

An Economic Analysis of the Appalachian Coal Industry Ecosystem

Transportation
Implications of Coal

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Executive Summary

Recognizing the realities of a changing energy landscape, the Appalachian Regional Commission (ARC) has commissioned a series of research initiatives that explore various aspects of Appalachian Coal Industry Ecosystems (CIE). This report describes the goals, execution, and findings of a CIE effort focused on rail freight access in the Appalachian Region.

For more than a century, railroads have played an important role in Appalachia's coal industry ecosystem. But that ecosystem is changing, and the long-run, downward trend in Appalachian coal production implies a large and lasting reduction in coal traffic for the Region's railroads. The recently encountered cyclical traffic lapse provided policymakers with a glimpse as to how rail carriers may adapt to more permanent traffic losses. Taken as a whole, this information suggests that preserving rail freight access in Appalachia's core may eventually become difficult.

Utilizing network modeling techniques developed at the University of Tennessee, the study team modeled railroad network flows under baseline (2011) traffic conditions and with the diminished coal flows predicted for 2036. Key findings include:

- Rather than unfolding evenly through time, the results suggest that the largest declines in railroad tonnage may have already been observed.
- Geographically, with only a few exceptions, any threats to rail access associated with reduced coal volumes seem to be constrained to Appalachia.
- While unwelcome, the magnitude of losses to rail access, either in the form of physical proximity or affordability, is not currently predicted to be catastrophic. However, this prediction depends pivotally on rail carriers' abilities to garner adequate revenues from remaining freight traffic.
- Continued access to eastern ports and the global connectivity they afford depends largely on Appalachian coal's competitiveness in international markets and the strength of those markets going forward.

The results suggest that, during 2015 and 2016, aggressive electric utility strategies (including accelerated plant retirements), combined with a pronounced cyclical downturn in coal demand, compressed more than a decade's worth of reduced coal consumption and transportation into a two-year span. Setting aside the broader effects of these events, the rapid reduction in coal-related railroad activity eliminated roughly 2,000 full-time railroad jobs and \$150 million in income from a region that can ill-afford such disruptions.

Still, for policymakers, there are two advantages in this outcome. First, beginning in late 2016 and continuing throughout 2017, coal production and transportation began to regain the more gradual, long-run path predicted by the West Virginia University forecasts. Barring any additional, unanticipated disruptions, this affords policymakers the opportunity to evaluate and implement policies that help ensure the preservation of stable rail-freight access in the face of further declines in coal outputs.

As importantly, the temporal compression in reduced coal activity forced the Region's railroads to act with an immediacy that provides valuable information regarding future network adjustments. Specifically, while the railroads have acted with deliberate speed, they have also avoided responses that are irreversible. In adjusting to the 2015-16 collapse of coal demands, the railroads have not abandoned trackage, have not razed or sold terminal facilities, and have shed unsustainable lines through leases rather than line sales. In aggregate, these actions suggest a railroad industry that is hesitant to permanently relinquish freight capacity.

If one accepts the long-run reduction in eastern railroad coal traffic as probable, the next question is whether existing or foreseeable non-coal traffic will be drawn to Appalachian-inclusive rail corridors by capacity made available through the loss of coal volumes. The analysis reported here suggests that this will not happen. The rail routes in and through Appalachia were built to access the Region's coal and timber. The railroad trunk lines that first connected the American East with the nation's interior were built around Appalachia, much like the Interstate highways that came a century later.

The final question is—absent robust coal volumes and without a probable substitute—whether surviving Appalachian freight traffic will generate sufficient activity to sustain the Region's rail access. The answer, for the moment, is a somewhat tentative *probably*. However, the key to this assurance is coal volumes that do not permanently fall too far below those predicted in the above analysis. Without the residual forecasted coal traffic, a positive outcome would be impossible.

Chapter 1: Introduction

Two points seem irrefutable. First, mining, preparing, and transporting coal has been an integral part of Appalachia's economy for more than a century. Second, coal-related commerce everywhere is changing in ways that will continue to challenge coal-dependent communities far into the future. Recognizing these realities, the Appalachian Regional Commission (ARC) has commissioned a series of research initiatives that explore various aspects of Appalachian Coal Industry Ecosystems (CIE). This report describes the goals, execution, and findings of a CIE effort focused on rail freight access in the Appalachian Region.

Why a Freight Rail Focus

The Appalachian Regional Commission was organized in the mid-1960s to help the Region attain economic parity with the nation. Early in that process, it became clear that one of the Region's chief disadvantages was its physical isolation. Accordingly, ARC's earliest and most enduring strategies have been to improve the physical mobility of both individuals and goods moving to, from, and within the Region. Because access is key to Appalachia's future in the global economy, protecting and improving all transportation modes are among the Region's foremost goals.

Continued transportation access via all transport modes is paramount, but the changes in the coal industry ecosystem are not affecting all transport modes equally. Roadway access and motor carriage are sustained by public policies and public-sector funding. Moreover, highway use is rarely coal-dependent. The Region's navigable waterways are another essential asset, and navigation traffic is heavily dependent on the movement of coal. Still, like the roadways, navigable rivers are maintained by the public sector. As such, private sector water carriers are, to a degree, insulated from the early effects of economic change.

In contrast, the Region's railroads—both its large, Class I carriers and its smaller short-lines—are almost all privately owned. For these firms, the loss of coal and related freight traffic is resulting in immediate financial pressures that demand near-term decisions about continued service and service-sustaining investments. The market forces that guide railroad decision-making afford little flexibility, sentiment, or broader community concern. In short, if Appalachia's changing coal economy poses threats to transportation resources, the Region's railroad access is its most vulnerable asset.

Goals and Organization

The work reported here is the third in a series of efforts recently undertaken by ARC. Motivated by concerns for the Region's rail networks, ARC's senior leadership gathered a group of independent scholars to prepare a briefing paper in January 2016 that described the emerging threat to Appalachia's rail freight access. This was followed by another Commission-sponsored effort (released in

March 2017) that evaluated the changing coal industry, the changes in the related demands for railroad transportation, and potential public-sector strategies.¹

The goal of the current initiative is to provide a level of detailed information that was not produced as part of either earlier effort. Specifically, the analysis reported here combines long-run coal production forecasts generated by West Virginia University with railroad network models developed at the University of Tennessee to estimate the locations and extent of coal-related railroad traffic losses. These predictions are then used to suggest if and where rail access may be lost altogether and how railroad rates may be affected in areas where access is retained.

Chapter 2 provides readers with a contextual foundation. It briefly traces the rail industry's role in the evolution of Appalachia's coal industry ecosystem and concludes with a discussion of the industry's current position. Chapter 3 outlines the rail-related CIE changes—both those that have already been observed and those that are predicted. This chapter also describes how private sector decisions are made regarding retaining or abandoning both services and infrastructure. The detailed information alluded to above is provided in Chapter 4, including indications of which rail routes are most vulnerable and how the costs of providing surviving railroad services may be affected. Finally, policy implications and alternatives are discussed in Chapter 5. Technical appendices include details on the study data and analytical techniques.

¹ For a full discussion of these effects see, Mark Burton, "Access vs. Isolation Preserving Appalachia's Rail Connectivity in the 21st Century: Part 2, Appalachian Regional Commission, Washington, DC, March 2017, <https://www.arc.gov/images/programs/transp/RailAccessinAppalachiaPartTwoFinal.pdf>

Chapter 2: The Evolving Role of Rail

A mid-20th century railroad map of Appalachia reveals a spaghetti bowl containing thousands of miles of main-line, branch-line, and mine-branch trackage operated by at least eight Class I carriers and dozens of smaller regional and short-line railroads. The rail routes existed almost solely to transport coal in every direction—east to the Tidewater for export, north for industrial users, and in every direction as a transportation and household fuel. Not surprisingly, the nature and extent of these operations closely mirrored business conditions in the coal industry and the changing demands of coal users. Beginning in the post-World War II era, this activity was supplemented (and ultimately replaced by) the movement of Appalachian steam coal to electricity-generating facilities. For the past 60 years, the fortunes of America’s railroads, its coal producers, and its power generators have been tightly bound together.

Railroads as a Source of Commerce and Employment

As with mining, technological advancements have dramatically reduced the labor requirements of freight railroads. As recently as 1956, the Class I railroads employed over one million full-time workers. Although freight traffic measured in ton-miles has more than tripled nationwide over the last sixty years, by 2016, Class I employment had fallen to just 153,000.²

Railroad employment within Appalachia has followed the national trend. However, the railroads still provide an important opportunity for regional labor. Table 1 shows the number of current (2015) railroad employees in Appalachian counties for all railroads. Based on this accounting, roughly 10 percent of all railroad jobs are in Appalachia, and 17 percent of all Class I railroad employment is within the Appalachian Region. Finally, like mining employment, railroad earnings are notably higher than regional averages. For 2016, annual railroad worker compensation averaged \$85,000. Thus, rail-related employment brings approximately \$2.2 billion in earnings to the Region each year.

Table 1: Railroad Employment in Appalachian Counties, 2015

State	Railroad Workers	State	Railroad Workers
Alabama	2,795	Pennsylvania	5,133
Georgia	1,868	South Carolina	331
Kentucky	2,096	Tennessee	2,624
Maryland	690	Virginia	3,842
Mississippi	473	West Virginia	2,971
North Carolina	429	ARC Region	26,009
New York	524	Non-Appalachia	240,733
Ohio	2,233	Total	266,742

Source: U.S. Railroad Retirement Board

² See Association of American Railroads, *Railroad Facts*, various years.

Appalachian Coal: Where It's Mined and Where It's Consumed

The March 2017 report cited above provides a more comprehensive description of coal transportation in the eastern United States (see Section 3, page 10). However, given its importance, a portion of that information has been updated for inclusion here.

Understanding the transportation of Appalachian coal requires three pieces of information. These include: (1) data describing where domestic coal is mined, (2) similar information detailing where and for what purposes coal is consumed (or exported), and (3) depictions (including cost and availability) of the transportation alternatives for moving coal from source to consumption.

Table 2 summarizes eastern production for 2015 and 2016.³ Roughly one-quarter of U.S.-produced coal was mined in Appalachia, while 13.5 percent was produced in the Illinois basin. Of the coal-producing Appalachian states, West Virginia was dominant, producing 11.0 percent of the national output.

Table 2: Coal Production in the Eastern U.S., 2015-2016

	2016 (Thousands of Short Tons)	2016 Percent of U.S Total	2015 n (Thousands of Short Tons)	Percentage Change
Alabama	9,643	1.3%	13,191	-26.9%
Illinois	43,422	6.0%	56,101	-22.6%
Indiana	28,767	3.9%	34,295	-16.1%
Kentucky (East)	16,772	2.3%	28,101	-40.3%
Kentucky (West)	26,096	3.6%	33,324	-21.7%
Maryland	1,616	0.2%	1,922	-15.9%
Mississippi	2,870	0.4%	3,143	-8.7%
Ohio	12,564	1.7%	17,041	-26.3%
Pennsylvania Total	45,720	6.3%	50,031	-8.6%
Tennessee	644	0.1%	897	-28.2%
Virginia	12,910	1.8%	13,914	-7.2%
West Virginia (Northern)	43,524	6.0%	47,785	-8.9%
West Virginia (Southern)	36,233	5.0%	47,848	-24.3%
East of the Mississippi River	280,781	38.5%	347,593	-19.2%
Appalachia Total	179,626	24.7%	220,730	-18.6%
Illinois Basin	98,285	13.5%	123,720	-20.6%
U.S. Total	728,364	100.0%	896,941	-18.8%

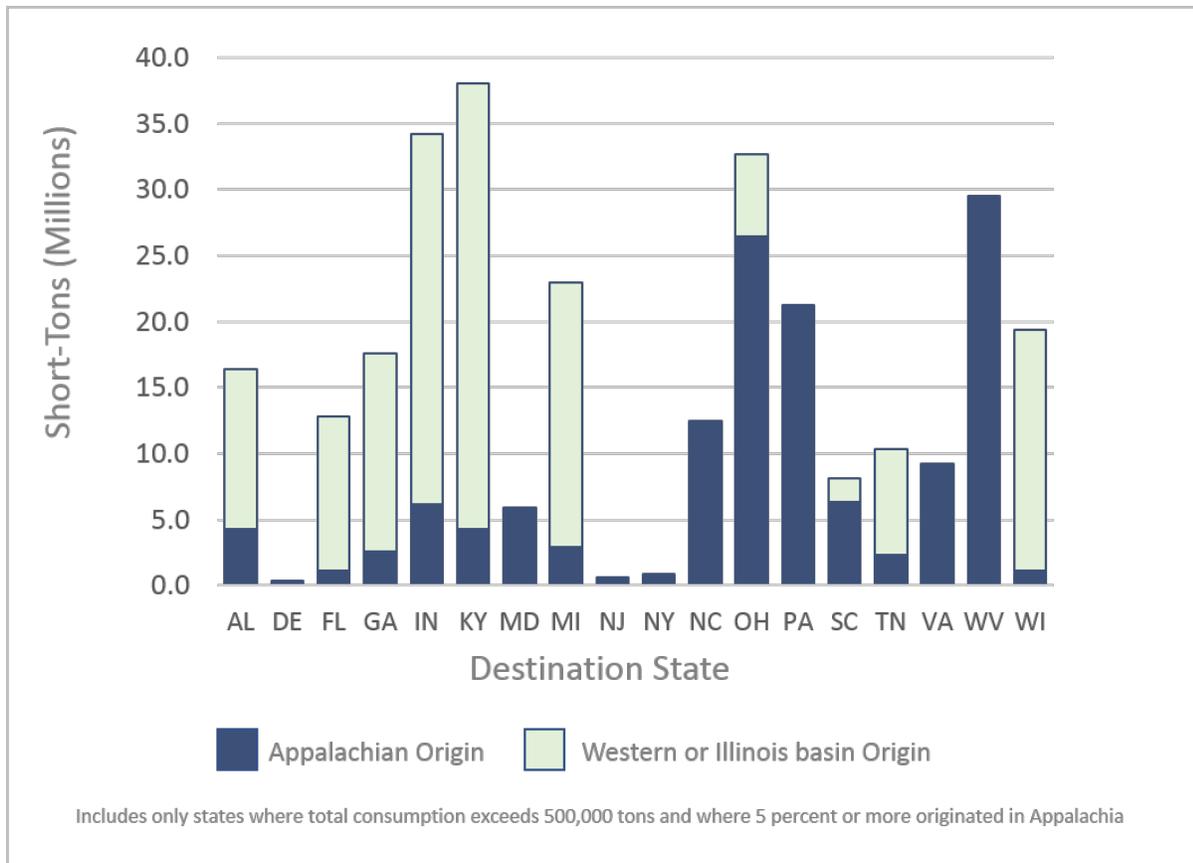
Source: Energy Information Administration

³ The current analysis focuses on production and consumption in states east of the Mississippi River unless explicitly noted otherwise.

In a typical year within the U.S., roughly 90 percent of all coal mined is consumed domestically, with only 10 percent going to export. However, the characteristics and location of Appalachian coal make it particularly attractive in broader global markets, and so export coal routinely accounts for 20-25 percent of the Region’s annual output. As the remainder of the current report highlights, the distinction between Appalachian coal used in domestic electricity production and coal mined for export has important implications for eastern railroads and the Region’s continued access to rail freight service.

Of the 80 percent of Appalachian coal that is not exported, nearly all of it is burned as steam coal within or near the Region. Figure 1 depicts coal shipments from Appalachian origins and the volume of western and Illinois basin coal consumed by the receiving states.

Figure 1: Consumption of Appalachian Coal, 2016



Source: Energy Information Administration

Appalachian Coal: How It's Moved

Much of the Region's coal is consumed relatively close to where it is mined and nearly all domestic consumption takes place east of the Mississippi River. When distances are sufficiently short (less than 100 miles) and volumes are small, coal is sometimes moved 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 "prep" 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 general consensus is that coal truck travel is both possible and efficient throughout the coal-producing region wherever there are roadways of any form. 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 on a system that is designed, constructed, and maintained by the U.S. Army Corps of Engineers (Corps). On most reaches of these waterways, maintaining adequate water depth depends on establishing navigation pools created by dams that can be transited through navigation locks.⁴ With very few exceptions, railroad infrastructure is privately owned by rail carriers who create, maintain, and operate freight rail systems. A thumbnail sketch of mainline railroad trackage and main-stem waterway system components are provided in Figure 2. The extent of these systems within the Region is summarized in Table 3.

Table 4 provides a summary of the freight transportation modes used to deliver coal to final destination states in 2016. Table 5 reverses the analytical lens and depicts the importance of coal traffic as a share of overall 2016 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, 87.3 percent of all regional coal shipments were delivered by rail or barge in 2016. Alternatively, 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 in 2016. At least historically, without the ability to move coal to where it is consumed, 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.

⁴ 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.

Figure 2: Simplified Regional Waterway and Railroad Networks



Source: Center for Transportation Research

Table 3: Summary of Regional Waterway and Railroad Infrastructures

Railroad Network		Waterway Network	
Primary Class I Carriers	CSXT, NS	Mainstem Ohio Miles	436
Total Freight RR Miles	16,970	Navigable Tributary Miles	768
Number of Short-Line Carriers	83	Mainstem Ohio 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

Table 4: Modes Used for 2016 Regional Coal Delivery (Thousands of Short-Tons)

State	Rail	Barge	Truck	Other	Total Domestic	Export	Total
Alabama	671	1,962	1,077		3,710	6,329	10,039
Illinois	13,632	17,304	3,054	6,071	40,060	6,250	46,311
Indiana	24,112	2,719	2,498	19	29,348	172	29,520
Kentucky (East)	11,410	1,409	1,413	70	14,302	1,255	15,557
Kentucky (West)	8,574	12,707	4,439		25,720	97	25,817
Maryland	22	10	1,518		1,550	209	1,759
Mississippi			3,053		3,053		3,053
Ohio	567	14,830	3,079		18,476	137	18,613
Pennsylvania (Anthracite)	19		166		185	401	586
Pennsylvania (Bituminous)	23,393	6,939	4,113	2,026	36,471	5,607	42,077
Tennessee	618	3	17		638		638
Virginia	4,375	1,790	2,803	252	9,220	5,004	14,223
West Virginia (Northern)	4,267	19,438	150	5,010	28,864	9,681	38,546
West Virginia (Southern)	16,071	7,597	1,881	1	25,549	14,387	39,936
STUDY REGION TOTAL	107,728	86,709	29,261	13,448	237,146	49,528	286,674

Source: Energy Information Administration

Table 5: Coal's Share of Regional Waterway and Rail Traffic in 2016

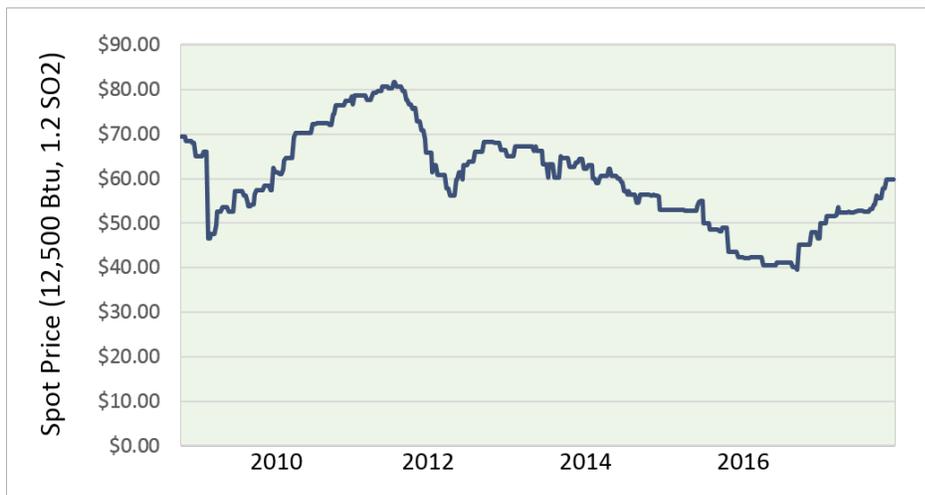
Railroad Origin State	Loaded Carloads - Coal	Loaded Carloads - ALL	Coal Percentage of Total	Ohio River Lock and Dam	2016 Coal Traffic Tons (X1K)	2016 Total Traffic Tons (X1K)	Coal Percentage of Total
Alabama	54,483	518,718	10.5%	Ohio 52	13,771	70,718	19.47%
Kentucky	258,996	636,346	40.7%	Ohio 53	8,171	63,695	12.83%
Ohio	85,412	1,211,763	7.0%	Belleville	25,487	40,485	62.95%
Pennsylvania	255,372	1,089,106	23.4%	Cannelton	25,510	52,367	48.71%
Virginia	126,038	523,994	24.1%	Meldahl	15,538	37,549	41.38%
West Virginia	549,538	690,684	79.6%	Dashiels	7,580	12,135	62.47%
ARC TOTAL	1,329,839	4,670,611	28.5%	Emsworth	7,576	10,979	69.01%
Illinois	295,001	4,935,567	6.0%	Greenup	13,393	35,584	37.64%
Indiana	170,060	750,285	22.7%	Hannibal	26,578	39,562	67.18%
Regional Total	1,794,900	10,356,463	17.3%	Myers	15,454	47,765	32.36%
US Total	5,352,604	32,335,465	16.6%	Markland	14,167	39,249	36.10%
				McAlpine	25,118	53,269	47.15%
				Montgomery	7,119	12,343	57.68%
				Newburgh	28,712	58,871	48.77%
				New Cumberland	14,253	23,953	59.51%
				Pike Island	15,571	26,158	59.53%
				Racine	28,225	43,345	65.12%
				Robert Byrd	12,703	30,498	41.65%
				Smithland	17,180	55,725	30.83%
				Willow Island	24,240	37,331	64.93%
				Ohio River Total	346,347	791,582	43.75%

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

Chapter 3: Understanding the New Normal

Markets for fuels—coal, petroleum, and natural gas—are global in nature and, therefore, subject to a wide variety of exogenous market forces that render them highly volatile. As an illustration, Figure 3 shows the average spot price for Central Appalachian (CAP) coal between January 2009 and December 2017. Observed prices, like those in the figure, as well as corresponding quantities, reflect both long-run trends and short-run disturbances. It is necessary to recognize both to understand the “new normal” in Appalachia’s coal economy.

Figure 3: Spot Market Prices for Central Appalachian Coal



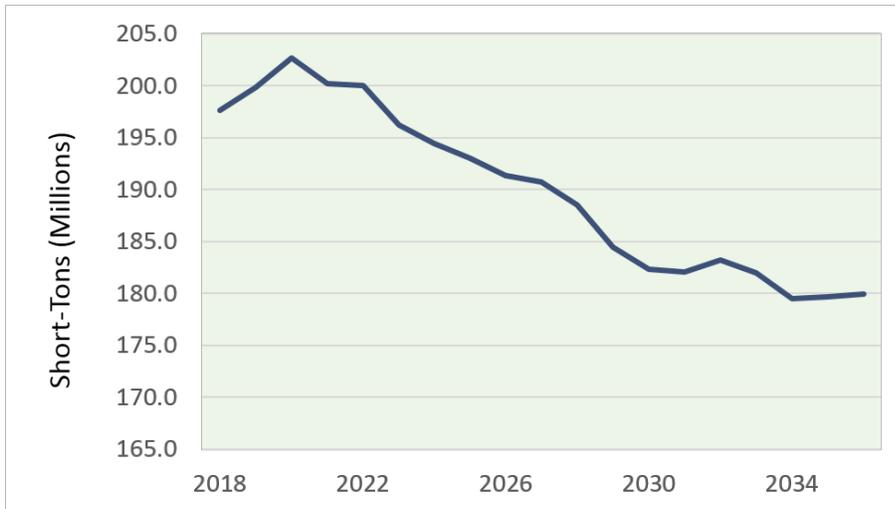
Source: The Energy Information Administration

Regarding the long-run trend, there is clear evidence that predicts steadily declining Appalachian coal production. In a companion piece to this report, economists from West Virginia University (WVU) describe both historical and predicted patterns of long-run coal production that forecast reduced coal outputs over a 25-year time horizon.⁵ This trend is depicted in Figure 4 and is the product of various long-run forces, including, but not limited to, North America’s ability to produce larger quantities of natural gas and ever-increasing global concerns about air quality.

However, there are also cyclical disruptions in the demand for Appalachian coal. During 2015 and much of 2016, the declining, long-run trend evident in the WVU forecast was amplified by a cyclical drop in coal demands. Together, these combined impacts led to a significant, albeit transient, decline in coal-related commerce.

⁵ See Bowen, et al, “An Overview of the Coal Economy in Appalachia,” Appalachian Regional Commission, January 2018.

Figure 4: Aggregated Appalachian Coal Production Forecast



Source: West Virginia University Forecast

Figure 5 illustrates U.S. railroad coal car-loadings from 2014 forward. Table 6 provides 2013-2015 coal traffic data for individual carriers. These data underscore the rapid and pronounced 2015-2016 drop in railroad coal traffic, particularly in the eastern U.S. In response, Appalachia’s railroads undertook a variety of actions. Norfolk Southern temporarily discontinued service over two routes in West Virginia and Ohio; leased a 300-mile secondary mainline route and a 44-mile North Carolina branch-line to a short-line holding company; closed its coal terminal in Ashtabula, Ohio; consolidated its division-level operations at Bluefield and Roanoke, Virginia; and closed its yard operations in Knoxville.

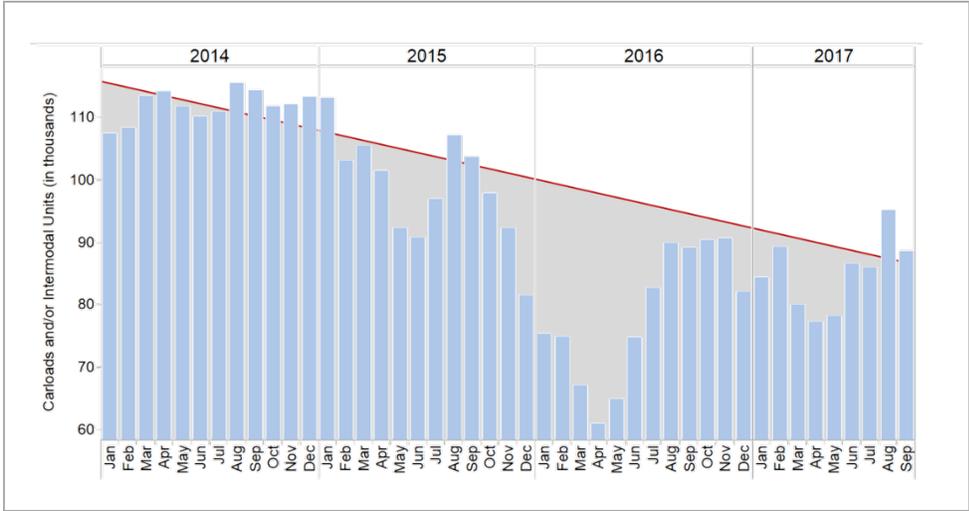
CSX was as equally aggressive in its response. It closed shop facilities in Erwin, Tennessee and Corbin, Kentucky; ceased yard operations at Russell, Kentucky; temporarily curtailed operations on portions of its route between Russell, Kentucky and Spartanburg, South Carolina; downgraded its route between Cincinnati and north Georgia; and ended division operations at Huntington, West Virginia.

In total, the actions noted above led to the elimination of roughly 2,000 direct, highly-compensated jobs in Appalachia, losses that were particularly difficult for the hardest hit communities. Further, from a policy perspective, the retrenchments signaled potential additional cuts and the possible loss of rail network access. However, on a forward-looking basis there are, at least, three positive factors.

First, very few of the facility closures have been followed by actions that are permanent. No buildings have been razed and no track has been abandoned. Second, in some areas where service had been suspended, it has been restored, at least nominally. Finally, most of the actions described above were taken in late 2015 or the first half of 2016. At present, planners for both CSX and Norfolk Southern have indicated that further coal-related system rationalizations are not pending.

In the last months of 2016 and through most of 2017, the cyclical factors that brought such disarray to U.S. coal producers have largely subsided, and coal production has inched toward recovery, but only to the point of rejoining the WVU-predicted long-run decline.

Figure 5: Monthly U.S. Coal Rail Car Loadings



Source: The Association of American Railroads

Table 6: U.S. Coal Rail Car Loadings, 2013-2015

	2013	2014	2015	Peak to Low Percent Change
U.S. Total	5,951,982	6,110,053	5,441,934	-10.9%
Eastern Railroads	2,208,515	2,258,236	1,866,615	-17.3%
Western Railroads	3,743,467	3,851,817	3,575,319	-7.2%
CSXT	996,540	1,009,831	810,077	-19.8%
Norfolk Southern	1,029,218	971,906	796,991	-22.6%
Canadian National (U.S)	182,757	276,499	259,547	-6.1%
BNSF	2,209,522	2,258,902	2,276,715	0.8%
Kansas City Southern	2,181	2,211	7,767	251.3%
Canadian Pacific (U.S.)	----	982	3,203	226.2%
Union Pacific	1,531,764	1,589,722	1,287,634	-19.0%

Source: The Association of American Railroads

Chapter 4: Future Rail Access in an Era of Diminished Coal

Railroads continue to play an important role in Appalachia’s coal industry ecosystem, but that ecosystem is changing. The long-run, downward trend in regional coal production implies a large and lasting reduction in coal traffic for the Region’s railroads and the recently encountered cyclical traffic lapse provides policymakers with a glimpse of how rail carriers may adapt to more permanent traffic losses. Taken as a whole, this information suggests that preserving rail freight access throughout Appalachia may eventually become difficult.

What remains in this section is an attempt to lend precision to this concern—to predict where traffic losses are likely to be greatest, to explore whether railroads have other uses for resulting excess regional capacity, to identify the railroad routes that are most vulnerable, and to estimate how diminished railroad activity will affect the costs of moving the non-coal traffic that remains. The remainder of this section briefly describes how the study team worked to address these issues, then presents the results of these efforts.

Modeling Railroad Activity Under Future Demands

In terms of evaluating what will happen to Appalachia’s rail access in a post-coal era, history is of little help. The Region’s railroads were built to transport coal. Even during periods of prolonged slack demand, coal producers and the Region’s coal-hauling railroads assumed that demands would rebound, and traffic would return. For 100 years, they were right.

Absent a historical record with which to make predictions, the next best choice is to model potential outcomes based on known physical and economic relationships and to simulate how substantially lower coal traffic volumes will affect railroad behaviors. That modeling process involves several specific steps. These are summarized in Figure 6, briefly discussed in the text that follows, and described in detail in the report’s appendices.

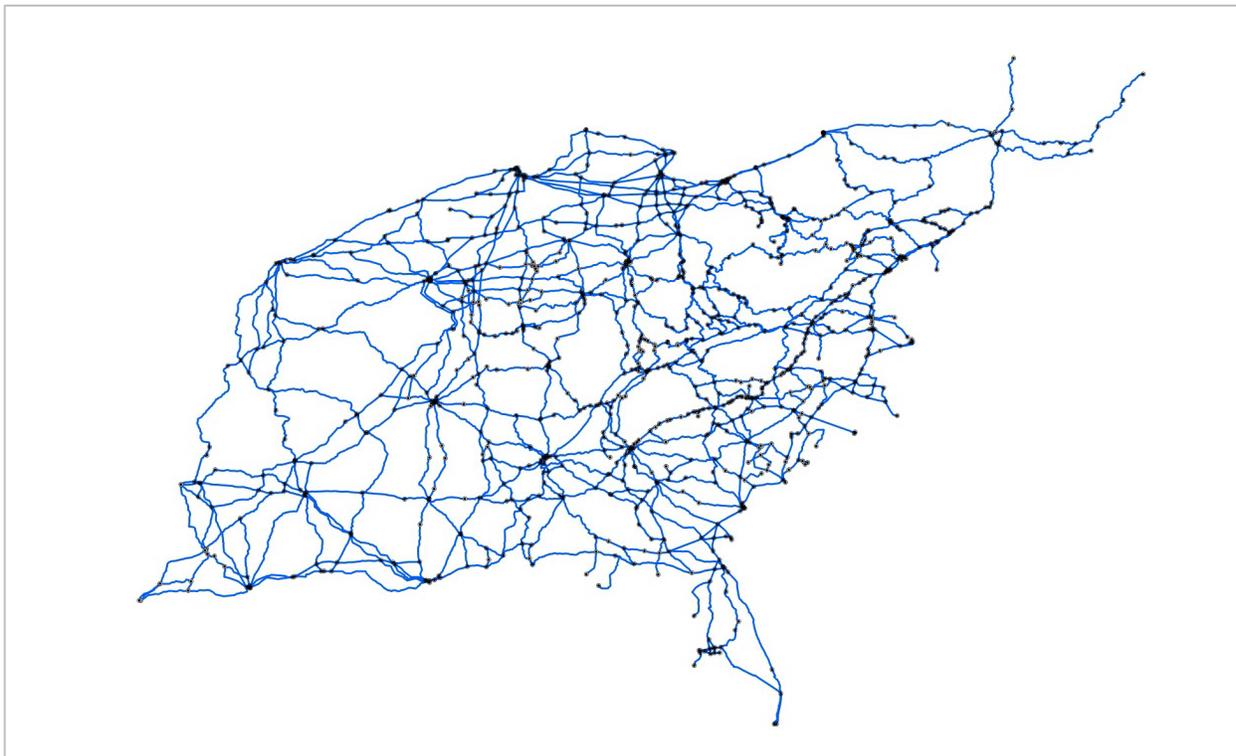
Figure 6: Modeling Process Summary

1. Model Building	2. Running Baseline Traffic Flows	3. Developing Reduced Coal Scenarios	4. Running Scenario Traffic Flows	5. Comparing Baseline and Scenario Results
GIS model of rail network that allocates traffic based on profits	Comparing model results with real-world flows helps validate model	Translate WVU coal forecasts into reduced railroad traffic.	Reallocate system traffic based on reduced coal activity.	Locate traffic losses, vulnerable routes, and cost changes for surviving traffic.

To model railroad traffic flows, the study team used *RAILNET*, a GIS-based optimization model developed at the University of Tennessee. Given a specified set of transportation demands, *RAILNET* routes railroad traffic over the railroad network in a way that simulates the profit-maximizing behavior of the Region's railroads. This is far more realistic than similar models that minimize transit distances or transit times. In the current application, the network, pictured in Figure 7, is confined to the Region east of the Mississippi River and includes both Class I railroad trackage and relevant short-line facilities.

Baseline traffic data were developed through the use of the Surface Transportation Board's 2011 Carload Waybill Sample (CWS). 2011 was picked as the baseline year because it was the year in which aggregate railroad industry coal revenues peaked and the last year in which coal volumes were near their historic highs.⁶

Figure 7: *RAILNET* Operating Network



Source: Center for Transportation Research

The same 2011 baseline data were used to create the scenario dataset. The study team did not attempt to forecast future traffic volumes for non-coal commodities. For coal movements originating in the eastern United States, the coal data were adjusted to reflect the WVU-predicted 2036 values as described above. Importantly, the rail traffic to, from, and within the study region includes coal mined

⁶ Industry-wide, railroad coal volumes peaked in 2007. See, Association of American Railroads, [Annual Statistics of Class I Railroads, 1978 - 2015](#).

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 constant over the 20-year time horizon.⁷

Future Railroad Traffic and Traffic Flows in Appalachia

The results of both the data preparation and the coal scenario simulations suggest that preserving rail freight access in Appalachia's core may be difficult. These findings underscore the dominance of coal traffic, the grave magnitude of the long-run predicted traffic declines, and the low probability that unneeded capacity on most coal-dominated routes will be absorbed by network traffic currently traversing alternative routings.

Lessons from the Scenario Data

Even before the *RAILNET* simulations, the scenario data provided useful insights.⁸ Figure 8 illustrates the total, state-specific coal traffic reductions predicted when 2011 coal production totals are replaced with the forecasted 2036 values. The estimated traffic losses are located in exactly the same places where early coal traffic declines have been most observable—eastern Kentucky and southern West Virginia.

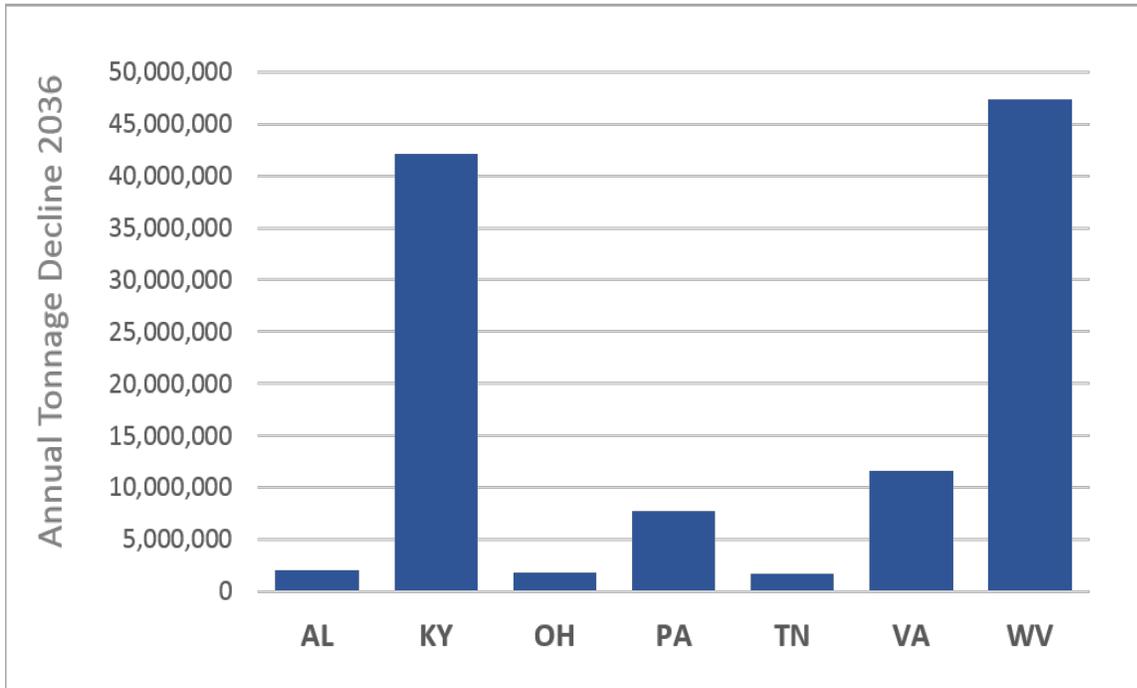
Figure 9 further decomposes the predicted losses in 2036 traffic volumes between Norfolk Southern and CSX. In total, predicted traffic losses are 67.5 million tons for CSX compared to 46.9 million tons for Norfolk Southern, signifying that both railroads will continue to be significantly impacted. However, the geographic pattern varies between the two railroads. In the case of CSX, volume declines are heavily concentrated in eastern Kentucky and southern West Virginia. While NS also will see significant declines in these regions, its overall coal traffic losses are more evenly distributed across the seven states where it currently originates coal movements.

The final finding attributable to the coal scenario data development is contained in Figure 10, which depicts the predicted 2036 coal losses as a share of current originating traffic for each railroad within each state. While neither this figure nor the data it depicts include terminating regional traffic or pass-through network use, it is nonetheless clear that at its predicted levels, declining coal traffic will dramatically affect the economics of providing freight rail service to the Region.

⁷ 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>

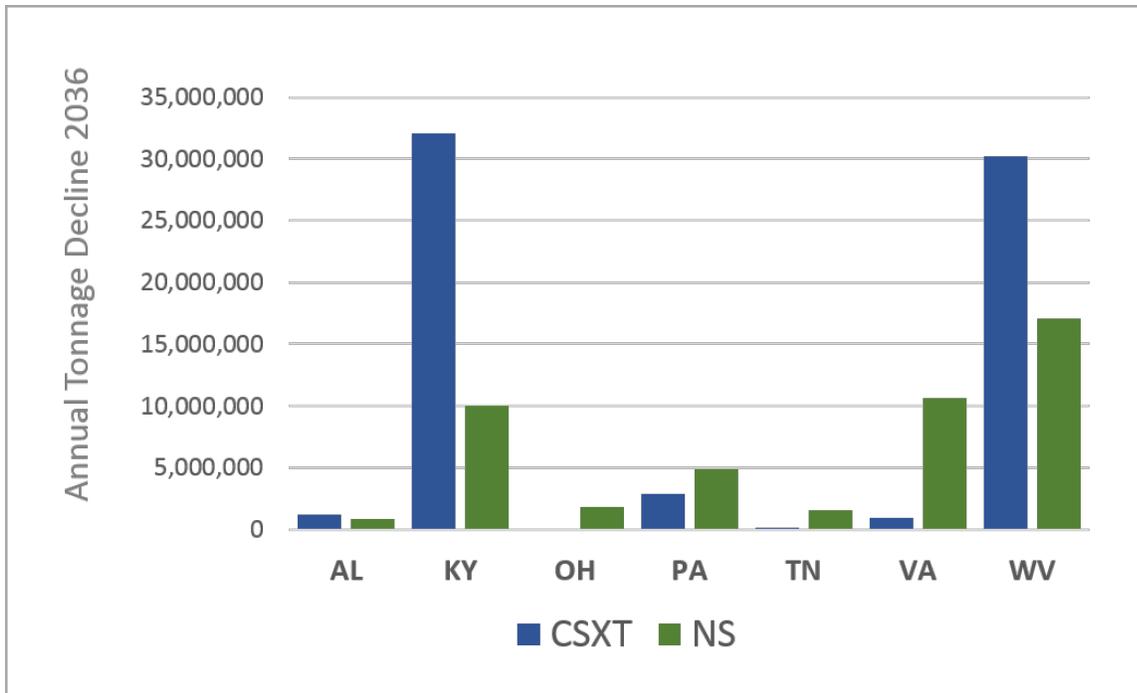
⁸ Reporting in this section is constrained by the reliance on the Carload Waybill Sample and a need to protect both shipper and carrier confidentiality.

Figure 8: Annual Losses to Railroad Coal Traffic Predicted by 2036



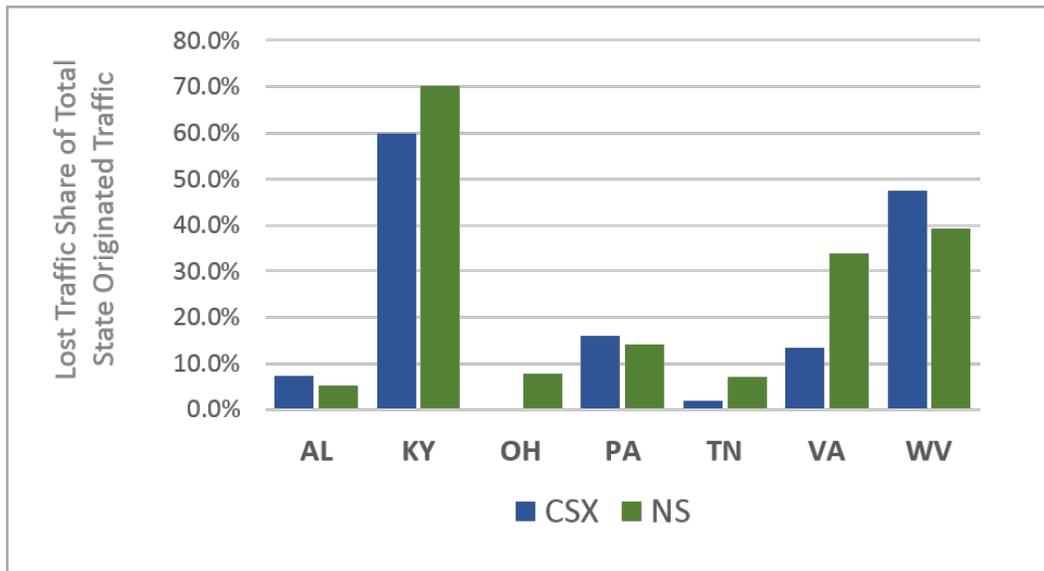
Source: Center for Transportation Research

Figure 9: Annual Carrier-Specific Losses to Railroad Coal Traffic Predicted by 2036



Source: Center for Transportation Research

Figure 10 - Coal Traffic Losses as a Share of Total Originating Traffic



Source: Center for Transportation Research

The RAILNET Simulation Results

The goal of the simulations was to provide stakeholders with useful information about the specific effects of reduced coal reliance on the demand for rail transportation and the railroad infrastructure that supports it. The simulations do that. Baseline estimates of link-specific traffic volumes approximate the observed distribution of railroad traffic in the southeastern U.S. in 2011. 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.

Figure 11 depicts the *RAILNET*-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.

Figures 12 and 13 depict rail traffic in the eastern U.S. based on forecasted 2036 Appalachian coal volumes.⁹ Figure 12 illustrates total forecasted regional tonnage and Figure 13 captures the difference between the coal scenario traffic and traffic under the 2011 baseline conditions. As above, units are gross tons including empties.

There are several important results. First, as expected, the coal-producing regions—particularly West Virginia and eastern Kentucky—experience the largest impact on predicted infrastructure use. As

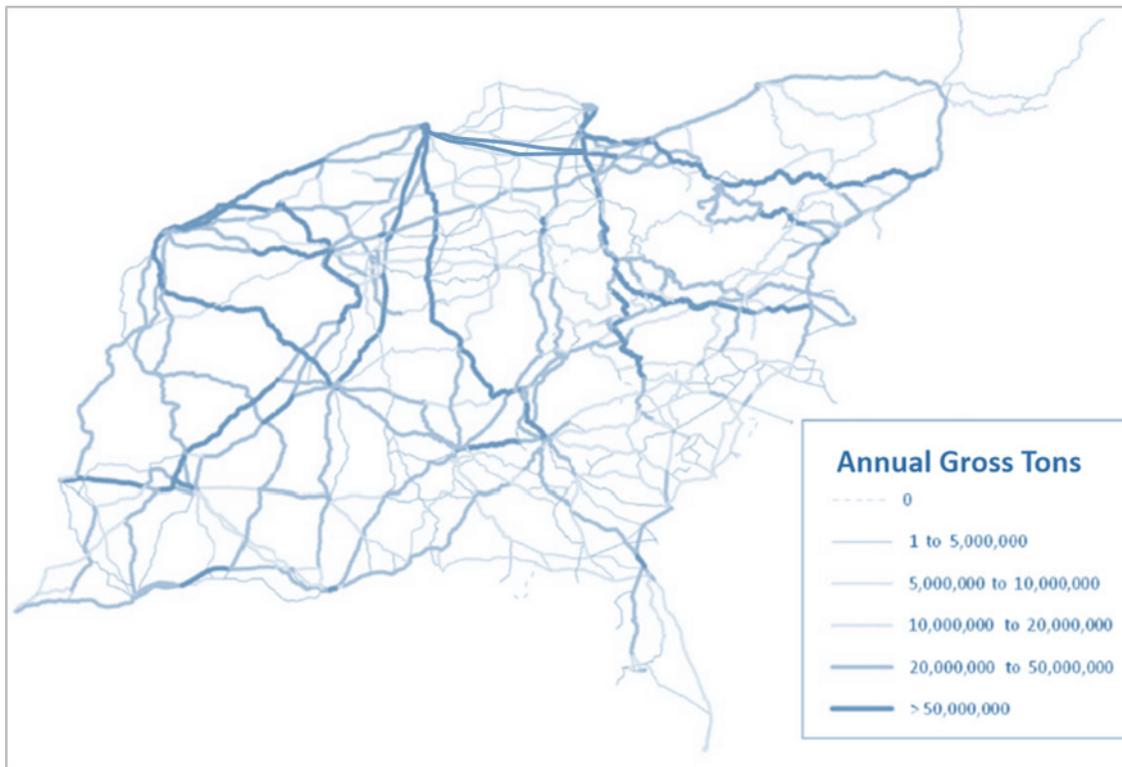
⁹ As described in Section above, the analysis changes only Appalachian coal volumes. All other (coal and non-coal) traffic volumes are at 2011 levels.

noted, these regions originate little else other than coal. Further, the model results suggest that diversions from other routes will not absorb newly available capacity on these coal-dominated route segments. Instead, the coal routes serving central Appalachia seem segregated from other rail network flows. This isolation leads to a second observation: With the exception of coal routes to export locations, the predicted infrastructure impacts of reduced coal reliance are concentrated in the coal-producing areas.

Together, the three figures highlight the importance of export coal volumes to the Region's rail carriers and suggest that 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, the latter of which is mined specifically for export. By necessity, the WVU forecasts used here consider coal produced within a state or within a substate region to be homogeneous. Though unavoidable, the resulting ambiguities introduce uncertainty in interpreting the results presented here.

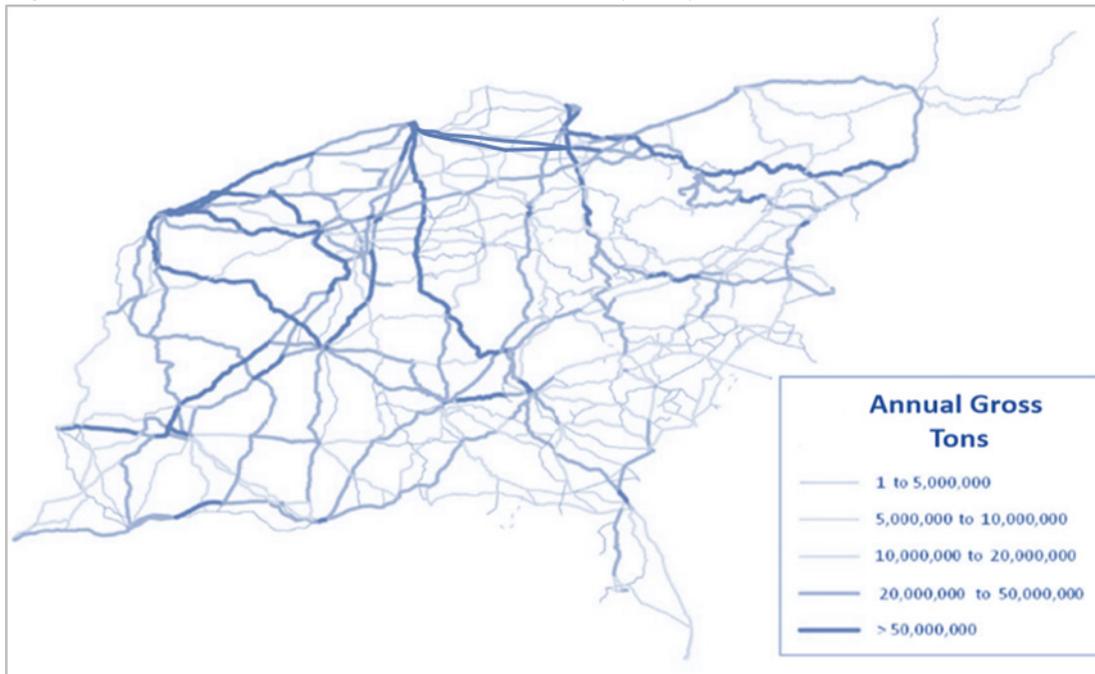
The results summarized in Figures 11, 12, and 13 suggest that specific routes may face traffic shortages that threaten their viability. Interestingly, many of these seemingly vulnerable routes have already lost traffic and undergone a change in status. This would seem to validate the model's performance. For example, the results predict the impact of reduced coal volumes on the CSX route between Russell, Kentucky and the Carolinas. As noted above, 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 northern Georgia. Again, this happened, with the carrier reducing track to Class 2 and closing locomotive maintenance facilities at Corbin, Kentucky. Loosely applied, the model output predicts approximately 150 miles of heavy-haul trackage will be subject to abandonment or sale and that roughly 1,200 route-miles will eventually be downgraded in terms of capacity. Much of this has already been observed.

Figure 11: RAILNET Distribution of Baseline (2011) Traffic



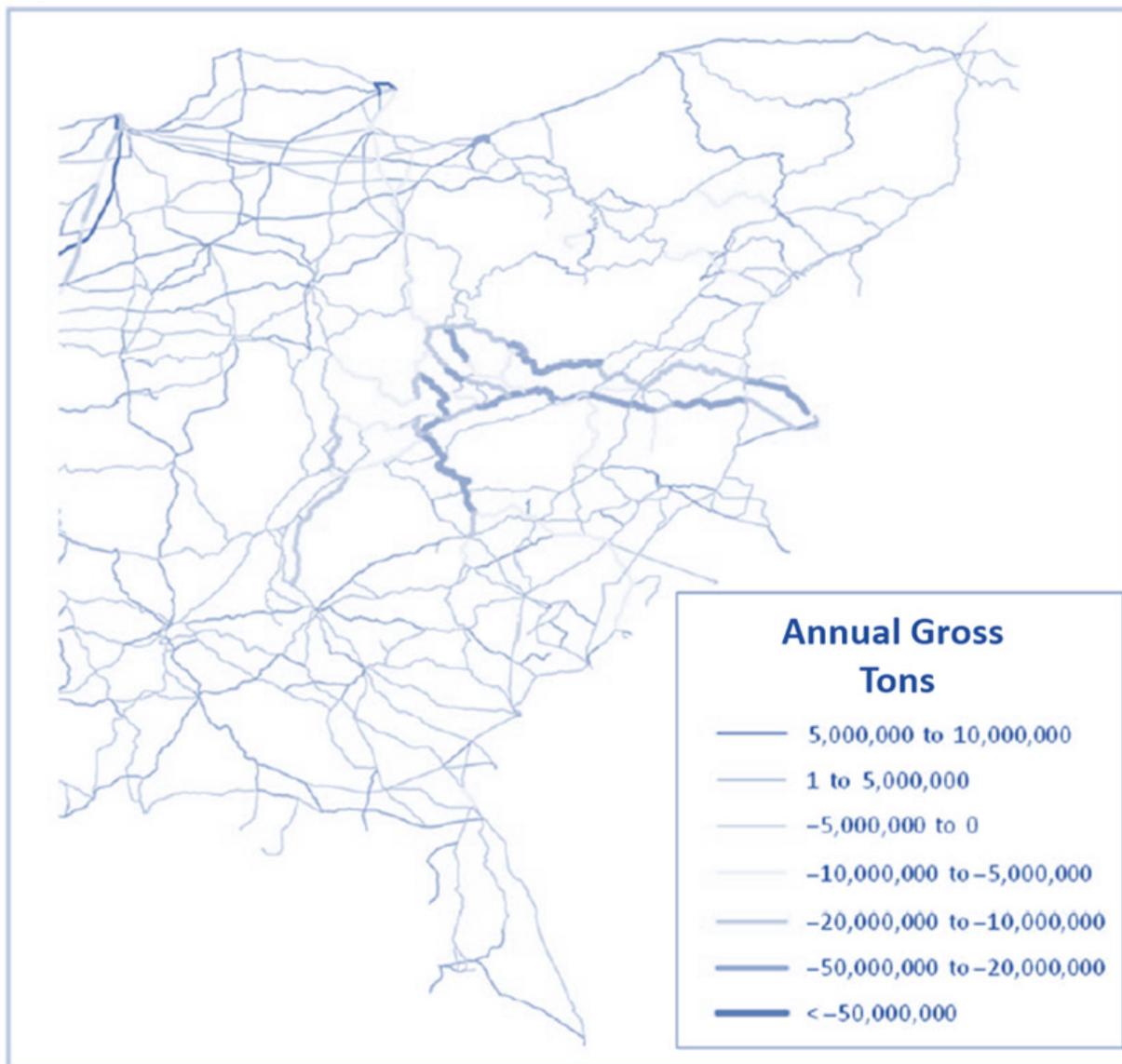
Source: Center for Transportation Research

Figure 12: RAILNET Distribution of Coal Scenario (2036) Traffic



Source: Center for Transportation Research

Figure 13: Differences Between Baseline and Coal Scenario Traffic Volumes



Source: Center for Transportation Research

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 7 provides carrier-specific predictions of losses to gross railroad ton-miles that reflect 2036 coal flows.¹⁰ Readers should bear in mind that (1) these are predicted, not actual changes, (2) changes are measured in gross ton-miles,

¹⁰ 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.

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 7: RAILNET-Predicted Reductions in Ton-Miles

Carrier	Increases in Gross Link Ton-Miles (Millions)	Decreases in Gross Link Ton-Miles (Millions)	Net Change in Gross Link Ton-Miles (Millions)
CSXT	3,824	34,554	-30,731
Norfolk Southern	3,157	30,529	-27,372
BNSF	949	9,348	-8,399
Florida East Coast		580	-580
Other Railroads	824	6,285	-5,450
TOTAL	8,754	81,296	-72,531

Source: Center for Transportation Research

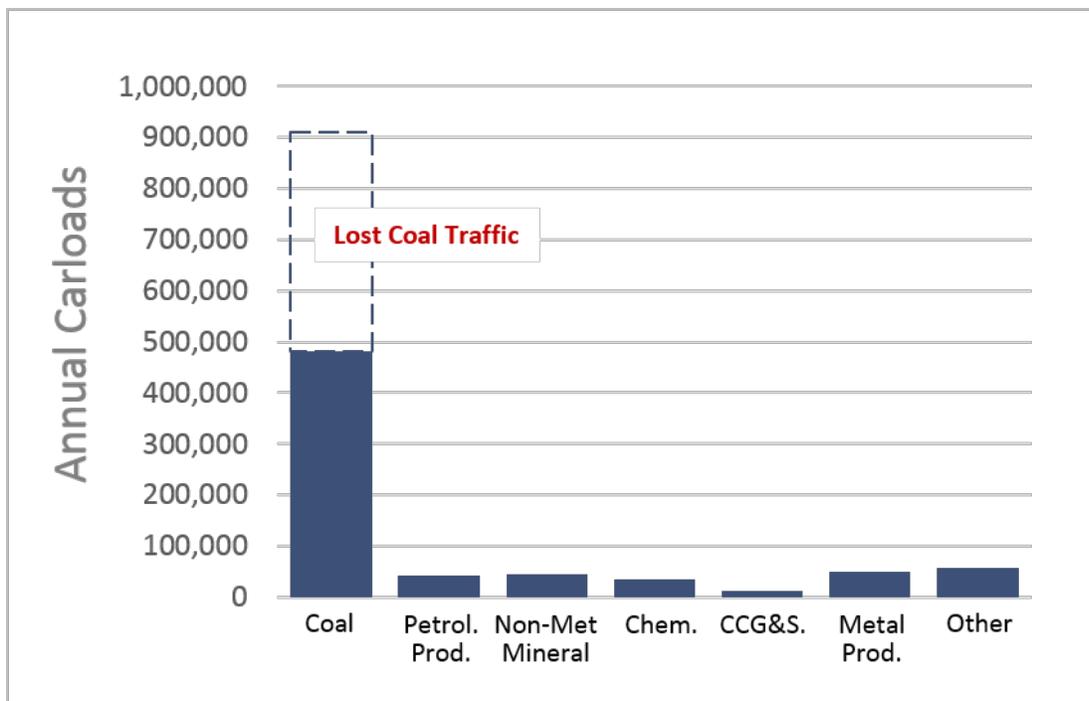
The Costs of Moving Surviving Traffic

Further reductions in coal traffic will clearly impact the role and profitability of regional rail operations. However, not all coal traffic will be lost, and non-coal commodities also move by rail to and from Appalachian communities. Therefore, it is important to anticipate how lost coal traffic may affect the underlying costs and rates for moving the surviving coal and non-coal rail traffic. To illustrate, estimated non-coal and surviving coal rail traffic for West Virginia in 2036 is summarized in Figure 14. Presumably, the demand for this traffic will remain, even as other coal traffic declines.

The cost that railroads incur to move a specific shipment depends heavily on how much other traffic is using the same routes required by the subject freight. In most cases, railroads exhibit what economists refer to as *economies of density*, in which individual shipment costs are lower when there is more (rather than less) overall traffic on route segments. It follows that the costs for moving the surviving coal and non-coal rail shipments to and from Appalachia will increase as coal traffic continues to decline.

As more fully explained in Appendix C, the RAILNET modeling platform used to estimate the traffic losses described above depends on cost parameters for different commodities and differing traffic volumes. Appendix D describes how these results were also used to estimate likely changes in unit costs attributable to diminished coal traffic. The results of these calculations are provided in Table 8.

Figure 14: Estimated Surviving West Virginia Rail Traffic (2036)



Source: Center for Transportation Research, Association of American Railroads

Table 8: Potential Impacts on Railroad Costs and Rates¹¹

Condition	Average Total Cost Per Ton-Mile	Hypothetical Ton-Mile Rate	Hypothetical Rate per Ton	Hypothetical Rate per Carload)
Baseline	\$0.0263	\$0.045	\$24.00	\$1,920
Short-Run	\$0.0752	\$0.114	\$68.40	\$5,472
Long-Run	\$0.0337	\$0.051	\$30.72	\$2,458

Source: Center for Transportation Research

Again, the full derivation of the values in Table 8 is provided in Appendix D. However, there are two important elements to discuss here. First, the table contains both short-run and long-run cost implications. Railroads design, modify, and maintain infrastructure based on expected use. Most of the potentially-affected regional trackage is currently built and maintained to sustain high-density, coal-dominated traffic. In the short-run, it is impossible to fully reduce the capacity of this infrastructure, even if it is only lightly used. Thus, the short-run cost effects of the lost traffic are substantial. In the

¹¹ The conversion of ton-mile rates to rates per ton and per carload are based on a hypothetical trip distance of 600 miles and a hypothetical loading weight of 80 tons per carload.

longer-run, however, carriers can do a great deal to reduce capacity so that the infrastructure is consistent with lower traffic volumes. Thus, the long-run effect of reduced traffic on the costs of continuing service for surviving traffic are not nearly as severe.

Next, the existence of common costs necessarily drives a wedge between unit costs and railroad rates. However, there is nothing that guarantees surviving coal traffic or the demands for transporting non-coal traffic will sustain the roughly 25 percent long-run rate increases projected in Table 8. If these markets cannot afford these rates, then there is a chance that additional traffic will disappear or be diverted to an alternative transport mode. This possibility makes conclusions regarding the future viability of regional rail access more fragile than they first appear.

Chapter 5: Policy Implications and Conclusions

This report summarizes the findings of a year-long study of the relationship between freight railroads and Appalachia's coal industry ecosystem. Based on already observed reductions in coal production and production forecasts produced by West Virginia University, the analysis attempts to anticipate the effects on the Region's railroads over a 25-year time horizon. The results presented here are preliminary and can be improved upon. Nonetheless, the findings hint at possible policy challenges and opportunities. In this final section, we enumerate these and close with a discussion of potential public-sector responses.

Key Findings

The analysis has generated four key findings. These include:

1. Rather than unfolding evenly through time, the results developed here suggest that the largest declines in railroad tonnage may have already been observed.

Comparing the data projections summarized in Section 3 to the coal traffic volumes actually observed between 2011 and 2016, it seems that much of the total forecasted decline in coal production, spread evenly over the 2011-2036 forecast period, has actually been observed within the forecast period's early years. This outcome is consistent with an electric utility strategy where coal-fired generating capacity is retired as early as possible. Thus, policymakers may have already observed much (if not the majority) of coal traffic declines predicted over the 25-year time horizon.

2. Geographically, with only a few exceptions, any threats to rail access associated with reduced coal volumes seem to be constrained to Appalachia.

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 13 exist in relative 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 local or regional and any policy responses to the challenges associated with reduced rail network access will likely need to originate at the same local or regional levels.

3. While unwelcome and detrimental, the magnitude of losses to rail access, either in the form of physical proximity or affordability, is not currently predicted to be catastrophic. However, this prediction is somewhat fragile and depends on carriers' abilities to garner adequate revenues from remaining freight traffic.

Generally, results do not point to a wholesale, widespread loss of rail access for the Region. However, the same results do suggest that railroad rates for remaining coal traffic and for other non-coal commodities will face substantial upward pressure. Specifically, the analysis identifies roughly 150 miles of Class I, mainline trackage that are highly vulnerable to sale or abandonment. The results also point to roughly 1,200 route-miles that are likely candidates to be downgraded or, perhaps, leased to a short-line. As importantly, the same results suggest that, even after infrastructure adjustments, Class I carriers will need to increase rates for surviving coal and non-coal rail traffic by more than 25 percent if the remaining traffic will sustain such increases.

4. Continued access to eastern ports and the global connectivity they afford depends largely on Appalachian coal's competitiveness in international markets and the strength of those markets going forward.

Finally, and to reiterate, the extent of predicted reduced coal traffic between Appalachia and eastern deep-draft ports (Norfolk, Hampton Roads, and Baltimore) depends almost exclusively on the demands for coal exports. While many factors can influence these volumes, changes in U.S. trade policies certainly can affect 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.

The Potential for Regional and State Responses

The results suggest that aggressive electric utility strategies, combined with a pronounced cyclical downturn, compressed more than a decade's worth of reduced coal consumption and transportation demand into a four- or five-year span. Setting aside the psychological effects of this collapse, the rapid reduction in coal-related railroad activity ripped roughly 2,000 full-time jobs and \$150 million in incomes from a region that can ill-afford such disruptions.

However, as perverse as it may seem, there are at least two advantages for policymakers in this compressed outcome. First, beginning in late 2016 and continuing throughout 2017, coal production and transportation began to regain the more gradual, long-run path predicted by the West Virginia University forecasts. Barring any additional, unanticipated disruptions, this course affords policymakers a little time to evaluate and implement policies that, as much as possible, ensure the preservation of stable rail-freight access in the face of further declines in coal outputs.

Second, and just as important, the temporal compression in reduced coal activity forced the Region's railroads to act with an immediacy that provides valuable information regarding future network adjustments. Specifically, while the railroads have acted with deliberate speed, they have also avoided responses that are irreversible. In adjusting to the 2015-16 collapse of coal demands, the railroads have *not* abandoned trackage, have *not* razed or sold terminal facilities, and have shed unsustainable lines through leases rather than line sales. In aggregate, these actions suggest a railroad industry that is hesitant to permanently relinquish freight capacity.

The previously referenced March 2017 ARC report provides an extensive discussion of steps that states can take to help ensure stable rail-freight access. These activities are summarized below.

State-Level Freight Planning

The most recent federal surface transportation bill, the *Fixing America's Surface Transportation (FAST) Act* continues to require that states develop statewide rail plans and that these plans be approved by the U.S. Secretary of Transportation.¹² In this light, every state should have available basic information describing the nature and extent of railroad infrastructure, carrier operations, and traffic composition. In addition to collecting and updating this information, states may wish to include freight plan elements that:

- Preserve the railroad infrastructure footprint if at all possible;
- Support quick (if not automatic) state responses to potential abandonments;
- Create or, at least, identify potential sources of funding; and
- Integrate rail planning as fully as possible into broader statewide freight planning and plans for economic development.

Experience shows that, once lost, the railroad "footprint" is difficult (or often impossible) to recreate. Moreover, while retaining rights-of-way is essential to rail capacity preservation, the ability to restore service to an inactive route may also depend on the presence and condition of the infrastructure on that right-of-way. This is particularly true of tunnels, bridges, and other high-dollar infrastructure components. North Carolina's program for retaining abandoned trackage is exemplary in this regard.

It is also important that states be prepared to act quickly in the face of potential abandonments. Federal reform legislation of the 1970s and 1980s included provisions that diminish the duration of abandonment proceedings. Moreover, railroad owners are not generally compelled to discuss system rationalization plans prior to executing them. Thus, it is easy for both on-line communities and state

¹² See 49 U.S. Code § 22702 as amended by Pub. L. 114-94, div. A, title XI, § 11315(a)(1), Dec. 4, 2015, 129 Stat. 1674.)

authorities to be surprised by proposed abandonments. However, the same reform legislation that accelerated abandonment proceedings also included provisions that compel incumbent railroads to sell subject lines to qualified buyers if these buyers are available and able to quickly engage.¹³

State-Level Short-Line Programs

If short-line railroads share any common attribute, it is that they are financially fragile. Accordingly, states that choose to actively rely on short-lines as a means of preserving railroad capacity must be prepared to either provide direct financial assistance or, at the very least, provide sub-state jurisdictions with the legal authority and technical support necessary to pursue non-state funding for short-line acquisition, rehabilitation, and operations. Within Appalachia, there are measurable differences in the form and availability of short-line funding.

Integrating Short-Lines and Economic Development

In 2015, the Tennessee Department of Transportation (TDOT) commissioned a confidential survey of short-line operators to gain their views on state-level programs. One of the most consistent themes noted by respondents was that state-level programs are most effective when integrated with larger state-level economic development actions.¹⁴ Unfortunately, state-level activities often fail to embrace a holistic, multi-agency approach to freight mobility. In the current setting, this means that short-line operators are too often unaware of industrial recruits and state-level economic developers are, sometimes, uninformed about short-line availability, capacity, or adaptability. In either case, both entities can be made better off by improved coordination—coordination that comes at a very low financial cost.

Opportunities for Jurisdictional Diversity

The spatial nature of transportation confounds traditional policy organization by jurisdiction. Thus, while individual state-level programs can provide opportunities to preserve freight-rail access, they are insufficient in some and not needed in others. Instead, larger preservation efforts may require a multistate approach and smaller efforts may simply require cooperation between specific communities in very localized settings.

¹³ Accelerated abandonment processes were components of both *the Railroad Revitalization and Regulatory Reform (4R) Act of 1976* and *the Staggers Rail Act of 1980*. Importantly, however, the Staggers Act also contained provisions creating the *Feeder Railroad Development Program* that allow qualified purchasers to intervene if there are viable alternatives that preserve railroad network access.

¹⁴ See, “Tennessee’s Short-Line Railroads Programs Policies and Perspectives,” Center for Transportation Research, The University of Tennessee, October 2016.

Cautions, Caveats, and Closing Thoughts

The economic landscape is littered with the spent reputations of those who wrongly predicted the behavior of energy markets. And the ever-increasing global nature of these markets only makes predictions more perilous. The entire body of work presented here is based on coal production forecasts that, while rigorously derived, may quickly be rendered invalid by unforeseeable events occurring a half-world away. To this, we add analytical techniques that rely on data that are, at best, fragile. In this light, the railroads' reluctance to permanently relinquish transportation capacity based on this form of analysis is not altogether surprising.

This caution notwithstanding, we would ask the more skeptical reader to revisit to Figures 4 and 5 (Section 3). If one removes the chaotic disruptions of 2015 and 2016, the (national) pattern of railcar coal loadings between 2011 and 2017 almost perfectly mirrors the Appalachian coal production forecasted by West Virginia University over the same timeframe. To the extent that these few years of data can validate the predicted fall in America's reliance on coal and the related impacts on railroad traffic, they do so.

If one accepts the long-run degradation in eastern railroad coal traffic as probable, the task of assessing its further effects on railroads and on rail access in Appalachia becomes more manageable. The next question is whether existing or foreseeable non-coal traffic will be drawn to Appalachian-inclusive rail corridors by capacity made available through the loss of coal volumes. The *RAILNET* simulations suggest that this will not happen. Transportation historians will find little surprise in this. The rail routes in and through Appalachia were built to access the Region's coal and timber. The railroad trunk lines that first connected the American east with the nation's interior were built *around* Appalachia, much like the Interstate highways were built a century later.

The final question is—absent robust coal volumes and without a probable substitute—whether surviving Appalachian freight traffic generate sufficient activity to sustain the Region's rail access. The answer, for the moment, is a somewhat tentative *probably*. However, the key to this assurance is in coal volumes that do not permanently fall too far below those predicted in the above analysis. Without the residual forecasted coal traffic, a positive outcome would be impossible.

Even under predicted conditions, sustaining freight-rail availability will not be easy. As coal volumes continue to decline, an increasingly small surviving traffic base will be asked to account for an ever-larger share of common network costs through higher freight rates. If this is not possible, the Class I carriers may well dispose of route segments that are, in aggregate measure, much greater than those described in Section 4. Those dispositions may come in the form of short-line spin-offs (if conditions allow) or they may entail line abandonments.

APPENDIX A: Defining the Appalachian Rail Network

Figure A-1 depicts the unpopulated railroad network used in this analysis. This duplicates a similar figure within the text except that A-1 also includes a very approximate representation of the Appalachian Region. This network, while not comprehensive, contains all major 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. Currently, the network includes the whole of the United States south of New England and east of the Mississippi River, as well as essential parts of the Canadian rail network. While less complete, network coverage west of the Mississippi River is sufficient to assure accurate eastern routings. In its present form, the model contains all necessary terminal and non-terminal interchange locations. However, the terminal nodes do not include facility-specific attributes. Link attributes are described in Table A-1.

Figure A-1: Unpopulated Rail Operating Network

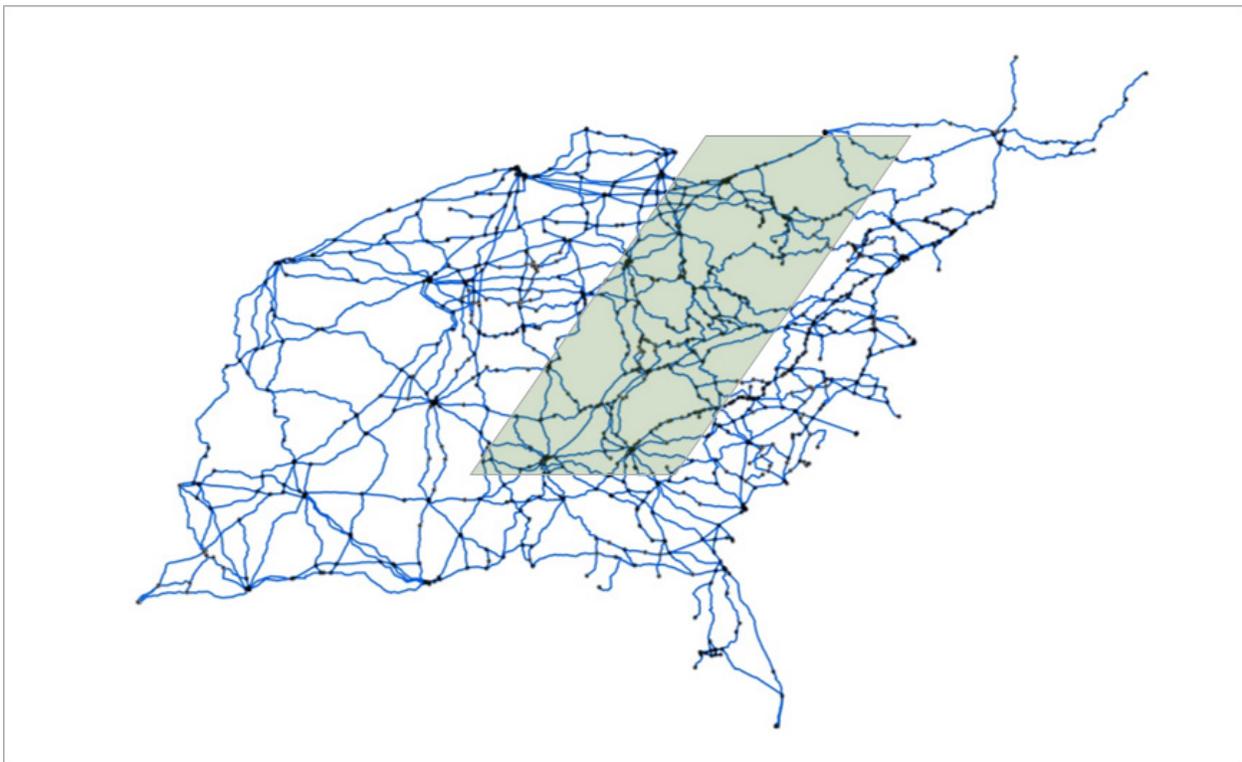


Table A-1 – Network Link Attributes

Attribute	Description
LENGTH	Link length
CAPACITY	Average number of 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	Maximum speed under optimal conditions
TRAVEL TIME	Link length / Free Flow Speed
P1,P2	Capacity function parameters
ML CLASS	FRA Track Class
LINK TYPE	Based on usage - yard tracks, directional operations etc.
SIGNAL	CTC, ABS, Manual Block
CAPACITY CODE	Based on siding spacing, reverse signals, etc.

Unlike traditional highway traffic models, the rail assignment model considers multiple commodities, with each commodity having a potentially different set of costs and priorities. The model also deals with the subdivision of the overall railroad network into subnetworks for specific companies, with transfers allowed only at designated points and at additional cost. The solution process identifies network flow assignments that minimize the overall system transportation cost. This system equilibrium approach is intended to replicate the behavior of railroad management as described above and produce network link volumes and performance levels closely approximating actual observed conditions.

APPENDIX B: Analytical Methodology, Assumptions, and Parameters

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

1. Developing a fully functional railroad network that 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 cost-minimizing behaviors;
6. Flowing scenario traffic over the same 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.

The Model Setting

Section 4 (p. 27) of the March 2017 ARC document cited in the main report carefully describes the process through which railroads make infrastructure decision. However, as a quick review, there are four points worth repeating.

1. Railroads operate networks where geographically dispersed origin-destination pairs often share common route segments. Very simply, this means that what happens at a seemingly removed location can have network effects in many different places. Theoretically, this network interdependence ties all network decision-making into one very large problem.
2. To a point, railroad routes are characterized by economies of density, whereby the unit cost for each shipment is lowered by the presence of additional traffic.
3. Railroad infrastructure is extremely long-lived. Many assets have lives that can be readily extended to between 50 and 100 years. Moreover, most of the costs associated with infrastructure development are sunk, meaning they are not recoverable if the railroad chooses to abandon service.
4. In North America, railroad infrastructure is privately owned. Historically, jurisdictions exchanged rights of way for the railroads' willingness to fulfill common carrier obligations, but the property and improvements belong to the railroads, so that public-sector input is often limited.

Again, theoretically, decision-making in this sort of network setting requires the solution of a complex network optimization problem, where capital, maintenance, and operating costs are balanced against the stream of expected revenues tied to each route segment

In practice, the data and forecasts needed to 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 capacities limit new, long-run business opportunities or when they impose clearly avoidable long-run costs. These periodic evaluations—as they pertain to changing coal traffic—are what is modeled here.

Baseline and Scenario Traffic Data

Baseline traffic data were developed through the use of the Surface Transportation Board’s 2011 Carload Waybill Sample (CWS). The baseline year is 2011 because it was the year in which aggregate railroad industry coal revenues peaked and the last year in which coal volumes were near their historic highs.¹⁵

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. Information for “off-network” railroad movements were excluded from the data.

Commodity group definitions were developed to 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. Commodity definitions, based on corresponding two-digit Standard Transportation Commodity Codes (STCCs), are provided in Table B-1. Summary statistics for the resulting data set are provided in Table B-2.

The 2011 baseline data were used to create the scenario dataset that reflects the 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 data were adjusted to reflect the predicted 2036 values as described above, in Table B-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 constant over the 20-year time horizon.¹⁶

¹⁵ Industry-wide, railroad coal volumes peaked in 2007. See, Association of American Railroads, Annual Statistics of Class I Railroads, 1978 - 2015.

¹⁶ 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 B-1 – Commodity Group Definitions

Study Commodity Group	Corresponding Two-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
99 Empties	

Source: Center for Transportation Research

Table B-2 – Baseline Traffic Summary Statistics

Commodity Group	Number of Records	Average Shipment Distance	Average Revenue Tons per Carload	Average Car Tare Weight	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

Source: Center for Transportation Research

Table B-3 – Coal Scenario Annual Coal Output (Tons in Millions)

Year	Eastern						Northern WV	Southern WV	
	Alabama	Kentucky	Maryland	Ohio	Penn.	Tenn.			Virginia
2011	19.07	67.93	2.94	28.17	59.18	1.55	22.52	41.85	92.81
2012	19.32	48.80	2.28	26.33	54.72	1.09	18.97	41.49	78.94
2013	18.62	39.50	1.93	25.11	54.01	1.10	16.62	42.39	70.40
2014	16.36	37.39	1.98	22.25	60.91	0.84	15.06	48.86	63.33
2015	13.19	28.10	1.92	17.04	50.03	0.90	13.91	47.79	47.85
2016	9.12	16.88	1.58	12.58	45.85	0.67	12.79	43.50	36.50
2017	8.95	16.41	1.75	12.87	52.73	0.66	15.04	48.94	39.44
2018	9.29	16.94	1.74	12.33	51.81	0.68	15.53	48.60	40.73
2019	9.94	17.11	1.74	12.47	52.39	0.70	15.68	48.66	41.13
2020	10.24	17.12	1.75	12.92	54.25	0.71	15.69	48.88	41.15
2021	10.55	16.83	1.70	12.58	52.86	0.71	15.43	49.07	40.46
2022	10.88	16.60	1.87	12.82	52.86	0.72	15.21	49.15	39.90
2023	11.19	16.15	1.80	12.36	50.96	0.73	14.81	49.40	38.83
2024	11.52	15.77	1.79	12.28	50.63	0.73	14.45	49.41	37.90
2025	11.85	15.45	1.78	12.21	50.32	0.74	14.16	49.40	37.14
2026	12.18	15.04	1.77	12.15	50.10	0.75	13.79	49.41	36.16
2027	12.54	14.66	1.80	12.37	50.98	0.76	13.43	48.99	35.23
2028	12.92	14.33	1.77	12.15	50.07	0.76	13.14	48.89	34.46
2029	13.23	14.02	1.69	11.61	47.87	0.77	12.85	48.77	33.69
2030	13.49	13.79	1.65	11.35	46.78	0.77	12.64	48.71	33.15
2031	13.70	13.60	1.66	11.39	46.94	0.78	12.46	48.83	32.68
2032	13.93	13.44	1.70	11.69	48.20	0.79	12.32	48.78	32.32
2033	14.16	13.33	1.68	11.52	47.49	0.80	12.22	48.72	32.05
2034	14.38	13.23	1.62	11.11	45.82	0.79	12.13	48.62	31.80
2035	14.59	13.14	1.63	11.19	46.14	0.80	12.05	48.51	31.60
2036	14.78	13.06	1.64	11.29	46.55	0.81	11.97	48.38	31.40

Source: West Virginia University

Cost Parameters

Based on the optimization 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 data were constructed from 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, short-line data were modified to reflect information from other sources.

APPENDIX C: An In-Depth Description of *RAILNET*

The purpose of the algorithm is to provide an analytical framework for realistically predicting traffic patterns within the rail network and for evaluating the effects of these flows on capacity. The model allows the study of congestion effects in the railroad system. The analyst may formulate and explore outcomes under differing traffic and network scenarios. Origin-destination (O-D) demand patterns for traffic (e.g., the traditional traffic generation and distribution steps) are generated externally and may reflect a variety of user interests.

Unlike traditional highway traffic models, the rail assignment model must consider multiple commodities, with each commodity having a potentially different set of costs and priorities. The model must also deal with 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 management as described above and produce network link volumes and performance levels closely approximating actual 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.¹⁷ 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.¹⁸ 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.¹⁹

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

¹⁷ See Dafermos, Stella C., "The Traffic Assignment Problem for Multiclass-User Transportation Networks," *Transportation Science*, 1971, pp. 73-87.

¹⁸ 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.

¹⁹ 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.

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 is intended to provide a strategic view of network flows, rather than a tactical or operating viewpoint. To this degree, individual train operations are not replicated, nor are the flows considered in terms of traffic blocks which could be used for operations planning. The statistics provided represent average characteristics of the system. Peaking, traffic disruptions, and other transient phenomena are not addressed.

It is assumed that the network is fixed and that no improvements are made that would affect traffic flows. The analyst may, of course, use the model to test hypothetical improvements. These network changes must be specified exogenously, however. 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.

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.

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 $\bar{A}_F = \cup_{m \in M} (i, j, m)_l$. If the link is undirected, then there is a corresponding set of reverse arcs $\bar{A}_R = \cup_{m \in M} (j, i, m)_l$.

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 which 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, $A_m \cap A_n = \{\emptyset\}, \forall m, n$.

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:

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

The complete facility loading in the network, called the *load pattern*, is given by vector $v = (v^p, p \in P)$.

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:

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

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:

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

Path k_w can be seen to consist of several subpaths, each of which belongs to a specific carrier:

$$\begin{aligned}
k_w &= k_w^{m_1} + k_w^{m_2} + k_w^{m_3}, \\
k_w^{m_1} &= ((i, n_1, m_1), (n_1, n_2, m_1), \mathbf{K}, (n_{s-1}, t_1, m_1)), \\
k_w^{m_2} &= ((t_1, n_s, m_2), (n_s, n_{s+1}, m_2), \mathbf{K}, (n_{u-1}, t_2, m_2)), \\
k_w^{m_3} &= ((t_2, n_u, m_3), (n_u, n_{u+1}, m_3), \mathbf{K}, (n_{u+z}, j, m_3)).
\end{aligned}$$

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 :

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

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:

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

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:

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

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 $\tau_{k_w} = (\tau_{k_w}^1, \tau_{k_w}^2, \mathbf{K}, \tau_{k_w}^p)$ 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 $v_a = (v_a^1, v_a^2, \mathbf{K}, v_a^p)$ and for transfer t is $v_t = (v_t^1, v_t^2, \mathbf{K}, v_t^p)$. 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.

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 \bar{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, $\bar{A} = \bar{A}_F \cup \bar{A}_R$. In the case of non-interacting two-way traffic, as with directional double track, $\bar{A} = \bar{A}_F$ if $a \in \bar{A}_F$, otherwise $\bar{A} = \bar{A}_R$. It is apparent then, for arc flows, that we must evaluate a portion of the load pattern defined as $v_{\bar{A}} \equiv \{v_a, a \in \bar{A}\}$.

Based upon the above assumptions, and the definition of \bar{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 $s_a = s_a(v_{\bar{A}})$. Since each commodity can have a distinct cost structure, the vector equation may be expressed as a set of p -scalar equations:

$$s_a^1 = s_a^1(v_{\bar{A}}^1, K, v_{\bar{A}}^p),$$

M

$$s_a^p = s_a^p(v_{\bar{A}}^1, K, v_{\bar{A}}^p).$$

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

$$s_t^1 = s_t^1(v_t^1, K, v_t^p),$$

M

$$s_t^p = s_t^p(v_t^1, K, v_t^p).$$

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 $s_a^p(v_{\bar{A}})v_a^p$. 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:

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

The total system cost for the entire load pattern is:

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

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 per unit of weight. First the case of arcs is examined and then that of transfers.

Arc Cost Functions

In this model, the 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:

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

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 can be 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 $v_{\bar{a}}$ can be 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 which converts the net weight of p to a number of equivalent trains:

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

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

$$V_{\bar{a}} = \sum_{p \in P} \sum_{a \in \bar{a}} f_a^p v_a^p. \quad (8)$$

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 is used to adjust 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. These will be discussed in a later section of the paper.

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, $T_{\bar{a}}(v_{\bar{a}}) f_a^p h_a^p$.

Transfer Cost Function

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:

$$s_t^p = \tilde{m}_t^p \tilde{f}_t^p \quad (11)$$

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.

Objective Function

The preceding sections provided a framework for defining the network, describing demand and load patterns, and defining costs for facility loadings. Of interest now is a mathematical expression which will produce 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.

Mathematical Program

The load pattern at which total generalized costs are minimized is called the system optimum (SO). Mathematically, the SO load pattern can be determined using the following non-linear program:

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

subject to:

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

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

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

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

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

Necessary and Sufficient Conditions

The solution of the above problem will yield the desired SO flow pattern for the network provided that 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 $s_a^p(v_a) v_a^p$ 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 mathematical conditions are defined in the following sections.

Necessary Conditions

The necessary conditions, which can be found in a number of texts, such as Sheffi²⁰, are as follows:

$$\tau_{k_w}^p (c_{k_w}^p - \lambda_w^p) = 0, \forall p, w, k_w \in K_w \quad (14)$$

and

$$c_{k_w}^p - \lambda_w^p \geq 0, \forall p, w, k_w \in K_w. \quad (15)$$

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 :

$$c_{k_w}^p = \frac{\partial Z}{\partial \tau_{k_w}^p}. \quad (16)$$

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 λ_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, λ_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 $c_{k_w}^p = \lambda_w^p$. Paths where $c_{k_w}^p$ is greater than the associated dual λ_w^p receive no flow.

²⁰ Sheffi, Yosef. Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods. Englewood Cliffs, NJ: Prentice-Hall, Inc, 1995.

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.

Sufficient Conditions

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 $v \neq 0, v^T H v > 0$. 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 $v^T H v$ contain only arc flows. By the criteria applied to arc cost functions, then, $v^T H v$ 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 we know to be 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.

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 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.²¹ Dafermos examines the multiclass assignment problem and proposes a two-stage solution procedure which has as its heart a decomposition of the problem by class.²² Sheffi 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 describe a solution procedure similar to Dafermos' which is used in their network model.²³

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 ,

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

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

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

²¹ Hu, T.C. Integer Programming and Network Flows. Reading, MA: Addison-Wesley Publishing Co, 1969.

²² Dafermos, Stella C. "The Traffic Assignment Problem for Multiclass-User Transportation Networks." Transportation Science, 1971, pp. 73-87.

²³ 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.

Terms $Z(v)$ and $\nabla Z(v)(v)^T$ are constants that may be omitted. This results in the revised objective function

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

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.

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 $\theta = 1$ 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: $0 \leq \theta \leq 1$.

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

Step 2. 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.

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:

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

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

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

In practice, the following simplifying assumptions can be made:

- The cost function for a given transfer is not affected by the flows at other transfers or by arc flows;
- The cost function for an arc is not affected by transfer flows; and
- 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

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

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

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

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

For transfers, the marginal cost becomes:

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

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 $\frac{\partial s_t^p}{\partial v_{\bar{t}}^{\bar{p}}} = 0$ and, therefore:

$$c_{\bar{t}}^{\bar{p}} = s_{\bar{t}}^{\bar{p}}. \quad (19e)$$

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, γ = 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 \bar{A} , is:

$$V_{\bar{A}} = \sum_{p \in P} \sum_{a \in \bar{A}} f_a^p v_a^p. \quad (21)$$

Substituting, the arc cost function then becomes:

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

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

$$\begin{aligned} \text{a)} \quad & \frac{\partial m_a^p l_{\bar{A}}}{\partial v_a^{\bar{p}}} = 0, \forall a \in \bar{A}, p; \\ \text{b)} \quad & \frac{\partial R_{\bar{A}} f_a^p h_a^p}{\partial v_a^{\bar{p}}} = 0, \forall a \in \bar{A}, p; \\ \text{c)} \quad & \frac{\partial R_{\bar{A}} f_a^p h_a^p k_1 \sum_{p' \in P} \sum_{a' \in \bar{A}} f_{a'}^{p'} v_{a'}^{p'}}{\partial v_a^{\bar{p}}} = k_1 R_{\bar{A}} h_a^p f_a^p f_{\bar{a}}^{\bar{p}}, \forall a \in \bar{A}, p; \\ \text{d)} \quad & \frac{\partial R_{\bar{A}} f_a^p h_a^p k_2 \left(\frac{\sum_{p' \in P} \sum_{a' \in \bar{A}} f_{a'}^{p'} v_{a'}^{p'}}{C_{\bar{A}}} \right)^\gamma}{\partial v_a^{\bar{p}}} = \\ & \frac{\gamma}{C_{\bar{A}}} k_2 R_{\bar{A}} h_a^p f_a^p f_{\bar{a}}^{\bar{p}} \left(\frac{\sum_{p' \in P} \sum_{a' \in \bar{A}} f_{a'}^{p'} v_{a'}^{p'}}{C_{\bar{A}}} \right)^{\gamma-1}, \forall a \in \bar{A}, p. \end{aligned}$$

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

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

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

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:

$$c_{\bar{a}}^{\bar{p}} = m_{\bar{a}}^{\bar{p}} l_{\bar{a}} + R_{\bar{a}} f_{\bar{a}}^{\bar{p}} h_{\bar{a}}^{\bar{p}} \left[1 + k_1 \sum_{p \in Pa \in \bar{A}} \sum_{a \in \bar{A}} f_a^p v_a^p + k_2 \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma} \right] + k_1 R_{\bar{a}} f_{\bar{a}}^{\bar{p}} \sum_{p \in Pa \in \bar{A}} \sum_{a \in \bar{A}} h_a^p f_a^p v_a^p + k_2 \frac{\gamma}{C_{\bar{A}}} \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma-1} R_{\bar{a}} f_{\bar{a}}^{\bar{p}} \sum_{p \in Pa \in \bar{A}} \sum_{a \in \bar{A}} h_a^p f_a^p v_a^p. \quad (23b)$$

Further reorganizing the terms, we obtain:

$$c_{\bar{a}}^{\bar{p}} = m_{\bar{a}}^{\bar{p}} l_{\bar{a}} + R_{\bar{a}} f_{\bar{a}}^{\bar{p}} h_{\bar{a}}^{\bar{p}} + k_1 R_{\bar{a}} f_{\bar{a}}^{\bar{p}} \sum_{p \in Pa \in \bar{A}} \sum_{a \in \bar{A}} [f_a^p v_a^p (h_{\bar{a}}^{\bar{p}} + h_a^p)] + k_2 R_{\bar{a}} f_{\bar{a}}^{\bar{p}} \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma-1} \left[\left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right) h_{\bar{a}}^{\bar{p}} + \frac{\gamma}{C_{\bar{A}}} \sum_{p \in Pa \in \bar{A}} \sum_{a \in \bar{A}} h_a^p f_a^p v_a^p \right]. \quad (23c)$$

A final reorganization yields the working form of the equation:

$$c_{\bar{a}}^{\bar{p}} = m_{\bar{a}}^{\bar{p}} l_{\bar{a}} + R_{\bar{a}} f_{\bar{a}}^{\bar{p}} \left[h_{\bar{a}}^{\bar{p}} + k_1 \sum_{p \in Pa \in \bar{A}} \sum_{a \in \bar{A}} [f_a^p v_a^p (h_{\bar{a}}^{\bar{p}} + h_a^p)] + k_2 \left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right)^{\gamma-1} \left[\left(\frac{V_{\bar{A}}}{C_{\bar{A}}} \right) h_{\bar{a}}^{\bar{p}} + \frac{\gamma}{C_{\bar{A}}} \sum_{p \in Pa \in \bar{A}} \sum_{a \in \bar{A}} h_a^p f_a^p v_a^p \right] \right]. \quad (24)$$

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. This aspect of the problem needs further examination. 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.

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.

APPENDIX D: Post-Processing Cost Calculations

The short-run and long-run cost calculations developed in Section 4 are calculated based on changes in traffic density and estimated relationship between traffic density and unit costs. Traffic density along individual route segments is a key determinant of freight rail transportation costs. From an analytical perspective, density and economies of density are the spatial analogue of scale economies.

Consider a route segment of a specific length denoted as j that is used within a number of shipments, i ($i=1\dots n$).²⁴ Economies of density suggest that for any time period t :

$$c \sum_n^{i=1} Q_{ijt} < c(Q_{1jt}) + c(Q_{2jt}) + \dots c(Q_{njt})$$

subject to:

$$\sum_n^{i=1} Q_{ijt} \leq D$$

where Q 's denote traffic quantities and D is a designed optimal traffic volume over route segment j beyond which unit costs escalate rapidly as traffic volumes approach the absolute physical capacity of the route segment. These relationships are depicted graphically in Figure D-1.

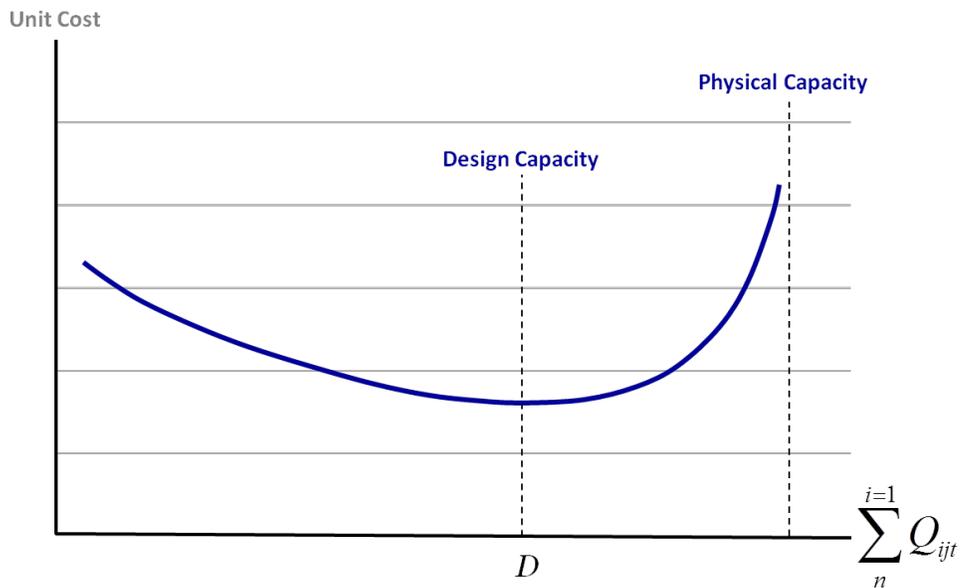
The STB cost data described in Section 4 include divisions by four density groupings. These are summarized in Table D-1. Therefore, based on corresponding traffic data, it was possible to allocate various cost elements to individual railroads, by density class and year. Data are available in this form from 1987 forward. These data were used to estimate density-specific cost functions for each density class that resemble the surface pictured in Figure D-1. These were then applied to the subject trackage based on estimated densities both before and after the changes in coal traffic.

²⁴ Note that these shipments may involve a variety of different commodities, customers, or diverse origin-destination pairs, so long as all shipments include j within the routing.

Table D-1 - Density Class Definitions

Density Class	Gross Ton-Miles pre Route-Mile
1	Density > 20 Million GTM/Track Mile
2	Density < 20 Million & > 5 Million GTM/Track Mile
3	Density < 5 Million & > 1 Million GTM/Track Mile
4	Density < 1 Million GTM/Track Mile

Figure D-1 - Unit Costs and Link Densities



Based on the RAILNET computations, 45 network links with a total distance of 1,166 miles will see traffic declines will move then from Density Class 1 to Density Class 2. However, in the short-run the operating carriers would be unable to immediately modify the characteristics of the affected trackage. Therefore, in the short-run, the carriers would be assumed to operate along the Density Class I cost structure, well to the right of the design capacity of that trackage.

However, as conditions allow, carriers would be expected to re-scale the affected trackage so that route characteristics are consistent with lower traffic densities, thereby, lowering unit costs. This results in an estimated short-run, per-ton-mile cost of \$0.114 and a long-run, per-ton-mile cost of \$0.051.