandonment on

In both the case of a service discontinuance or an application for abandonment, the final decision rests with the Surface Transportation Board (STB). If there has been no local freight activity along the line for two years or more, the process is more or less automatic. However, any party with a legitimate interest can express those interests with the STB's evaluation process. Moreover, the governing statutes promote the accommodation of shippers or local jurisdictions that can (a) arrange for a service alternative through external subsidies or a line sale or (b) preserve the existing right of way through a "trails" initiative.

3.3.3 Selling or leasing a route to another railroad

In the last quarter of the 20th century, rail industry regulatory reforms were capped by the *Staggers Rail Act of 1980* and are directly credited with a surge in short-line activity. After peaking at approximately 700, the number of U.S. short-lines fell to roughly 200, by 1980.[25] However, the Staggers-related changes to abandonment processes, led to a burst in branch-line spinoffs by the nation's larger railroads. Babcock, et al, (1997) indicate the formation of 227 new short-line railroads between 1980 and 1989.[26]

The short-lines formed in the decades after Staggers have faced various fates. Many of the Staggers-related short-lines prospered; some did not. Some of the smallest short-lines of the 1980s and 1990s were combined with other short-lines or acquired by holding companies, and some were reabsorbed by the Class I railroads that divested them or by competing Class I's.

In a sense, the fact that not every short-line railroad prospers is irrelevant. In a time of tremendous structural change, the short-line alternative allowed Class I railroads to make badly needed reductions to their large, multistate networks, while simultaneously allowing communities to preserve railroad network access. In some cases, this preservation may have proven unnecessary; in other cases, the continued rail access afforded through short-line development has had very visible economic impacts.

Short-lines clearly play a prominent role in Appalachian rail network access. Table 7 summarizes the scope and scale of the region's short-line railroads. To a large degree, the amount of short-line activity within any given state reflects the magnitude and nature of the freight traffic left behind in the wake of Class I railroad route rationalizations. However, the strength of local and state-level programs has also affected the extent of short-line activity.

Many of today's 550-plus short-lines were spun-off from Class I railroads. A smaller number have never been components of larger railroads and are a throwback to the 19th century industry structure. Presently, holding companies that often operate properties in widely disparate geographic regions control a large number of America's short-line railroads. Holding companies generally manage short-lines in ways that retain a localized focus and small-scale cost advantages, while simultaneously pursing the large-scale procurement, equipment management, and human resources advantages more typically associated with Class I railroads. Table 8 details holding company activity within the study region.

Regional and Urban Areas: A Case Study," *Journal of Business Case Studies* – Second Quarter 2014 Volume 10, Number 2, pp. 147-54.

[25] See Fischer, et al (1981).

[26] For a further, popular discussion of Staggers and short-line railroads, see Stagl (2008).

Table 7. Appalachian Region Short-Lines

State	Short-line miles	Number of shortlines	Average length
Alabama	295	8	36.9
Georgia	123	4	30.8
Kentucky	196	2	98.0
Maryland	52	2	26.0
Mississippi	280	6	46.7
North Carolina	90	2	45.0
New York	256	6	42.7
Ohio	1,768	10	176.8
Pennsylvania	1,176	15	78.4
South Carolina	102	3	34.0
Tennessee	289	12	24.1
Virginia	175	1	175.0
West Virginia	657	12	54.8
TOTAL/AVERAGE	**5,459**	**83**	**65.8**

Source: Center for Transportation Research

Table 8. Holding Company Presence in Appalachian States

Owning entity	Short-line miles	Number of properties	Average length, mi.
Genessee & Wyoming	1,415	14	101.1
Gulf & Ohio	73	2	36.5
Iron Horse Resources, Inc	59	1	59.0
OmniTRAX	120	1	120.0
Paducah & Louisville	158	1	158.0
Patriot Rail	128	2	64.0
Pioneer	132	3	44.0
R.J. Corman	407	3	135.7
Watco	765	4	191.3
TOTAL/AVERAGE	**3,257**	**31**	**99.3**
Percent of Total	**(62.2%)**	**(39.2%)**	**(151.0%)**

Source: Center for Transportation Research

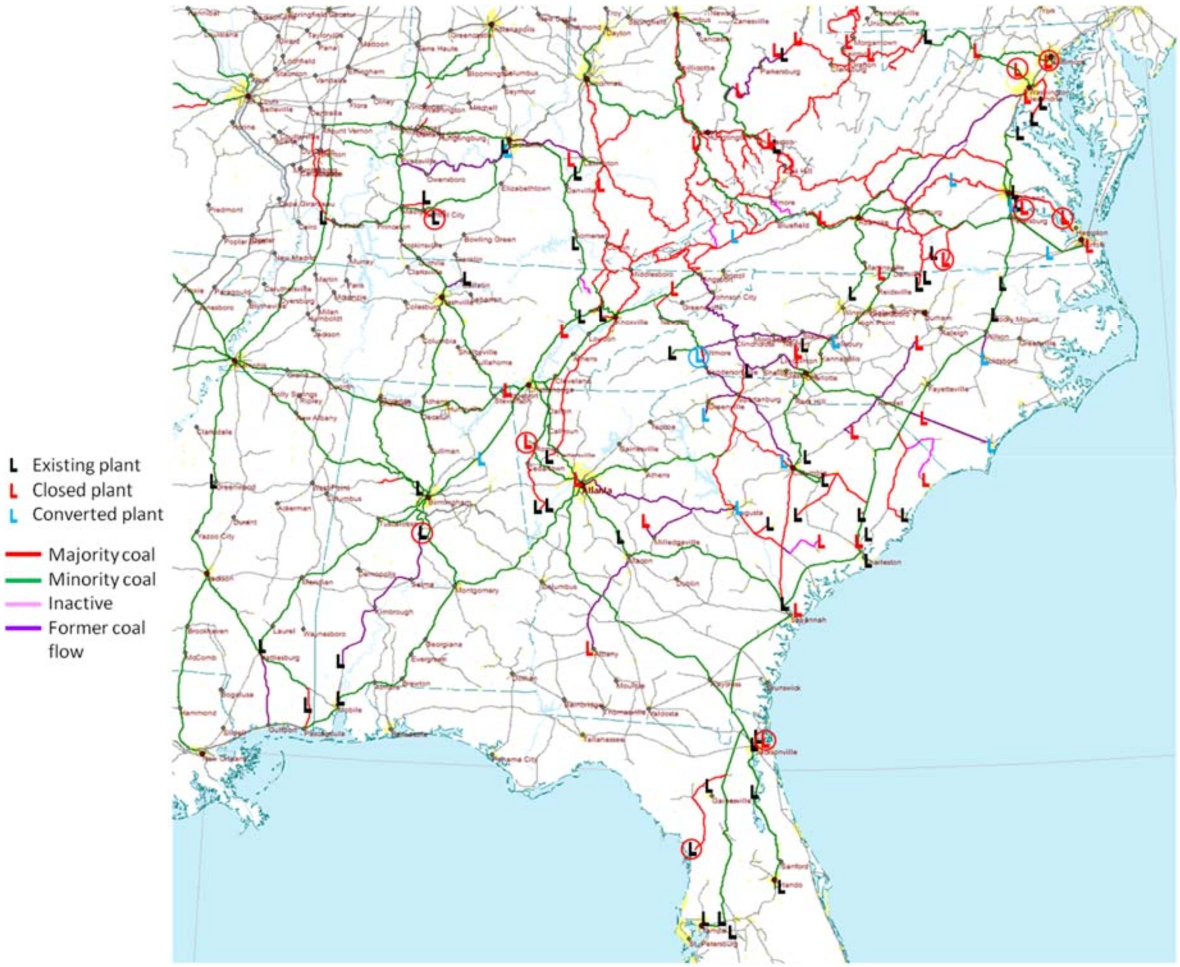
3.4 Future drivers of railroad network rationalization

Section 2 concludes with state-specific forecasts of future eastern coal production. However, not all of the affected coal volumes move by rail. Forecasted reductions are unevenly distributed across coal producing states, and there are similar asymmetries in the distribution of projected impacts across railroads.

Like Figure 8 in Section 2, Figure 11 depicts observed and planned coal-fired facility closures. However, Figure 11 depicts the subset of closures that may affect the southeastern U.S. freight rail network.

Finally, Figure 12 combines data describing 2011 coal movements by rail with the 2036 West Virginia University forecasts for coal production to illustrate the distribution of coal carloads in a base year and at the end of the forecast horizon.[27]

[27] As further discussed in Section 4, 2011 was the base year because railroad revenues from the movement of coal peaked prior to a subsequent precipitous decline in coal volumes.



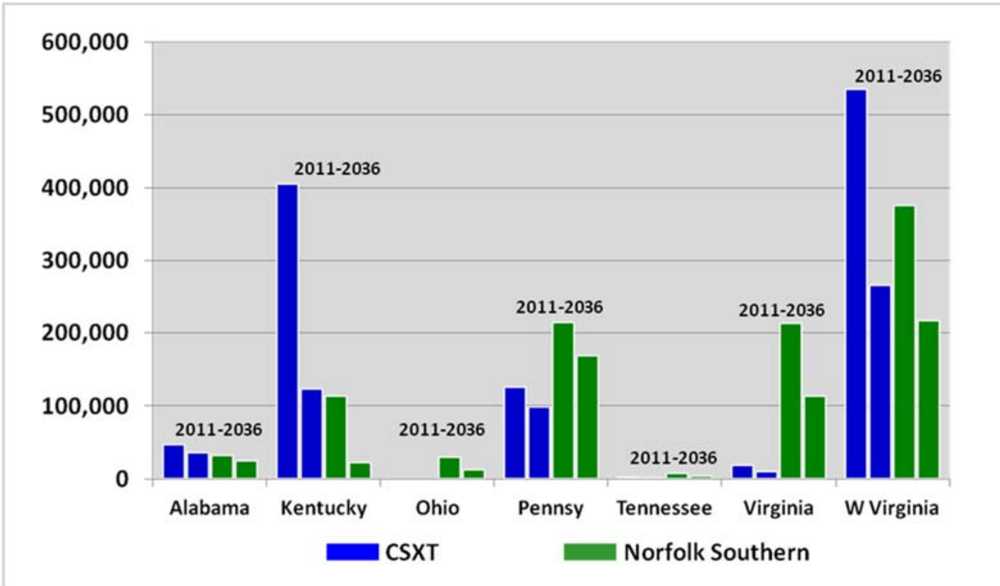
Source: Center for Transportation Research

Figure 11. Observed and Scheduled Coal-Fired Plant Closures in the Southeast

The distinctions between NS and CSX are evident. While the total volumes and shares of domestic coal for NS and CSX are similar, the 2011 geographic origination patterns are not and the disparities are even more apparent when we turn to the forecasted volumes.

The clearest example is eastern Kentucky. This region is of negligible importance to NS, but a huge source of activity for CSX. It is also the region forecasts predict production to suffer the greatest decline. Finally, eastern Kentucky is the region that, at least historically, has produced the largest share of the steam coal destined for the deep South – Georgia, South Carolina, and Florida. Much of this traffic has already disappeared, but the data suggest that much of what remains will dissipate by 2036.

The same pattern – one that more challenging for CSX – is also observed/predicted for West Virginia. In 2011, CSX had a measurable advantage over NS in terms of originating West Virginia car loadings. Both railroads have seen declines in these traffic volumes and further erosions to remaining coal traffic are likely. However, the data suggest this will affect CSX far more than NS. As the figure illustrates, by 2036, total West Virginia railroad coal originations will have fallen by 40 percent from their 2011 levels. Forecasts indicate that CSX and NS will have roughly equal shares of the West Virginia coal that remains.



Source: Center for Transportation Research

Figure 12. Observed and Predicted Coal Traffic in Carloads (2011 and 2036)

Next, in 2011, CSX originated very little coal traffic in Virginia, though it exports significant volumes of coal at Newport News. Norfolk Southern carries nearly all the rail hauled Virginia coal. It follows that the production declines predicted for Virginia fall disproportionately on NS. Finally, the production and railroad transportation pattern forecasted for Pennsylvania is similar to that of Virginia except that the disparity between NS and CSX is not as great, nor is the predicted magnitude of production decline.

4. MODELING LONG-RUN RAIL NETWORK CHANGES

The data and narratives provided in the preceding sections describe already-observed reductions in eastern coal production, a corresponding decline in railroad coal traffic, and the initial actions taken by eastern railroads in response to this pattern. However, the text also points to continuing reductions in coal production and coal transportation over the coming two decades. Accordingly, the region's railroads are likely to make additional and more permanent adjustments to their infrastructure and operations. Prediction of these long-run adjustments is at the core of the current research.

4.1 MODEL GOALS AND STRUCTURE

Section 3.3 describes the decision-making process that rail managers must use regarding which network segments to improve and which segments to downgrade or discard through spinoffs or abandonment if their managerial goal is to maximize productive efficiency and firm profitability. Theoretically, this decision-making process requires the solution of a complex, intertemporal network optomization problem, where capital costs, maintenance costs, and operating costs (that adequately refelct traffic densities) must be balanced against the stream of expected revenues under various network configurations operating scenarios. Moreover, because railroad assets are long-lived, the appropriate time horizon usually spans several decades.

In practice, the dynamic data and data forecasts needed to undertake and solve this complex problem over a 30-50 year timespan do not exist. Thus, as a second-best alternative senior railroad industry managers typically develop shorter-run operating plans that treat network extent and configurations as largely fixed. Railroads revisit network issues only periodically, when network segment capacities limit new, long-run business opportunities or impose clearly avoidable long-run costs. These periodic evaluations – as they pertain to changing coal traffic – are what we attempt to model.

The modeling process involves several specific steps. These are enumerated here, then discussed individually in the following text. Process steps include:

1. Developing a fully function railroad network that effectively captures individual link capacities and which can accommodate observed railroad behaviors;
2. Assembling a largely disaggregated population of baseline railroad traffic;
3. Simulating the effects of reduced coal production on future traffic volumes;
4. Developing operating cost parameters by traffic type;
5. Flowing the baseline traffic over the current rail network based on a cost-minimizing optomization algorythm;
6. Flowing scenario traffic over the baseline network; and
7. Comparing optimal baseline and scenario traffic flows to identify specific railroad route segments that may be made vulnerable by declining coal traffic.

4.2 The railroad network

Figure 13 depicts the unpopulated railroad network developed for use here. This network, while, not comprehensive contains all princippal Class I, mainline route segments by carrier, as well as a number of essential secondary mainline, branch-line, and short-line segments. In addition to ownership, the network links reflect trackage and haulage rights. At the present time, the network includes the whole of the United states south of New England and east of the Mississippi River. While less complete, network coverage west of the Mississippi River is suffient to assure accurate eastern routings. In its present configuration, the model contains all necessary terminal and non-terminal interchange locations. However, the terminal nodes do not include facility-specific attributes. Table 9 lists link attributes and Table 10 provides overall network summary statistics.

Table 9. Network Link Attributes

Attribute	Description
LENGTH	Link length, miles
CAPACITY	Practical number of daily trains under optimal conditions
NO. OF RAILROADS	Number of railroads with operating rights (ownership, trackage, haulage, etc.)
RAILROADS NOS.	AAR identifiers for each railroad with operating rights
NO. OF TRACKS	Number of mainline tracks
FREE FLOW SPEED	Travel speed under optimal conditions, mph
TRAVEL TIME	Link length / free flow speed (hrs.)
P1,P2	Link capacity function parameters
ML CLASS	FRA Traffic Density Classification
LINK TYPE	Based on usage - yard tracks, directional operations etc.
SIGNAL	CTC, ABS, Non-signaled
CAPACITY CODE	Based on terrain, track configuration, etc.

Table 10. Network Summary Statistics

Description	Value
Number of links	1,429
Number of nodes	1,007
Number of interchange locations	760
Number of railroads	38
Total length of links (miles)	43,705

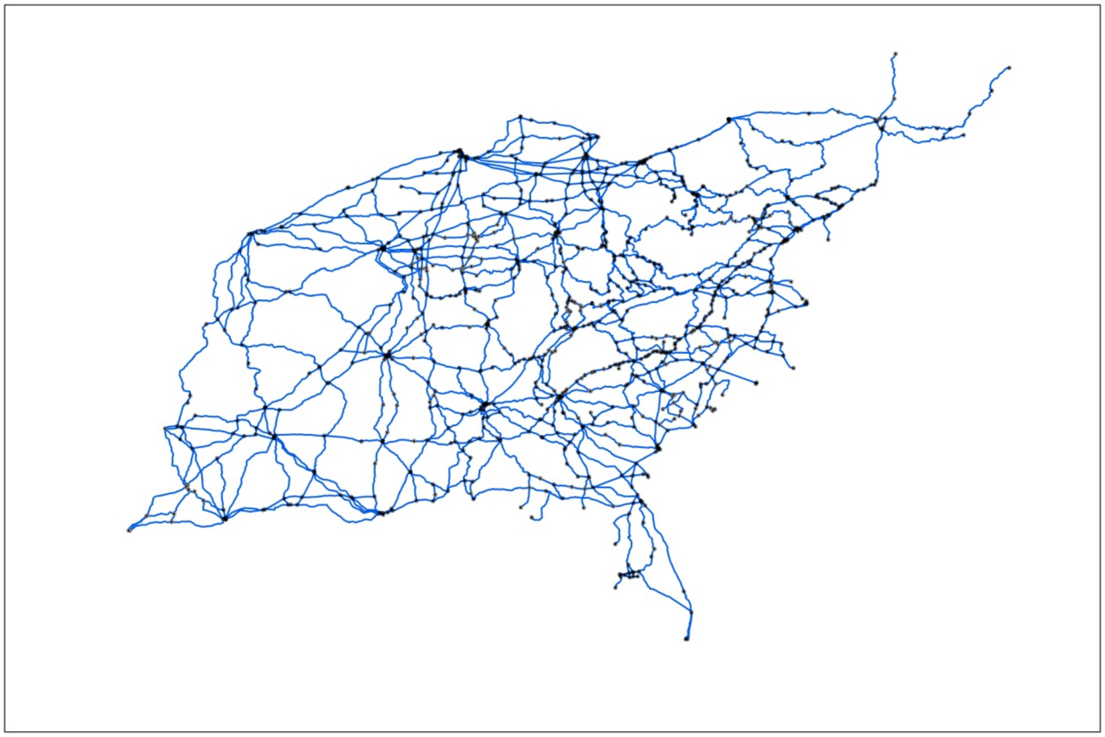


Figure 13. Unpopulated Rail Operating Network

4.3 Baseline and scenario traffic data

The Surface Transportation Board's 2011 Carload Waybill Sample (CWS) provided the source for baseline traffic data. As discussed previously, 2011 was the year in which aggregate railroad industry coal revenues peaked and the last year in which coal volumes were near their historic highs.[28]

Traffic volumes, measured in both tons and carloads, were aggregated, based on originating railroad, origin county, destination county, and commodity category. In addition to shipment volumes, the CWS data were also used to determine average shipment distance, average revenue tons-per-carload, average car tare weights, and the average number of interchanges associated with each record.

Commodity group definitions reflect cost differences associated with differing equipment types, commodity values, and operating requirements, while at the same time keeping the number of observations at a manageable level. Tables 11 and 12 provide, respectively, commodity definitions based on corresponding two-digit Standard Transportation Commodity Codes (STCCs) and summary statistics for the resulting data set.

[28] Industry-wide, railroad coal volumes peaked in 2007. See, Association of American Railroads, Annual Statistics of Class I Railroads, 1978 – 2015.

Table 11. Commodity Group Definitions

Study commodity group	Corresponding 2-digit STCCs
1 Grain	01, 08, 09
2 Low-Value Bulk	10, 14, 29, 32, 40
3 Coal	11
4 Chemicals and Petroleum	13, 28
5 Manufactured Products	19-27, 31, 33-39
6 Other (Intermodal)	41-47
91-96 Empties	

Table 12. Baseline Traffic Summary Statistics

Commodity group	Number of records	Average shipment distance, miles	Average revenue tons per carload	Average car tare weight, tons	Average number of cars per record	Total (expanded) tons
1	2,892	926	94	34	377	91,276,492
2	7,011	824	87	36	336	212,816,277
3	1,045	585	115	26	5,321	663,689,327
4	8,421	926	88	36	224	160,798,924
5	14,720	1,056	71	39	397	260,174,517
6	1,831	1,578	16	74	4,710	108,573,822

During processing, a GIS based algorithm matched shipment origin and destination points with appropriate nodes in the study network. The processing logic removed records for "off-network" movements (i.e., those external to the study network). Flow records with one external endpoint (either origin or destination) had the point replaced with an appropriate gateway. Gateways used in this network represent Chicago, Kansas City, Fort Worth, and San Antonio. The shipment originating carrier, origin, destination, and commodity influenced the gateway choice.

The processing step also created an empty car record for each shipment. Specific information of empty car movements was unavailable, yet consideration of empty cars is critical in traffic analysis. Our empty movement record simply exchanged the origin and destination of the parent shipment record. Thus, the assumption was that empties moved back in the reverse direction of the corresponding load. While this is generally a simplification of reality, it is valid for some high volume bulk movements such as coal and grain. Movement tonnage was the empty weight of the cars used in the shipment.

The 2011 data is the basis for the scenario dataset that reflects 2036 coal production forecasts. For non-coal commodities, we did not attempt to forecast future traffic volumes. For coal movements originating in the eastern U.S., the 2011 data were adjusted to reflect the predicted 2036 values depicted in Table 3. Importantly, the rail traffic to, from, and within the study region includes coal mined in regions outside Appalachia (e.g., the Illinois basin or the Powder River basin). Based on EIA production forecasts, we assumed that production in those non-

Appalachian regions would remain almost constant over the 20-year time horizon.[29] As with the baseline, we generated appropriate empty car movements to match the loads.

4.4 Operating costs

Based on the optomization process (described below), it was necessary to develop operating cost parameters for individual railroads and specific commodity groups. With the help of the Association of American Railroads (AAR), these parameters were constructed using the STB's annual R-1 operating and financial data as reported in AAR documents.

The available data report information for each of the seven Class I railroads, as well as aggregated values for eastern and for western railroads. They do not provide information pertaining to short-line operations or costs. The eastern railroad aggregations were used as a basis for determining short-line data. However, where possible, these data were modified to reflect information from other sources. Table 13 reports a summary of calculated cost parameters.

[29] See U.S. Department of Energy, Energy Information Administration, *Annual Energy Outlook: 2017*, Supplemental Tables, "Coal Supply, Disposition, and Prices," https://www.eia.gov/outlooks/aeo/data/browser/#/?id=15-AEO2017&cases=ref2017&sourcekey=0

Table 13. Cost Parameters
Cost values in 2014 dollars, weights in tons

RR-Code	Commod. group	Train cost / hr, $	Cost / gross-ton-mile, $	Terminal-processing-cost / car, $	Terminal-cost / car-hr, $	Transfer-cost / car, $	Car-payload, tons	Car-tare-wt, tons	Gross car wt, tons	Cars per Train	Gross train wt, tons
BNSF	1	662.72	0.03	49.41	1.87	94.64	88	22	111	70	7,735
	2	512.92	0.04	53.49	1.74	94.27	89	31	120	67	8,036
	3	924.41	0.03	55.57	1.67	94.28	118	24	142	100	14,208
	4	690.10	0.04	26.89	2.57	95.98	85	34	119	67	7,953
	5	665.54	0.04	24.78	2.93	87.25	61	28	90	67	6,024
	6	664.14	0.06	37.52	2.24	95.33	13	10	23	67	1,573
CN	1	586.36	0.03	70.38	1.04	98.52	100	22	123	70	8,577
	2	268.69	0.05	76.14	0.87	97.75	87	31	118	40	4,735
	3	810.52	0.02	77.87	0.80	98.09	115	24	139	100	13,903
	4	367.18	0.04	48.99	1.71	99.82	85	34	119	40	4,765
	5	361.16	0.04	39.38	2.34	90.41	74	28	102	40	4,103
	6	371.58	0.04	45.88	1.81	99.94	22	10	32	40	1,293
CP	1	532.19	0.03	90.29	0.88	83.21	101	22	123	70	8,598
	2	283.63	0.05	97.42	0.70	81.66	77	31	108	47	5,058
	3	727.02	0.00	99.47	0.60	82.68	50	24	74	100	7,414
	4	387.60	0.06	71.86	1.46	84.30	77	34	111	47	5,205
	5	375.02	0.05	71.99	1.63	79.02	49	28	77	47	3,618
	6	379.26	0.09	76.76	1.31	84.00	15	10	25	47	1,186
CSX	1	416.16	0.03	98.11	1.09	69.27	75	22	98	50	4,885
	2	285.77	0.05	101.02	1.00	68.85	88	31	119	42	5,059
	3	814.04	0.06	103.16	0.93	68.98	110	24	134	100	13,369
	4	386.73	0.06	76.54	1.76	70.59	79	34	112	42	4,770
	5	379.87	0.06	69.59	2.26	62.72	64	28	93	42	3,928
	6	374.34	0.06	84.51	1.51	70.06	14	10	24	42	1,006

Table 13. Cost Parameters (cont.)
Cost values in 2014 dollars, weights in tons

RR-Code	Commod. group	Train cost / hr, $	Cost / gross-ton-mile, $	Terminal-processing-cost / car, $	Terminal-cost / car-hr, $	Transfer-cost / car, $	Car-payload, tons	Car-tare-wt, tons	Gross car wt, tons	Cars per Train	Gross train wt, tons
KCS	1	520.63	0.04	140.21	1.12	26.06	103	22	125	50	6,243
	2	409.72	0.06	145.87	0.95	25.51	89	31	120	49	5,855
	3	1013.10	0.05	147.98	0.88	25.61	114	24	138	100	13,753
	4	546.97	0.05	118.60	1.80	27.36	86	34	120	49	5,865
	5	529.97	0.06	113.64	2.31	17.10	69	28	97	49	4,749
	6	526.74	0.10	129.96	1.45	26.66	13	10	23	49	1,141
NS	1	477.15	0.05	102.95	1.19	61.29	102	22	124	50	6,220
	2	305.45	0.07	108.46	1.03	60.76	91	31	122	40	4,854
	3	926.00	0.07	110.77	0.95	60.84	110	24	134	100	13,406
	4	405.01	0.09	85.90	1.73	62.27	74	34	108	40	4,301
	5	396.29	0.08	81.51	2.12	54.98	57	28	85	40	3,404
	6	395.61	0.07	92.42	1.52	61.90	13	10	24	40	937
UP	1	603.46	0.04	18.74	2.26	113.36	106	22	128	70	8,963
	2	396.50	0.06	24.63	2.09	112.75	92	31	123	58	7,062
	3	833.08	0.04	26.75	2.01	112.90	117	24	141	100	14,122
	4	536.26	0.06	0.00	2.86	114.49	81	34	114	58	6,578
	5	520.12	0.06	0.00	3.29	105.99	62	28	91	58	5,213
	6	518.07	0.06	8.34	2.59	113.97	14	10	24	58	1,362
OTHER	1	537.89	0.04	71.42	1.52	83.08	94	22	116	60	6,950
	2	527.64	0.06	76.42	1.37	82.38	88	31	118	66	7,872
	3	595.96	0.06	78.22	1.30	82.69	115	24	139	100	13,877
	4	556.76	0.06	50.74	2.16	84.31	81	34	115	66	7,647
	5	553.21	0.06	45.95	2.60	76.03	63	28	91	66	6,069
	6	552.74	0.06	59.72	1.88	83.76	14	10	24	66	1,573

5. THE *RAILNET* OPTIMIZATION ALGORITHM

The algorithm provides an analytical framework for realistically predicting traffic patterns within the rail network. It considers the effects of these flows on capacity, allowing the study of congestion effects. The analyst may formulate and explore outcomes under differing traffic and network scenarios. Externally specified origin-destination (O-D) demand patterns for traffic (e.g. the traditional traffic generation and distribution steps) may reflect a variety of user interests.

Unlike traditional highway traffic models, a rail assignment model must consider multiple commodities, with each commodity having a potentially different set of costs and priorities. The model also reflects the subdivision of the overall railroad network into subnetworks for specific companies, with transfers allowed only at designated points. The solution hypothesizes a network flow assignment that minimizes the overall system transportation cost. This system equilibrium approach should replicate the behavior of railroad operators, producing network link volumes and performance levels closely approximating observed conditions.

System equilibrium (SE) formulations for freight modeling – like the formulation used here – are now routine. In the 1970s, Dafermos, formulated an SE assignment model for examining multiclass flow problems, which included multi-commodity freight flow assignments.[30] Friesz, et al, describe the use of a multi-commodity freight network equilibrium model that specifically attempts to reconcile the user-optimized (shipper) and system-optimized (carrier) aspects of the freight flow problem.[31] This model performs a combined distribution, mode split, and assignment from the shipper standpoint. The resulting origin-destination flows and generalized routes provide inputs to a carrier submodel. This module computes system equilibrium flows for each mode/carrier. This model, while broader in scope than needed for this study, nevertheless contributes many useful ideas. Subsequent works by Harker, Crainic, et al, and Guélat, et al, further explore the theory of SE freight flow assignment.[32]

5.1 Design criteria and objectives

The objective of the model is to predict, given a matrix of commodity flows between origin and destination pairs, the likely volume of flow on each link in a rail network. The flow patterns should accurately reflect the underlying decision logic used by shippers and railroad managers in routing traffic. Given a flow volume and a service function for each facility, the average travel time, and thus delay, can be calculated for that facility.

The model provides a strategic level view of network flows, rather than a tactical or operating viewpoint. To this degree, flows do not replicate individual train operations, nor do they reflect

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[30] See Dafermos, Stella C., "The Traffic Assignment Problem for Multiclass-User Transportation Networks," *Transportation Science*, 1971, pp. 73-87.

[31] Friesz, Terry L. et al., "*The Northeast Regional Environmental Impact Study: Theory, Validation and Application of a Freight Network Equilibrium Model*." Report ANL/ES-120 prepared by Argonne National Laboratory, Argonne, Ill. for U.S. Department of Energy, 1981.

[32] See Harker, Patrick T., "*Predicting Intercity Freight Flows*," VNU Science Press, Utrecht, The Netherlands, 1986; Crainic, T.G., Florian, M., and Léal, J., "A Model for the Strategic Planning of National Freight Transportation by Rail." *Transportation Science*, vol. 24, no. 1, 1990, pp. 1-24; and Guélat, J., Florian, M., and Crainic, T.G, "A Multimode Multiproduct Network Assignment Model for Strategic Planning of Freight Flows," *Transportation Science*, vol. 24, no. 1, 1990, pp. 25-39.

traffic blocks used for operations planning. The statistics provided represent average characteristics of the system and do not address peaking, traffic disruptions, and other transient phenomena.

The network is fixed, and the model makes no improvements that would affect traffic flows. Of course, the analyst may use the model to test hypothetical improvements by exogenously specifying network changes. The model formulation reflects:

1. the flow of multiple separate commodity classes, each having a distinct rate structure;
2. the network topology of the modeled railroad system, including line haul arcs, terminals, and transfer points;
3. corporate ownership of network elements;
4. service characteristics of various network elements, such as line haul links and terminals; and
5. restrictions on the movement of commodities over specific carriers or network elements as needed to reflect operational practice.

5.1.1 Carriers and shippers

We assume that the transportation market consists of a set *M* of transportation providers or carriers $(m \in M)$. In this study, the carriers are railroads, although, in general, this is not a requirement. The set *M* may include carriers representing other modes of transportation, with appropriate adjustments to the physical network and cost attributes.

Carriers are assumed in the model to be cost minimizing entities. In economic terms, the firms are cost efficient. The carriers supply services, singly or in concert, between various origin-destination (O-D) pairs. An origin or destination may be a physical node in the network or an abstract node representing a demand centroid. This choice is left to the analyst. In general, however, because of the strategic planning orientation of the model, demand nodes represent centroids of mass for some shipper community in a region.

To reflect shipper demands, the construct contains a set *W* of O-D pairs. Some volume of a commodity or commodities flows between each O-D pair *w* in *W*. We denote the set of commodities as *P*, with *p* denoting an individual commodity. A commodity may represent a product, as in coal or grain, or a specific type of service, such as intermodal transportation. Empty cars returning to the point of loading may also be modeled as a commodity. It is assumed that each commodity has distinct cost characteristics.

The demand for transportation is fixed exogenously. Via measurement or some external procedure such as trip distribution or an input-output type model, the volume of flow for each commodity between each O-D pair is determined and provided as an input to the model. The model does not, therefore, replicate the decision making process of shippers in selecting markets for goods based upon economic principles.

The matrix of flow quantities between all O-D pairs is designated *Q*, with submatrix Q^p denoting the flow of commodity *p*. For consistency, units for all flows in *Q* are specified in a measure of weight, normally tons or metric tons. All flow values must be non-negative.

5.1.2 Links, nodes, and the complete network

In scale, the modeled transportation network represents a region or nation. The topology of this network describes the physical transportation network with little aggregation or abstraction.

Define L to be the set of all links in the network. For the most part, these links represent physical transportation facilities such as line haul track segments and classification yards or terminals. We may, in certain cases, add abstract links as in the case of a demand centroid connector. Associated with each link is a vector of attributes defining its physical and service characteristics.

In general, links in the real world network are undirected. For reasons which will become clear as the formulation proceeds, we represent the network as a set of N nodes and A directed arcs. Each undirected link is represented equivalently as a set of directed forward and reverse arcs.

There is no restriction against carriers sharing a physical link $l = (i; j), l \in L$, as in the case of joint track or trackage rights in the railroad industry. So that we can model each carrier individually, we wish for the subnetworks to maintain separate representations for such shared physical facilities. The forward arc representing link l for carrier m is then specified as $a = (i, j, m)_l$. There may also be a corresponding reverse arc $a' = (j, i, m)_l$. The subscript accounts for the case where we have parallel physical arcs between i and j.

Each link l is represented, therefore, in the network by a set of forward arcs $\overline{A}_F = \cup_{m \in M} (i, j, m)_l$. If the link is undirected, then there is a corresponding set of reverse arcs $\overline{A}_R = \cup_{m \in M} (j, i, m)_l$.

Nodes in the model physically represent junctions between line segments or locations where line characteristics change, as from single to multiple track. Nodes may also represent sources or sinks for traffic flow.

Connections between carrier subnetworks take place at a set T of designated transfer locations. The network is intermodal if transfers exist between carriers of different modes. Given a node $t \in \{N_m \cap N_n\}$, the transfer between carriers m and n at this node may be designated as $t_{m,n}$. Transfers are directed, and for transfer $t_{m,n}$, its counterpart $t_{n,m}$ may or may not be defined. Henceforth, we will use the designation t without subscripts to refer to an individual transfer.

In this model, transfers have a vector of cost attributes, but are assumed not to have capacity constraints or to experience congestion effects. If transfer congestion effects are desired, the network structure can be modified by adding logical links through which flow to the transfer point must pass. We assume otherwise that carriers provide line haul service as necessary to handle transfer flows.

The complete network is therefore represented by $G = (N, A)$, where N is the set of nodes and A is the set of directed arcs which connect these nodes. The arcs represent the set of L physical and logical links. Each carrier m operates a subnetwork G_m that consists of N_m nodes and A_m directed arcs. The complete network therefore consists of the union of the carrier subnetworks, with $N = \cup_{m \in M} N_m$ and $A = \cup_{m \in M} A_m$. The set T of transfers defines connections where flows may pass between the subnetworks. We see that, in general, subnetworks may share nodes, as at transfers, but arcs are unique to a carrier. In other words, $A_m \cap A_n = \{\varnothing\}, \forall m, n$.

5.1.3 Commodity flows

The volume of commodity *p* on arc *a* is given by v_a^p. Likewise, the volume of commodity *p* through transfer *t* is v_t^p. Both v_a^p and v_t^p must be non-negative. The vector of network facility volumes for commodity *p* is:

$$v^p = \begin{pmatrix} (v_a^p), a \in A \\ (v_t^p), t \in T \end{pmatrix}.$$

Vector $v = (v^p, p \in P)$, called the *load pattern*, gives the complete facility loading in the network.

Next, we derive a relationship between path flows and arc/transfer flows. For a given O-D pair, *w*, the volume of commodity *p* flowing between *w* is $q_w^p, q_w^p \in Q^p$. Define K_w as the set of paths through the network connecting *w*. If, for *w*, *i* is the origin node and *j* is the destination node, a path $k_w, k_w \in K_w$, can be expressed as:

$$k_w = (i, n_1, n_2, \ldots, t_1, n_s, n_{s+1}, \ldots, t_2, n_u, n_{u+1}, \ldots, j).$$

Here, n_x represents an ordinary node in the chain and t_y represents a transfer. Alternately, the path may be expressed as a chain of arcs:

$$k_w = \big((i, n_1, m_1), (n_1, n_2, m_1), \ldots, (n_{s-1}, t_1, m_1), (t_1, n_s, m_2), (n_s, n_{s+1}, m_2), \ldots,$$
$$(n_{u-1}, t_2, m_2), (t_2, n_u, m_3), (n_u, n_{u+1}, m_3), \ldots, (n_{u+z}, j, m_3)\big).$$

Path k_w consists of several subpaths, each of which belongs to a specific carrier:

$$k_w = k_w^{m_1} + k_w^{m_2} + k_w^{m_3},$$
$$k_w^{m_1} = \big((i, n_1, m_1), (n_1, n_2, m_1), \ldots, (n_{s-1}, t_1, m_1)\big),$$
$$k_w^{m_2} = \big((t_1, n_s, m_2), (n_s, n_{s+1}, m_2), \ldots, (n_{u-1}, t_2, m_2)\big),$$
$$k_w^{m_3} = \big((t_2, n_u, m_3), (n_u, n_{u+1}, m_3), \ldots, (n_{u+z}, j, m_3)\big).$$

Denote the flow of commodity *p* on path k_w as $\tau_{k_w}^p$, which must be non-negative. To assure flow conservation, the flows of *p* on all paths in K_w must sum to the total specified flow volume of *p* between O-D pair *w*:

$$\textstyle\sum_{k_w \in K_w} \tau_{k_w}^p = q_w^p. \qquad (1)$$

The set of all paths between all O-D pairs over which commodity *p* might flow is $K = \cup_{w \in W} K_w$. The relationship between arc flows and path flows for *p* is expressed as:

$$v_a^p = \textstyle\sum_{k \in K} \delta_a^k \tau_k^p \qquad (2)$$

where: $\delta_a^k = \begin{cases} 1 \text{ if arc } a \text{ is in path } k \\ 0 \text{ otherwise.} \end{cases}$

The equivalent relationship between transfer flows and path flows is:

$$v_t^p = \sum_{k \in K} \delta_t^k \tau_k^p \qquad (3)$$

where: $\delta_t^k = \begin{cases} 1 \text{ if transfer } t \text{ is in path } k \\ 0 \text{ otherwise.} \end{cases}$

Note that for a particular path k_w, the total flow is the vector $\tau_{k_w} = (\tau_{k_w}^1, \tau_{k_w}^2, \ldots, \tau_{k_w}^p)$ which contains a flow (possibly zero) for each commodity. The indexed set $\tau \equiv \{\tau_k, k \in K\}$ contains all path flows in the network. This set is called the *flow pattern*. The equivalent load pattern for arcs and transfers is constructed using the relationships in (2) and (3). The load vector for arc a is $v_a = (v_a^1, v_a^2, \ldots, v_a^p)$ and for transfer t is $v_t = (v_t^1, v_t^2, \ldots, v_t^p)$. The load pattern is then the indexed set $v \equiv \{v_a, a \in A\} \cup \{v_t, t \in T\}$, which is a restatement of the earlier definition.

5.1.4 Costs and flow/cost relationships

Given a pattern of flows, we are now interested in determining the cost characteristics of those flows. The cost of a flow pattern is equivalent to the cost of the corresponding load pattern. Thus, we may look at costs for loads on individual facilities.

Average Costs The average cost of a flow unit of commodity p on arc a is given by s_a^p and on transfer t by s_t^p. Both s_a^p and s_t^p must be non-negative. The vector of network average facility unit costs for commodity p is:

$$s^p = \begin{pmatrix} (s_a^p), a \in A \\ (s_t^p), t \in T \end{pmatrix}.$$

Vector $s = (s^p, p \in P)$ provides the average unit costs for all facility/commodity combinations.

For a given commodity, the unit cost on a facility is normally considered to be a function of the load pattern. In general, we therefore can say that $s_a = s_a(v)$ and $s_t = s_t(v)$. Realistically, however, it can be questioned whether, for example, there are cost interactions between arcs or transfers representing different physical facilities. In our model, therefore, we assume:

a) The cost functions for a given transfer are not affected by the flows at other transfers or by arc flows. This infers that flows at $t_{m,n}$ do not interact with flows for $t_{n,m}$
b) The cost function for an arc is not affected by transfer flows; and
c) The cost function for an arc is only affected by flows on arcs which represent the same physical link. There is no interaction between flows on separate physical links.

The real world railroad system behaves similarly.

Under assumption (c), the cost function for an arc can be affected by the flows on other arcs representing the same physical facility. The interaction between flows is apparent, for example, on a single track railroad line represented in the model by a forward arc and a reverse arc. The delay characteristics for such a line are a function of the total traffic in both directions. We then define $\overline{A}$ as a set of interacting arcs representing a physical link, $l = (i; j)$, $l \in L$, connecting nodes i and j. In general, for most railroad line classes where two-way traffic interacts, $\overline{A} = \overline{A}_F \cup \overline{A}_R$. In the case of non-interacting two-way traffic, as with directional double track, $\overline{A} = \overline{A}_F$ if $a \in \overline{A}_F$, otherwise $\overline{A} = \overline{A}_R$. It is apparent then, for arc flows, that we must evaluate a portion of the load pattern defined as $v_{\overline{A}} \equiv \{v_a, a \in \overline{A}\}$.

Based upon the above assumptions, and the definition of $\overline{A}$, the form of the average cost function can be made more specific for each facility type. The average cost vector for arc a is now $s_a = s_a(v_{\overline{A}})$. Since each commodity can have a distinct cost structure, the vector equation may be expressed as a set of p-scalar equations:

$$
\begin{aligned}
s_a^1 &= s_a^1(v_{\overline{A}}^1, \ldots, v_{\overline{A}}^p), \\
&\vdots \\
s_a^p &= s_a^p(v_{\overline{A}}^1, \ldots, v_{\overline{A}}^p).
\end{aligned}
$$

Transfers have no interaction, and therefore, no equivalent to $\overline{A}$. The average cost vector for transfer t is $s_t = s_t(v_t)$, with the corresponding set of p-scalar equations:

$$
\begin{aligned}
s_t^1 &= s_t^1(v_t^1, \ldots, v_t^p), \\
&\vdots \\
s_t^p &= s_t^p(v_t^1, \ldots, v_t^p).
\end{aligned}
$$

Total Costs The preceding section defined average cost relationships to the flow pattern. The total cost for the flow pattern is the practical measure of interest, however. As with the average unit cost, the total cost can be expressed in terms of the facility load pattern. The total cost for the flow of commodity p on arc a is $s_a^p(v_{\overline{A}})v_a^p$. The corresponding total cost for a transfer t is $s_t^p(v_t)v_t^p$. The total cost of the flow for product p is then:

$$\sum_{a \in A} s_a^p(v_{\overline{A}})v_a^p + \sum_{t \in T} s_t^p(v_t)v_t^p. \tag{4}$$

The total system cost for the entire load pattern is:

$$\sum_{p \in P}\left(\sum_{a \in A} s_a^p(v_{\overline{A}})v_a^p + \sum_{t \in T} s_t^p(v_t)v_t^p\right). \tag{5}$$

5.1.5 Facility cost functions

To compute costs, specific average cost functions which adhere to the requirements of the previous section are needed. These functions yield a generalized cost expressed as cost/unit of weight. First the case of arcs is examined and then that of transfers.

Arc Cost Functions. In this model, average cost function applies to arcs which model line-haul track segments.

Line-haul cost function. The line haul average cost function is hypothesized to provide a generalized cost having a weight-distance based component and a time based component. The function has the form:

$$s_a^p(v_{\bar{A}}) = m_a^p l_{\bar{A}} + T_{\bar{A}}(v_{\bar{A}})\, f_a^p h_a^p \qquad (6)$$

where: m_a^p = the cost per net ton-mile for commodity *p* on arc *a*;

$l_{\bar{A}}$ = the length of the arc's physical link;

h_a^p = train cost per hour for commodity *p* on arc *a*;

$T_{\bar{A}}(v_{\bar{A}})$ = travel time on arc *a*, given load pattern $v_{\bar{A}}$;

f_a^p = commodity conversion factor, weight to trains.

Subsequent sections discuss these terms and their explanatory variables.

Weight-distance cost term. The weight-distance component $m_a^p l_{\bar{A}}$ reflects cost elements such as track maintenance, equipment wear, allocated overhead costs, etc. Such items are normally measured as a cost per net or gross ton-mile of carriage. We use the $\bar{A}$ subscript on the length variable to denote a link specific attribute. Given a gross-weight to payload ratio, m_a^p is adjusted quite easily to reflect the gross ton-mile cost. We assume that the mileage based coefficients are constant over all flow volumes.

Time cost term The second component of the cost function is the time cost of transporting the commodity over the arc. This term accounts for costs such as fuel, labor, time value of locomotives and equipment, and time value of the commodity being transported. These cost categories are measured in cost per unit time, typically dollars per hour. The discrete unit of many of these costs is the train, and travel time over a line segment is typically viewed on a per-train basis.

The travel time is, of course, a direct function of the total volume, in trains, on the link. If the load pattern $v_{\bar{A}}$ is converted to the equivalent number of trains, a congestion function can be used to compute the average link travel time. To do this, we define for each commodity *p* and arc *a*, a factor f_a^p that converts the net weight of *p* to a number of equivalent trains:

$$f_a^p = \frac{\omega_m^p + \varepsilon_m^p}{\omega_m^p \chi_m^p \alpha_a} \qquad (7)$$

where: $a \in A_m$

ω_m^p = weight of commodity *p* in a loaded car for mode *m*;

ε_m^p = tare weight of an empty car for commodity *p* on mode *m*;

χ_m^p = trailing gross weight of a train of commodity *p* on mode *m*;

α_a = calibration factor for arc *a*.

The number of trains V_a^p on arc *a* of commodity *p* is then $f_a^p v_a^p$. The total number of trains, $V_{\bar{A}}$, defined by load pattern $v_{\bar{A}}$, is

$$V_{\bar{A}} = \sum_{p \in P} \sum_{a \in \bar{A}} f_a^p v_a^p \,. \tag{8}$$

This approach is similar to that employed by Crainic, Florian, and Léal, who report good agreement with observed volumes on Canadian railroads.

There are several points related to this approach which should be noted. First, equation (8) yields, in general, a non-integer number of trains. Since we are considering average flow, and not modeling detailed operations, this is acceptable. Second, the trailing gross weight of a particular train type does not include locomotive weights. Third, the arc calibration factor α_a adjusts train weights on arcs representing links with operating restrictions, such as grades or short sidings, which do not permit operation of the "average" train. It may also be used to increase weights. Finally, for a given product *p*, values of ω and ε are recommended to be constant for carriers which interchange traffic. Different values may be appropriate where transloading takes place at a transfer point. Otherwise, there will be a flow imbalance in terms of cars at transfer points, although weight flow conservation constraints will not be violated.

Given a congestion function, the average travel time $T_{\bar{A}}$ for the arc can be determined as a function of the train volume $V_{\bar{A}}$. Since $V_{\bar{A}}$ is, in turn, a function of the load pattern $v_{\bar{A}}$, then $T_{\bar{A}} = T_{\bar{A}}(v_{\bar{A}})$. In formulating our assignment model formulation, we may use, in general, any congestion function. The solution procedure requires the congestion function to meet certain criteria discussed in a later section.

The time cost term needs to be expressed in terms of cost per unit weight. The product of $T_{\bar{A}}(v_{\bar{A}})\, h_a^p$ has units of cost per train-hour. Multiplying this by f_a^p will yield units of cost per unit weight. The complete cost term is, therefore, $T_{\bar{A}}(v_{\bar{A}})\, f_a^p h_a^p$.

<u>Transfer Cost Function</u> In this model, transfer locations have no congestion effects or capacity limits. The cost model for a transfer is designed simply to reflect a commodity specific cost per car for performing the transfer:

$$s_t^p = \tilde{m}_t^p \, \tilde{f}_t^p \tag{11}$$

where:	$\tilde{m}_t^p$	=	the cost per car of commodity *p* using transfer *t*;
	$\tilde{f}_t^p$	=	cars per ton of commodity *p* using transfer *t*.

The cost $\tilde{m}_t^p$ may reflect factors such as an average time cost for the transfer, administrative charges, or delivery costs.

Railroad routing practice usually minimizes the number of transfers, since a transfer normally represents delay to the shipment. Of the set of transfer points available to a large railroad, historic traffic patterns will favor a subset for the majority of interchange activity. Other interchanges will have relatively little traffic. If the predicted flow pattern is to replicate actual conditions, the transfer cost function should reflect this hierarchy.

5.2 Objective function

The preceding sections provided the network definition, described demand and load patterns, and defined costs for facility loadings. These form the basis of a mathematical expression producing the load pattern in the network.

In this model, the objective is to select the load pattern that minimizes total generalized costs. The use of generalized costs reflects total logistics costs, and, in an environment of competition, carriers and shippers will, it can be argued, work together to minimize total costs. Since the model is based upon fixed demands, the shippers are not explicitly included as agents. The generalized cost may, however, contain components, such as the time value of commodities, to implicitly represent shipper interests. These cost components decrease the utility of routes with poor service characteristics. From a carrier standpoint, since the time frame of the model is short term, rates are assumed to be fixed. By minimizing costs, a carrier will maximize the portion of revenue brought to the bottom line.

5.2.1 Mathematical program

The load pattern minimizing total generalized costs is called the system optimum (SO). Mathematically, the SO load pattern is determined using the following non-linear program:

$$\min Z = \sum_{p\in P}\left(\sum_{a\in A} s_a^p(v_{\bar{A}})\, v_a^p + \sum_{t\in T} s_t^p(v_t^p)\, v_t^p\right) \qquad (12)$$

subject to:

$$\sum_{k_w\in K_w} \tau_{k_w}^p = q_w^p, \forall p, w \qquad (1)$$

$$\tau_{k_w}^p \geq 0, \forall p, w, k_w \in K_w \qquad (13)$$

$$v_a^p = \sum_{k\in K} \delta_a^k \tau_k^p, \forall a, p \qquad (2)$$

$$v_t^p = \sum_{k\in K} \delta_t^k \tau_k^p, \forall t, p\,. \qquad (3)$$

The constraints (1) and (13) assure flow conservation on paths. Constraints (2) and (3) transform path flows into arc and transfer flows.

5.2.2 Necessary and sufficient conditions

The solution of the above problem yields the desired SO flow pattern for the network when certain necessary and sufficient conditions are met. Convexity of the feasible region is guaranteed by the fact that constraints (1), (2), and (3) are linear equalities. A second requirement is that equation (12) be convex. This can be guaranteed if all of the arc and transfer performance functions are convex, positive, and monotone increasing, and, therefore, the product $s_a^p(v_{\bar{A}})\, v_a^p$ is convex over the range of flows v_a^p. The objective function will then be convex since the sum of a series of convex functions is itself convex. The following sections define the mathematical conditions.

Necessary Conditions The necessary conditions, which can be found in a number of texts, such as Sheffi (6), are as follows:

$$\tau_{k_w}^p (c_{k_w}^p - \hat{c}_w^p) = 0, \forall p, w, k_w \in K_w \tag{14}$$

and

$$c_{k_w}^p - \hat{c}_w^p \geq 0, \forall p, w, k_w \in K_w . \tag{15}$$

Equations (1) and (13), the flow conservation constraints, must also be met.

Variable $c_{k_w}^p$ represents the marginal total cost for moving product *p* over path k_w:

$$c_{k_w}^p = \frac{\partial Z}{\partial \tau_{k_w}^p} . \tag{16}$$

The marginal cost, well known in economic theory, is the addition to total costs of adding an additional incremental unit of commodity *p* to the flow on path k_w. The marginal cost for commodity *p* on path k_w is then

$$c_{k_w}^p = \sum_{a \in A} \delta_a^{k_w} c_a^p + \sum_{t \in T} \delta_t^{k_w} c_t^p$$

where $\delta_a^{k_w}$ and $\delta_t^{k_w}$ are indicator variables as in equations (2) and (3).

Variable $\hat{c}_w^p$ is the dual variable for the corresponding constraint in equation (1). According to the duality theory of linear programming, this dual variable is the cost of adding an increment of commodity *p* to the total flow between O-D pair *w*. Thus, $\hat{c}_w^p$ is also a marginal cost. From equation (14), for O-D pair *w* flow of commodity *p* on path $k_w \in K_w$ is non-zero only when $c_{k_w}^p = \hat{c}_w^p$. Paths where $c_{k_w}^p$ is greater than the associated dual $\hat{c}_w^p$ receive no flow.

Although the marginal costs are herein expressed in terms of paths, equivalent arc and transfer formulations are easily derived. Facility marginal costs are discussed in detail in a subsequent section of the paper.

<u>Sufficient Conditions</u> The condition for the existence of a unique minimum to the multi-commodity SE problem is that the objective function be strictly convex. If the Hessian of *Z* (the matrix of second derivatives of *Z*) is positive definite, this is sufficient to demonstrate strict convexity, and, thus, the existence of a unique minimum. The Hessian, *H*, is positive definite if, for $v \neq 0, v^T Hv > 0$. In the formulation, elements of *H* relating to arcs are positive, since arc cost functions will be strictly convex, positive, and monotone increasing. Transfers, however, have a linear cost function which yields a second partial derivative of zero. The reader can verify that, under these conditions, terms in $v^T Hv$ contain only arc flows. By the criteria applied to arc cost functions, then, $v^T Hv$ cannot be non-positive and *H* must be positive definite.

The properties of convex function addition can also prove the uniqueness of the result. We know that objective function is convex because the sum of convex functions is always convex. The objective function in this program is the sum of strictly convex functions (arc costs) and convex functions (transfer costs). If the result of the addition of convex and strictly convex functions is strictly convex, then the program will guarantee a unique minimum.

Strict convexity requires that, given any two distinct points x_1 and x_2,

$$z[\theta x_1 + (1-\theta) x_2] < \theta z(x_1) + (1-\theta) z(x_2)$$

for any value of $\theta, 0 < \theta < 1$. Let $f(x)$ be a strictly convex function of *x*, and $f(y)$ be a convex function of *y*. Two sets of points, (x_1, y_1) and (x_2, y_2), contain distinct values of *x* and *y*. If the sum of $f(x)$ and $f(y)$ is strictly convex, then

$$f[\theta x_1 + (1-\theta) x_2] + f[\theta y_1 + (1-\theta) y_2] < \theta[f(x_1) + f(y_1)] + (1-\theta)[f(x_2) + f(y_2)].$$

If $f(y)$ is convex, but not strictly so, then $f(y)$ must be linear on *y*, since $f''(y) = 0$. It is recognized, therefore, that

$$f[\theta y_1 + (1-\theta) y_2] = \theta f(y_1) + (1-\theta) f(y_2).$$

These terms cancel in the inequality, leaving

$$f[\theta x_1 + (1-\theta) x_2] < \theta f(x_1) + (1-\theta) f(x_2)$$

which is true since $f(x)$ is strictly convex. Therefore, we have shown that the sum of convex and strictly convex functions is strictly convex.

Since transfer flow cannot occur in the objective function without arc flow, the objective function must always be strictly convex in the vicinity of the optimum, and, therefore, Z is a global minimum.

5.3 Solution Algorithm

The mathematical program set forth can best be described as having a non-linear, multivariable, convex objective function with linear constraints. Solution approaches that provide insight into this particular programs are provided in a number of references. In his text on network flows, Hu (7) discusses some of the unique issues associated with multi-commodity flow formulations, namely that the constraint matrix is not unimodular and that the tremendous number of potential columns in the solution algorithm hint at a column generation based solution procedure. Dafermos (1) examines the multiclass assignment problem and proposes a two-stage solution procedure which has as its heart a decomposition of the problem by class. Sheffi (6) describes efficient two-stage algorithms for solving the single commodity, non-linear SO problem which might be extended for the multi-commodity problem. These include linear approximation procedures such as the Frank-Wolfe algorithm. Guélat, Florian, and Crainic (5) use a solution procedure similar to Dafermos' in their network model.

5.3.1 Algorithm overview

The constraint set defines a convex polytope encompassing the feasible region. The heart of the solution procedure is as follows. First, obtain an initial feasible flow pattern, *v*. This will represent a point on the surface of the polytope. Then, with each step of the algorithm, find a new feasible extreme vector, *w*, which improves the objective function. The two vectors *v* and *w* define a line in *n*-space. Using a linear search procedure, find the value of θ which minimizes the convex combination of *v* and *w*,

$$v_{new} = (1-\theta)v + \theta w. \tag{17}$$

The algorithm continues until $v_{new} \approx v$.

The above procedure is generally referred to as a convex combinations algorithm. The important step of determining the new feasible extremal vector *w* is the critical step. The procedure is to use the gradient of the objective function to formulate a linear approximation to the objective function. Minimizing this linear approximation to the value of the objective function subject to a system of linear constraints has as its solution a corner of the feasible space. The objective function of this program is

$$\min Z(w) = Z(v) + \nabla Z(v) \cdot (w-v)^T. \tag{18a}$$

Omitting constant terms $Z(v)$ and $\nabla Z(v)(v)^T$ yields the revised objective function

$$\min Z(w) = \nabla Z(v) \cdot (w)^T = \sum_i \left(\frac{\partial Z(v)}{\partial v_i} \right) w_i. \tag{18b}$$

The term $\frac{\partial Z(v)}{\partial v_i}$ is simply the marginal cost with respect to v_i. When the problem has the structure of a network, a feasible optimal solution for equation (18b) may be found using a straightforward shortest path algorithm.

In the multi-commodity flow problem, the vectors *v* and *w* are of dimension $P(A+T)$. By decomposing the problem by commodity, the vector size may be reduced to $(A+T)$, which represents a substantial savings in computer storage. This approach was advocated in both the aforementioned papers by Dafermos (1) and Guélat et al. (5) During each iteration of the algorithm, a linear approximation subproblem is solved for each commodity, using marginal costs with respect to the flow of that commodity. Flows of the other commodities are held fixed.

We consider that, for the multi-commodity problem, the constraint coefficient matrix is not unimodular. This means that, given integer flows for each commodity, optimal arc and path flows will generally not be integer. In a strategic planning model such as this one, non-integrality of the solution is not a problem, since quantities are generally large and the solution represents, at best, average conditions.

5.3.2 Algorithm description

The following paragraphs summarize the steps in the solution algorithm.

Step 0. Initialization Determine an initial feasible flow vector, *v*. This can be done using an iteration of Step 1 with initial marginal costs corresponding to a zero flow state and θ = 1 for each commodity subproblem.

Step 1. Flow Vector Update For each commodity $p \in P$, perform the following sequence of steps:

a) Given *v*, compute marginal costs, c_a^p and c_t^p, for all arcs $a \in A$ and transfers $t \in T$.

b) For each O-D pair $w \in W$ having a corresponding flow $q_w^p \in Q^p$, solve the shortest path problem using c_a^p and c_t^p as facility costs. Assign q_w^p to this path.

c) Let y^p be the load vector resulting from Step 1b, with *y* being the corresponding overall load pattern. Using a one-dimensional search algorithm, solve the problem
$\min(1-\theta)Z(v)+\theta Z(y)$

subject to: $0 \le \theta \le 1$.

d) Let $v^p = (1-\theta)v^p + \theta y^p$.

Step 3. Stopping Criterion The algorithm terminates if the iteration count exceeds a predetermined number or if the current value of the objective function is within a predefined tolerance of the previous value. Otherwise, return to Step 1.

Guélat et al. (5) prove that convex combinations algorithms which decompose the problem by commodity will converge when the objective function and constraints are convex.

5.3.3 Marginal cost functions

The solution algorithm uses functions to compute two types of costs: marginal total costs and average total costs. Derivations for the marginal cost functions are now provided.

We have two types of facilities of interest: arcs and transfer nodes. In general, the marginal cost $c_{\bar{a}}^{\bar{p}}$ for transporting product $\bar{p}$ on arc $\bar{a}$ is:

$$c_{\bar{a}}^{\bar{p}} = s_{\bar{a}}^{\bar{p}}(v) + \sum_{p \in P}\left(\sum_{a \in A}\frac{\partial s_a^p(v)}{\partial v_{\bar{a}}^{\bar{p}}}v_a^p + \sum_{t \in T}\frac{\partial s_t^p(v)}{\partial v_{\bar{a}}^{\bar{p}}}v_t^p\right). \tag{19a}$$

The equivalent function for transfer facility $\bar{t}$ is:

$$c_{\bar{t}}^{\bar{p}} = s_{\bar{t}}^{\bar{p}}(v) + \sum_{p \in P}\left(\sum_{a \in A}\frac{\partial s_a^p(v)}{\partial v_{\bar{t}}^{\bar{p}}}v_a^p + \sum_{t \in T}\frac{\partial s_t^p(v)}{\partial v_{\bar{t}}^{\bar{p}}}v_t^p\right). \tag{19b}$$

In practice, the following simplifying assumptions can be made:

a) The cost function for a given transfer is not affected by the flows at other transfers or by arc flows;
b) The cost function for an arc is not affected by transfer flows; and
c) The cost function for an arc is only affected by flows on arcs which represent the same physical link. There is no interaction between flows on separate physical links.

These do not seem to conflict with real world behavior of the railroad system.

We define $\bar{A}$ as the set of logical arcs representing a physical link, $l = (i; j)$, $l \in L$, connecting nodes *i* and *j*. Arc $a = (i, j, m)_l$ then represents a service of mode *m* using *l*. In general, *l* is an undirected link, so that for each arc $a = (i, j, m)_l$, there is a corresponding reverse arc $\acute{a} = (j, i, m)_l$.

We may have any number of modes using *l*, each represented by corresponding logical arcs. The set $\bar{A}$ is, therefore

$\{a \in A | a = (i, j, m)_l \, or \, a = (j, i, m)_l, m \in M\}$.

The load pattern for $\bar{A}$ is denoted by $v_{\bar{A}}$.

If an arc $a \notin \bar{A}$, then by assumption (c), $\partial s_a^p / \partial v_a^{\bar{p}} = 0$. This said, the marginal cost function for arcs can be simplified to:

$$c_a^{\bar{p}} = s_a^{\bar{p}}(v_{\bar{A}}) + \sum_{p \in P} \sum_{a \in \bar{A}} \frac{\partial s_a^p(v_{\bar{A}})}{\partial v_a^{\bar{p}}} v_a^p . \quad (19c)$$

For transfers, the marginal cost becomes:

$$c_t^{\bar{p}} = s_t^{\bar{p}}(v_t) + \sum_{p \in P} \frac{\partial s_t^p(v_t)}{\partial v_t^{\bar{p}}} v_t^p . \quad (19d)$$

We further assume, however, that transfers are uncapacitated using the rationale that railroads will dispatch trains to handle interchange traffic as necessary. The capacities of the adjacent arcs will then govern transfer volumes. This leads to the conclusion that $\partial s_t^p / \partial v_t^{\bar{p}} = 0$ and, therefore:

$$c_t^{\bar{p}} = s_t^{\bar{p}} . \quad (19e)$$

The total cost function forms were described previously without specific reference to the form of the congestion function used to compute arc travel times. We now address the problem of deriving a working form of the arc marginal cost function. Arc travel time is, of course, a direct function of the arc attributes and the total volume, in trains, on that link. We use a polynomial link travel time function having the form:

$$T_{\bar{A}} = R_{\bar{A}} \left[1 + k_1 t_{\bar{A}} + k_2 \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma} \right] \quad (20)$$

where:

	$R_{\bar{A}}$	=	free flow travel time, hours, for arcs in $\bar{A}$;
	k_1, k_2, □	=	empirical constants;
	$V_{\bar{A}}$	=	total daily train volume for arcs in $\bar{A}$;
	$C_{\bar{A}}$	=	total capacity, trains per day, for arcs in $\bar{A}$.

This polynomial link travel time function has the desirable properties of being continuous, convex, everywhere positive, monotone increasing, and twice differentiable. Furthermore, the same basic polynomial form, with the appropriate selection of constants, can be used to estimate terminal delay as a function of volume. This allows terminals to be modeled as a special class of link.

The total train volume over the link, i.e. the arcs in $\overline{A}$, is:

$$V_{\overline{A}} = \sum_{p \in P} \sum_{a \in \overline{A}} f_a^p v_a^p . \tag{21}$$

Substituting, the arc cost function then becomes:

$$s_a^p = m_a^p l_{\overline{A}} + R_{\overline{A}} f_a^p h_a^p \left[1 + k_1 \sum_{p \in P} \sum_{a \in \overline{A}} f_a^p v_a^p + k_2 \left(\frac{\sum_{p \in P} \sum_{a \in \overline{A}} f_a^p v_a^p}{C_{\overline{A}}} \right)^{\gamma} \right]. \tag{22}$$

For a given arc $\overline{a}$ and commodity $\overline{p}$, we are faced with the partial differentiation of this function with respect to the volume $v_{\overline{a}}^{\overline{p}}$ in computing the arc marginal cost. This may be done most easily by considering the separate terms in the equation, as follows:

a) $$\frac{\partial m_a^p l_{\overline{A}}}{\partial v_{\overline{a}}^{\overline{p}}} = 0, \forall a \in \overline{A}, p ;$$

b) $$\frac{\partial R_{\overline{A}} f_a^p h_a^p}{\partial v_{\overline{a}}^{\overline{p}}} = 0, \forall a \in \overline{A}, p ;$$

c) $$\frac{\partial R_{\overline{A}} f_a^p h_a^p k_1 \sum_{p' \in P} \sum_{a' \in \overline{A}} f_{a'}^{p'} v_{a'}^{p'}}{\partial v_{\overline{a}}^{\overline{p}}} = k_1 R_{\overline{A}} h_a^p f_a^p f_{\overline{a}}^{\overline{p}}, \forall a \in \overline{A}, p ;$$

d) $$\frac{\partial R_{\overline{A}} f_a^p h_a^p k_2 \left(\frac{\sum_{p' \in P} \sum_{a' \in \overline{A}} f_{a'}^{p'} v_{a'}^{p'}}{C_{\overline{A}}} \right)^{\gamma}}{\partial v_{\overline{a}}^{\overline{p}}} =$$

$$\frac{\gamma}{C_{\overline{A}}} k_2 R_{\overline{A}} h_a^p f_a^p f_{\overline{a}}^{\overline{p}} \left(\frac{\sum_{p' \in P} \sum_{a' \in \overline{A}} f_{a'}^{p'} v_{a'}^{p'}}{C_{\overline{A}}} \right)^{\gamma - 1}, \forall a \in \overline{A}, p .$$

The full marginal cost equation for the arc, commodity combination then becomes:

$$c_{\overline{a}}^{\overline{p}} = m_{\overline{a}}^{\overline{p}} l_{\overline{a}} + R_{\overline{A}} f_{\overline{a}}^{\overline{p}} h_{\overline{a}}^{\overline{p}} \left[1 + k_1 \sum_{p \in P} \sum_{a \in \overline{A}} f_a^p v_a^p + k_2 \left(\frac{\sum_{p \in P} \sum_{a \in \overline{A}} f_a^p v_a^p}{C_{\overline{A}}} \right)^{\gamma} \right] +$$

$$k_1 R_{\bar{A}} f_{\bar{a}}^{\bar{p}} \sum_{p \in P} \sum_{a \in A} h_a^p f_a^p v_a^p + k_2 \frac{\gamma}{C_{\bar{A}}} R_{\bar{A}} f_{\bar{a}}^{\bar{p}} \sum_{p \in P} \sum_{a \in A} h_a^p f_a^p \left(\frac{\sum_{p' \in P} \sum_{a' \in \bar{A}} f_{a'}^{p'} v_{a'}^{p'}}{C_{\bar{A}}} \right)^{\gamma - 1} v_a^p . \tag{23a}$$

We recognize that, from equation (21), $\sum_{p \in P} \sum_{a \in \bar{A}} f_a^p v_a^p = V_{\bar{A}}$, the total train volume over the link. The terms within the parenthesis in equation (23a) are then recognizable as the volume/capacity ratio for the link. Rewriting equation (23a) yields:

$$c_{\bar{a}}^{\bar{p}} = m_{\bar{a}}^{\bar{p}} l_{\bar{a}} + R_{\bar{A}} f_{\bar{a}}^{\bar{p}} h_{\bar{a}}^{\bar{p}} \left[1 + k_1 \sum_{p \in P a \in A} \sum f_a^p v_a^p + k_2 \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma} \right] +$$

$$k_1 R_{\bar{A}} f_{\bar{a}}^{\bar{p}} \sum_{p \in P} \sum_{a \in A} h_a^p f_a^p v_a^p + k_2 \frac{\gamma}{C_{\bar{A}}} \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma - 1} R_{\bar{A}} f_{\bar{a}}^{\bar{p}} \sum_{p \in P} \sum_{a \in \bar{A}} h_a^p f_a^p v_a^p . \tag{23b}$$

Further reorganizing the terms, we obtain:

$$c_{\bar{a}}^{\bar{p}} = m_{\bar{a}}^{\bar{p}} l_{\bar{a}} + R_{\bar{A}} f_{\bar{a}}^{\bar{p}} h_{\bar{a}}^{\bar{p}} + k_1 R_{\bar{A}} f_{\bar{a}}^{\bar{p}} \sum_{p \in P a \in A} \sum [f_a^p v_a^p (h_{\bar{a}}^{\bar{p}} + h_a^p)] +$$

$$k_2 R_{\bar{A}} f_{\bar{a}}^{\bar{p}} \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma - 1} \left[\left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right) h_{\bar{a}}^{\bar{p}} + \frac{\gamma}{C_{\bar{A}}} \sum_{p \in P a \in \bar{A}} \sum h_a^p f_a^p v_a^p \right] . \tag{23c}$$

A final reorganization yields the working form of the equation:

$$c_{\bar{a}}^{\bar{p}} = m_{\bar{a}}^{\bar{p}} l_{\bar{a}} + R_{\bar{A}} f_{\bar{a}}^{\bar{p}} \left[h_{\bar{a}}^{\bar{p}} + k_1 \sum_{p \in P a \in A} \sum [f_a^p v_a^p (h_{\bar{a}}^{\bar{p}} + h_a^p)] + \right.$$

$$\left. k_2 \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma - 1} \left[\left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right) h_{\bar{a}}^{\bar{p}} + \frac{\gamma}{C_{\bar{A}}} \sum_{p \in P a \in \bar{A}} \sum h_a^p f_a^p v_a^p \right] \right] . \tag{24}$$

Given that the specified forms of the arc and transfer cost functions, the objective function is strictly convex and the algorithm will converge to a global minimum. If transportation firms exhibit economies of density, however, average unit costs decline with increasing volume to a point, and then increase as the firm incurs additional costs for handling traffic. This well known U-shaped average cost curve is convex, but not monotone increasing. In this case, the terms $s_a^p (v_{\bar{A}}) v_a^p$ will not generally be convex, and, therefore, the objective function will be non-convex. This means that the program solution will not have a unique minimum. The algorithm may converge to a minimum, but there is no guarantee that this is the global minimum. Examination of this aspect of the problem continues. If we consider, however, that our network consists only of major routes, each having a reasonable volume of traffic, we may apply only the increasing side of the cost function.

5.3.4 Shortest path algorithm

Step 1b of the solution algorithm uses a shortest path algorithm (SPA) to solve the minimum marginal cost path problem for each O-D pair $w \in W$ with $q_w^p > 0$. For each iteration over a commodity, *p*, the SPA finds candidate paths between origin-destination pairs for flow enhancement. The arc and transfer costs used in the solution of these shortest path problems represent the sum of the current unit cost and the marginal cost for *p* based upon (*v*).

A version of the standard Moore algorithm generates these paths. Modifications to the SPA account for some unique requirements of the model structure. First, the algorithm produces paths which account for the decomposition of the overall network into a series of carrier subnetworks connected at transfer points. This is done using an arc-chain path rather than a node chain path. The arc-chain formulation also simplifies path tracing during the arc loading process. Second, if flow q_w^p has a designated originating carrier, the SPA must ensure that the path starts with this carrier.

5.4 RAILNET implementation

The research updated and enhanced a version of the RAILNET code dating from the 1990s. That version, programmed in Fortran 77, ran on an old IBM compatible PC under the MS-DOS operating system. The hardware and software limitation of that era constrained the problem size severely. In addition, processor performance and capabilities made for lengthy run times. The size of the network and flow matrices necessitated improvement of the program for this study.

As implemented, the RAILNET suite actually consists of three programs: NETBLD, COMMODTY, and RAILNET. NETBLD validates the formatted data sets describing the study network and prepares a set of indexed binary data files for subsequent use by COMMODTY and RAILNET. COMMODTY then validates the origin-destination data set against the study network and prepares a set of compact binary data files containing the commodity data. RAILNET then uses the compact network and commodity data to develop flows. All three programs can either interact with the user or accept control input from a file.

Given memory addressing and program size limitations of the era in which the original codes were developed, they could not solve problems of this study's size. Simply recompiling the codes was not an option; extensive structural modifications were necessary to remove these limitations. This was not a trivial task.

The team converted much of the code to use features of the modern Fortran 90 standard. Modification of data structures and indices removed many of the addressing limitations affecting problem size. In addition, the recoding process removed most hard limits on problem size. Revisions to the solution algorithm accommodated the expanded problem size and improved efficiency. Code improvements also resulted in more informative diagnostic messages and output reports. During this phase, the team elected not to implement a windowing interface for the program suite, though this remains a future goal.

Given the complexity of the codes, the steps described above required great care. Programming employed the Intel Fortran compiler under Microsoft Visual Studio. These tools permitted source code management, module compiling and linking, and interactive debugging. Test networks with known solutions permitted validation of program functions. The process identified and corrected several minor bugs in the original codes. Recoding using structured constructs improved program logic. Adding many additional comments and improving code formatting will make future changes easier, given the many thousands of program lines spread out over numerous source files.

The resulting codes are fully compliant with the Microsoft 32-bit memory model. They easily and efficiently handled the study network with origin-destination files of over 43,000 records. The typical RAILNET runtime for the study problem was less than one minute. Typically, the algorithm converged on the optimum solution in 7-10 iterations using less than two megabytes of dynamic memory. Perhaps just as importantly, the stage has been set for additional future program improvements.

6. RESULTS AND RECOMMENDATIONS

The goal of the current research is to provide a meaningful first step in helping stakeholders to better anticipate the effects of reduced coal reliance on the demand for rail transportation and the railroad infrastructure that supports it. Based on this goal, the analytical results described below represent a solid achievement. First, baseline estimates of link-specific traffic volumes approximate the observed distribution of railroad traffic in the southeastern U.S. in 2011. As importantly, the traffic flows predicted under forecasted 2036 coal volumes correlate well with the observed effects of already declining coal volumes and provide valuable insights into future outcomes. At the same time, the application of the modeling components described above points to abundant opportunities for additional improvements.

6.1 Baseline rail traffic

Figure 14 depicts the model-generated, link-specific railroad flows, based on actual shipment origins, destinations, and transported tonnages. Moreover, while this figure does not reflect values for individual commodities, commodity-specific tallies are one of many available model outputs. The units are gross tons, including empty cars, on each link.[33]

While rail industry experts may spot occasional anomalies, in large, these model-generated flows reflect the patterns and volumes of actual 2011 rail freight movements in the study region. Moreover, where there are variances, they often reflect complex, real-world railroad operating considerations that the routing algorithm does not currently capture.

6.2 Rail traffic under reduced coal reliance.

Figures 15 and 16 depict rail traffic in the eastern U.S., based on forecasted 2036 Appalachian coal volumes.[34] Figure 15 illustrates total forecasted regional tonnage and Figure 16 captures the difference between the coal scenario traffic and traffic under the 2011 baseline conditions. Units are, again, gross tons including empty cars on each link. There are several noteworthy outcomes.

First, as would be expected, the coal-producing region – particularly West Virginia and eastern Kentucky experience the largest impact on predicted infrastructure use. These regions originate and terminate little other than coal. Further, the model results suggest that traffic diversions from other routes will not absorb newly available capacity on these coal-dominated route segments. Indeed, the coal routes serving central Appalachia seem largely segregated from other rail network flows. This seeming isolation leads to a second observation. With the exception of coal routes to export locations on the East Coast or the Great Lakes, the predicted infrastructure impacts of reduced coal reliance are concentrated in the coal producing areas.

[33] Reporting in this section is constrained by the reliance on the Carload Waybill Sample and a need to protect both shipper and carrier confidentiality.

[34] As described in Section 4.3, the analysis changes only Appalachian coal volumes. All other (coal and non-coal) traffic volumes are at 2011 levels.

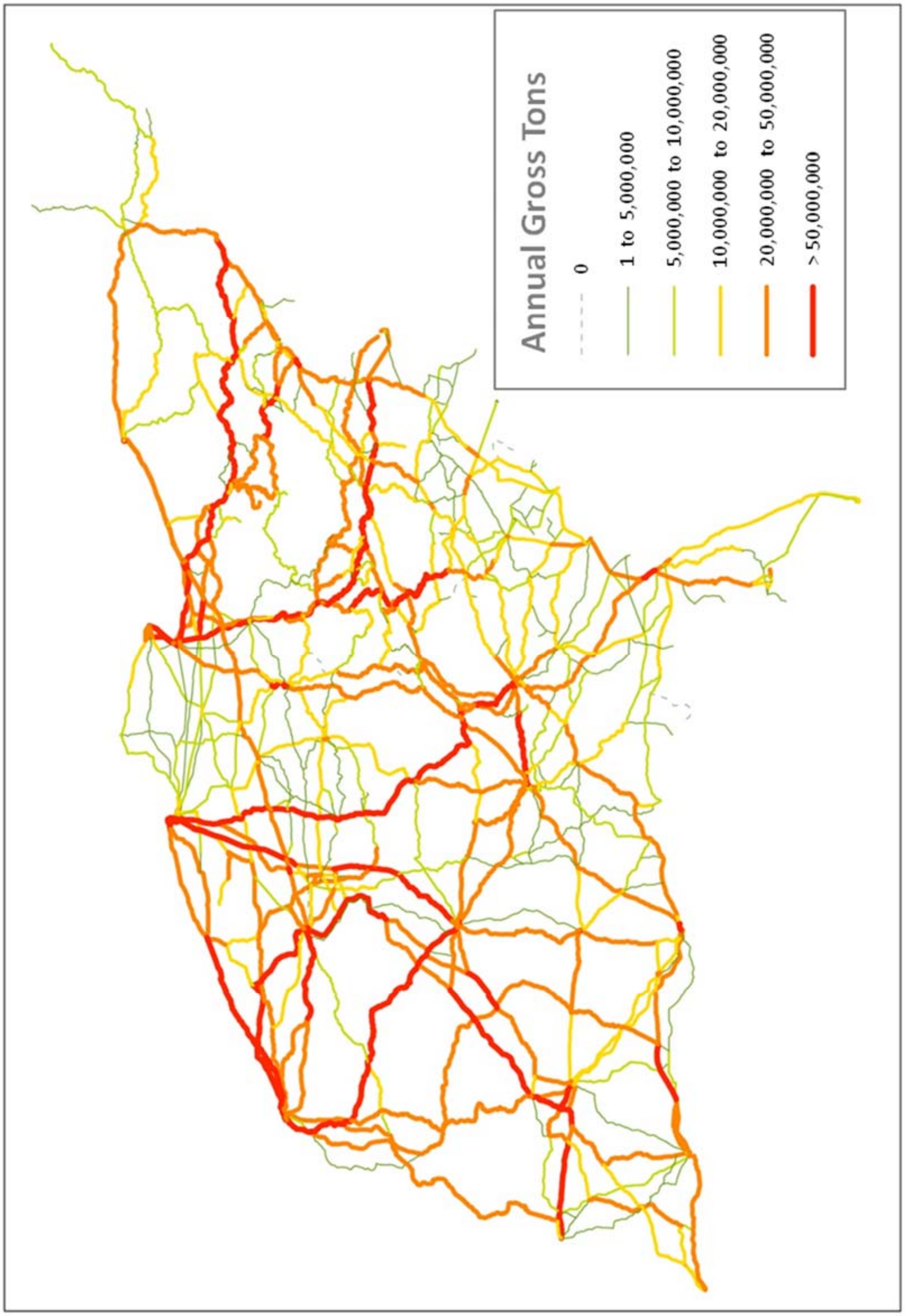

Figure 14. Baseline 2011 Railroad Flows

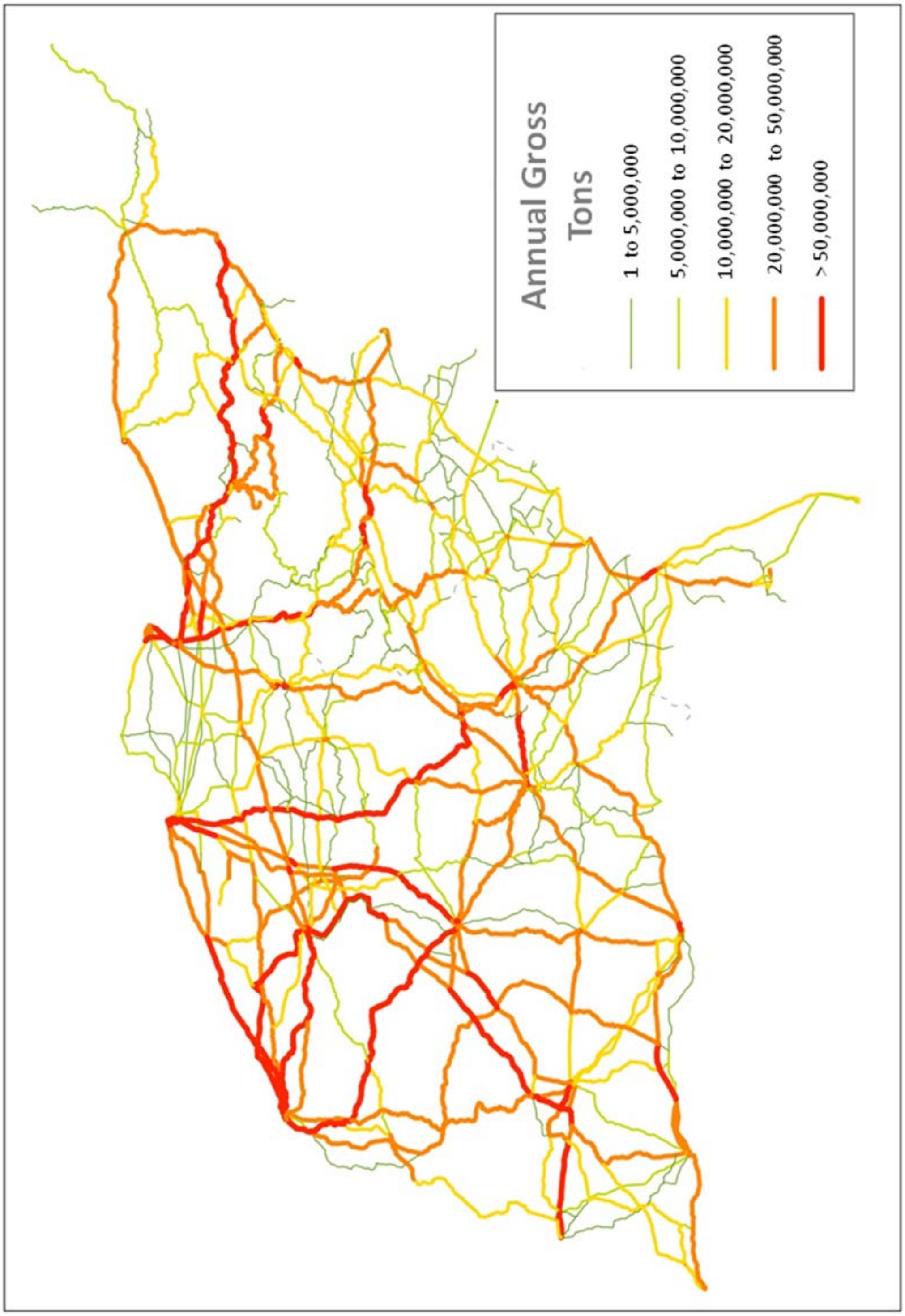

Figure 15. Predicted Railroad Flows with Forecasted 2036 Coal Volumes

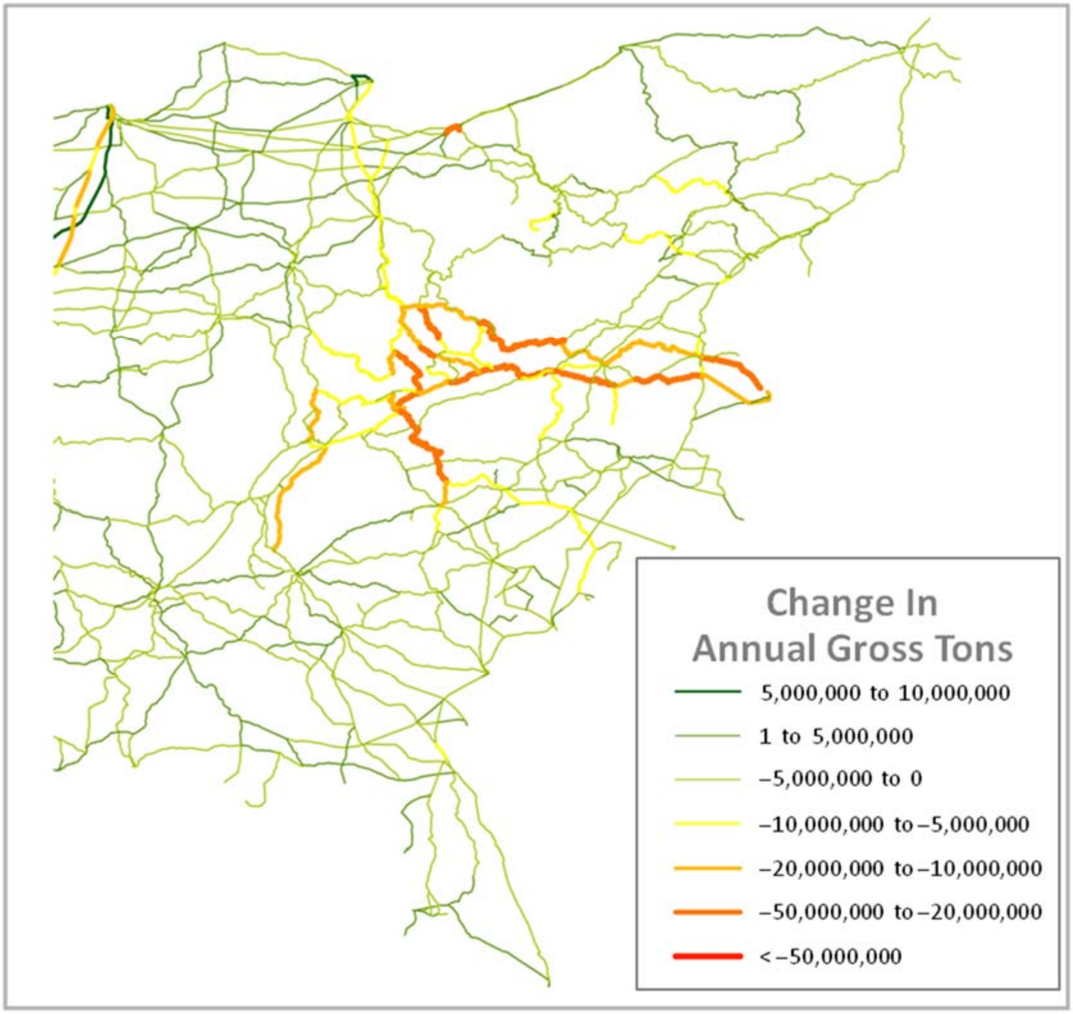

Figure 16. Differences in Predicted Traffic with Reduced Appalachian Coal Production

Together, the three figures highlight the importance of export coal volumes to the region's rail carriers and suggests that, in particular, the two mainline routes between southern West Virginia and Virginia's deep draft ports may be vulnerable. However, this conclusion may be attributable, at least in part, to the forecasts' inability to distinguish between steam coal and metallurgical coal or coal mined specifically for export. By necessity, the WVU forecasts used here consider coal produced within a state or within a sub-state region to be homogeneous. Unfortunately, the resulting ambiguities that may influence the results presented here.

The results summarized in Tables 15 and 16 suggest that specific routes may face traffic shortages that threaten their viability. Interestingly, many of these seemingly vulnerable routes have already lost traffic and undergone a change in status. This would seem to validate the model's performance. For example, the results predict the impact of reduced coal volumes on the CSX route between Russell, Kentucky and the Carolinas. As Section 3.1 and Figure 10 indicate, this has occurred, with CSX responding by reducing the FRA track class on some segments, suspending service on other portions of the route, and closing shop facilities at Erwin, Tennessee. Similarly, the model predicts traffic losses for the CSX route between Cincinnati and north Georgia. Again, this happened, with the carrier reducing track to class 2 and closing locomotive maintenance facilities at Corbin, Kentucky.

The predicted impacts to rail route segments are largely confined to central Appalachia and are shared roughly equally by CSX and Norfolk Southern. Still, these two dominant eastern railroads are not the only affected carriers. Other regional carriers also suffer traffic losses. Table 14 provides carrier-specific predictions of losses to gross railroad ton-miles that reflect 2036 coal flows.[35] Readers should bear in mind that (1) these are predicted, not actual changes, (2) changes are measured in gross ton-miles, and (3) while the vast majority of traffic changes reflect lost coal movements, some link-specific traffic changes may be affected by alternative routes for non-coal traffic.

Table 14. Carrier-Specific Changes in Gross Railroad Ton-Mile
(Values Reported in Millions)

Carrier	Increases in gross link ton-miles	Decreases in gross link ton-miles	Net change in gross link ton-miles
CSXT	3,823.7	34,554.2	**(30,730.6)**
NS	3,157.0	30,529.0	**(27,372.0)**
BNSF	949.1	9,348.2	**(8,399.1)**
CN	744.4	4,890.6	**(4,146.2)**
FEC	-	579.6	**(579.6)**
BB	-	578.8	**(578.8)**
CFE	9.3	262.5	**(253.2)**
AGR	1.0	210.2	**(209.2)**
Other RRs	79.8	582.7	**(502.9)**
TOTAL	**8,764.2**	**81,535.8**	**(72,771.5)**

6.3 Potential policy implications

The results presented here are preliminary and can be improved upon. Nonetheless, even at this early analytical stage, the findings hint at possible policy challenges and opportunities.

First, if we compare the data projections summarized in Section 5.2 to the coal traffic volumes actually observed between 2011 and 2016, it seems that much of the forecasted decline in coal production spread evenly over the 2011-2036 period was actually front-loaded into the forecast period's early years. This outcome is consistent with utility strategies where coal-fired generating capacity is retired as early as possible. Thus, policy-makers may have already observed the majority of coal traffic declines predicted over 25-year time horizon.

Second, the evidence described above suggests that the ongoing and future traffic impacts attributable to reduced coal reliance are (and will continue to be) largely constrained to Appalachia. The implication is that the coal routes highlighted in Figure 16 exist in relative

[35] The model also predicts a small number of net traffic gains. However, because these outcomes are not yet validated, Table 14 does not include them.

isolation from other railroad network activities. It follows that, diminished coal volumes will continue to threaten freight rail access in Appalachia's coal producing regions, but that this threat is not likely to spread to other segments of the eastern U.S. Thus, discussions that compare current challenges to the broader eastern rail network collapse barely avoided during the 1970s are without foundation. Any railroad problems associated with declining coal reliance are likely localized and any policy responses to the challenges associated with reduced rail network access will need to originate at the same local levels.

Finally, and to reiterate, the extent of predicted reduced coal traffic between Appalachia and eastern deep draft ports depends almost exclusively on the demands for coal exports. While many factors can influence these volumes, changes in U.S. trade policies certainly can influence coal exports. Any modification of trade policy that diminishes the competitiveness of Appalachian coal in global markets is also likely to further strain rail access between Appalachia and East Coast ports.

6.4 Further model validation and refinements

To reiterate, the work described here combines elements from many sources to create a single analytical platform. Elements include

- a highly specialized GIS depiction of the domestic railroad network;
- disaggregated data describing the population of freight rail movements in a subject year;
- forecasts of coal production over a 25-year time horizon;
- cost parameters that capture route-specific cost differences under varying levels of link use; and
- a complex routing algorithm that optimizes traffic routings, while simultaneously reflecting exogenous influences such as carrier sovereignty, institutional restrictions on interchange; and carrier-specific operating plans that include elements like directional running.

Each of these component areas provides opportunities for modeling improvements. These include:

6.4.1 GIS network elements

Accurately and thoroughly representing the physical railroad network and its cost characteristics is critical to the analysis. Therefore, the study team continually corrects and improves the network representation. In addition to this ongoing vigilance, there are, at least, three possible ways to improve the underlying GIS rail network and measurably enhance model performance.

The first potential improvement involves modifying the linkage between network displays and the underlying data. Currently, the displays reflect the underlying data, but it is not possible to modify this data through on-screen manipulations. Creating a two-way linkage between the data and the display would significantly expedite the ongoing network modifications previously described.

The second possible network enhancement would be to develop terminal-specific cost and performance attributes. The *RAILNET* platform is already capable of incorporating this important information into routing optimizations. However, the data necessary to exploit this capacity has proved elusive.

Finally, the GIS network representation includes data on link capacity that preclude link use beyond established thresholds. However, below these thresholds, unit costs are largely linear and, therefore, do not fully reflect economies of density that reward the concentration of additional traffic on links where there is unused capacity. Improving this representation would require link-specific functions relating traffic density to unit costs. It is worth exploring how to develop these functions efficiently.

6.4.2 Network flow data

The network flow data derive from the STB's annual Carload Waybill Sample and, therefore, are susceptible to the statistical issues inherent in any use of sample data. While there is no way to directly address these limitations, further exploring their implications is important to more accurately routing actual flows (versus those depicted in the CWS) and effectively interpreting model outputs.[36]

6.4.3 Forecasts and scenario development

The value of the analytical construct described here lies in its ability to predict changes to railroad network flows under varying scenarios. In the current application, the scenario depicts reduced demands for coal transportation and the details of this application clearly underscore influence of the exogenous information used in scenario development.

As described above, the effects of reduced coal production on rail traffic between West Virginia and Virginia's deep draft ports depends heavily on the specific demands for Appalachia's export coal. Unfortunately, it is not currently possible for forecasters to distinguish between coal produced for export versus domestic consumption. Thus, forecasted changes in productions are "averaged" across export and domestic markets. This makes it extremely difficult to validate the export-related results described in Section 5.2.

As with the baseline flow data, it may be impossible to directly improve forecasts used in scenario development. However, at very least, analysts must be careful to recognize these sorts of limitations as they provide interpretations of model results.

6.4.4 Cost parameters

Network cost parameters combine with traffic demands and network configuration to yield an optimal set of railroad routings. Therefore, establishing the best possible set of cost parameters is essential. The discussion of possible GIS improvements describes the value of improving cost data for individual network elements and the way that traffic densities are reflected in network link costs. However, far short of these ambitious improvements, validation exercises (not reported here) suggest that further refinement of the cost parameters already in use can lead to better model prediction. This is particularly true in two areas. First, the carrier-specific parameters used to capture shipment transfer (terminal) and carrier interchange costs can be made more precise. Second, the unavailability of short-line cost data must be addressed more effectively.

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[36] For example, transit movements, re-billed movements, and movements under accounting "Rule 11" can obscure information detailing interchange and actual commodity flows. To some extent, the CWS includes tools for addressing these issue movements. However, to this point, this information has not been fully exploited.

6.4.5 The RAILNET *routing algorithm*

Section 4.5 describes the numerous and complex steps used to translate managerial prerogatives, network attribute, operating characteristics and traffic demands into a predicted set of optimal network flows. Not surprisingly, the corresponding computational tasks are both plentiful and complicated. Technical refinements could reduce this complexity and improve model performance. Table 15 summarizes a subset of these potential refinements, their importance, and their perceived difficulty.

Table 15. RAILNET Suite, Representative Future Refinements

	RAILNET suite modification item	Priority	Difficulty
1.	Adapt code to employ modern Windows interface.	HIGH	MED
2.	Adapt code to use alpha symbols for carrier and commodity identification.	LOW	LOW
3.	Integrate separate model components into a single application.	LOW	HIGH
4.	Revise algorithm structure to improve efficiency.	LOW	MED
5.	Rewrite program code in modern programming language (e.g., C#).	LOW	HIGH
6.	Provide spreadsheet or DBF output capability for run results	LOW	MED
7.	Provide integrated demand data editing and display.	MED	HIGH
8.	Remove artificial 16-bit limits on network and demand data matrices.	MED	MED

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