UNIT COAL TRAIN NETWORKS: DEVELOPMENT AND APPLICATION OF A COMPUTER SIMULATION MODEL

by

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B.S., Physics
Massachusetts Institute of Technology, 1992

Submitted to the Department of Civil and Environmental Engineering in partial fulfillment of the requirements for the degree of

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ABSTRACT

Unit coal train operations are a critical component of the railroad industry. In the U.S.
approximately 40% of the tonnage moved and 20% of the revenue generated by Class I
railroads is from coal transportation. Over 85% of the coal carried by rail is carried
using unit train service, service characterized by the shipment of bulk commodities in
large blocks of cars or trainloads between a small set of origins and destinations. A
computer simulation model, UTRAIN, has been developed for analyzing the operations
of large-scale unit coal train networks. The model simulates the movement of
individual trains through a large network, and can be used to predict cycle times
between selected origins and destinations, equipment utilization, line congestion, and
other parameters of importance to railroad planners. The model is well suited for
predicting network performance and comparing alternative operating strategies.

The simulation model has been applied to study the effects of heavy axle load
operations on unit coal train operations. Cycle times, equipment requirements,
operating and maintenance costs were determined for representative East and West
coal distribution networks for a base case of operations with 100-ton cars with 33 ton
axle loads. The base case was compared to cases with high-capacity cars with 2-axle
trucks and axle loads of 33 to 45 tons, and with high-capacity cars with 3-axle trucks
and axle loads of 30 to 39 tons. The results indicate that heavy axle load operations
result in overall savings in combined operating and track maintenance costs of 3 to 5%
for the East network and 1 to 5% for the West network. Overall the optimal axle load
was found to be 36 tons. The critical factor in achieving savings is the net capacity per
train. Increasing the car cross section, and shortening the car to avoid increasing axle
loads, increased net capacity per train 17% and resulted in cost savings of 3 to 4%.
Additional cost savings may likely be realized by maximizing the cross section (height
and width) of coal cars, and then adjusting car length to optimize axle load.

Thesis Supervisor: Carl D. Martland
Title: Senior Research Associate
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_Bituminous coal._

-William Barton Rogers, last words.

Thanks for assistance in writing this thesis must go to William Barton Rogers, who founded the fine institution in which this thesis was written, who created a legacy of excellent teachers and researchers from which I have learned a great deal, and who, in his last words, provided me a thesis topic.

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CHAPTER 1: INTRODUCTION

1.1 Background

Coal consumption in the U.S. is at record levels and is growing at a rate of approximately 1.5% per year [127]. The largest market for coal is in sales to electric utilities. Over half of electricity generation in the U.S. is performed with coal [24], and electric utilities consume approximately 940 million tons of coal per year [127]. Coal is mined in 26 states, but the major coal-producing regions are Appalachia (in West Virginia and Kentucky) and the Powder River Basin (in Wyoming and Montana) [1].

Transportation accounts for approximately one-third of the purchase price of coal [123]. Over 60% of coal is transported by rail [117]. Coal accounts for approximately 40% of the tonnage and 20% of the revenues of the rail industry [2]. Of the coal transported by rail, over 85% is carried through unit train service, service characterized by the shipment of bulk commodities in large blocks of cars or trainloads between a small set of origins and destinations [6]. Compared to general merchandise service, unit train service provides improved cycle times, increased equipment utilization, high-speed loading and unloading, and reduced costs.

Although unit coal train service is highly efficient, railroads face a range of challenges in providing the service. These including meeting demand for additional capacity, especially in the Powder River Basin; reducing costs, either to meet shipper demands or compete with other carriers; and determining how best to integrate unit train operations with other types of operations, including intermodal and general freight.
One means for increasing capacity and reducing costs of unit coal train service is through heavy axle load operations. In the context of freight railroad operations, heavy axle loads (HAL) are generally defined as axle loads greater than the standard of 33 tons. Although increasing axle loads can provide additional capacity and increased efficiency, increasing axle loads also tends to result in higher track maintenance costs that may offset the capacity and efficiency gains.

A model or approach that could be used to analyze issues in operations of unit coal train networks would be a valuable tool for use by or for the U.S. railroads. Based on the description of unit coal train operations presented in this chapter, a model or approach for analyzing unit coal train operations would need to address the following areas:

- **Large-scale networks:** Unit trains operate on networks with up to approximately 200 trains traveling to and from a set of up approximately 50 origins and 50 destinations.

- **Unscheduled Operations:** Whereas general merchandise and intermodal trains operate on a daily or weekly schedule, unit trains often are unscheduled, or cycle between a small set of origins and destination in a pattern that appears unscheduled compared to other traffic.

- **Medium Level of Detail:** The model or approach would need to have enough detail to examine individual train movements, address network effects, and predict a range of performance measures, including cycle times, equipment utilization, and track utilization.

- **General Framework:** Any model or approach should be applicable to the unit coal train operations of all North American railroads. The present research effort is not directed towards a particular network or railroad.
This thesis describes a computer simulation model, UTRAIN, for use in analyzing the operations of a unit coal trains over a large-scale network. Also, the thesis describes the application of UTRAIN to studying the effects of heavy axle loads on representative coal distribution networks.

UTRAIN is the first general model for analyzing the operations of a large-scale unit coal train network at the level of detail required for estimating cycle times, equipment utilization, and other parameters of importance in analyzing unit coal train operations.

1.2 Structure of the Thesis

Chapter 2 of the thesis provides background information on coal and unit trains. The chapter outlines the coal market, describes the characteristics and technology of unit train service, and explores issues in unit coal train operations.

Chapter 3 is a literature review and review of industry practice. The literature review emphasized books and articles on railroad operations research published in the ten years from 1987 to 1996. The review focused on models and approaches applicable to analyzing coal and unit train transportation, but examined other areas within freight railroad operations research. In addition, the review included work for the Association of American Railroads by the MIT Rail Group, and included a discussion of industry practice in network planning and strategic planning of unit train operations.

Chapter 4 describes the development of UTRAIN, a computer simulation model for analyzing the operation of unit coal trains over a large-scale network. The chapter discusses the motivation for developing a simulation model, outlines the model structures, and details the algorithms in the model.
Chapter 5 describes the application of UTRAIN to studying the effects of heavy axle load operations on the operating and maintenance costs for representative East and West coal distribution networks. The chapter describes previous HAL research, documents the equipment and network parameters used for the study, describes the analysis methodology, and presents the study results.

Chapter 6 summarizes the results from each of the preceding chapters. Also, this chapter recommends directions for further research.
CHAPTER 2: COAL AND THE UNIT TRAIN

Understanding the issues involved in operations of unit coal trains requires background in the coal market and in unit train technology. Section 2.1 describes the market for coal, and describes the role the railroads play in coal transportation in the U.S. and Canada. Section 2.2 presents the concept of unit train service, describes its basic characteristics, and discusses its evolution. Section 2.3 discusses the technology involved in unit train operations, including vehicle, track, and load and unloading technology. Section 2.4 discusses issues concerning unit train operations.

2.1 Coal

2.1.1 Coal Demand

In his thesis on reliability, competition and management issues in coal transportation, Stafford [123] described the U.S. market for coal. Approximately 78% of the coal mined in the U.S. is used for electric utilities. Other major markets include export coal, with 10% of the total, other industries, with 8% of the total, and coke plants, with 4% of the total [123].

In 1995 U.S. electric utilities consumed approximately 940 million tons of coal [127]. Consumption of coal by electric utilities grew at an average rate of 1.5% per year between 1991 and 1995. Figure 2-1 summarizes the consumption of coal by electric utilities from 1991 to 1995 by geographical region. Consumption was heaviest in the East North Central Region, and lightest in the Pacific Region and New England. The growth rate in recent years is consistent with long-trends in coal consumption. U.S. coal consumption is at record levels, and is approximately 50% greater than in the mid 1970’s [1].
In the last 20 years, U.S. electric utilities have increasingly turned towards coal for electricity generation rather than other sources, such as oil, natural gas or nuclear energy. In 1995 coal was used for 57% of electricity generation in the U.S., compared to 44% in 1975 [24]. Although no new coal-fired plants were being built in 1995, it was estimated that only 55% to 58% of coal-fired capacity was being used, and that the optimal value (if there was enough demand) was 70% [24].

Air pollution is a major issue in coal-fired electricity generation. Burning coal releases sulphur dioxide (SO₂), which in turn causes acid rain. SO₂ can be reduced through the
use of scrubbers to filter emissions, or through use of low-sulphur coal. The Clean Air Act Amendments of 1990 required the major coal-burning utilities to reduce SO₂ emissions. However, rather than simply require every utility to meet a particular emissions standard, the act stipulated that the utilities would annually receive emissions credits, and that over time the number of emissions credits issued would drop by specified amounts. Each utility could choose to reduce its emissions, using scrubbers, low-sulphur coal or other technology, and then bank or sell its extra emissions credits. Alternatively, the utility could choose not to reduce emissions and purchase extra emission credits on the open market. As a result of the Clean Air Act Amendments, utilities have shifted their coal consumption towards low-sulphur coal rather than install scrubbers or shift to other means of electricity generation [27], and SO₂ emissions have dropped even while coal consumption has continued to rise.

2.1.2 Coal Supply

In the United States the major coal-producing regions are Appalachia (primarily in West Virginia and Kentucky) and the Powder River Basin (primarily in Wyoming and Montana). Other states with significant coal production include Alabama, Illinois, Indiana, New Mexico, North Dakota, Ohio, Pennsylvania, Texas and Virginia [1]. In 1988, 63% of the coal produced in the U.S. came from mines east of the Mississippi River (32% from West Virginia and Kentucky) and 37% came from mines west of the Mississippi River (18% from Wyoming and Montana) [1].

Significant growth in coal production is occurring in the Powder River Basin. Coal from this region is low in sulphur relative to Appalachian coal, making it more appealing for utilities seeking to lower SO₂ emissions. Equally important, many utilities have found that its price is competitive with that of Appalachian coal, even including transportation costs [117]. In 1960, the region accounted for only 3% of the nation's coal, but the Federal Clean Air Act of 1970 and the oil embargo of 1973 stimulated
additional development [134]. Production expanded from 14 million to 142 million tons between 1960 and 1977 [134]. In 1990 production reached 200 million tons per year [27]. Production reached 285 million tons per year in 1995, and is projected to reach 360 million tons by 2005 [27].

The largest port for exporting coal in the U.S. is Norfolk [135]. Other ports from which coal is exported include Baltimore, Charleston, Cleveland (primarily to Canada), Los Angeles, Mobile, New Orleans, and Philadelphia [1]. Export coal is a more significant component of the coal industry in Canada [135]. There coal from western mines is transported to Pacific ports such as Vancouver and Prince Rupert. Canadian coal destined for domestic consumption is typically hauled east to facilities on the Great Lakes such as Thunder Bay.

2.1.3 Coal Transportation

In the U.S. most coal is hauled by rail. Figure 2-2 summarizes the distribution of coal hauled in the U.S. by mode. In 1994 the railroads carried over 60% of the coal produced in the U.S. In addition, as shown in the figure, use of other modes has remained relatively constant. Railroads have been used to handle most of the increase in coal production in recent years. Approximately one-third of electric utility coal is carried intermodally; for instance, each year 170 millions tons of coal are carried by truck or rail to inland waterways [133]. In the figure coal is assigned to one mode only; if it was carried using multiple modes, it is assigned to the mode used for the largest portion of the haul.

All five of the major U.S. railroads carry significant amounts of coal. Burlington Northern Santa Fe (BNSF) and Union Pacific (UP) are the major coal-carrying railroads in the West; Norfolk Southern (NS), CSX and Conrail serve the East.
Figure 2-2. Distribution of Coal by Transportation Mode

BNSF and UP, the railroads serving the Powder River Basin, have experienced significant growth in coal traffic, and added capacity on lines leading in and out of the basin in response to major capacity problems [117][138][139]. For instance, in 1995 shortly after completion of the merger between Burlington Northern and Santa Fe, the CEO of BNSF announced a $1.2 billion capital improvement program to add capacity in areas such as the Powder River Basin. At that time the BNSF line into the Powder River Basin handled up to 70 trains per day, and was single track in some places [25]. Union Pacific has begun to install triple track along the 108-mile line in Nebraska between North Platte and Gibbon, which handles 120 trains per day [39]. In addition, in June of
1996, UP took the unusual step of closing its 162-mile line between South Morrill and North Platte for six days. In this time UP performed an entire season's worth of maintenance and installed double track on 13 miles of the line (the line normally handles 50 to 60 trains per day) [26], [83].

2.2 Unit Train Service

This section introduces issues and concepts necessary for analyzing unit train service. Section 2.2.1 provides a definition of unit train service. Section 2.2.2 outlines the development of unit train service in the U.S. and Canada, and Section 2.2.3 discusses critical factors that have enabled the development of unit train service.

2.2.1 Definition of Unit Train Service

The phrase unit train service denotes a type of rail service with certain characteristics, but lacks specific definition. Here unit train service is defined as a type of rail service characterized by the movement of bulk commodities by rail in large blocks of cars or trainloads. Unit train service generally, but not necessarily, involves special rate agreements between the commodity shipper and rail carrier, highly efficient loading and unloading of the bulk commodity at the origin and destination of the shipment, and service between a small set of origins and destinations.

Unit trains usually avoid switching of cars at terminals. However, in some cases, such as for grain trains, unit trains are assembled from several large blocks of cars from different customers. Once empty, unit trains generally are sent directly back to the origin, but other return strategies may be used (e.g., staged or haphazard returns). Unit train service is widely used for shipping coal, grain and other bulk commodities.

Different authors have proposed variations on the above definition. Armstrong [6] wrote that the unit train is “a system including efficient, rapid loading and unloading
facilities matched up with whole trains (or large blocks) of cars (and often, locomotives) assigned to the service. . .” He added that unit train service usually includes a long-term contract specifying volume and scheduling. Armstrong noted that although unit trains are widely used for shipping coal, they are also used for shipping semi-finished steel, orange juice, hot liquid sulfur, grain, crude oil, fertilizer, and double stack containers.

Morris [103] distinguished between three different types of unit train service, all of which are captured using the above definition: trainload service, shuttle service, and integral service. Trainload service involves shipping an entire train with a single commodity from an origin to destination in a single move without intermediate handling at a rail terminal. The rate paid by the customer reflects the savings of shipping a large amount of freight at once, but the customer does not have a long-term contract with specified volumes and schedules. Morris cited export grain trains as an example of trainload service.

Morris described shuttle service as involving a dedicated set of equipment that moves between one origin and destination. The utilization rate for shuttle trains is quite high, as the shipper and carrier generally have a long-term contract with specifications for shipment volumes and schedules. A semi-shuttle train might operate in a similar manner, but between multiple origins and destinations.

Writing in 1967, Morris presented integral train service as a future development in unit train service. This type of service is characterized by the use of specially designed trains, built for maximum efficiency, with dedicated power or even built-in motive power and minimum crews. One might argue that today’s unit coal trains approximate this concept, or that they are closer to shuttle trains.
Warren [134] suggested a definition similar to that of Morris's definition of shuttle service. In discussing unit trains and coal, he wrote that unit train service must "comprise a separate train that transports a specified commodity from a stated point of origin to a designated terminal point." Also, tariffs for unit trains stipulate the number of cars per train and the minimum annual tonnage to be shipped.

Table 2-1 summarizes the general characteristics of unit train service, compared to general (or carload) freight service. Note that in many respects unit train service is similar to intermodal or double stack service, in which intermodal containers are carried on flat cars. In fact, both Armstrong [6] and Bailey [14] characterized intermodal service as a type of unit train service. However, according to the definition presented in this study, intermodal service is distinct from unit train service. The distinction between them is that freight shipped in intermodal service is containerized freight with diverse origins and destinations, whereas the freight being carried in unit train service is a bulk commodity with a single (or limited number of) origin and destination.

### Table 2-1 General Characteristics of Unit Train Service

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Unit Train Service</th>
<th>General Freight Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipment Size</td>
<td>Trainload, or large blocks of cars</td>
<td>Carload</td>
</tr>
<tr>
<td>Commodity</td>
<td>Bulk commodity</td>
<td>Varies</td>
</tr>
<tr>
<td>Rate Structure</td>
<td>Special rate with specified shipment volumes and schedules</td>
<td>Carload rate</td>
</tr>
<tr>
<td>Terminal Handling</td>
<td>Minimal</td>
<td>Multiple terminals per shipment</td>
</tr>
<tr>
<td>Equipment Utilization</td>
<td>Very high emphasis</td>
<td>Lower emphasis</td>
</tr>
</tbody>
</table>

**2.2.2 Development of Unit Train Service**

Unit trains are widely used in the U.S. and Canada for hauling bulk commodities, especially coal. In the case of coal, the overwhelming majority that is hauled by
railroads is hauled using unit train service. Armstrong [6] estimated that as of 1988, 85% of coal hauled by U.S. railroads was hauled under contract (unit train) rates. The percentage has likely increased since 1988. By comparison, Warren [134] estimated that in 1977 for the Western U.S. coal mines, unit trains were used for shipping less than half the coal carried by the railroads.

Although the extent to which unit trains are used is much greater now than it has been in the past, unit train service is not a recent innovation. Armstrong pointed out that large-scale movements of bulk commodities from a single origin to destination “date back to the early days of railroading.” In an address to the Railway Systems and Management Association in 1967, Forbes of the Norfolk and Western [47] supported the same point, writing that the Norfolk and Western had been shipping trainloads of coal since the turn of the century.

In the same address, Wallace [47] added that unit train service was not a recent innovation on the Pennsylvania Railroad (PRR), either. He wrote:

Unit trains are nothing new -- often our present day insists on isolation of its activities from our historical and cultural matrix so that everything we do is new; but as we have defined and described the unit train, the old-time circus train certainly was a unit train. Circus trains move under an all provision contract package unusually complete and ‘advanced’ even for today. The PRR ‘first’ on unit train operation was solid trains of 40 cars of export grain moved from Fort Wayne to Baltimore during 1898 and 1899.

Despite the fact that the concept of unit train service was developed in the 19th century, not until the 1960’s did use of unit train service expand significantly. Whikehart [17] wrote that “The origin of the modern unit train is found in bulk materials movements of
the late 1950’s and early 1960’s." He cited the use of unit trains for shipping iron ores to ports in Canada and the Upper Lakes as the first application of the "modern unit train." In these cases captive shippers moved large amounts of bulk commodities from a single origin to a single destination, and relied on highly efficient loading and unloading technology to reduce their shipping costs.

For the U.S. railroads the policy until the 1960’s was that railroads could not establish special rates for large-volume shipments [6]. This naturally discouraged use of unit trains, which are generally economical only when the shipper and railroad can agree to a long-term arrangement where the shipper agrees to specifications for shipment volumes and schedules.

However, the momentum for transporting bulk commodities more cheaply and efficiently forced changes in policy. Morris [103] noted that unit trains first used on the Southern Railway in 1960 between the mines and power plant of the Southern Electric Generating Company in Alabama. However, he wrote, the use of unit train service began on a broad scale after March of 1962. At that time President Kennedy sent legislation to Congress requesting that Congress provide the right of eminent domain for the construction of coal pipelines. In describing the railroads’ reaction, Morris wrote: "Within months most major coal carrying railroads were operating unit trains, and in addition to offsetting the proposed legislation, closed the coal pipeline then in operation."

Operating unit trains requires substantial capital investment in efficient loading and unloading facilities, as well as in rolling stock, and requires long-term agreements between shippers and carriers. These factors may initially have been a barrier to developing unit train service. However, once railroads began operating unit trains on a
larger scale, the advantages of unit train service became apparent, and the use of unit trains further increased. Warren [134] documented the growth of unit train service in the Western Interior region of the U.S. He wrote that unit train service in the region began on a small scale in 1962 with service between Gallup, New Mexico and Joseph City, Arizona. By the end of 1969, there were seven unit train operations shipping over five million tons annually, and by 1977 there were 40 trains shipping over 65 million tons annually.

The development of unit train service gained additional momentum with the passage of the Staggers Act in 1980 [6]. This act deregulated the railroads, and allowed railroads to establish special rates for individual shippers. Thus, after 1980 railroads and shippers had more freedom to bargain on contracts specifying price, service, volume and scheduling.

2.2.3 Factors Enabling Unit Train Service

This section itemizes the factors that enabled the development of unit train service, most of which mentioned in the preceding discussion. The critical factors are:

- Marketing
- Technology
- Mergers
- Reduced Price

Clearly an important factor in developing unit train service is marketing. A railroad must have the ability to deal directly with individual shippers to determine how to best serve their needs, and must have the flexibility to provide the service they require. If the railroad and shipper cannot agree to a long term contract, and agree that one or both will invest in efficient technology for making unit train service viable, then unit train service is not an option. Electric utilities that use coal can commit to purchasing
large amounts of a bulk commodity at regular intervals. Of the customers of railroads, electric utilities are ideal candidates for unit train service. As mentioned above, unit train service existed long before deregulation, but deregulation gave the railroads more flexibility in working with shippers, enabling more innovative marketing.

Technology is another enabling factor in the development of unit train service. For unit train service to be viable, there must be technology available that makes shipping bulk freight by unit trains more efficient than shipping it as carload freight. Technologies that reduce train cycle times and increase equipment utilization accomplish this task by significantly reducing transit times and equipment costs. These technologies include advanced systems for rapidly loading and unloading bulk commodities and rail cars specialized for rapid loading and unloading, and for holding as much of a particular commodity as possible. Unit train technology is discussed further in Section 2.3.

Mergers are another enabling factor. Unit train operations generally involve special contracts and may require special priority in dispatching to minimize cycle times. If it is a challenge for a single railroad to achieve these, then the process is even more complicated if multiple railroads are involved. Thus, railroads generally are better prepared to offer unit train service if the shipment is entirely over the railroad’s own lines. A result of railroad mergers is that as the number of railroads has shrunk, the number of opportunities for single-line moves has increased. This trend tends to favor unit train service. This tendency was noted at least as early as 1967. Forbes [47] wrote: “The problems of interline unit train movements are so magnified that we can safely say that the first requirement for top unit train performance is a single line haul. . . . In a sense, therefore, we can say that the progress of the merger movement and the potential of unit trains go hand in glove.”
Ultimately, the most important factor enabling development of unit train service is price. Unit train service has developed because railroads and shippers save money by using unit train service rather than general freight service. Reduced prices are realized through innovative marketing arrangements, specialized technologies, and single-line moves, but except for the fact that these factors result in reduced prices, unit train service would not have developed as it has.

Relative to general freight service, unit train service is approximately 40% to 50% less costly. This range, though approximate, has remained constant since the late 1960’s. In 1967, based on historic data on tariffs, and a carefully-prepared cost function, Bailey [14] reported that, measuring revenue per ton-mile, revenues from unit train operation are approximately half those from general freight (0.633 cents per ton-mile for unit trains versus 1.266 cents for general freight). Bailey concluded that biggest reductions in costs come from bypassing terminals and improved equipment utilization. Another source from the same period reported that unit train operations represent a cost reduction of approximately 50% [60].

More recent statistics on rail revenues support the 40% to 50% range for savings from unit trains. Statistics from 1986 indicate that the revenue per ton-mile for shipping coal was approximately 40% lower than the revenue per ton-mile for bulk commodities shipped as general freight, such as pulp, chemicals or stone [1]. Stafford reported that in 1989 the average rail revenue for hauling coal was $11.94 per ton. For the same year the average revenue per ton for all freight hauled by Class I railroads was $19.29 per ton [2]. Thus, in 1989 the revenue per ton for coal (over 80% of which hauled using unit trains) was 40% less than the average rate.
Table 2-2 summarizes the tonnage originated and revenue generated by Class I railroads in 1995 [2]. In 1995 coal represented 40.5% of the tonnage originated by Class I railroads, but only 21.8% of revenue. Based on the table, the average revenue per ton for shipping coal was 46% lower than the average cost for all freight, and 59% lower than the cost for non-coal freight. Note that these revenues are per ton and not per ton-mile; comparing revenues per ton-mile for coal and non-coal freight would likely show a more modest savings. Nonetheless, both old and recent figures support the point that where unit train service is feasible, it can be provided at a cost significantly lower than that of general freight service. The potential for price reductions has been an enabling factor in development of unit train service.

2.3 Unit Train Technology

This section describes the technology involved in unit coal train operations, including technological aspects of loading and unloading facilities, rolling stock, and dispatching and routing. Background information concerning these components is helpful for understanding the simulation model presented in Chapter 4. In representing an entire unit train network, the simulation model does not address these components at a detailed level. However, having information concerning the detailed components of a system frequently helps develop intuition concerning how well a system-level model represents reality.

2.3.1 Coal Cars

There are two basic types of rail cars used for shipping coal: gondola cars and hopper cars. A typical gondola car is shown in Figure 2-3. Gondola cars have high sides, flat bottoms and open tops. These cars are loaded from above and unloaded by rotating the car using a rotary dumper. The advantages of gondola cars include their relative simplicity and their flexibility for use for other types of service (although this is rarely done when the cars are used for unit trains).
Table 2-2 1995 Class I Railroad Tonnage Originated and Revenues

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Tons Originated</th>
<th>Revenue</th>
<th>Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tons (000)</td>
<td>$ (millions)</td>
<td>% of Total</td>
</tr>
<tr>
<td>Coal</td>
<td>626,874</td>
<td>7,356</td>
<td>21.8</td>
</tr>
<tr>
<td>Farm products</td>
<td>154,363</td>
<td>3,020</td>
<td>6.5</td>
</tr>
<tr>
<td>Chemicals</td>
<td>139,421</td>
<td>4,597</td>
<td>13.6</td>
</tr>
<tr>
<td>Non-metallic minerals</td>
<td>110,318</td>
<td>875</td>
<td>2.6</td>
</tr>
<tr>
<td>Food &amp; kindred products</td>
<td>90,568</td>
<td>2,464</td>
<td>7.3</td>
</tr>
<tr>
<td>Lumber &amp; wood products</td>
<td>51,283</td>
<td>1,385</td>
<td>4.1</td>
</tr>
<tr>
<td>Metals &amp; products</td>
<td>47,500</td>
<td>1,242</td>
<td>3.7</td>
</tr>
<tr>
<td>Metallic ores</td>
<td>43,622</td>
<td>394</td>
<td>1.2</td>
</tr>
<tr>
<td>Stone, clay &amp; glass</td>
<td>43,007</td>
<td>1,044</td>
<td>3.1</td>
</tr>
<tr>
<td>products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petroleum &amp; coke</td>
<td>41,768</td>
<td>954</td>
<td>2.8</td>
</tr>
<tr>
<td>Waste &amp; scrap</td>
<td>37,735</td>
<td>685</td>
<td>2.0</td>
</tr>
<tr>
<td>Pulp &amp; paper</td>
<td>35,763</td>
<td>1,543</td>
<td>4.6</td>
</tr>
<tr>
<td>Motor vehicles &amp; equip.</td>
<td>27,437</td>
<td>3,184</td>
<td>9.4</td>
</tr>
<tr>
<td>All other</td>
<td>99,974</td>
<td>5,037</td>
<td>14.9</td>
</tr>
<tr>
<td>Subtotal, Non-Coal</td>
<td>922,760</td>
<td>26,426</td>
<td>78.2</td>
</tr>
<tr>
<td>Total</td>
<td>1,549,634</td>
<td>33,782</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Source: Railroad Facts 1996, Association of American Railroads

Hopper cars differ from gondola cars in that hoppers have sloped sides and doors to allow coal to be dumped out of the bottom of the cars. Hopper cars are a natural design for applications where the commodity being shipped is emptied into a bin or another hopper. Historically, hopper cars each had two to four chutes for emptying the
commodity being shipped, and were used for shipping coal, ore, grain and other commodities. Often two commodities were shipped in different directions with the same equipment (i.e., coal in one direction and ore in the other), but this is less common now.

As unit train service became more established, shippers became more concerned about the cost of unloading cars, and alternative hopper car designs were developed [74]. Hoppers specialized for coal service have additional chutes (typically a total of five chutes) relative to conventional hoppers and can be unloaded more easily and quickly. Figure 2-4 shows a typical hopper car. Hopper cars may be emptied in motion over a trestle, or they may be rotary dumped.

Unloading of gondola and hopper cars is complicated by the fact that coal tends to freeze during shipment in colder climates. When coal freezes there is a risk that it will stick to the inside the car or come out of the car in large chunks. If the coal comes out in large chunks it can damage any equipment beneath the train, such as belts used for carrying away the coal. When coal freezes in the cars, the cars must be thawed or shaken. Frozen coal is particularly problematic for hopper cars. For this reason, in colder areas of North America, gondola cars are generally preferred to hopper cars [42].

As of the late 1980’s coal gondola and hopper cars typically were made of steel and designed to hold approximately 100 tons of coal. Dow [42] described the standards for gondola cars used by Canadian Pacific (CP) as of 1989. The CP standard car weighed 263,000 pounds loaded, 52,200 pounds empty, and was 58 feet, 7 inches long. An interesting feature of the CP car was that the inside of the car was tub-shaped.
Figure 2-3. Typical Gondola Car

Figure 2-4. Typical Hopper Car
In the 1990’s railroads turned towards newer designs with aluminum rather than steel and heavier axle loads. Although aluminum cars have been in use since the 1960’s [60], aluminum has been used more in recent years, primarily as its use leads to reduction in tare weight. Heavier axle loads typically have been achieved either by filling 263,000-pound cars to the limit (typically to a weight of 286,000 pounds), or by using cars designed to hold up to 315,000 pounds.

In 1995 and 1996 Welty [138], [139] described several newer aluminum car designs. Johnstown America produced the Auto-Flood five-hopper, the BethGon Coalporter four-hopper and the smooth-sided Aeroflo BethGon Coalporter (a gondola). These had lading capacities approximately 20 tons greater than steel cars and had tare weights of approximately 43,500 for the gondolas and 49,600 to 51,400 pounds for the hoppers. Thrall Car sold the Avalanche car (either as hopper or rotary dump) and the MaxGon gondola. These had load capacities of 234,800 to 242,300 pounds and tare weights of 51,000 pounds for the Avalanche or 43,700 pounds for the MaxGon. Trinity Industries sold the Aluminator and Aluminator II (gondolas with alternative, bottom-dump designs). Welty also reported that Johnstown America had produced a new type of car, called a TroughTrain, for Burlington Northern. The all-aluminum TroughTrain consisted of 22 cars (each car was 278 feet long with 13 jointed segments), and could hold 17,000 tons of coal.

2.3.2 Loading Facilities

Loading facilities have been designed to quickly and efficiently load unit coal trains. The state-of-the-art facilities load trains at a rate of 3,000 to 4,000 tons per hour, and are based on technology developed in the 1950’s and 1960’s. In Western North America most facilities can handle an entire 100-car train at once, and can load the train in-motion in 3 to 4 hours. At older facilities, primarily in more mountainous areas in the
East, fewer cars can be handled at once, and loading typically requires 20 to 24 hours.

The state-of-the-art in technology for loading unit coal trains has changed relatively little in the last 30 years. In 1967 techniques for loading coal included placing coal in open storage and moving to trains using underground conveyor belts or front-end loaders, or placing coal in silos and moving to trains using belts and chutes [103]. A loading rate of 3,000 tons per hour was cited for facilities using silos [103].

Also in 1967 Harrington [60] described the loading facilities of the coal mine Old Ben Number 24, owned by Old Ben Coal Corporation. At this mine a 100-foot high steel stacking tower was used to form a 38,000 ton conical coal storage pile. Coal from the pile was withdrawn through 14 reclaim slots. The reclaim hoppers could hold 15,000 tons of coal, enough to fill 105 rail cars. Coal was delivered to trains using three feeders, that together operated at a rate of 3,600 tons per hour. The only personnel required for the loading operation were the loading operator and the train crew. In the same article Hanson [60] described similar loading facilities at the Burning Star Number 2 Mine owned by Consolidated Coal Company. There the facilities included a 29,000 ton conical coal pile, and could load coal at a rate of 3,000 tons per hour.

More recent descriptions of loading facilities are similar to those described above. A Conrail publication from 1986 [33] described the facilities at High Power Mountain in West Virginia. There BethEnergy Mines operated a mine with a 36,000 ton storage facility, and could load 140-car unit trains at a rate of 4,000 tons per hour.

A description of coal train loading procedures and facilities in Canada was prepared by Wheadon [141]. Wheadon described facilities designed to load a 100-car train in 3 to 4 hours (a rate of approximately 3,300 tons per hour). At these facilities coal typically was
stored in a pile large enough to fill two trainloads. The pile was maintained using a front-end loader and bulldozer. Coal was loaded into the reclaim hopper, and transported from the reclaim hopper into a surge bin. From the surge bin coal was loaded to the train using an 8.9-foot wide, 4.3-foot deep flood chute. Coal was weighed as it was loaded using either track scales, or a belt weigh feeder or a weigh bin scale between placed between the surge bin and flood chute. Loading tracks at the Canadian facilities were either loop tracks or, where a loop was not feasible, a “runaround” track parallel to the main line.

Figure 2-5 depicts a typical coal loading facility, based on the descriptions and figures from Harrington [60] and Wheadon [141]. The figure shows a coal silo, processing facility, storage pile, and surge bin. Coal is moved between them using belts. Coal is loaded to the train through a chute, and the train is weighed using track scales.

![Diagram of coal loading facility]

**Figure 2-5. Typical Unit Coal Train Loading Facility**
2.3.3 Unloading Facilities

Although the processes of unloading and loading unit coal trains are different, the development of facilities for unloading coal trains has paralleled the development of loading facilities. In the 1950's and 1960's the technology developed significantly, but it has since remained relatively constant.

The two basic techniques for unloading unit coal trains are to dump individual cars or pairs of cars using a rotary dumper, or to dump the cars in-motion as they pass on a trestle over a pit or hopper. Gondola cars and hopper cars may be rotary dumped, as long as at least one coupler on each car is a rotary coupler. Only hopper cars may be dumped while in motion. If the coal freezes during transport then the cars may need to be thawed or shaken before dumping. Thawing is generally preferred to shaking as it causes less damage to the cars. Frozen coal is less of a problem when rotary dumping is used, so this technique is preferred in colder climates.

Harrington described the unloading facilities at Sioux Plant of the Union Electric Company in St. Louis (supplied by the Old Ben Number 24 Mine described above) [60]. At this plant semi-automatic bottom-dump hopper cars moved over a trestle, dumping coal into hoppers below the train. Each hopper car required 23 seconds to unload, but the overall unloading rate was limited to 3,000 tons per hour by the belt that took coal from the hoppers to storage. Each car of the 67-car train held 105 tons of coal, for a total of 7,000 tons per trainload. No thawing shed was required for the operation as the trip from mine to utility was only 10 hours.

Although 3,000 tons per hour is a typical unloading rate for cases where there is limited storage space underneath the train, much higher unloading rates are achievable when storage space is not an issue. Typically, unloading hopper cars moving on a trestle
requires 30 seconds per car, a rate of approximately 12,000 tons per hour [74]. Rotary dumping requires approximately 2 minutes per car (approximately 3,000 tons per hour); however, multiple cars may be dumped simultaneously to achieve higher rates. For instance, Whikehart [17] described a plant with multiple rotary dumpers that unloaded coal at a rate of 12,000 tons per hour.

Dow described the rotary dumper unloading facilities in use by Canadian Pacific at Robert’s Bank [42]. There two rotary dumpers were used: a single dumper and a dual dumper. A car positioner was used to move cars into position for dumping. The rotary dumpers required approximately two minutes per cycle. Unloading a train required approximately two hours. In cold weather extra time was required for thawing the cars. Each car required 90 seconds in the thaw shed; 20 minutes were required for thawing an entire train.

Wheadon described comparable unloading facilities in use at Thunder Bay in Canada [140]. There cars were dumped into hoppers using rotary dumpers. Wheadon stated that rotary dumpers operated at a rate of 25 to 40 cars per hour and dual rotary dumpers (or tandem rotary dumpers) operated at a rate of 65 cars per hour. Coarse coal was dumped at an angle of 140 degrees, fine coal at 160 degrees and frozen coal at 180 degrees.

Thaw sheds were used at Thunder Bay, but Wheadon pointed out that thawing is intended to separate coal from the sides of the cars, not to break up frozen coal. Because frozen coal could fall out of the cars in 10x5x2 foot pieces, “grizzly” bars were installed under the dumpers and above the hoppers to break up the pieces of frozen coal.
Manning [90] described trestle and rotary dump unloading facilities in the U.S. in 1989. The minimum unloading time was achieved using hopper cars unloading in-motion on a trestle over a pit. For this system, $\frac{1}{2}$ hour was required to unload a 110 car train. If hopper cars were unloaded over a hopper then rate was limited by the "takeaway" system, typically limited to 3,000 to 4,000 tons per hour.

Concerning rotary dump facilities, Manning explained that in the U.S. typically single car dumpers were used with a train positioner. Each car required 30 to 35 seconds to dump. Factoring in time to move the train, the rate was approximately 35 cars or 3,200 tons per hour. At most typical facilities, four hours was allotted for unloading each train.

Figure 2-6 depicts a typical unit coal train unloading facility, based on a diagram by Keniston [74]. In the facility shown in the figure, cars are dumped using a rotary dumper. Once dumped, the coal falls into a hopper, and is carried to a storage pile using conveyor belts.

![Diagram of typical unit coal train unloading facility]

Figure 2-6. Typical Unit Coal Train Unloading Facility
2.4 Issues in Unit Train Operations

As discussed in Section 2.3 and 2.4, the modern concepts of unit train service and technology developed in the 1950's and 1960's. Since that time, designers of new facilities have tended to duplicate proven designs rather than further develop the state of the art [74]. Nonetheless, railroads face a range of old and new challenges in providing unit train service. These including meeting demand for additional capacity; further reducing costs, either to meet shipper demands or compete with other carriers; and determining how to best integrate unit train operations with other types of operations, including intermodal and general freight.

As noted in Section 2.1.3, the railroads serving the Powder River Basin have experienced major challenges in expanding capacity to meet demand. Both the BNSF and UP had major problems with Powder River Basin operations that forced them to add capacity. For instance, Welty reported that in 1994 that Burlington Northern (now BNSF) and Chicago & North Western (since bought by UP) had "the summer from hell" as they could not meet demand on their shared line due to capacity constraints [137]. The line was operating at 97% of its theoretical capacity and suffered frequent, serious delays.

Competition is another major issue in coal transportation. Although one can find many instances in which a utility appears to be a captive shipper to a railroad, and the railroad monopolistically exploits its advantage (or at least tries to) [23], recently competition appears to be on the increase. In the case of Powder River Basin coal, recent articles document that BNSF and UP are competing aggressively against one
another, resulting in lower prices increased use of Powder River Basin coal, in markets as far away from the basin as Georgia [27], [139].

Competition is an issue in the East, to the extent that the eastern railroads compete with each other, as well as with the western railroads. In a recent meeting with NS concerning unit train operations, representatives from the railroad emphasized that NS realized the need to make constant improvements to its operations in an effort to reduce costs, and looked to improved technology for opportunities to do so [109].

Barge shippers compete with the railroads, also. Where barge shipments are feasible, barging is generally less costly than rail transportation. Some industry watchers project that as the electric utility industry is deregulated, utilities along rivers will exploit their price advantage by producing additional electricity and using long-line transmission (wheeling) to provide lower-cost electricity to high-cost areas [117], [133].

Another important issue is the integration of unit train operations with scheduled operations. This issue is particularly important when railroads merge, or when a railroad undergoes an effort to improve its planning and operations. In a presentation to the MIT Center for Transportation Studies, Adriene Bailey of CSX listed areas where additional research is required for helping automate the development of railroad operating plans [15]. The areas she listed were:

- Developing an optimization-based approach for general freight car blocking.
- Integrating power and crew resources in operating plan development.
- Including commercial requirements in development of the operating plan.
- Integrating the scheduled and unscheduled (unit train) networks while delivering velocity and reliability on both.
Although unit coal train service is a large, highly-efficient and well-established service for U.S. railroads, meeting demand for additional capacity (especially in the Powder River Basin), further reducing costs of service and integrating unit train and scheduled operations present important challenges to the railroads. U.S. railroads will likely continue to face these issues in years to come.
CHAPTER 3: LITERATURE REVIEW AND REVIEW OF INDUSTRY PRACTICE

Chapter 2 explores issues in coal and unit trains and concludes with a discussion of issues in operating unit coal trains over a large network. Important issues U.S. railroads face in operating unit coal trains include meeting demand for additional capacity (especially in the Powder River Basin), further reducing costs of service and integrating unit train and scheduled operations.

This chapter reviews analytical methods for exploring issues in unit coal train operations. Although the available literature provides relatively few examples of models and approaches for analyzing unit train operations, a significant amount of recent research has explored related topics in railroad operations. In addition, railroads analyze issues in unit train operations on a daily basis. Little publicly available literature describes the railroads' approach, but review of the available information on methods used in industry is essential for determining how to improve on the state-of-art in analysis methods.

The primary goal of the review is to identify approaches or models that have been used for analyzing unit coal train operations. Particular attention is given to models used for analyzing coal transportation and unit train network operations. Also, the review describes other recent research in railroad operations. Studying other research efforts in areas outside of unit coal train operations may provide models and approaches that could be applied to unit trains, and helps place the current research effort in context.
The review covers three main sources of research on railroad operations: MIT research, other academic research, and information on industry practice. Research performed at MIT is included because, for the last 25 years MIT researchers have been funded by the Association of American Railroads (AAR), U.S. railroads, and Federal Railroad Administration (FRA) to study issues in railroad operations, reliability, heavy axle loads, and other areas related to unit train operations. From 1975 to 1981 the AAR, U.S. railroads, and the FRA funded MIT railroad research as part of the Freight Car Utilization Program and the Freight Equipment Management Program. In 1983 MIT became an AAR-affiliated laboratory. Research on railroad issues, funded by the AAR, has continued at MIT since 1983.

A literature review was conducted to identify research efforts in railroad operations described in the literature from 1987 to 1996. Table 3-1 lists the publications included in the review. Information on industry practice was collected through the available literature, through memoranda and notes from past projects at MIT performed for railroads, and through notes on interviews and discussions with personnel at three major North American railroads: Union Pacific (UP), Norfolk Southern (NS) and Canadian National (CN).

At each step in the review, consideration was given to what models or approaches have been used to analyze unit coal train operations, and to what related models developed in railroad operations research exist that could be used for this purpose. Initial review of the available literature suggested that few, if any, models or approaches had been developed for analyzing unit train operations. Most common railroad large-scale network models work under the assumption that all traffic is scheduled and that the schedule repeats daily or weekly, but unit train operations are unscheduled.
Table 3-1 Publications Included in the Literature Review

<table>
<thead>
<tr>
<th>Publication</th>
<th>Years (19-+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA Bulletin</td>
<td>87 - 96</td>
</tr>
<tr>
<td>COMRAIL Proceedings</td>
<td>87, 90, 92, 94, 96</td>
</tr>
<tr>
<td>Heavy Haul Proceedings</td>
<td>82, 86, 91</td>
</tr>
<tr>
<td>Interfaces</td>
<td>87 - 96</td>
</tr>
<tr>
<td>Journal of the Transportation Research Forum</td>
<td>87 - 96</td>
</tr>
<tr>
<td>Transport Reviews</td>
<td>87 - 96</td>
</tr>
<tr>
<td>Transportation</td>
<td>87 - 96</td>
</tr>
<tr>
<td>Transportation Planning and Technology</td>
<td>87 - 96</td>
</tr>
<tr>
<td>Transportation Research – A</td>
<td>87 - 96</td>
</tr>
<tr>
<td>Transportation Research – B</td>
<td>87 - 96</td>
</tr>
<tr>
<td>Transportation Research Record</td>
<td>87 - 96</td>
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<tr>
<td>Transportation Science</td>
<td>87 - 96</td>
</tr>
<tr>
<td>World Conference on Railway Research Proceedings</td>
<td>96</td>
</tr>
</tbody>
</table>

Many optimization models have been developed for studying railroad networks. However, these typically assume that operations are scheduled, and tend to model a large network with relatively little detail (such as for strategic planning of a nation’s freight flows) or a small network with greater detail.

A large number of simulation models have been developed and applied to railroad operations, but most involve a very high level of detail, and are intended for analyzing line operations. Simulation models with a medium level of detail have been developed, but were typically developed and applied to a specific project, and thus may not be general enough to apply to other networks. However, if an appropriate model or approach could be identified, its application could simplify the present research effort,
and could be of benefit to North American railroads. Thus, a detailed review was required.

Section 3.1 describes the work related to unit train operations performed at the MIT Center for Transportation Studies by the MIT Rail Group. Section 3.2 reviews the literature on analysis tools for unit coal train networks and related areas. Section 3.3 describes approaches currently used in the railroad industry for analyzing unit train operations. Section 3.4 presents the conclusions of the review.

3.1 Description of Related MIT Research

In the past 25 years a number of researchers at MIT have investigated issues related to unit trains and the operations of freight train networks. This section summarizes the major areas of related research performed at the MIT Center for Transportation Studies by researchers in the MIT Rail Group. The research has included analysis of line operations, investigation and development of network models for analyzing train operations, and exploration of issues specific to unit trains. These research efforts are described in the following sections, grouped loosely according to area of research.

3.1.1 Line Operations

In the 1990's several researchers in the MIT Rail Group explored issues in railroad line-haul performance. This research was different from the work on reliability and network operations discussed in the following section in that it focused on operations of trains on lines between terminals, whereas much of the other work examined terminal operations and performance over an entire network.

In 1991 Dontula developed a model for analyzing the line-haul operations of a single-track railroad [41]. Dontula's model, called LINSIM, simulated trains as they traveled in both directions along a line. In using the model, one specified the train schedule for
each direction; the physical parameters of the line, such as the location of sidings and speed limits on segments of the main line and on sidings; and the probability of rail defects, train failures, or other events that could result in slow orders or line closures. The model simulated three weeks of operations. Trains were dispatched onto the line according to the schedules, although actual train departure times were varied slightly (by a random amount) from the schedule. Once on the line, trains were dispatched using a limited look-ahead strategy. Donto developed dispatching rules to ensure that trains would not collide or block each other. Model outputs included the mean trip time, standard deviation of trip time, and mean delay from train meets, slow orders and track closures.

Donto used LINSIM to study the capacity of a hypothetical single-track line. He showed that as a line neared capacity, delay and the standard deviation of trip time generally increased significantly. However, a scheduled railroad could operate at reliably at capacity if there were no engineering delays and if trains ran on time. Donto showed that slow orders and track closures had a significant effect on capacity.

Romps built upon the LINSIM model created by Donto [114], expanding the capabilities of LINSIM to include simulation of track maintenance windows. With Romps' revisions a user could specify single or daily maintenance events at some point along the line. Romps showed that including delay from track closure due to maintenance increased mean trip time, the standard deviation of trip time, and mean delay. As a case study, Romps discussed the maintenance requirements for the representative coal routes studied in the AAR Heavy Axle Load Phase I Economic Analysis. He showed that although track maintenance increased with heavier trains, delays from increased maintenance were more than offset by the reduction in delay from reducing the number of train meets.
Robert and Martland extended Romp's analysis by projecting the annual distribution of track maintenance windows for the representative coal routes studied in the AAR Heavy Axle Load Phase II Economic Analysis [113]. Using those projections, along with results from LINSIM runs, they quantified the delay and reliability of the representative coal routes, and showed how these measures varied for heavy axle loads. Together, the three studies summarized above present the development and application of a powerful simulation model for exploring issues in railroad line-haul performance, and, in particular, for exploring how performance varies when train meets, maintenance delays, other events are considered.

3.1.2 Network Models

In 1972 Joseph F. Folk reported on the initial work performed at MIT on rail network models. In his review of network models of the rail industry, Folk described both simulation models and optimization models developed for use in the industry [45]. By 1972 several researchers had developed network simulation models for analyzing railroads. Folk reviewed the Allman Model, the Frisco Model (an expanded version of the Allman developed by the St. Louis-San Francisco Railway), the CN Model (an expanded version of the Frisco Model developed by Canadian National Railways), several Southern Railway models, the Southern Pacific Network Simulation Model, and the AAR Network Model.

Folk concluded that the AAR Model was the most advanced of those reviewed. It allowed the user to simulate the operations of an entire railroad network, including line and terminal operations, over the course of days and weeks, and allowed for testing of different operating policies, such as running trains of varying lengths or running schedule-dependent trains versus volume-dependent trains. Output produced by the model included histories of train arrivals and departures at each yard, traffic histories
over selected links, and train histories for selected trains. However, the model was
costly to operate, requiring 12 to 18 person months of effort to prepare for a single set of
simulation runs.

In the same report Folk reviewed network optimization models, including Thomet's
model for optimizing schedules, work at Queen's University for optimizing routing,
other scheduling models, and a rail network optimization model developed by
Williams at the Federal Railroad Administration. Folk cautioned that little work had
been done to validate the optimization models.

Folk's research was concerned with investigating trip time reliability. From the review
of network models, Folk concluded that the CN and AAR models could be used to
explore reliability, but that it was cheaper and easier to use a model specially developed
for analyzing reliability. Folk developed such a model, and described the model in a
1972 report [46]. Folk's model simulated the movement of rail cars through a simple
network, measuring the number of missed connections at yards, standard deviation of
transit times in the network, and the mean delay. The network consisted of two large
yards, with flows in and out of the large yards to sets of smaller yards. Trains traveled
between the large yards in one direction only. Folk experimented with different arrival
time distributions for incoming traffic, train make-up policies, train lengths, numbers of
yards, scheduled connection times, and other factors.

Following Folk's work, a number of researchers further explored issues concerning
railroad reliability. A major development of the railroad reliability research was the
development of the PMAKE function, which relates the probability that a freight car
will make its scheduled connection at a terminal to the time scheduled for making the
connection and other independent variables [94]. Martland described the applications
of PMAKE analysis in a 1982 article [96]. Martland explained that through development of the PMAKE function, MIT had "developed an effective methodology for predicting the performance of cars as they move through classification yards." In 1990 Martland used PMAKE functions to estimate the effect of Advanced Train Control Systems on terminal performance [93].

The concept of the PMAKE function was used in the development of a network model for general freight service, the MIT Service Planning Model [101]. The Service Planning Model was an analytical model for calculating the trip time and reliability for general freight moves over a network, based on train schedules, PMAKE functions for each terminal in the network and trip times between each terminal. Although the Service Planning Model is not useful for analyzing unit train operations, given that unit trains generally bypass terminals, it was successfully used to analyze network performance of general freight service.

Assarabowski [11] developed a simulation model for studying the operations of an assigned fleet. Assigned fleets are similar to unit train fleets in that the cars of an assigned fleet operate between a small number of origins and destinations, and like unit trains, travel loaded in one direction and empty in the other. However, cars of an assigned fleet do not necessarily stay together in large blocks or trainloads as unit train cars do. The Assarabowski Model simulated movement of cars over a network with one origin and multiple destinations. At the origin node an inventory of empty cars was held. Cars were filled and released to the railroad for transportation to one of the destination nodes. The trip time between nodes was modeled as a random variable; each car was assigned a trip time independent of the cars loaded before or after it. At the destination node cars were unloaded and released to the railroad for transportation.
back to the origin. The model was successfully applied to analysis of shipments of the Milwaukee Road for the Miller Brewing Company.

Following development of the Assarabowski Model and development of the Service Planning Model, the MIT Rail Group used the Service Planning Model in a study of the operations of the Atchison, Topeka and Santa Fe Railway’s (ATSF) Northern and Southern Divisions. Richard Gray of ATSF supplemented the study with a careful analysis of bulk handling operations on the Northern and Southern divisions [50]. Gray pointed out that the Service Planning Model could not be used to evaluate alternative operating strategies for unit train operations, but speculated that the Assarabowski Model could be used to do so.

Martland considered the issue [95] and concluded: “I suspect the [Assarabowski] model could be used, but only with some modification. It would provide a good example for someone starting from scratch to build a bulk distribution model.” After Martland came to this conclusion in 1980, no additional work was performed at MIT to develop a unit train network model until the current research effort, which began in 1996 with a review of Assarabowski’s work.

Recent work in analysis of rail network operations includes research performed by Matland [100], Kwon [84] and Dong [40]. Martland studied railroad network models, comparing more successful and less successful models and modeling approaches. Kwon explored issues in managing heterogeneous traffic on railroad networks. He developed two basic simulation models: one for examining the affects on trip time, reliability and logistics costs of varying the way different priorities of freight are handled in making up trains, and one model for optimizing the routing of heterogeneous traffic over a network.
Dong explored the differences in network operations for two different basic operating strategies: scheduled and flexible operations [40]. Dong developed a detailed simulation of a hump yard, and quantified how the yard would be operated using either strategy. Also, he connected a series of yards together using a simple model of line operations to show how the effects of different yard operating strategies effect the performance of a network.

3.1.3 Unit Trains

The MIT Rail Group has conducted several studies regarding issues in unit train operations, although none of these efforts involved development of a network model for analyzing unit train operations. In 1988 Martland studied the application of unit train technology to the Egyptian Railways [99]. Martland reported that for developing countries the fundamental strategies for maintaining a competitive freight railroad were: to focus on traffic for which rail has a competitive advantage over truck, to replace general subsidies with specific payments for services or projects, and to allow railroads to improve productivity and adjust the size of their workforce. In many developing countries these strategies tended to lead towards increased use of unit trains for shipment of bulk commodities.

Also, Martland discussed measures of unit train performance, including equipment costs, operating costs and cycle times. The development of unit train service on the Egyptian Railways was described, and the implications for other developing countries of the experience of the Egyptian Railways were presented. Martland concluded that the relative simplicity and efficiency of unit train operations made offering unit train service an attractive alternative for other developing countries. However, unit train service required coordination between different departments of a railroad, restructuring of railroad marketing, and development of accurate cost functions.
Stafford researched reliability, competition and management issues in coal shipping in the U.S. [123]. His research summarized general characteristics of coal consumption and production, described the elements of coal logistics costs, and described several representative coal movements: a long-distance western coal movement, a short-distance western movement, and an eastern coal movement. Stafford documented the costs in shipping coal, and presented issues facing shippers and carriers from the perspective of mine, utility and railroad. Finally, Stafford presented additional details concerning coal shipping at Conrail. Stafford's research provides very useful background information for understanding issues concerning unit coal train operations in the U.S.

Another research effort performed at MIT relating to unit train service was performed in 1994 by Kwon, Martland and Little [85]. This effort was study of origin-destination trip times for covered hopper cars moved by unit train service. The data for the study was obtained using the AAR Car Cycle Analysis System, designed for analysis of car cycle time. Data were collected for over 350,000 car cycles, approximately 10% of the covered hopper movements reported for 102 origin-destination pairs between December 1990 and November 1991. For each origin-destination pair statistics were generated for mean trip time, standard deviation of trip time, n-day percent about the mean, and maximum n-day percent. The study reported that the average cycle time was 24 days for all hopper cars and 15 days for hopper cars in unit train service. The average trip time was 5.3 days, the standard deviation of trip time was 2.0 days, and the maximum 2-day percent was 61%. Based on this data, the report concluded that hopper car traffic was generally more reliable than box car traffic, but cycle time and reliability varied considerably depending on type of service (general or unit train service) and specific origin-destination pair.
3.2 Literature Review

A research of the available academic literature was performed to help determine what models and approaches could be used for analyzing network operations of unit coal trains, and to relate this study to other recent research on railroad operations. The focus of the review was on research in railroad operations published in the ten-year period from 1987 to 1996. Table 3-1 lists the publications that were included in the review.

Articles and reports published prior to 1987 generally were not included in the review. However, several pre-1987 references were found that were specifically related to unit coal train operations, and these were included in the review. Also, articles from Heavy Haul Proceedings from 1982 and 1986 were included in the review, as some described particularly relevant research, and were not reviewed elsewhere.

For the publications listed in Table 3-1, articles relating to the following areas were reviewed:

- unit train operations
- coal transportation
- freight railroad network operations
- freight railroad line scheduling/dispatching models
- freight railroad terminal models
- freight railroad line or network capacity determination
- development of freight railroad operating plans

Articles relating exclusively to passenger railroad operations, railroad maintenance, trackside technology (such as installation of Advanced Traffic Control Systems), railroad management, and other areas were not included in the review.
Other publications, besides those listed in the table, were searched for relevant articles using the Compendex database for the years 1987 to 1996. This search produced several additional articles, particularly with regard to modeling coal transportation. These articles were included in the review.

All of the articles reviewed concerned the development and/or application of models for use in analyzing coal transportation or rail operations. The review was organized by the scope and type of models developed or used. The scope of each model is that of a line, a terminal, or a network. Line models concern operations of trains over a rail line or a small set of lines, and are typically used for train scheduling, dispatching or capacity analysis. Line models do not involve modeling of trains at terminals. Terminal models analyze the performance of a rail terminal, and are typically used for testing operating strategies or predicting or optimizing terminal performance. Network models concern both line and terminal operations, and are typically used for designing operating plans, predicting network flows, or testing operating strategies.

Two basic types of models were reviewed: performance models and supply models. Performance models are used to predict how a line, terminal or network will perform based on a particular operating strategy or scenario. Most simulation models may be characterized as performance models. Supply models determine how to manage transportation supply based on a set of demands or operating constraints. Most optimization models used for modeling railroad operations may be characterized as supply models.

The following sections present the results of the review. Section 3.2.1 summarizes other literature reviews. Section 3.2.2 describes literature pertaining to models of line performance. Section 3.2.3 describes literature pertaining to models for line supply,
primarily used for optimizing scheduling. Section 3.2.4 describes literature pertaining to terminals. Section 3.2.5 describes literature pertaining to network performance, and Section 3.2.6 describes literature pertaining to network supply. Within each section, the literature generally is described in the chronological order in which it was published.

3.2.1 Other Literature Reviews

A number of researchers have reviewed the pre-1987 literature pertaining to railroad operations and coal transportation. In 1980 Assad published general reviews of models for rail transportation [10] and rail networks [9]. Harker described the state-of-the-art in predictive analysis of freight transportation systems in 1985 [58]. In 1987 Crainic described the state-of-the-art in modeling multimode freight transportation [35], and Dejax and Crainic reviewed models for rail fleet management [37]. Also in 1987, Waters and Uyeno summarized models for use in logistics planning and management for coal exports [135]. Their book, Export Coal Logistics: Management, Models and Moving Coal, described existing models based on queuing theory, linear programming, computer simulation, and inventory theory.

Since 1987 several more researchers have reviewed the literature pertaining to railroad operations. Crainic described the development of strategic network models for rail freight transportation planning [36]. In 1994 Schwanhäußer described probabilistic and simulation models developed in German-speaking countries for use in modeling railroad line operations, including the SIMU line simulation model developed at the Technical University of Hannover [119]. Also in 1994 Cook provided a general background on freight network models [34] and Rao described network planning models and discussed current practice in the rail industry [106]. Recently Martland reviewed approaches to rail network modeling [100]. In 1995 Hallowell summarized developments in line performance models [55], and in 1996 Kraay summarized developments in real-time scheduling for railroads [79].
3.2.2 Performance Models for Line Operations

A significant portion of the railroad operations research literature published between 1987 and 1996 relates to performance models for analyzing line operations. Most such models described in the literature are detailed simulation models used for analyzing delays from train meets and passes, testing dispatching strategies, determining line capacity, and scheduling track maintenance. The review concentrated on literature pertaining to freight railroads. However, some of the articles found in the literature and included in the review described models applicable to both passenger and freight rail operations.

The 1982 *Heavy Haul Proceedings* included several articles related to modeling line performance. Hanks described the approach to planning for traffic growth followed by the Canadian National Railway (CN) [56]. Hanks presented graphs relating the number of trains operating on a rail line to train running time and delay. In addition, he described the computer models CN used to determine capacity in a detailed manner, including the Line Interactive Model. Also in the 1982 *Heavy Haul Proceedings*, Kloer described the Burlington Northern Railroad's (BN) approach to capacity planning [76]. BN used the Line Capacity Model for detailed study of particular lines, but developed rules-of-thumb based on simulation runs to quickly evaluate line capacity for a large number of line segments. Kloer described specialized situations modeled using the Line Capacity Model, such as modeling delay caused by track maintenance.

Several articles published in 1988 presented analytical approaches to calculating train delay and line capacity. Greenberg presented a set of queuing models for predicting delay caused by train meets [51]. The models were developed for single-track lines with low-speed operations where capacity of sidings is not a limiting factor. Greenberg compared the predictions of the queueing models to simulated operations of freight
trains on the Alameda Corridor in California. Comparison of the queuing models with simulated operations indicated that the queuing models produced results comparable to the simulation model except where limited siding capacity affected train delay. Milan presented a similar model for analyzing rail line capacity [102]. Milan's model was a queueing model developed for use in analyzing the bottleneck (most congested) segment of a single-track line. The model could be used to predict train delay over the bottleneck segment, and thus determine the maximum capacity of the line.

Kraft presented a series of analytical models for use in rail line capacity analysis [81], including a model for "jam capacity" analysis, and an analytical model called the Multiple Train Interaction model that expanded upon earlier work performed by E.R. Petersen. Kraft compared the results of these models with the results of a detailed simulation, and concluded that analytical models provided a low-cost alternative to detailed simulation for estimating line capacity.

In 1990 Chen described an analytical model for estimating delay on single-track lines with scheduled traffic [30]. His two-moment model assumed that trains depart according to schedule, but with some variation about the scheduled times. Harker extended this work to apply to partially double-tracked lines [59].

Several articles in the 1991 Heavy Haul Proceedings dealt with the relationship between track maintenance and line performance. Baoyi presented an analytical approach to estimating the effect of track maintenance on line capacity [18]. Baoyi presented charts and graphs for estimating the effect of maintenance on capacity, and concluded that track maintenance, by causing train delay, has a significant effect on annual capacity. Szymkowiak described CN's system for managing conflicts between train service and track maintenance on its rail lines [124]. The CN system included a number of different
components for use in tactical planning of rail operations. The system could be used to
display the location of trains and create time/distance charts. As a user entered in data
on where maintenance would be performed, the system alerted the user of conflicts
between trains and maintenance events. Aspebakken described BN's Service
Maintenance Planning (SMP) system [8]. SMP was used primarily as a decision support
tool for plotting time/distance diagrams of trains on a line, and planning how to
schedule track maintenance given a particular train schedule.

Much of the literature pertaining to rail line performance described the development
and/or application of detailed line simulation models. As discussed in Section 3.1.2,
several railroad simulation models had been developed by the early 1970's, but the
general concern with using simulation models was the cost of developing and running
the models. Judging by the large number of simulation models described in the recent
literature, the cost of model development was not as significant an issue in the 1990's as
it was previously.

In 1991 Van Dyke described the development and application of ALK Associates' Line
Capacity Analysis System (LCAS) [131]. LCAS was developed based on Kraft's Chessie
Line Capacity Simulation Model. Van Dyke explained that LCAS was a multi-track
dispatching model that simulated the movement of trains, determined the locations of
train meets and passes, and that could be used to determine line capacity. Van Dyke
used the model to study the capacity of the Beijing-Shanghai Railroad Corridor for the
Chinese Ministry of Railways. The analysis involved other models as well, including
the Princeton Transportation Network Model for examining network traffic densities
and routing, and ALK's Automated Blocking Model for testing different railroad
marshaling plans. However, Van Dyke's article concentrated on the development and
application of LCAS. Van Dyke further described LCAS in a 1992 article for the Third
International Conference on Computer Aided Design, Manufacture and Operations in the Railway and Other Advanced Mass Transit Systems (COMPRAIL 92) [129].

At COMPRAIL 92, Wolf described a line performance model developed for the Norfolk Southern Railroad (NS) [143]. Historically, NS had relied on two models for line capacity analysis: the Over the Road Model, a line simulation model obtained by the Southern Railway from Missouri Pacific, and the Line Capacity Model, a more simplified model. In response to increasing needs for line capacity analysis, NS developed the Dispatch Analysis Model, another simulation model for determining line capacity, testing schedules, and evaluating the effect of maintenance on operations. Wolf described the features of the model, and reported that it had successfully been used by NS for planning purposes.

At COMPRAIL 90, Kos described the SIMU line simulation model developed at the University of Hannover [78]. Development of this model continued following Kos' article, and in 1996 Kaminsky described a more recent version of SIMU [70]. Also, Kaminsky explained that SIMU was integrated with models for routing trains (INVOZUG), creating timetables (SIMUPLAN) and assigning rolling stock (DISPO) to produce an approach for modeling network supply.

A number of other line simulation models were presented at COMPRAIL 92 and 96. Galaverna described a line simulation model developed in Italy for capacity analysis of rail and transit lines [49]. At COMPRAIL 92, Lidén described a line simulation model called TTS developed for use in Sweden [89]. At COMPRAIL 96, Bergmark described a newer version of the Swedish model called SIMON [19]. In 1992 Riley described VISION line simulation developed for use on the Thameslink project in Great Britain and a similar model called RAILPLAN used for planning for the Swedish X2000 high
speed rail system [108]. Tsiflakos described the simulation modeling approach used at British Rail and proposed a framework for integrating detailed line simulation models with network models [126]. In two different articles, Siu [121] and Okumura [104] discussed the application of object-oriented programming to railroad simulation. Komaya proposed a framework for integrating simulation and scheduling in railroad planning [77]. At COMPRAIL 96, Asuka (and Komaya) described a method for using microscopic and macroscopic simulation models for modeling line performance [12].

Several other recent articles discuss models for line performance. Van Hook discussed the line performance models used for planning capacity improvements for the Burlington Northern Santa Fe Railway (BNSF), following creation of the railroad from the merger of Burlington Northern (BN) and ATSF [132]. The BN and ATSF used different line performance models. ATSF used the Dispatch Planning Model, and BN used the Line Capacity Model. Van Hook explained that both models predicted line performance as a function of a train schedule, but that the Line Capacity Model was more complex, and included the capability of modeling random events on a line, such as track closure due to maintenance events or unscheduled unit train moves. BNSF decided to use the Dispatch Planning Models for shorter line segments, and the Line Capacity Model for longer, more complex line segments.

In 1995 Higgins discussed the issue of modeling the risk of delay on a rail line [62]. He explained that although mathematical programming models have been used to optimize train schedules (as discussed in the following section), optimized schedules may be unstable. That is, a schedule that is optimal, judged using a particular objective function and assuming deterministic conditions, could lead to highly unreliable operations for variety a reasons, such as if there is little "slack" in the schedule. Higgins proposed an analytical model for calculating the probability of train delay and for
estimating mean delay. The model was applied to an optimized train schedule. Higgins concluded that delay risk should be included in future models for optimizing train schedules.

In a 1996 article Hallowell discussed a problem similar to Higgins': predicting on-time performance for a rail line with an optimized schedule [55]. Building upon a two-moment model for estimating delay developed previously [30], [59], Hallowell developed a model called the Target Time Generator (TTG) for predicting which trains on a line would be late, and estimating their tardiness. Comparison of the results from TTG to simulated results indicated that the model could predict which trains would be late, but estimates of arrival times were best for double-track lines or single-track lines with "loose targets."

3.2.3 Supply Models for Line Operations

Whereas performance models for line operations typically are analytical or simulation models for predicting how a line will perform given a train schedule and/or other conditions, supply models for line operations determine how to schedule or operate trains over a line to meet a set of objectives. Most supply models developed for line operations are optimization models for developing train schedules.

In 1987 Kraft presented a branch-and-bound model for optimizing train schedules [80]. Branch-and-bound is a common approach to solving integer programming problems, but given that using branch-and-bound results in computation times that grow exponentially with problem size, this approach tends to be practical only for relatively small problems. Kraft tested the model using scheduled data from CSX, and concluded that optimizing schedules could reduce train delay by 15% on average, and up to 55% in some cases.
In 1990 and 1991 Jovanovic published two articles that developed a framework for applying optimization methods to computer-aided train dispatching [67], [68]. In another article Jovanovic presented a model for helping develop optimal train schedules, the Schedule Analysis System (SCAN) [69]. Jovanovic explained that SCAN was a tactical scheduling model. The user provided the model with a train schedule, SCAN checked to determine whether or not the schedule was feasible, and then modified the schedule to improve it. To do this SCAN formulated the train scheduling problem as a mixed-integer programming problem, and made limited use of simulation methods. All trains were required to be scheduled (including unit trains), and all variables were assumed to be deterministic. With Jovanovic's formulation the problem was computationally tractable for much larger problem sizes than were previous optimization models.

Smith described how the use of improved scheduling methods would affect railroad service [122]. For the Advanced Railroad Electronics System (ARES) Program at BN, Smith used SCAN to estimate the benefits of improved scheduling. He concluded that improved scheduling would have a positive impact on service, but the value of improved service depended upon one's assumptions regarding how much railroad customers valued improved service.

Higgins published two recent articles on optimizing train schedules for single-track lines [61], [63]. He formulated integer programming problems for both optimal train scheduling and optimal siding location for a single-track line. Higgins discussed applying the model to short-term tactical planning, as well as to strategic planning applications, such as determining optimal locations for sidings and planning for infrastructure improvements.
3.2.4 Freight Rail Terminals

This section discusses recent literature relating models for rail terminal operations. All of the articles on terminals included in the review relate to terminal performance models rather than supply models. Performance models have recently been developed for analyzing general freight, intermodal and coal terminals.

As discussed in Section 3.1.2, Martland developed the PMAKE for use in analyzing terminal operations [96], and in 1990 used PMAKE analysis to estimate the effect of Advanced Train Control System on terminal performance [93]. In 1992 Keaton analyzed the effect of optimizing train timetables on terminal performance [72]. Cases were examined in which trains arrived at a terminal without regard to processing time, and using a timetable designed to minimize terminal delay. Keaton reported that optimizing timetables could significantly reduce terminal delay.

Several articles in the review concerned operations of intermodal terminals. Ferreira discussed the issue of measuring terminal performance [44]. He developed a set of performance measures for measuring terminal performance, and presented a simulation model for determining how performance of an intermodal terminal in Australia would vary under different operating strategies. Sarosky reported on an intermodal terminal simulation model developed by the Consolidated Rail Corporation (Conrail) [118]. Using the simulation package SLAM, Sarosky developed a simulation model for determining train dwell times, truck dwell times and truck parking requirements for a Conrail terminal, and for testing different terminal operating strategies. Weigel described a railroad intermodal terminal model developed by the Union Pacific Railroad [136]. The Intermodal Capacity Planning Model simulated arrival, loading, unloading, switching and departure of intermodal trains, and was used to estimate
terminal performance, estimate capacity, and calculate appropriate cutoff times for shipment of intermodal containers.

Wong presented a simulation model for analyzing coal handling at a thermal power station [144]. The model was used to plan the unloading facilities for a coal-fired thermal power station that would receive coal by ship. Wong's simulation modeled the ship arrivals, unloading, coal stacking, reclaiming, and coal consumption, as well as machine breakdowns and other stochastic events.

Two articles from COMPRAIL 96 discussed simulation of rail marshaling (hump) yards [75], [28]. Klima described the development of RBSIM, a hump yard simulation model under development in Slovakia. Klima explained that RBSIM was to include detailed representation of the operations of a hump yard, and would present a range of output statistics, including reports on utilization of locomotives, arrival tracks, and the hump. Cenek discussed RBSIM's modeling of movement of trains switching a hump yard [28].

In 1996 Martland and Little described the use of PMAKE functions and the Intermediate Terminal Model (ITM) for analyzing terminal operations [98]. They explained that the ITM was developed in 1994 to analyze hump yards for CSX and the Union Pacific Railroad. The ITM was an analytical model that could be used to estimate terminal performance based on the pattern of inbound arrivals, processing times, connection reliability (PMAKE function), and unit costs.

3.2.5 Performance Models for Network Operations

Early network performance models discussed in previous sections include those reviewed by Folk [45], the Service Planning Model, and the Princeton Transportation Network Model. Compared to line performance models, the network models are broader in scope, and account for interaction between different lines and between lines
and terminals. However, the network models tend to model line operations in less
detail than the line performance models. Also, although most of the line performance
models are intended only for modeling scheduled operations, most of the network
performance models in the review depict or can be used to model unscheduled
operations, such as unit train operations.

Two articles in the review discussed a network model of the unit train operations of the
Mount Newman Mining Company Railroad [22], [115]. The first of the two articles,
written by Brown in 1982, described the operations of the railroad, and the simulation
model TRAINOPS [22]. The Mount Newman Mining Company Railroad was a 420-
kilometer railroad that operated between an iron ore mine and Port Hedland, Australia.
The model TRAINOPS simulated movement of trains along the line, loading and
unloading of trains. The model was used to evaluate the cost and performance of
eleven different operating strategies. In 1991 Rucinski described the Mainline
Operations Model (MOM), a similar model to TRAINOPS [115]. MOM was used to
simulate the changes in performance resulting from alternative track configurations,
planned track maintenance, unplanned events (such as rail breaks), or schedule
changes.

In 1988 Leonard presented an analytical model for analyzing network performance [88].
The model was developed as a decision support system for evaluating alternative
operating and investment strategies for the railways of Southern Africa. Based on an
extensive set of user inputs, the model applied formulas for determining capacity,
performance, operating costs and maintenance costs. As a case study the model was
applied railroad network of Botswana. Leonard estimated the effects of several
different operating scenarios, including different signaling methods, increasing train
size, and increasing traffic.

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Another network performance model was described by Bammi in 1990 [16]. Bammi developed a simulation model for analyzing the transportation of pipe from three ports and three mills throughout the U.S. to a pipeline construction project along the northern U.S. border. The simulation model included estimates of transportation, loading and unloading times, and was used to determine the time need to ship the required amount of pipe from the different sources.

In 1991 Ash described a simulation model developed to compare the cost and capacity of shipping coal across Canada (from Western to Eastern Canada) using different transportation strategies [7]. Ash compared shipping coal by a combination of rail and ship (the standard practice) to direct shipment by rail, shipment by high-efficiency rail, shipment by ship through the Panama Canal, shipment of coal slurry by pipeline, and avoiding shipment by building power plants at mine mouths. Ash's model was very broad in scope, but was not intended to model movement by individual trains (as was done in many of the rail simulation models).

Allen published an article describing the use of three different models for analyzing the operations of the Cape Breton Development Corporation (CBDC) in Nova Scotia, Canada [5]. The CBDC mined coal and transported the coal by rail over a short distance between their coal mines and a port. To improve the efficiency of its operations, the CBDC developed a simulation model representing its operations, and used the model to test different operating strategies. Strategies tested included using longer trains, using more trains, adding loading facilities, and managing locomotives differently. The simulation indicated that better locomotive was the most effective strategy. Based on the results of the simulation, the CBDC then developed a simple queuing model to
screen a large number of alternatives, and developed Gantt charts to best present alternative strategies to management.

Cook described a performance modeling effort performed for the Chinese Ministry of Railways [34]. For this project a network model was required that provided detailed estimates of parameters not modeled in many general network models, such as link capacity, cost and transit time, but that did not require the same amount of input data as a detailed line simulation model. The Facility Performance Model (FPM) was developed for the project. The FPM was an analytical model for estimating the capacity and cost of individual links in a rail network based on general data (less detailed than that required for a line simulation model) concerning the physical characteristics of the links, a set of technical parameters, and a set of unit costs.

Rao described the process by which a railroad determined its needs in developing a network model [106]. In describing the process of how the railroad adopted a network model, Rao described the capabilities of existing network models, summarized what models were in use at major U.S. railroads, a presented the motivation of one railroad in developing a network model.

Two recent articles provided examples of network performance models applied to studying issues in railroad service. Kraft developed a simple network simulation model to explore the effects of demand variability on service reliability [82]. As discussed in Section 3.2, Kwon used a network simulation model to test the impact on performance of different service differentiation strategies [86].

In 1995 Dessouky developed a rail network simulation model to analyze operations for the Alameda Corridor Project in Los Angeles [38]. Dessouky modeled the unloading
and loading of trains, as well as line-haul movements of individual trains. He found that delays at complex junctions rippled through the network, especially as the number of trains operating on the network increased. However, the simulation indicated that total train delay for the three railroads operating along the Alameda Corridor (ATSF, Union Pacific and Southern Pacific) would decrease by 38% if operations were consolidated from three different single track lines to one double track line.

3.2.6 Supply Models for Network Operations

A number of different researchers have explored the use of supply models for solving problems in railroad network operations. Under the broad category of network operations there are several more specialized topics that have been the subject of the most research in recent years. These include development of operating plans, which includes development of plans for routing, scheduling and blocking trains; optimizing empty car distribution; optimizing locomotive distribution; and strategic planning of freight flows. Recent research in each of these areas is discussed below.

Improving the development of operating plans has been addressed using a range of different models. In 1990 Van Dyke discussed the models offered by ALK Associates for improving operations and service planning [128]. Van Dyke developed the Automated Blocking Model (ABM) for assigning rail cars to blocks (a block is a group of cars that moves together between an origin and destination). In addition ALK developed the Train Scheduling System (TSS) for helping design train schedules, and offered the Service Planning Model (SPM), developed at MIT, for predicting trip times and reliability. Of these models, both the ABM and TSS were supply models, in that they suggested the best way to use railroad resources to provide transportation supply sufficient to meet demand. The ABM and the TSS were not optimization models intended to provide best solution to block and schedule all railroad traffic, but ALK recommended their use as a tool in planning and assisting in general studies of
operating strategies. The SPM was a performance model, but was intended to be used together with the ABM and TSS. All of these models were intended for use at a tactical or strategic level. In 1988 Van Dyke discussed the issues involved in dynamically managing block plans, to simplify the procedures and improving the efficiency of railroad blocking [130].

In 1989 Keaton presented a mathematical programming formulation for use in optimizing an operating plan [71]. The problem was to minimize train cost, car time cost and yard classification cost subject to constraints on train size the number of blocks and trip times. Given that Keaton's formulation was an integer programming problem, he suggested a heuristic method to quickly obtain approximate solutions, and a Lagrangian relaxation approach to solve the problem to optimality. In 1992 Keaton presented a dual adjustment method for implementing the Lagrangian relaxation approach [73].

Adams suggested a framework for implementing a rail traffic flow control system, a means for managing rail operations in real time [4]. Adams pointed out that railroads were managed using operating plans developed months in advance, and that having the ability to change the operating plan dynamically in response to changing conditions could lead to more efficient operations.

Martinelli suggested two approach for optimizing operating plans [92], [91]. Although a number of researchers have suggested mathematical programming formulations for optimizing plans, the solution time required for realistically sized networks is often prohibitive. Martinelli described how to use neural networks [92] or a genetic algorithm [91] as an alternative to other solution techniques.
In 1995 Kraay presented a model for optimizing train schedules, one element of railroad operating plans [79]. Kraay extended upon the work in optimizing train schedules for a single line (discussed in Section 3.2.3), formulating the scheduling problem for an entire network. Kraay suggested a heuristic for quickly solving the problem, and tested the solution heuristic using the schedules for a portion of the network of a major U.S. railroad.

Huntley described the approach to train routing and scheduling used at CSX Transportation [66]. CSX developed the Computer-Aided Routing and Scheduling System (CARS) to help route and schedule its trains. Given a plan for a particular type of service, CARS displayed the plan graphically, estimated statistics on cost and service for the plan, evaluated the plan, and attempted to improve on the plan by optimizing based on a set of user-defined objectives. Huntley described how CARS was used to help optimally route and schedule CSX grain trains.

Empty car distribution and fleet management are two additional areas of research in rail network operations. The challenge is to determine how to distribute rail cars or containers through a network to best meet existing and predicted demand. Extensive work in these areas was performed between 1975 and 1985 through the AAR-FRA Freight Car Utilization Program and the Freight Equipment Management Program. In 1989 Haghani formulated a combined model for empty car distribution, as well as train routing and makeup [54]. To solve the problem he suggested a heuristic decomposition technique, and tested it using real data from a portion of the rail network (four nodes and five links) in the Chicago area.

In 1990 Chih described a fleet management model developed by ALK Associates, the Routing and Inventory Logistic System (RAILS) [32]. RAILS was developed to help
manage the double stack trains of American President Intermodal. API ran the model several times a day with a planning horizon of fourteen days to help determine how to manage its inventory of intermodal containers.

Adamidou examined the empty car distribution problem using game theory [3]. Adamidou discussed the fact that individual railroads each try to optimally manage their fleets, and that the distribution of empty cars represents the equilibrium resulting from each railroads efforts at maximizing its profits. The freight car distribution problem was formulated as an N-player, network-based, multi-commodity, non-cooperative, nonzero sum game. A solution approach was presented and tested for a two-railroad problem.

In 1996 Holmberg discussed computational experiments performed with a previously formulated empty car distribution model [64]. Holmberg compared the results and computation time using three different solution methods: a Lagrangian heuristic, an implementation based on a partitioning method, and solution using the mathematical programming package CPLEX. Holmberg reported that CPLEX provided an efficient method for solving the problem.

Two articles from 1990 discussed network supply models for analyzing locomotive distribution. Hornung discussed the design and prototyping of a system for providing information and management support for managing locomotives on the Canadian National Railway [65]. Chih described ALK's Locomotive Distribution System (LDS) [31]. LDS was designed to manage locomotive distribution in real time. The model performed six basic tasks: forecasting supply and demand for locomotives, generating a time-space network representing a mathematical programming formulation of the locomotive distribution problem, optimizing locomotive distribution, scheduling
maintenance, building consists of locomotives for specific trains, and presenting the data to human controllers for final decision-making.

Several articles in the review presented optimization models for strategic planning of freight flows. Osleeb described the Coal Logistics System (COLS), prepared for the U.S Corps of Engineers for use in coal logistics planning [105]. Based on data on coal mines (locations, capacities, type of coal and price), alternative transportation modes (costs and links for rail, barge, and ocean transportation), and demand, the model calculated the least-cost means of satisfying demand. Compared to previous models for strategic planning of coal logistics, such as U.S. Department of Energy's Coal Supply and Transportation Model (from 1983), COLS contained more detail on transshipment of coal using multiple modes (such as rail and barge), and more detail on ocean shipping.

Two articles published in 1990 describe the freight transportation models within a system for strategic analysis and planning of national freight transportation systems, STAN [52], [36]. Guélat described the multi-mode, multi-product network assignment model in STAN [52]. The model used a Gauss-Seidel Linear Approximation Algorithm to assign freight flows to transportation modes. Crainic described STAN's model for rail transportation [36]. STAN modeled in detail the geographical properties of the rail network, but the representation of operations on the network was necessarily less complicated than that of a simulation model. Nonetheless, the model of rail operations included a traffic-dependent estimate of train delay, and included flows of empty rail cars where necessary. STAN was used for strategic planning of freight flows for Brazil.

3.3 Review of Industry Practice

This section contrasts the literature on rail operations research presented in Section 3.2 to industry practice. Section 3.3.1 summarizes the role of models in railroad planning, and describes the general concerns of industry planners to adapting models from
research efforts to industry use. Section 3.3.2 discusses industry practice with regard to planning unit coal train operations.

3.3.1 Role of Models in Railroad Planning

The railroad industry has a history of developing and using computer models as an aid in planning. In many cases, individual railroads have developed their own computer models "in-house," while in other cases railroads have purchased standard models from a small set of companies specializing in railroad operations models. A number of the research efforts described in Section 3.2 were conducted or funded by U.S. railroads. In particular, railroads have actively developed models for line performance, as evidenced in the articles describing the line simulation models used by BN, ATSF, CN and NS. Also, some railroads have developed network supply models. For instance, CSX has developed the CARS model for train scheduling and routing [66], and NS has developed the ABC system to simplify blocking [100].

Companies that specialize in selling operating models to the railroad industry include ALK & Associates, Multimodal Applied Systems and Mainline Management Services. ALK offers a series of different models, such as the line capacity model LCAS, the network planning models SPM, ABM and TSS, and the locomotive fleet planning model LDS [131], [128], [31]. Of these models, the SPM is particularly well established, and has been used by most major U.S. railroads [100].

Multimodal offers the model Multirail. Multirail was not described in any of the articles in the literature review, but based on the author's experience, Multirail is a graphically-oriented, user-friendly model for designing routes and blocking plans, similar in function (though not in form) to the network models offered by ALK [110]. Multirail has been used by a number of major U.S. railroads, particularly for determining how to restructure operating plans following a merger. Multirail does not
have any optimization features for line operations, except that managers can use the model as a tool in optimizing their planning, but future versions of the model will incorporate the line model SCAN [125].

Mainline Management Services offers the Operations Cost Model (OCM), and a suite of tools that supplement OCM, such as the Service Planner and the YardMaster [100]. OCM was developed in the 1970's by the U.S. Railway Association, and was been used by most major railroads for evaluating the effects of changing operations on operating costs.

Martland discussed the challenges in applying network models developed through research for use in the rail industry [100]. He described the features of successful modeling approaches, such as the SPM and OCM, and compared these to less successful approaches, such as simulation and optimization. Martland reported that network simulation models have been used for testing new operating plans, but are too cumbersome for developing new plans. Optimization models have thus far failed to work as well as existing control systems in optimizing the many aspects of railroad operations, and the models often have been developed with greater attention to methodology than to the practical requirements for successful implementation.

As a result of the concerns discussed by Martland, the models used by the rail industry are typically not as algorithmically advanced as many of the supply models described in the review. However, many of the models developed by the rail industry and described in Section 3.2, and newer commercially-available models such as Multirail, are particularly strong in collecting and displaying data for use by human decision-makers.
3.3.2 Planning Unit Coal Train Operations

With regard to planning unit coal train operations, relatively few of the models described in the review relate to unit coal trains, and none of the models in the review have been used by a major U.S. railroad for network planning of unit coal train operations. Also, none of the commercially available models described above are appropriate for planning unit train operations.

With or without network models, U.S. railroads do plan and conduct unit coal train operations quite regularly. As an aid in their planning and operations they use both manual methods and in-house models. As discussed in Chapter 2, coal traffic is a significant source of revenue for all of the major U.S. Class I railroads; unit coal train service is particularly significant at UP, BN and NS. Strategic planning of unit train operations at the major U.S. railroads, and tactical planning at railroads besides UP, is typically performed using manual methods [111], [97], [15], [109]. Train cycle times are established based on historic data and rules-of-thumb, and goals for unit coal train service typically are dictated either by contractual arrangements or by the goal to move as much coal as possible using the available resources. The most frequently cited problems with manual methods are that they are time-intensive, and do not provide adequate means for predicting or responding to changing conditions.

One major U.S. railroad, UP, has developed in-house a model for helping plan unit train operations. UP has developed the Bulk Train Planner [27]. Essentially, the Bulk Train Planner communicates with UP's Transportation Control System to display real-time information on the location of unit coal trains. UP managers use the information from the Bulk Train Planner, in addition to rules-of-thumb based on previous experience, to make changes in operations where necessary. However, the model has not been used
extensively for strategic planning of unit train operations [111]. The Bulk Train Planner has been in use at UP for approximately two years.

3.4 Conclusions of the Review

The detailed literature review was performed to identify approaches or models that have been used for analyzing unit coal train operations. Particular attention was given to models used for analyzing coal transportation and unit train network operations. MIT railroad research, academic research published between 1987 and 1996, and information obtained on industry practice in unit coal train operations were included in the review.

No general model or approach was identified that could readily be applied to analyzing a large-scale network with unscheduled operations at a medium level of detail. However, the available literature suggested a number of significant results, as summarized below. The most significant results are printed in italics.

The literature review included five examples of models that have been used for analyzing the operations of a unit train network at an appropriate level of detail. The research performed for the Mount Newman Mining Company provides the most complete example of analyzing the operations of a unit coal train network [22], [115]. Bammi [16], Ash [7] and Allen [5] developed simulation models for analyzing unit train or coal transportation networks at a detailed enough level to experiment with different operating strategies and predict vehicle cycle times. However, in each of these cases, the literature described only one application of each model. No author discussed how his or her model could be applied to a more general network, as required for general analysis of issues in unit coal train operations.
Most of the models described in the literature could be categorized either as simulation models, optimization models, or analytical models that do not involve optimization. The simulation models provide examples of how to model rail lines and rail networks, but all included in the review were either: (1) developed to model a particular project (such as the five discussed above), or (2) were intended to model a portion of a network in great detail. Most of the detailed simulation models were line simulation models. *In either case, applying the simulation approaches used in the literature to a more general network model would be very difficult.*

Two exceptions to this conclusion are models developed by Dessouky [38] and Assarabowski [11]. Dessouky developed a general modeling methodology for simulating double-track or single-track lines, and applied the methodology to analyzing operations for the Alameda Corridor Project in Los Angeles. Although the methodology could be used for modeling line operations, Dessouky did not discuss his approach to terminal, loading and unloading operations. Assarabowski produced a simulation model for analyzing assigned fleets that could be expanded and adapted to analysis of unit train operations [11].

*The optimization models presented in the literature do not provide examples of approaches that could be used to predict detailed variables such as cycle times over a large-scale network.* All of the optimization models included in the review either modeled a small network or a piece of a network in great detail and could not easily be extended to a large network, or they modeled a large network at a low level of detail. Optimization models in the latter category include strategic models that include little or no detail on individual operations between specific origins and destinations.

The available literature did not provide examples of other (non-optimization) analytical models being applied to unit coal train networks, but lacking simulation or
optimization models, industry practitioners rely on other analytical approaches not discussed in the literature.

A number of commercially available railroad network models have been developed, requiring a medium level of detail and incorporating a combination of modeling techniques. These have been used for developing operating plans and analyzing railroad mergers. However, the available network models, like much of recent railroad research, concentrate on scheduled operations. Thus, the most powerful network models, such as SPM, ABM, and Multirail, cannot easily be used for evaluating unit train operations.

The railroad industry has a history of developing and using computer models as an aid in planning. A number of the research efforts described in the review were conducted or funded by U.S. railroads. However, the models used by the rail industry are typically not as algorithmically advanced as many of the supply models described in the review. Railroad decision makers are necessarily less concerned with applying advanced modeling methods and more interested in using methods with which they are familiar and believe to be proven effective. Many of the recent models developed by the rail industry and the newer commercially-available models are particularly strong in collecting and displaying data for use by human decision-makers.

Railroads have used simulation methods for analyzing line operations, but have not made extensive use of network simulation, other than in the earlier efforts described by Folk. There are very few examples of successful applications of optimization methods at U.S. railroads.

Strategic planning of unit train operations at the major U.S. railroads, and tactical planning at railroads besides UP, is typically performed using manual methods. Train
cycle times are established based on historic data and rules-of-thumb, and goals for unit coal train service typically are dictated either by contractual arrangements or by the desire to move as much coal as possible using the available resources. UP has developed the Bulk Train Planner for displaying real-time information on the location of unit coal trains. UP managers use the information from the Bulk Train Planner, in addition to rules-of-thumb based on previous experience, to make changes in operations where necessary. The model has been used primarily as an aid in real-time operations management and has been used somewhat in tactical planning. However, the Bulk Train Planner has not been used extensively for strategic planning of unit train operations.

In summary, the review indicates that no general model has been developed and is available for analyzing network operations of unit coal trains. However, several efforts suggest very useful approaches to modeling railroad networks or unit freight train operations. The following chapter presents a general model for analyzing unscheduled unit train operations over a large-scale network.
CHAPTER 4: DEVELOPMENT OF THE SIMULATION MODEL

The literature review presented in Chapter 3 revealed a number of useful approaches to modeling railroad networks, but no model appropriate for general analysis of unit coal train networks. This chapter describes UTRAIN, the model developed for analyzing network operations unit coal train operations. UTRAIN was designed to simulate the operation of a unit coal train network, and to test the effects of different operations scenarios and control strategies. For instance, for different operating scenarios one may wish to test the effects of increasing track capacity for a particularly congested line segment, increasing the number of servers at a critical terminal, or changing the number of trains operating on the network.

UTRAIN is a simulation model. Simulation is a powerful tool, but a great deal of human judgment is required in developing an accurate, useful and credible simulation model. Section 4.1 discusses important considerations in using simulation for the present research effort.

Section 4.2 describes the structure of the model. UTRAIN represents a complete unit coal train network. Individual trains move through the network, filling orders for shipment of coal between specified origins and destinations. Tracks on which trains travel are represented as arcs. Loading facilities, unloading facilities and other places where trains stop or where arcs meet are represented as nodes. The flow of the network may be interrupted by a number of events, including movement of other types of traffic over the network, track closure due to maintenance, or other occurrences. Running the model requires at set of input parameters for the trains, orders, arcs, nodes and events.
Each model run produces output detailing train cycle times, equipment utilization, line utilization, average time trains spend at each node, and other parameters.

Section 4.3 describes the algorithmic aspects of UTRAIN. Data structures were developed for representing the network elements. Algorithms were developed for file input and output, indexing and re-labeling network elements, computing shortest paths, and for simulating network operations.

4.1 Considerations in Developing a Simulation Model

Winston [142] defined simulation as “a technique that imitates the operation of a real-world system as it evolves over time.” Law and Kelton explained that in using simulation, one makes a set of assumptions regarding a system, and then uses a computer to evaluate those assumptions numerically, gathering data to estimate the true characteristics of the system [87].

Simulation is a powerful tool, and has been used extensively in modeling of transportation systems. The literature review described in Chapter 3 included a number of examples of the use of simulation in researching railroad operations. Recent examples of the use of simulation to model transportation systems include applications of simulation to air traffic networks, highway traffic networks, and logistics networks [20], [43], [48].

However, the mere fact that simulation is a widely-used method for researching transportation systems does not indicate that simulation is the most appropriate method for analyzing unit coal train operations. Indeed, if a system can be modeled analytically, then analytic methods should be used to calculate exact values for the parameters of interest [87]. Shannon explained that simulation should be used if a complete mathematical formulation of the problem does not exist, or if analytical
methods of solving the mathematical model have not been developed or are too time-consuming [120]. Simulation is the most practical method for analyzing unit coal train network operations because no analytical approach appears to be feasible that could model a reasonably sized unit coal train network at the appropriate level of detail.

Besides being easier to implement for the present research effort than analytical methods, simulation has several other advantages. Simulation has been widely used in line capacity models in the rail industry (though not as much for network models), and rail planners are generally familiar with this approach. If a simulation model can be shown to accurately predict actual conditions, railroad planners will tend to place greater faith in the simulation results, compared to results found using methodologies perceived to be new to the rail industry. Also, simulation models are well-suited for handling constraints in capacity (on rail lines and in rail facilities), for conducting what-if analyses, for exploring network effects, and for demonstrating analysis results (such as through computer animation of the simulation's operations).

Simulation also has significant potential disadvantages. Shannon cautioned that developing and running simulations can be time-consuming, that a simulation may appear to reflect the real world but actually fail to do so, and that simulation tends to give imprecise results [120]. Also, simulation models tend to be "data-hungry," requiring a large amount of user-supplied input to generate a result. Also, although simulation is well suited for answering "what-if" questions, performing optimization with a simulation model is a slow process [142].

In discussing the principles of valid simulation modeling, Law and Kelton highlighted the issue of determining the appropriate level of detail for a simulation model [87]. It is in this area where particular attention has been devoted in the development of
UTRAIN. Law and Kelton wrote that in developing a simulation model, one must carefully consider what measures to evaluate, and make sure that the model addresses the right problem. Also, they warned that many modelers include an excessive amount of detail in their models. Law and Kelton recommended the use of "experts" or sensitivity analysis to determine the appropriate level of detail, and that the simulation model be designed in such a way that more detail could be added if necessary. Finally, they cautioned that the level of detail in a model should be consistent with the available data.

The intent behind development of UTRAIN was to create a simulation model that represented the operations of a unit coal trains at a medium level of detail, and at a network-wide scope. The model was designed to track the movement of individual trains through a large network; predict origin-destination cycle times, equipment utilization, track utilization, time spent in yards, and other important parameters; and include all important factors that may have a major impact on network performance. These factors include capacity constraints for lines and terminals; delays caused by other traffic, track maintenance, or random events (inclement weather, rail breaks, and so forth); and network effects. In determining the level of detail for the model, a balance was sought between minimizing the level of user-supplied data to that which is available and easily determined, and including enough detail to accurately determine the measures of interest.

4.2 Model Structure

This section describes the structure of the simulation model. Section 4.2.1 presents the elements of the network simulated by UTRAIN. Section 4.2.2 and 4.2.3 list the model input and output parameters, respectively. Section 4.2.4 discusses the representation of different operating scenarios and strategies.
4.2.1 Elements of the Network

As discussed in Section 4.1, a major challenge in developing a simulation model of a complex system is in determining exactly what elements of the system to simulate, and in what detail. In UTRAIN the major network elements included in the simulation are arcs, nodes, train, orders and events. UTRAIN simulates each of these elements in 5-minute time steps over the course of days, weeks or months, as specified by the user. These elements, and the actual processes or objects to which they correspond are described in the following paragraphs.

*Arcs* are the tracks on which trains travel. An arc is a piece of track that connects two nodes. Trains may travel in either direction on an arc, but the travel speed may be different in different directions. For instance, if a track is on a grade trains will move faster going downhill than uphill. UTRAIN keeps track of where trains are on an arc, the direction in which they are traveling, and times of the last departure from the arc and last arrival on the arc (in each direction).

The model does not simulate the actual movement of trains onto sidings, or other such detailed activities. Rather, track capacity and the allowable departure and arrival frequencies are specified, and trains must operate within these limits when traveling on an arc. Trains moving in the same direction on a particular arc are not allowed to pass each other.

The operating speed of a particular train depends on the distance to the nearest train moving in the opposite direction. If there is no train moving in the opposite direction within a specified "critical" distance (typically determined by siding spacing), then the train moves at the specified maximum speed. When there is a nearby train, the train moves at a specified fraction of the maximum speed. The user specifies, for each
direction of travel, both the critical distance (within which trains slow down) and the percent by which trains reduce speed within the critical distance. For instance, one might specify that meeting trains reduce speed by 50% when within 10 miles of each other, or one might specify that trains in one direction stop while trains in the other direction continue at full speed. In this manner, the model simulates the slowing down of oncoming trains for meets.

*Nodes* are locations at which arcs end. A node must be connected to at least one arc, and may be connected to no more than three. UTRAIN allows for four types of nodes: through nodes, yard nodes, supply nodes and demand nodes. All of the nodes are specified using the same data structures, but certain statistics are recorded for yard nodes only, and in reality, different operations occur at different types of nodes.

*Through nodes* are the most straightforward type of nodes. These exist only to allow a segment of track to branch into two paths. No train processing is performed at through nodes.

*Yard nodes* are the most complex type of node. Figure 4-1 is a diagram depicting the activities that occur at a yard. First, trains must enter the yard. A train may be kept from entering the yard if there are no available tracks, or if too little time has passed since the last arrival. Once trains arrive they are placed in a queue for processing. Priority is given to trains serving a customer, and according to time of arrival in the yard. Also, when a train arrives in the yard its power (set of locomotives) is removed and placed in a separate queue for servicing. This corresponds to fueling and inspection of locomotives. Occasionally locomotive repairs are required, resulting in additional servicing time for the power.
Trains are serviced separately from their power. The servicing involves inspecting the cars, and pulling out "bad orders," individual cars found to be defective. A limited number of trains may be serviced simultaneously. After trains are serviced they wait to depart until power is available, the required amount of time has passed since the last departure from the yard, and required amount of time has passed since the last arrival on the next arc in the train’s route.

Supply nodes and demand nodes are similar to yard nodes, except at these nodes power is not serviced, and the service time corresponds to time required for loading (at supply nodes) or unloading (at demand nodes) the train.

Trains move along arcs and through nodes. Statistics are kept on whether a train is loaded or empty, whether it is serving a customer or available for service, and where it is going. Trains do not choose their route in the simulation. Routes between each
origin and destination are determined at the beginning of the simulation (this is a fair representation of actual practice) and all trains moving between a particular origin and destination are routed in the same manner. At each node on the route the train "looks" at the matrix of routes to find the next arc the train should take to get to its destination. If the train reaches a supply node, the train is loaded and routed to the appropriate demand node. Or if the train is at a demand node it is unloaded.

*Orders* are requests for a certain number of shipments to be delivered from a particular supply node to a particular demand node. At a specified time within the simulation an order is placed on the queue of orders. When a train is unloaded, the queue of orders is scanned and the train is assigned to fill the next available order. Generally, the train that had just delivered a shipment will take the same order again, if the order is for multiple shipments. The user specifies whether a particular train can fill any order (that is, whether the train can ship between any origin and destination), or if the train can ship only to a specific set of demand nodes.

*Events* are special occurrences, typically occurrences that delay train operations. For each arc there is a user-specified daily probability that the arc will be closed either for maintenance or due to some random occurrence. Also, for each arc, the number of other (non-unit trains) on the arc per day is specified. Arrivals of "other" trains on the arc are generated at random within a specified window, and these trains disappear from the simulation once departing the arc.

The user may specify other events to occur at a specific point during the simulation. The user may alter the capacity or status of individual arcs, nodes or trains. This capability can be used for what-if analyses, such as to study the impact of a delay on a line, or to simulate unpleasant events.
Certain events control program flow. These events include commands for the simulation to stop, commands for the simulation to start or stop recording detailed information on train movements, commands to re-initialize the system-wide statistics (such as after an appropriate warm-up period).

4.2.2 Model Input

UTRAIN requires input files specifying parameters for arcs, nodes, trains, orders and events. The parameters required for arcs are listed in Table 4-1. For each arc the input file specifies: the nodes the arc connects, maximum speed, train capacity (typically limited by siding spacing), train arrival and departure frequencies, number of "other" trains per day, daily probability of a four-hour track closure, daily probability of an eight-hour track closure, distance within which oncoming trains reduce speed (typically the siding spacing), and the factor by which oncoming trains reduce speed.

Parameters required for nodes are summarized in Table 4-2. For nodes the user must specify the type of node (yard, demand, supply or through node), number of tracks, number of servers, train arrival and departure frequencies, range of possible service times (a uniform distribution is assumed) and initial units of power on hand. For power the user may specify up to 3 possible times for power servicing, and the probability of each. This reflects the fact that servicing power frequently does not take very long, but there is a probability that repairs will be required, requiring additional time.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID Number</td>
<td>integer</td>
<td>can be non-sequential</td>
</tr>
<tr>
<td>Description</td>
<td>text</td>
<td>no more than 10 characters</td>
</tr>
<tr>
<td>Inbound Node</td>
<td>integer</td>
<td>must match an id in the node file</td>
</tr>
<tr>
<td>Outbound Node</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>miles</td>
<td></td>
</tr>
<tr>
<td>Capacity</td>
<td>num trains</td>
<td>maximum for either direction</td>
</tr>
<tr>
<td>Arrival Period</td>
<td>minutes</td>
<td>time between successive arrivals and departures</td>
</tr>
<tr>
<td>Departure Period</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inbound Speed Limit</td>
<td>mph</td>
<td>limit for trains in the inbound direction</td>
</tr>
<tr>
<td>Outbound Speed Limit</td>
<td></td>
<td>limit for trains in the outbound direction</td>
</tr>
<tr>
<td>Other Inbound Trains</td>
<td>num trains</td>
<td>number of other inbound and outbound</td>
</tr>
<tr>
<td>Other Outbound Trains</td>
<td></td>
<td>trains per day</td>
</tr>
<tr>
<td>Inbound Critical Dist.</td>
<td>miles</td>
<td>distances within which oncoming inbound and outbound trains reduce speed</td>
</tr>
<tr>
<td>Outbound Critical Dist.</td>
<td></td>
<td>and outbound trains reduce speed</td>
</tr>
<tr>
<td>Inbound Speed Reduc.</td>
<td>% reduction in speed</td>
<td>% reduction in speed for oncoming trains within the critical distance</td>
</tr>
<tr>
<td>Outbound Speed Reduc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-Hour Maint. Prob.</td>
<td>% probability</td>
<td>Daily probability of a 4-hour or 8-hour maintenance window</td>
</tr>
<tr>
<td>8-Hour Maint. Prob.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For trains the user specifies the initial node for each train, and the array of demand nodes the train may serve (or whether the train can serve any demand node). For orders the user specifies the time the order is filed, the supply node, demand node and number of shipments ordered. For events the user specifies the time of the event, the type of event and additional information based on the type of event. The user provides an identification number for each element. These numbers should be integers, but they need not be ordered or consecutive.
4.2.3 Model Output

UTRAIN creates five output files. These files contain varying levels of detail and different types of information concerning the results of the simulation. The user can suppress creation of four of the five files to speed simulation run time (suppressing all files would provide no information on the outcome of the simulation), and can use events to query UTRAIN for detailed information at any time in the simulation.

The summary file presents summary results for any time period specified by the user (the periods are specified beforehand in the event input file). The summary statistics this file contains are listed in Table 4-3. As indicated in the table, the file records statistics including: the start and end times for the interval, number of trains busy filling
orders at the start and end of the intervals, average train utilization, number of shipments, average and standard deviation of the time required to fill an order, average and standard deviation of the cycle time, number of yard moves, and average and standard deviation of the yard service time and total yard time. The summary output file also includes statistics on utilization and average times for each arc, node and train.

Table 4-3. Simulation Summary Statistics

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start and End Time</td>
<td>days</td>
</tr>
<tr>
<td>Trains Filling</td>
<td>number of trains</td>
</tr>
<tr>
<td>Orders at Start and End</td>
<td></td>
</tr>
<tr>
<td>Avg. Train Utilization</td>
<td>%</td>
</tr>
<tr>
<td>Num. Shipments</td>
<td>integer</td>
</tr>
<tr>
<td>Avg., SD of</td>
<td>days</td>
</tr>
<tr>
<td>Time to Fill Order</td>
<td></td>
</tr>
<tr>
<td>Avg., SD of</td>
<td>days</td>
</tr>
<tr>
<td>Cycle Time</td>
<td></td>
</tr>
<tr>
<td>Num. Yard Moves</td>
<td>integer</td>
</tr>
<tr>
<td>Avg. &amp; SD of Yard Service Time</td>
<td>hours</td>
</tr>
<tr>
<td>Avg. &amp; SD of Total Yard Time</td>
<td>hours</td>
</tr>
</tbody>
</table>

The other output files contain detailed information about arcs, nodes, orders and the state of the entire network at user-specified times. The arc, node and order files are written to whenever a train departs an arc, departs a node or fills an order, respectively.

4.2.4 Testing Operating Scenarios and Strategies

An important goal in developing UTRAIN was to provide a means for testing different operations scenarios and control strategies. For different operating scenarios one may wish to test the effects of increasing track capacity for a particularly congested track.
segment, increasing the number of servers at a critical terminal, or changing the number of trains operating on the network. Testing different operating scenarios is relatively straightforward. To compare the results of different scenarios, the user must first run UTRAIN using the original parameters, change the appropriate parameters in the input files, rerun the model, and then compare results.

For different operating strategies, one may test whether giving priority to loaded trains results in better or worse network performance, or one may want to test the effect of holding trains in yards to avoid congestion on lines (or vice-versa). For the initial development of UTRAIN, only very straightforward operations control strategies were implemented, and the strategies were made part of the program code (in other words, they are not user-specified, unless the user happens to be a C programmer). Straightforward strategies were implemented primarily because most unit train networks are operated in a very straightforward manner. Railroad managers (with some notable exceptions) do not try to develop complex algorithms for dispatching trains or deciding whether or when to hold trains, particularly not in real time.

Nonetheless, operating rules are used, even if they are not explicit or consistently applied. Railroads frequently limit the number of trains on a line to the number of available sidings, especially if the line is used by other types of traffic. The logic behind this idea is that all of the trains must be able to clear a line to allow a high-priority train (such as an intermodal train) to pass. Also, headways between trains are generally held to some line-dependent minimum, such as one train every 30 minutes. Although it is possible to platoon trains, UTRAIN does not provide this feature.

Within yards priority is given to particular types of traffic, and loaded trains may have priority over empty trains. There are different operating strategies for providing
power. Sometimes trains may receive the first power available; other times a train must wait for the units to be serviced that brought it to the yard. Yard managers generally have an estimate of how much traffic is on its way to the yard, and an estimate of “power on hand” in the next 8 hours. Generally the goal is to move trains through a yard as quickly as possible, but in some cases trains may be held to reduce line congestion. Managers tend to prefer congestion in a yard to congestion on a line, but it is not uncommon for a yard to become full, causing congestion along a line as trains must pull off onto sidings while waiting to enter the yard.

Within UTRAIN, priority is given to trains filling an order compared to trains that are not filling an order. Minimum headways are imposed for trains entering and leaving any node, and the capacity of every line is specified. Generally trains are moved along the line and through yards as quickly as possible. However, when a train is prepared to leave a node, it is allowed to depart only if the next node on its route has available capacity for departures. When a train departs a yard it takes the first available power, regardless of what train brought the power to the yard.

4.3 Algorithmic Development

This section describes the development of algorithms for UTRAIN. Figure 4-2 is a block diagram depicting the major algorithmic elements of UTRAIN. The algorithms for each of the elements are discussed in the following sections. Section 4.3.1 describes the data structures designed for the simulation. Section 4.3.2 describes the file input/output routines. Section 4.3.3 describes the algorithms for indexing and re-labeling network elements. Section 4.3.4 describes the algorithms used for calculating shortest paths. Section 4.3.5 describes the algorithms used for the actual simulation, and Section 4.3.6 presents additional information on program coding.
4.3.1 Data Structures

A significant amount of time in developing UTRAIN was devoted to determining appropriate data structures for storing information on the network elements. On the one hand the data structures needed to contain all of the information necessary for running the simulation. Also, clarity in the coding was considered relatively important for any future work others may perform using the program code. On the other hand, memory was a concern. Data structures that require large blocks of contiguous memory are a particular problem on personal computers.

The approach used was to create different data structures for each type of network element. A global array of pointers to data structures was created for each type of network element - arcs, nodes, and so forth. The use of global variables helped reduce complexity in coding, and was found to be faster than passing pointers to data structures for each routine. Since the arrays are arrays of pointers to blocks of memory, rather than arrays of blocks of memory, large contiguous blocks of memory are not required (except for the array of routes). Also, using arrays allowed for efficient implementation of heaps.

Besides the data structures for arcs, nodes, trains events and orders, data structures are defined for storing summary results, for keeping a matrix of routes from every node to every other node, and for implementing a generic heap. The generic heap is used in several places, such as for servicing power within each node and performing shortest path calculations. Within the arc data structure, queues are used for tracking progress of trains along the arc.
4.3.2 File Input and Output

Approximately one-quarter of the program code is devoted to file input and output routines. Although not complicated algorithmically, it is important to note the following concerning these routines:

- The data in the input files should be comma-delimited, with a separate line for each network element.
- For input files UTRAIN expects to find arc information in the file “utrain.arc,” node information in the file “utrain.nod,” train information in “utrain.tm,” order information in “utrain.ord” and event information in “utrain.evt.”
- Items in the input files need not be sorted.
- For the output files UTRAIN writes summary results in “utrain.001,” arc data in “utrain.002,” node data in “utrain.003,” order data in “utrain.004” and the detailed
network state in "utrain.005."

- UTRAIN overwrites old output files.

4.3.3 Indexing and Re-labeling

Once the network elements are read from input files, it is still necessary to sort the data arrays and re-label references to arcs, nodes and trains. The arrays must be sorted because the user may not have prepared input files with elements numbered in sequence. For instance, Arc 1 of the arc file might specify that the arc is connected to Node 5 and Node 10. However, Node 5 is not necessarily the fifth node read from the node input file, and Node 10 is not necessarily the tenth.

The following steps are executed to provide correct indexing between different network elements:

- The arrays of network elements are sorted. Arcs, nodes and trains are sorted in order of increasing identification number. Orders and events are sorted in order of increasing time. The sorting is performed using the heap sort algorithm described by Brassard [21], which takes time in the order of \( n \log (n) \). This algorithm is well-suited for use with the particular type of data structure chosen, and is fast.

- Next, for each type of network element, references to other network elements are re-labeled. For instance, if Arc 1 is connected to Node 5, but Node 5 is actually the first node in the list of nodes, the reference is changed from 5 to 1. The re-labeling is performed by successive binary searches. Each binary search is in the order of \( \log (n) \), so successively re-labeling each reference takes time in the order of \( n \log (n) \), where \( n \) is the sum of all network elements. The binary search routine used is similar to that presented in Brassard [21].
4.3.4 Shortest Path

Once sorting and re-labeling are complete, it is possible to supplement the input data with additional, calculated values, and to build an array of routes from every node to every other node. These calculations are performed only once; although multiple paths may exist in a rail network, it is unusual for trains to be routed differently once a particular route has been established.

Dijkstra's Algorithm, implemented using a heap, is called successively to calculate shortest paths. The steps followed in calculating supplemental information, and building the array of routes are:

- First, supplemental information is calculated for each arc. The (ideal) trip time over the arc is calculated using the speed limit, length of the arc, and expected servicing time at the destination node.

- Next, supplemental information is calculated for each node. For each node, certain values are set to 0, and the power initially assigned to the node is added to the heap of power. Also, for each node every arc is scanned to see if the arc is connected to the node. In this way, adjacent nodes and connecting arcs are calculated for each node.

- Next, supplemental information is calculated for each train. For each train certain values are set to 0. Also, the train is added to the heap of serviced trains at its default node, and its power is added to the heap of power. Also, supplemental information is calculated for each order.

- The array of routes is built next. Initially, for any pair of nodes the trip time is recorded if the nodes are adjacent, along with the index of the arc connecting the nodes.

- Next, Dijkstra's algorithm is executed for each node. Since a heap is used, the shortest path calculations take time in the order of \( n^2 \log (n) \). For a typical rail
network, the network is relatively sparse, with the number of arcs approximately equal to the number of nodes.

- Finally the routes are determined. Dijkstra’s algorithm returns the previous node - the last node reached before the destination node. However, to streamline the simulation it is necessary to know the first arc to take when at the origin node. After a train moves to a new node, it then looks for the next first arc - the first arc of the rest of its trip.

4.3.5 Simulation Algorithms

The routines for performing the simulation together comprise only one-third of the program code, but it is in looping through these routines that most of the running time is spent. Further, the simulations routines are not particularly complex compared to the routines for calculating the shortest paths or re-labeling the file input. The primary challenge is one of bookkeeping, one of updating all of the appropriate variables whenever a train moves along an arc or through a node. Also, it is necessary to verify that every potential move is “legal,” in the sense that it does not result in exceeding capacity on an arc or in a node, or violate other rules of the simulation.

The simulation runs in time steps. At each time step (the step size has been defined as five minutes, which is considered appropriate for freight train operations) the simulation handles any events that need to occur, updates statistics, moves trains along arcs, and moves trains through nodes. The steps followed at each time step are described below:

- **Handle Events:** At the beginning of each time period UTRAIN examines the event heap to determine whether any new user-specified events have occurred since the last time step. The simulation handles any event - such as by printing output to files, stopping the simulation or updating the values of a particular arc, node or
train. After an event is handled its time is changed to a very large number, and the event is sifted down to the bottom of the heap.

- **Update Statistics:** Next, relevant summary statistics are updated. Other statistics are updated whenever an action is completed, such as when a shipment is delivered to a demand node.

- **Assign Trains:** The simulation loops through every train. If a train is not in the process of filling an order, the simulation loops through the orders to find one the train may fill. The train is assigned the first available order it can fill from the list of orders. A train may be allowed to fill any order, or it may be assigned to serve a particular set of demand nodes.

- **Update Arcs:** Next, trains are moved along arcs. Each arc has a queue of trains moving in each direction. For each train on the arc the routine determines the maximum movement in that time step, which depends on the speed limit and the locations of trains on the arc, as specified by the user. Next, each train is moved. The trains are not allowed to pass one another.

- **Update Nodes:** Next trains are moved into, within and out of nodes. First, given a particular node, the node tries to receive incoming trains. The routine looks in random order at each of the three tracks entering the node, and if there are trains to receive, and if the appropriate amount of time has passed since the last train arrival, and if the node has available capacity the node receives the train. When a train is moved from an arc to a node a set of bookkeeping operations must be performed. At this point the power is removed from the train, assigned a service time, and added to the heap of power.
After trains are moved into the node, the routine tries to service trains. If there are trains to be serviced and there are available servers, then servicing begins. When a train has completed servicing, the simulation checks to see whether the train is at either its supply node or demand node. If it is at its supply node, it is marked as loaded, and given as its destination the demand node. If the train is at its demand node (and it has a load), then the train has completed its shipment. The shipment is recorded, the order information is updated, and the simulation attempts to assign the train to a new order. Lacking an order, it is sent to its default node.

Finally, trains are moved from the node onto arcs. The simulation scans through the arcs connected to the node in random order. If there are trains waiting for departure to a particular arc, and if an appropriate amount of time has elapsed since the last departure, if there is available capacity on the arc, and if there is power available, the train is assigned to the arc. The procedure for allowing trains to depart from the yard is a point where operating rules can have a significant impact on the simulation. Trains are allowed to depart a node only if the next node on their route has available capacity for departures.

4.3.6 Program Coding

The program was coded in the C programming language using Borland C++ version 5. The initial programming and program testing was performed on a Pentium (P90) personal computer with 16 MB of memory running under Windows 95. Final model runs were performed on a Pentium (P200) with 32 MB of memory running under Windows 95. The only known, system-specific line of code is one that initializes an array of type “huge.” This is a feature in Borland C++ to circumvent the problem of needing to reserve a block of memory of greater the 64K. There may be other system-specific functions or definitions in the include files, all taken from the Borland library.
CHAPTER 5: APPLICATION OF THE MODEL: UNIT COAL TRAINS AND HEAVY AXLE LOADS

This chapter describes the application of UTRAIN to studying the effects of heavy axle loads on unit coal train operations. In the context of freight railroad operations, heavy axle loads (HAL) are generally defined as axle loads greater than the standard of 33 tons. Increasing axle loads can provide additional capacity and increased efficiency in bulk train operations. However, increasing axle loads tends to result in higher track maintenance costs that may offset the capacity and efficiency gains. The overall savings from HAL may be quite significant. Saleeby estimated that for a heavy haul line with 50 MGT of traffic annually, shifting to heavy axle loads could save up to $36,000 per track mile per year, a savings of $36 million per year for a 1000-mile line [116].

Since 1988 the Association of American Railroads (AAR) has been operating a test train with 39 ton axle loads at the Facility for Accelerated Service Testing (FAST) at the Transportation Test Center (TTC) in Pueblo, Colorado [107]. To date, over 500 million gross tons (MGT) of traffic has been accumulated on the test track at FAST. Following each of three phases of the HAL testing, the AAR and MIT have conducted economic analyses of heavy axle loads operations using the results from the tests at FAST.

The study described in this chapter builds upon and extends previous HAL economic analyses. For this effort, operating and maintenance costs have been calculated for representative East and West coal distribution networks for a range of axle loads and operating scenarios. UTRAIN has been used to determine the cycle time and capacity for each network, and has been used to show how the cycle time and capacity vary as a function of axle load. The study was performed by the MIT Rail Group for the AAR.
This chapter focuses on the UTRAIN analysis; an AAR Working Paper by Chapman [29] details other aspects of the study.

The results indicate that HAL operations result in overall savings for unit coal train operations on representative East and West coal distribution networks. The critical factor in achieving cost savings is increasing the net capacity of unit coal trains. A key conclusion is that additional cost savings may likely be realized by maximizing the cross section (height and width) of coal cars, and then adjusting car length to optimize axle load [29]. Further, the study provides an example of how UTRAIN can be used, together with other models, to model the operations of unit coal trains at a systems level.

Section 5.1 presents additional background on the study and summarizes the results. Section 5.2 describes the equipment scenarios that were tested. Section 5.3 describes the test networks. Section 5.4 discusses the analysis methodology, and Section 5.5 presents the conclusions.

5.1 Background

This section presents background information relevant to the study, and summarizes the study results. Section 5.1.1 summarizes previous HAL research. Section 5.1.2 describes the motivation for the study. Section 5.1.3 summarizes the study results.

5.1.1 Previous HAL Research

The AAR has performed three phases of HAL testing at FAST, each followed by an economic analysis. In Phase I, the goal was determine whether operations with axle loads above the 33 tons allowed for interchange service were technically feasible and economically desirable [57]. The economic analysis examined the operating and maintenance costs of a typical East coal route, a typical West coal routes, a mountainous
route, and a level route. The costs were calculated for operations with 33 ton axle loads, 36 tons axle loads (using the same car design as the 33 ton case, but with the cars overloaded to hold more coal) and 39 ton axle loads. The economic analysis concluded that operation with increased axle loads was technically feasible and was economically desirable under favorable circumstances [57].

The Phase II analysis evaluated the economics of HAL operations using improved models and assuming the use of improved track components and revised costs. The results of the Phase II analysis are summarized in Table 5-1 [57]. The analysis indicated that compared to the base case with 33 ton axle load operations, operations with 36 ton axle loads results in cost savings of 2% to 7%, and operations with 39 ton axle loads resulted in savings of -1% to 1%. Heavy axle loads are more economical in cases where trains are length-limited rather than weight-limited, because in the length-limited cases HAL trains carry more coal per train.

<table>
<thead>
<tr>
<th>Route</th>
<th>Axle Load</th>
<th>Length or Weight-Limited</th>
<th>Percentage Cost Savings Relative to the Base</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Operating Costs</td>
</tr>
<tr>
<td>East</td>
<td>36</td>
<td>Length</td>
<td>8.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weight</td>
<td>3.8%</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>Length</td>
<td>3.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weight</td>
<td>3.0%</td>
</tr>
<tr>
<td>West</td>
<td>36</td>
<td>Length</td>
<td>8.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weight</td>
<td>3.7%</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>Length</td>
<td>5.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weight</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

Phase III of the HAL testing concentrated on the economics of advanced trucks. Advanced trucks differ from standard trucks in that they are steerable, and thus tend to reduce fuel consumption and rail wear on curves. The final results of the economic
analysis were not published as of May 1997. The preliminary results are consistent with the Phase II analysis, and indicate that the use of advanced trucks is economically justified for 33, 36 and 39 ton axle loads.

5.1.2 Motivation for the Present Study

The present study builds upon and extends the HAL economic analyses. Based on review of the previous work, the MIT Rail Group hypothesized that the previous results could be significantly enhanced through development of a network scope, extending the range of axle loads studied, and taking a new approach to modeling equipment design. These areas are discussed in the following paragraphs.

Whereas the previous HAL analyses focused on the costs of operating representative coal routes, this study is concerned with the costs of operating coal distribution networks. The routes studied in previous analyses are representative of East and West main lines. The main lines carry the most traffic and require the most track maintenance. While a large portion of the track over which unit coal trains operate is high quality, high traffic density line, much of it is of lower quality and lower traffic density. Quantifying the total cost of unit coal train operations requires consideration of operations over both the main lines and branch lines in a coal distribution network.

Further, heavy axle loads may have a significant effect on network operations. If net traffic is held constant, then increasing the net capacity per train (through increasing axle loads or other means) leads to a reduction in the number of trains required to move the required amount of coal. As trains are removed from the network, congestion is reduced and cycle times tend to improve, leading to a further reduction in the number of trains required. However, modeling the cycle time effect requires analysis at a network level.
On the other hand, heavy axle loads may lead to deterioration in network operations performance, as heavy axle loads tend to increase track maintenance. As discussed in Chapter 3, Romps studied the effects of track maintenance on operations [114]. Robert and Martland used Romp’s approach to study the effects of track maintenance on reliability for the HAL Phase II East and West length-limited coal routes [113]. They showed that although heavy axle loads increase track maintenance and, thus, delay from track closures; this increased delay is offset by a reduction in the number of trains. UTRAIN offers the opportunity to examine the effects of heavy axle loads on operations at a network level.

This study differs from previous analyses in the range of axle loads studied. The HAL economic analyses focused on three axle loads: 33 tons, 36 tons and 39 tons. The results tended to show that operations at 36 tons were most economical. However, the optimal axle load for unit coal train operations could conceivably be above 39 tons or below 33 tons, particularly if different car or truck designs are considered. This study examines operations with axle loads of 30 to 45 tons for aluminum cars with 2-axle or 3-axle advanced trucks.

The axle load of a car is largely a function of equipment design. For this study a new approach to modeling was required for examining a range of axle loads. In previous studies, two car types were examined: a “100-ton car,” designed to hold 100 tons of coal with an axle load of 33 tons; and a “125-ton car,” designed to hold 125 tons of coal with an axle load of 39 tons. The 36 ton axle load case was modeled as an overloaded 100-ton car. The 100-ton car (operating as designed or overloaded) and 125-car are commercially available coal cars. Both are the same length, but the 125-ton car is taller.
Examining a range of axle loads requires assuming either that commercially available cars are sub-optimally loaded (either loaded for more or less than designed), or that some other car could be designed to meet a particular axle load. The approach taken for this study was to use the box design for the 125-ton car for all cases except the base case, but lengthen or shorten the box to meet a particular axle load. This allows for distinguishing between the effects of axle load, car capacity and net-to-tare ratio for a range of different cases.

5.1.3 Result Summary

This section summarizes the analysis results. A total of 22 cases were analyzed. For each the East and West network, the following cases were considered:

- **Base Case**: 33 ton axle loads
- **2-Axle Trucks, 36-Inch Wheels**: 33, 36 and 39 ton axle loads
- **2-Axle Trucks, 38-Inch Wheels**: 39, 42 and 45 ton axle loads
- **3-Axle Trucks, 36-Inch Wheels**: 30, 33, 36 and 39 ton axle loads

For all cases, cars were assumed to be aluminum cars with advanced trucks. The base case represents operations with the standard 53-foot long 100-ton car. All other cases are based on cars of varying length, but the same height and width as the 125-ton car. Both the East and West networks were assumed to be length-limited. Demand was held constant for each network across all cases. Bridge maintenance costs were not included in the calculations.

For the East and West base cases, operations costs (measured in dollars per 1,000 net ton-miles) are approximately 27% lower than the costs projected for the HAL Phase III economic analysis [53], primarily as a result of the assumption that aluminum cars would be used. Track costs (excluding bridges) for the East and West base cases are
approximately 27% higher. Overall, costs for the East and West base cases are approximately 20% lower than the costs projected in the HAL Phase III analysis.

The results indicate that, compared to the base case, all other cases result in increased net train capacity and decreased cycle time. Together these effects result in reduced operating costs. However, heavy axle loads result in increased maintenance that tends to offset the savings in operating costs. Figure 5-1 summarizes the percentage savings for each case relative to the base case.

Overall the optimal axle load for the cases analyzed is 36 tons. For the East network, given the assumptions made concerning equipment design, the greatest cost savings could be achieved using cars with 3-axle trucks operating at axle loads of 39 tons. However, such cars would be extremely long (over 70 feet long) and may not be feasible. If long cars with 3-axle trucks are feasible, then their use could result in savings of approximately 5% relative to the base. The maximum savings using cars with 2-axle trucks is comparable but lower. For 2-axle trucks operating with axle loads of 36 tons, the cost savings is 4% relative to the base.

For the West network, using cars with 3-axle trucks and axle loads of 36 tons would result in cost savings of just over 5%. However, as for the East network, the 3-axle cars would be very long (approximately 70 feet), and may not be feasible. Using cars with 2-axle trucks and axle loads of 36 tons would result in cost savings of 5%.
Figure 5-1. Summary of Cost Savings Relative to the Base Case
The results suggest that net train capacity is the critical parameter in achieving cost saving for unit coal train operations. Holding axle loads at 33 tons, moving from cars with the cross section of the 100-ton car to cars with the cross section of the 125-ton car increases net train capacity by 14%, and results in cost savings of 3 to 4%. In the latter case, the cars are shorter (45 feet rather than the standard 53 feet) but there are more cars per train, assuming length-limited trains. Lengthening cars can further increase the net train capacity. Longer cars result in heavier axle loads, but better utilize the limited train length. However, the extra savings from adjusting car length and axle load are less than the initial savings from increasing the cross section of the car.

Future research should be directed towards maximizing the cross section of coal cars, and towards quantifying the limiting parameters in car design. A case with a car that holds more coal per linear foot than the 125-ton car would likely outperform any of the cases analyzed in this study. The study assumes that it is feasible to adjust axle load by changing the car length, but changing car lengths would likely require changes to rotary dumpers and other components of loading and unloading facilities. If the cross section of coal cars can be increased, but car lengths are constrained to 53 feet, then the optimal axle load for unit coal train operations may be greater than 39 tons.

There are several important caveats to the study results. Much of the projected savings result from improvements in cycle times predicted using UTRAIN. For networks not operating near capacity there would still be cost savings from HAL operations, but the savings would be more modest because there would not be a significant improvement in cycle time.

Further, distributed power may be necessary to handle the heavier trains modeled in the study. In some cases, premium track components would have to be used; e.g.,
premium rail (340 Brinell) may be necessary on high density lines in order to control defects. A number of assumptions were made concerning equipment design and costs; the assumptions made concerning 3-axle trucks are based on very limited data.

Finally, there are many complex issues relating to equipment ownership, pricing, and incentives for equipment utilization. Many electric utilities purchase their own equipment, and may not have incentives to pay for more expensive equipment that leads to operating savings for a railroad. A railroad may be able to cut costs through shifting to heavy axle operations, but cost savings through reduced cycle times and reduced line congestion may be difficult to quantify. Railroads and electric utilities will need to work together to realize the maximum savings from HAL operations.

5.2 Description of Equipment Parameters

The basic equipment parameters used for the study were taken from information compiled by the AAR and summarized in the spreadsheet “3AXLE.WK1,” dated March 24, 1997. The spreadsheet includes dimensions for several box and truck types. Table 5-2 summarizes the relevant data on box types from the spreadsheet. As indicated in the table, the box for the 100-ton car and for the 125-ton car are the same length and width. However, the box for the 125-ton car is heavier and holds 25 tons more coal. The box for an aluminum 125-ton car weighs 543 pounds per foot and holds 5,603 pounds of coal per foot.
Table 5-2 Car Box Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value by Car Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100-ton Car</td>
</tr>
<tr>
<td>Box Length (ft)</td>
<td>47.7</td>
</tr>
<tr>
<td>Length over Pull Face (ft)</td>
<td>53.1</td>
</tr>
<tr>
<td>Car Body Weight (lbs)</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>41,600</td>
</tr>
<tr>
<td>Aluminum</td>
<td>21,600</td>
</tr>
<tr>
<td>Net Weight (lbs)</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>200,000</td>
</tr>
<tr>
<td>Aluminum</td>
<td>220,000</td>
</tr>
<tr>
<td>Gross Weight (lbs)</td>
<td>263,000</td>
</tr>
<tr>
<td>Axle Load (tons)</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 5-3 summarizes the relevant data on truck types from the spreadsheet. As indicated in the spreadsheet, a 2-axle truck with 36-inch diameter wheels weighs 9,200 pounds. This is the truck found on the 100-ton car. A 2-axle truck with 38-inch wheels weighs 11,019 pounds (this is the truck found on the 125-ton car), and a 3-axle truck with 36-inch wheels weighs 17,460 pounds. The values presented in Tables 5-2 and 5-3 were applied to evaluate a range of cases with different equipment parameters, as discussed in the following paragraphs.

Table 5-3 Truck Weights

<table>
<thead>
<tr>
<th>Truck Type</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Axle Truck</td>
<td></td>
</tr>
<tr>
<td>36” Wheels</td>
<td>9,200</td>
</tr>
<tr>
<td>38” Wheels</td>
<td>11,019</td>
</tr>
<tr>
<td>3-Axle Truck</td>
<td></td>
</tr>
<tr>
<td>33” Wheels</td>
<td>16,005</td>
</tr>
<tr>
<td>36” Wheels</td>
<td>17,460</td>
</tr>
<tr>
<td>38” Wheels</td>
<td>19,230</td>
</tr>
</tbody>
</table>

In previous HAL analyses, three different sets of equipment parameters were evaluated: a 100-ton car with axle loads of 33 tons, an overloaded 100-ton car with 36 ton axle loads, and a 125-ton car with 39 ton axle loads. Examining other cases requires making additional assumptions about equipment design. For instance, a car with axle
loads of 38 tons could be modeled as a 125-ton car that has not been fully loaded, or it can be modeled as a fully-loaded car that is slightly shorter than the 125-ton car.

In this study the base case consists of operations with 106-car trains with aluminum 100-ton cars and advanced trucks (since the cars are aluminum they hold approximately 112 tons of coal, but have axle loads of 33 tons). For all other cases, the train length is the same, the cars are aluminum, and advanced trucks are used, but the cross section of the car is equivalent to that of the 125-ton car, and the car length is adjusted to meet a specified axle load. Thus, cars are assumed to be fully loaded at every axle load. Three truck types are considered: a 2-axle truck with 36-inch diameter wheels, a 2-axle truck with 38-inch wheels, and a 3-axle truck with 36-inch wheels. The maximum acceptable axle load for 36-inch wheels is assumed to be no more than 39 tons. However, no detailed analyses of the practical axle load for 36-inch wheels was identified in the study.

Figures 5-2 to 5-5 show how the equipment parameters vary as a function of axle load for the car types considered in the study. Figure 5-2 is a graph of net car weight versus axle load. For a given axle load, the net car weight is greatest for cars with 3-axle trucks, as the weight of the car is distributed over 6 axles rather than 4. The net weight for cars with 2-axle trucks and 36-inch wheels is slightly greater than that for cars with 38-inch wheels, because the heavier 38-inch wheels increase the tare weight and allow for slightly less net weight per car. Figure 5-3 is a graph of car length versus axle load. Note that based on the cross section for the 125-ton car, a car with 3-axle trucks would be over 70 feet long for axle loads greater than 36 tons. A car with 2-axle trucks and 33 ton axle loads would be approximately 45 feet long, 8 feet shorter than the standard length of approximately 53 feet. Cars with 2-axle trucks and 36-inch wheels are slightly
longer cars with 38-inch wheels, because the cars with 36-inch wheels hold slightly more coal, requiring additional length.

Figure 5-4 plots net weight per train as a function of axle load. The net weight per train is significantly greater than that of the base case for all cases with the cross section of the 125-ton car. Assuming length-limited trains, net weight per train increases with axle load because heavier axle loads translate into longer cars and a greater percentage of the total train length being used to haul coal. However, the axle load effect on train capacity is small compared to the effect of increasing the car cross section. Note that the points in Figure 5-4 do not reflect integer constraints on the number of cars per train; integer constraints were applied in the analysis.

Figure 5-5 is a graph of net-to-tare ratio versus axle load. The net-to-tare ratio is relatively high (greater than 4.5) for all of the cases considered, including the base case. In the HAL Phase II analysis, the ratio was 3.4 for the 100-ton car and 3.6 for 125-ton car [57]. The high net-to-tare ratio is a result of the assumption that aluminum cars would be used for all cases. The net-to-tare ratio is lowest for cars with 3-axle trucks, as the tare weight per axle is high compared to the cars with 2-axle trucks.
Figure 5-2. Net Weight per Car vs. Axle Load

Figure 5-3. Car Length versus Axle Load
Figure 5-4. Net Weight per Train versus Axle Load

Figure 5-5. Net-to-Tare Ratio versus Axle Load
5.3 Description of the East and West Networks

This section describes the two rail networks analyzed in the study: a typical Eastern and a typical Western coal distribution network. For each network operations were analyzed for eleven scenarios.

The parameters for the networks we have developed are based on discussions with representatives of U.S. railroads, and on previous work performed for the AAR [112]. The networks should be similar to actual rail networks, but are nonetheless idealizations, and are not intended to completely replicate the networks of particular railroads. Section 5.3.1 describes the East network and Section 5.3.2 describes the West network.

5.3.1 East Coal Distribution Network

Figure 5-6 depicts the Eastern coal distribution network. The circles at the center of the network represent locations where coal is loaded onto trains. Loaded trains are routed in one of three directions (traffic is evenly distributed in each direction). Each train passes through a run-through facility where its power is inspected and fueled, the train is inspected, and bad orders are removed. Trains unload coal at the triangles at the edge of the network. After unloading they are routed back towards the center of the network. They pass through the run-through facility and back to the loading area, and the cycle is repeated.
The trip from the loading to unloading facilities is 360 miles, and the cycle time is typically 3.8 days. Trains operate at a speed of 35 miles an hour, but often must slow down or stop for train meets or due to line congestion. Congestion is worst near the center of the network. A total of 56 coal train sets operate at once on the network, resulting in 90 MGT of traffic annually. At the center of the network and at the edges near the unloading points all of the traffic is from coal trains. Throughout the rest of the network there is an average of 6 trains per day (about 20 MGT per year) in other traffic, such as intermodal or general merchandise traffic.
Not including extra time from congestion delay, train loading takes an average of 18 hours, servicing takes an average of 4 hours, and unloading takes an average of 18 hours. At run-through facilities there is space for 4 trains, but service may occur simultaneously on no more than 2. Also, at these facilities there is a 20% chance that a train's power will require additional time for maintenance (either 12 hours for moderate maintenance or 40 hours for heavy maintenance). In this case, the train is given the next available power, which may be extra power at the facility or power from other trains still in servicing.

Overall the network is somewhat congested, but the number of trains operating on the network could be increased by approximately 10% before the network reached capacity. Any additional trains operating on the network may be expected to create additional delay for other trains, and removing trains from the network may be expected to reduce cycle times of the remaining trains.

Table 5-4 summarizes key operating parameters for the East network. The table shows the gross annual traffic in millions of gross tons (MGT) both for coal trains and other traffic, track speed, track type (single or double), track capacity, and track length by type of track segment. There are 9 different types of track segments, as labeled in Figure 5-6. Segment 1 is a spur line to a loading facility. Segments 2, 3 and 4 are heavily used by coal trains, but not by other traffic. Segment 5, 6 and 7 are main line segments similar to the East coal route in previous HAL analyses. Segment 8 is a less heavily used branch line, and Segment 9 is a spur leading to an unloading facility. Except for Segment 3, all track segments are single track.
Table 5-4. Operating Parameters for the East Network

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value by Track Segment</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>Number in Network</td>
<td>12</td>
</tr>
<tr>
<td>Length (miles)</td>
<td>10</td>
</tr>
<tr>
<td>Train Speed (mph)</td>
<td>35</td>
</tr>
<tr>
<td>Track Type (Single/Double)</td>
<td>S</td>
</tr>
<tr>
<td>Capacity (miles between trains)</td>
<td>10</td>
</tr>
<tr>
<td>Annual Coal Traffic (MGT)</td>
<td>7.5</td>
</tr>
<tr>
<td>Annual Other Traffic (MGT)</td>
<td>0.0</td>
</tr>
<tr>
<td>Annual Total Traffic (MGT)</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 5-5 summarizes the distribution of track by degree of curvature. Table 5-6 lists the number of turnouts per mile by track segment and type of turnout. Table 5-7 summarizes the distribution of track metallurgy by track segment and degree of curvature. The critical parameter is the Brinell hardness (BHN) of the rail. Tangent track is typically 270 or 300 BHN; in recent years 300 BHN rail has been increasingly used, especially on high-density lines. Premium rail (greater than 300 BHN) may be used on curves.

The track parameters for the mainlines are identical to those used for the HAL routes, but on lower density lines the track tends to be of lower quality, and there are more curves and turnouts. As for the HAL routes, compared to the West, in the East there are generally more curves, more turnouts, and less use of premium rail

Table 5-5. Distribution of Track Curvature for the East Network

<table>
<thead>
<tr>
<th>Track Curvature (degrees)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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</tr>
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</tr>
<tr>
<td>2</td>
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<td>18%</td>
<td>18%</td>
<td>18%</td>
<td>18%</td>
<td>18%</td>
<td>18%</td>
<td>20%</td>
</tr>
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<td>8</td>
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<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
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119
Table 5-6. Distribution of Turnouts for the East Network

<table>
<thead>
<tr>
<th>Turnout Type</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard No. 20</td>
<td>0.50</td>
<td>0.60</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.60</td>
<td>0.60</td>
<td>0.55</td>
</tr>
<tr>
<td>Premium No. 20</td>
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<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>Standard No. 16</td>
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<td>0.12</td>
<td>0.10</td>
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<td>0.10</td>
<td>0.12</td>
<td>0.12</td>
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</tr>
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<td>0.80</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.70</td>
<td>0.70</td>
<td>1.00</td>
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Table 5-7. Distribution of Track Metallurgy for the East Network

<table>
<thead>
<tr>
<th>Curvature (degrees)</th>
<th>Metallurgy (BHN)</th>
<th>Percent of Given Curvature with Specified Metallurgy by Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>270</td>
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<td></td>
<td>370</td>
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</tr>
<tr>
<td>8</td>
<td>340</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>370</td>
<td>0%</td>
</tr>
</tbody>
</table>

Concerning grades, Segment 1, 2, 3 and 4 have steeper grades and the other segments are similar to the typical East route from the AAR HAL Phase II analysis [57]. Unless otherwise specified, the values used in modeling the networks (such as train lengths, locomotives per train, grinding policy, and so forth) are the same as those used in the AAR HAL Phase II analysis for the length-limited cases.

5.3.2 West Coal Distribution Network

Figure 5-7 depicts the Western coal distribution network. This network has a different structure than the East network, but operates in a similar fashion. Trains are loaded at the circles at the top of the network, pass through the large run-through facility at the center of the network, through one of 4 smaller run-through facilities, and then are
unloaded at one of the triangles. After unloading trains are routed back along the same path and the cycle is repeated.

Figure 5-7. West Coal Distribution Network

The trip from the loading to unloading facilities is 1300 miles, and the cycle time is typically 5.8 days. Trains operate at a speed of 35 miles an hour, but often must slow down or stop for train meets or due to line congestion. Congestion is worst near the large run-through facility. A total of 100 coal train sets operate at once on the network, resulting in 120 MGT of traffic annually. At the ends of the network near the loading and unloading points all of the traffic is from coal trains. Throughout the rest of the network there is an average of 6 trains per day (about 20 MGT per year) in other traffic, such as intermodal or general merchandise traffic.
Not including extra time from congestion delay, train loading takes an average of 3 hours (significantly faster than the East), servicing takes an average of 4 hours, and unloading takes an average of 8 hours. At the large run-through facility there is space for 14 trains, but service may occur simultaneously on no more than 8. At each of the four smaller facilities there is space for 8 trains, but service may occur simultaneously on no more than 4. Also, at both the large and small facilities there is a 20% chance that a train’s power will require additional time for maintenance (either 12 hours for moderate maintenance or 40 hours for heavy maintenance). In this case, the train is given the next available power, which may be extra power at the facility or power from other trains still in servicing.

Overall the network is more congested than the East network and operates at a level near capacity. Any additional trains operating on the network may be expected to create additional delay for other trains.

Table 5-8 summarizes key operating parameters for the West network. For this network there are 10 types of track segments, as indicated in Figure 5-7. Segment 1 is a spur line to a loading facility. Segment 2 is a branch line used exclusively for coal trains. Segment 3, 4 and 5 are main line segments similar to the West coal route in previous HAL analyses. Segments 6 and 7 are main lines, but carry a greater proportion of other types of traffic. Segments 8 and 9 are branch lines with relatively little traffic, and Segment 10 is a spur leading to an unloading facility. Except for Segments 4 and 5, all track segments are single track.
Table 5-8. Operating Parameters for the West Network

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value by Track Segment</th>
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<td>Length (miles)</td>
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<tr>
<td>Train Speed (mph)</td>
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</tr>
<tr>
<td>Track Type (Single/Double)</td>
<td>S</td>
</tr>
<tr>
<td>Capacity (miles between trains)</td>
<td>10</td>
</tr>
<tr>
<td>Annual Coal Traffic (MGT)</td>
<td>15.0</td>
</tr>
<tr>
<td>Annual Other Traffic (MGT)</td>
<td>0.0</td>
</tr>
<tr>
<td>Annual Total Traffic (MGT)</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 5-9. Distribution of Track Curvature for the West Network

<table>
<thead>
<tr>
<th>Track Curvature (degrees)</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>65%</td>
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<td>83%</td>
<td>83%</td>
<td>83%</td>
<td>83%</td>
<td>75%</td>
<td>75%</td>
<td>68%</td>
<td>60%</td>
</tr>
<tr>
<td>2</td>
<td>20%</td>
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<td>16%</td>
<td>16%</td>
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<td>15%</td>
<td>15%</td>
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<td>18%</td>
</tr>
<tr>
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<td>10%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
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<td>7%</td>
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<td>0%</td>
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<td>2%</td>
</tr>
</tbody>
</table>

Table 5-10. Distribution of Turnouts for the West Network

<table>
<thead>
<tr>
<th>Turnout Type</th>
<th>Turnout Spacing by Track Segment (turnouts/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
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<tr>
<td>Standard No. 20</td>
<td>0.65</td>
</tr>
<tr>
<td>Premium No. 20</td>
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</tr>
<tr>
<td>Standard No. 16</td>
<td>0.10</td>
</tr>
<tr>
<td>Total</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Table 5-9 summarizes the distribution of track by degree of curvature. Table 5-10 lists the number of turnouts per mile by track segment and type of turnout. Table 5-11 summarizes the distribution of track metallurgy by track segment and degree of curvature. The parameters for the mainlines are identical to those used for the HAL routes, but on lower density lines the track tends to be of lower quality, and there are more curves and turnouts.
Table 5-11. Distribution of Track Metallurgy by the West Network

<table>
<thead>
<tr>
<th>Curvature (degrees)</th>
<th>Metallurgy (BHN)</th>
<th>Percent of Given Curvature with Specified Metallurgy by Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>270</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>0%</td>
</tr>
<tr>
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<td></td>
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<tr>
<td>8</td>
<td>340</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>370</td>
<td>0%</td>
</tr>
</tbody>
</table>

Concerning grades, Segments 1, 2 and 3 have steeper grades and the other segments are similar to the typical West route from the HAL analysis [57]. Unless otherwise specified, the values used in modeling the networks (such as train lengths, locomotives per train, grinding policy, and so forth) are the same as those used in the AAR HAL Phase II analysis for the length-limited cases.

5.4 Analysis Methodology

This section describes the analysis methodology used for the study. Section 5.4.1 discusses the use of UTRAIN to determine cycle times and equipment requirements for each case, given the network structure, track maintenance requirements, and level of demand. Section 5.4.2 discusses the TRACS and HALTRACK models used to determine track maintenance requirements as a function of network structure, axle load, and level of demand. Section 5.4.3 describes the cost model used to calculate the combined operating and maintenance costs for each case.

5.4.1 UTRAIN Analysis

The analysis of network operations was performed using UTRAIN. As discussed in
Chapter 4, UTRAIN models the actual operations of a full unit train network, including loading and unloading, inspection and servicing, and line operations of trains traveling between a number of different origins and destinations.

For this study, UTRAIN was used to determine the cycle time and equipment requirements for meeting demand for each case studied. In moving from the base case to heavier axle loads, fewer train sets are required to meet the same demand (assuming length-limited trains), for two major reasons:
- Each car holds more coal, so even if each train set has the same cycle time, fewer train sets are required.
- Removing train sets from the network reduces congestion, which acts to decrease cycle times. With a faster cycle, the number of train sets may be further reduced, as each remaining train set is more productive.

On the other hand, for heavier axle loads maintenance requirements increase, causing additional track closure, and potentially more train delay, which increases cycle time. Also, heavier trains require more time for loading and unloading; for train capacities greater than the base case, additional coal was assumed to be loaded and unloaded at a rate of 3,000 tons per hour.

For each of the cases analyzed, the track maintenance requirements were first determined as described in Section 5.4.2. Next, an initial estimate was made of the number of train sets required to meet demand. The simulation was run and the results were examined. If UTRAIN showed that demand could not be met with specified number of train sets, more train sets were added and the simulation was run again. If the simulation showed that there were extra train sets, and that more coal was been shipped than necessary, then the simulation was re-run with fewer trains. This process
was repeated until the minimum cycle time and number of train sets required to meet demand was determined.

For each iteration of UTRAIN, 20 simulation runs were performed: 10 with summer conditions, and 10 with winter conditions (most scheduled maintenance occurs in summer months, increasing track closure time). Each simulation run yielded the cycle time and number of train cycles completed over the course of one month of operations. The results from each simulation run were saved. The average, standard deviation, and standard error of the cycle times were computed for each set of 10 runs. In all cases, the standard deviation (for a set of 10 runs) was less than 0.03 days, resulting in a standard error of less than 0.01 days. Since UTRAIN calculates cycle times results to the nearest one-hundredth of a day, no additional runs were deemed necessary to improve the statistical accuracy of the results.

The results used for a particular iteration were obtained by averaging the results over the 20 simulation runs. The process was performed for each of the 22 cases.

Two Excel spreadsheets were developed to streamline the use of UTRAIN. The spreadsheet "EASTNET.XLS" was used for runs with the East network, and "WESTNET.XLS" was used for runs with the West network. The spreadsheets store all parameters for the UTRAIN input files, as well as the summary results from each model run. Each spreadsheet contains macros for creating export files, running UTRAIN, and importing the results. In using one of the spreadsheets, the user performs the following steps:

- **Adjust Parameters:** The user adjusts the number of trains, capacity per train, summer or winter maintenance conditions, or other parameters.
• **Export:** The user presses the button labeled "Export," and the spreadsheet exports the network parameters to files for use by UTRAIN.

• **Simulate:** The user presses the button labeled "Simulate," and the spreadsheet runs UTRAIN 10 times, saving the summary results from each model run.

• **Import:** The user presses the button labeled "Import," and the spreadsheet imports the summary results for the last 10 model runs and reports the average and standard deviation of the cycle time and amount of coal shipped.

### 5.4.2 Track Maintenance Analysis

The analysis of track maintenance requirements was performed using the AAR TRACS model and the HALTRACK model used in previous analyses of heavy axle loads. This section describes the use of TRACS and HALTRACK, and how the track maintenance projections for this study relate to those of previous heavy axle load analyses.

The TRACS model [13] provides a state-of-the-art computer modeling approach that combines engineering deterioration models with life-cycle costing techniques to estimate track maintenance costs as a function of track components, track condition, traffic mix and volume, maintenance policies, and unit cost inputs. The basic TRACS approach is to estimate track component deterioration rates as a function of the stresses induced by each specified car type, and to determine the cumulative deterioration that triggers maintenance activities, resulting in a time series of maintenance costs.

Similar to the approach followed in previous HAL analyses, for this study TRACS was used to project component lives for rail, ballast and ties. Component lives for turnouts were projected using TRACS's damage factor exponent approach, but calibrated to the results from the HAL Phase II economic analysis [57]. The component lives were used as input for HALTRACK, a spreadsheet model designed to project equivalent uniform
annual cost (EUAC) of track maintenance for the East and West coal routes evaluated in previous HAL analyses [57], [112].

The assumptions listed in the previous section were used as input for TRACS and HALTRACK. Where additional input data were required (unit costs, maintenance productivity rates, and so forth), assumptions were made to ensure consistency with previous HAL analyses. As a test, the approach described in this section was used to project maintenance requirements for the East and West coal routes evaluated previously. Although individual component lives may differ, the overall results are quite consistent with the results of the HAL Phase III analysis.

Given track maintenance requirements, annual hours of track closure were determined in the same manner as that described by Robert and Martland [113]. Maintenance hours were derived from maintenance costs using a set of track maintenance productivity rates. An additional set of assumptions was used to determine how the maintenance would be divided into track maintenance windows for summer and winter months. For each track segment of each network for each case analyzed calculations were made of the percentage of summer and winter days with no maintenance, with 4-hour maintenance windows and 8-hour maintenance windows. This data was used in UTRAIN.

5.4.3 Cost Analysis

A simple cost model was developed to compare the costs per net ton-mile calculated for each case. Track maintenance costs were determined using HALTRACK, as described in Section 5.4.2. Operating costs were determined using unit costs from the HAL Phase III economic analysis [53]. The total variable cost, excluding bridges, is the sum of the track maintenance and operating costs. Fixed costs were not considered in the study.
In previous HAL analyses, operating costs were calculated for the following categories: train crews, locomotive ownership, locomotive maintenance, car ownership, car maintenance, and fuel. The basic approach of this study was to use unit costs for the East and West length-limited base cases for the East and West base cases. The unit costs from the HAL Phase III length-limited 125-ton car cases were used for all other cases. The following paragraphs detail the assumptions made in applying the unit costs for each category from the HAL Phase III analysis.

*Train Crew* costs were assumed to vary as a function of train miles. The train crew cost per train mile was calculated from the HAL Phase III data [53].

*Locomotive Ownership* costs were assumed to vary as a function of the number of train days. The locomotive ownership cost per train day was calculated from HAL Phase III data [53]. Note that this approach implicitly assumes that the number of locomotives per train is the same for this study as previously.

*Locomotive Maintenance* costs were assumed to vary as a function of the number of train miles. The locomotive maintenance cost per train mile was calculated from HAL Phase III data [53]. As for the locomotive ownership costs, this approach implicitly assumes that the number of locomotives per train is the same for this study as previously.

*Car Ownership* costs were assumed to vary as a function of car type and length. The EUAC per car day was used in the calculations. For the HAL Phase III analysis the EUAC was calculated based on the initial cost, rebuild cost, and scrap value of the car [53]. In this study, the same approach was used. For car lengths longer than the standard 53 feet, the initial cost was increased by $700 per foot. For lengths less than 53
feet the cost was reduced by $700 per foot. The estimate of $700 per foot was considered reasonable, as it resulted in approximately equal initial costs for the 100-ton car and a car 2-axle trucks, 36-inch wheels and the 125-ton car cross section, shortened to accommodate 33 ton axle loads.

*Car Maintenance* costs were assumed to vary as a function of axle load the number of car miles. The car maintenance cost per car mile was calculated from HAL Phase III data [53]. The variation as a function of axle load was based on the difference between 33-ton and 36-ton axle loads in the HAL Phase III data. Costs for cars with 3-axle trucks were assumed to be 50% higher than costs for cars with 2-axle trucks.

*Fuel* costs were assumed to vary as a function of gross ton miles. The fuel cost per train mile was calculated from the HAL Phase III data [53].

### 5.5 Results

This section presents analysis results. Section 5.5.1 summarizes the results of the UTRAIN analysis. Section 5.5.2 summarizes the operating, track maintenance and total costs for each case. Section 5.5.3 provides additional insights on the relationship between capacity, cycle times and heavy axle loads, and Section 5.5.4 presents the conclusions.

#### 5.5.1 UTRAIN Results

UTRAIN was used to determine the cycle time and equipment requirements for each case studied. The analysis results indicate that increasing train capacity has a positive effect on operations. Increasing capacity per train, either through making cars higher or longer, reduces the number of trains required to move the required tonnage. Including network effects provides a further, positive effect, as reducing the number of train sets eases congestion and decreases cycle times. However, if the increase in capacity comes
through increased axle loads, the positive effect is partially offset by increased delay from track maintenance.

Table 5-12 summarizes the results for cycle times and train set requirements calculated using UTRAIN. The first three columns of the table identify each case by the network, car type and axle load. The fourth column lists the net capacity per train, and the fifth column lists the car length. The next two columns list the cycle time and number of train sets required, assuming not network effects (cycle time is held constant). The eighth and ninth columns list the cycle time and number of train sets required, determined using UTRAIN. The last column gives the extra percent reduction in the number of train sets, assuming network effects.

For the East network Table 5-12 indicates that increasing train capacity results in a reduction in cycle time of up to 6 hours, from an initial value of approximately 3 days and 18 hours. Even without considering the change in cycle time, the increase in train capacity results in a reduction in the number of train sets required. The cycle time reduction increases equipment savings by 4% to 6%.

For the West network the results are similar. Increasing train capacity results in a reduction in cycle time of up to 11 hours from an initial value of 5 days and 19 hours. The cycle time reduction increases equipment savings by 5% to 6%.

The results indicate that for the East and West networks modeled in this study, reducing the number of train sets by increasing axle loads eases network congestion and has a beneficial effect on cycle times. The cycle time effect is greater for the West network than for the East network, as the West network operates closer to capacity.
The following section translates these cycle time and equipment savings into cost savings.

### Table 5-12 Cycle Times and Equipment Requirements

<table>
<thead>
<tr>
<th>Network</th>
<th>Car Type</th>
<th>Axle Load (tons)</th>
<th>Net Wt per Train (tons)</th>
<th>Car Len (ft)</th>
<th>No Network Effects</th>
<th>With Network Effects</th>
<th>% Extra Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cycle Time (days)</td>
<td>Num. Train Sets</td>
<td>Cycle Time (days)</td>
<td>Num. Train Sets</td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>Base</td>
<td>33</td>
<td>11,872</td>
<td>53</td>
<td>3.76</td>
<td>54</td>
<td>3.76</td>
</tr>
</tbody>
</table>
|         | 2-Axle
36" | 33               | 13,883               | 45           | 3.76              | 47                  | 3.55            | 44              | 6%              |
|         |          | 36               | 14,010               | 49           | 3.76              | 46                  | 3.52            | 43              | 6%              |
|         |          | 39               | 14,053               | 53           | 3.76              | 46                  | 3.54            | 43              | 6%              |
|         | 2-Axle
38" | 39               | 14,143               | 53           | 3.76              | 45                  | 3.53            | 43              | 4%              |
|         |          | 42               | 14,169               | 57           | 3.76              | 45                  | 3.54            | 43              | 4%              |
|         |          | 45               | 14,327               | 60           | 3.76              | 45                  | 3.52            | 42              | 6%              |
|         | 3-Axle
38" | 30               | 14,226               | 58           | 3.76              | 45                  | 3.51            | 42              | 6%              |
|         |          | 33               | 14,320               | 64           | 3.76              | 44                  | 3.51            | 42              | 4%              |
|         |          | 36               | 14,481               | 70           | 3.76              | 44                  | 3.50            | 42              | 4%              |
|         |          | 39               | 14,609               | 76           | 3.76              | 44                  | 3.50            | 41              | 6%              |
| West    | Base     | 33               | 11,872               | 53           | 5.81              | 111                 | 5.81            | 111             | 0%              |
|         | 2-Axle
36" | 33               | 13,883               | 45           | 5.81              | 96                  | 5.41            | 89              | 6%              |
|         |          | 36               | 14,010               | 49           | 5.81              | 94                  | 5.35            | 87              | 6%              |
|         |          | 39               | 14,053               | 53           | 5.81              | 94                  | 5.38            | 87              | 6%              |
|         | 2-Axle
38" | 39               | 14,143               | 53           | 5.81              | 93                  | 5.39            | 87              | 5%              |
|         |          | 42               | 14,169               | 57           | 5.81              | 93                  | 5.36            | 86              | 6%              |
|         |          | 45               | 14,327               | 60           | 5.81              | 92                  | 5.36            | 85              | 6%              |
|         | 3-Axle
38" | 30               | 14,226               | 58           | 5.81              | 93                  | 5.37            | 86              | 6%              |
|         |          | 33               | 14,320               | 64           | 5.81              | 92                  | 5.36            | 85              | 6%              |
|         |          | 36               | 14,481               | 70           | 5.81              | 91                  | 5.34            | 84              | 6%              |
|         |          | 39               | 14,609               | 76           | 5.81              | 90                  | 5.34            | 83              | 6%              |

#### 5.5.2 Comparison of Total Costs by Scenario

The operating and maintenance costs for each case were calculated using the methodology presented in Section 5.4. This section summarizes the results of the cost
calculations. Chapman [29] presented additional details regarding the costs for each case, particularly the regarding track maintenance costs.

Table 5-13 summarizes the costs for the base case for the East and West network. The table shows the percent of the cost from track maintenance cost and from each component of operations. In addition, the individual components are compared to the cost for the East and West length-limited base case from the HAL Phase III analysis (minus bridge costs) [53].

<table>
<thead>
<tr>
<th>Network</th>
<th>Cost Component</th>
<th>Percent of Total Cost per Net Ton-Mile (%)</th>
<th>Increase in Cost per Net Ton-Mile re HAL Phase III (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>Crew</td>
<td>10%</td>
<td>-9%</td>
</tr>
<tr>
<td></td>
<td>Loco. Ownership</td>
<td>28%</td>
<td>-32%</td>
</tr>
<tr>
<td></td>
<td>Loco. Maintenance</td>
<td>6%</td>
<td>-9%</td>
</tr>
<tr>
<td></td>
<td>Car Ownership</td>
<td>19%</td>
<td>-40%</td>
</tr>
<tr>
<td></td>
<td>Car Maintenance</td>
<td>6%</td>
<td>-9%</td>
</tr>
<tr>
<td></td>
<td>Fuel</td>
<td>12%</td>
<td>-15%</td>
</tr>
<tr>
<td></td>
<td>Operations Total</td>
<td>81%</td>
<td>-27%</td>
</tr>
<tr>
<td></td>
<td>Track Maint. Total</td>
<td>19%</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>100%</td>
<td>-21%</td>
</tr>
<tr>
<td>West</td>
<td>Crew</td>
<td>17%</td>
<td>-9%</td>
</tr>
<tr>
<td></td>
<td>Loco. Ownership</td>
<td>18%</td>
<td>-42%</td>
</tr>
<tr>
<td></td>
<td>Loco. Maintenance</td>
<td>9%</td>
<td>-9%</td>
</tr>
<tr>
<td></td>
<td>Car Ownership</td>
<td>11%</td>
<td>-49%</td>
</tr>
<tr>
<td></td>
<td>Car Maintenance</td>
<td>8%</td>
<td>-9%</td>
</tr>
<tr>
<td></td>
<td>Fuel</td>
<td>15%</td>
<td>-17%</td>
</tr>
<tr>
<td></td>
<td>Operations Total</td>
<td>79%</td>
<td>-28%</td>
</tr>
<tr>
<td></td>
<td>Track Maint. Total</td>
<td>21%</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>100%</td>
<td>-20%</td>
</tr>
</tbody>
</table>

For the East base case the table shows that operating costs are 79% of the total cost considered (signals, customer service, bridges, and other items are not included), and track maintenance costs are 21%. The largest components of the operating costs are
locomotive ownership and car ownership. Relative to the HAL Phase III analysis, operating costs are 27% lower and track costs are 27% higher, for a net reduction of 21%. The operating costs are lower because the present study assumes the use of aluminum cars, and because of differences in assumptions about cycle times. Track costs tend to be higher because in the present study there is a mix of low and high-density line, but the previous analyses concentrated on costs for main lines only.

For the West base case the results are similar. The table shows that operating costs are 81% of the total cost, and track maintenance costs are 19%. The largest components of the operating costs are locomotive ownership and crew. Relative to the HAL Phase III analysis, operating costs are 28% lower and track costs are 27% higher, for a net reduction of 20%.

Table 5-14 summarizes the costs of each case relative to the base cost. For each case the table lists the percent savings in operating costs, track maintenance costs and total costs relative to the base case. For instance, for the East network, shifting to the cross section of the 125-ton car while holding axle load constant results in a savings of nearly 4% in operating costs, 1% in track costs and 3% overall.

Relative to the East and West base case, operating costs are lower for all other cases. The savings in operating costs range from 4% to 9% in the East and 5% to 10% in the West. Track maintenance costs appear to be approximately linear as a function of axle load. Savings of up to 6% are predicted for cases where axle loads are reduced; cost increases of up to 33% are predicted for axle load increases. Overall, all of the cases represent savings in the range 1% to 5% relative to the base.
Table 5-14 Summary of Cost Savings Relative to the Base

<table>
<thead>
<tr>
<th>Network</th>
<th>Car Type (axles/wheel diameter)</th>
<th>Axle Load</th>
<th>Cost Savings Relative to the Base (%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Operating Costs</td>
<td>Track Costs</td>
</tr>
<tr>
<td>East</td>
<td>2-Axle Trucks 36&quot; Wheels</td>
<td>33</td>
<td>3.8%</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36</td>
<td>5.9%</td>
<td>-1.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39</td>
<td>6.7%</td>
<td>-9.3%</td>
</tr>
<tr>
<td></td>
<td>2-Axle Trucks 38&quot; Wheels</td>
<td>39</td>
<td>6.1%</td>
<td>-11.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42</td>
<td>7.0%</td>
<td>-14.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>8.7%</td>
<td>-18.8%</td>
</tr>
<tr>
<td></td>
<td>3-Axle Trucks 38&quot; Wheels</td>
<td>30</td>
<td>4.1%</td>
<td>2.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>33</td>
<td>5.9%</td>
<td>-1.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36</td>
<td>7.8%</td>
<td>-9.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39</td>
<td>9.3%</td>
<td>-12.8%</td>
</tr>
<tr>
<td>West</td>
<td>2-Axle Trucks 36&quot; Wheels</td>
<td>33</td>
<td>5.0%</td>
<td>1.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36</td>
<td>6.8%</td>
<td>-1.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39</td>
<td>7.6%</td>
<td>-12.3%</td>
</tr>
<tr>
<td></td>
<td>2-Axle Trucks 38&quot; Wheels</td>
<td>39</td>
<td>7.4%</td>
<td>-13.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42</td>
<td>8.4%</td>
<td>-14.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>9.6%</td>
<td>-33.3%</td>
</tr>
<tr>
<td></td>
<td>3-Axle Trucks 38&quot; Wheels</td>
<td>30</td>
<td>4.8%</td>
<td>6.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>33</td>
<td>6.5%</td>
<td>-2.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36</td>
<td>8.2%</td>
<td>-5.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39</td>
<td>9.5%</td>
<td>-15.9%</td>
</tr>
</tbody>
</table>

5.5.3 Heavy Axle Load Operations and Capacity

This section provides additional insights concerning the interaction between heavy axle loads, cycle times, train capacity and network capacity for coal distribution networks. These parameters are all closely related, as described in the following paragraphs.

The interaction between cycle time and network capacity is relatively straightforward. Essentially, the average cycle time varies little with the amount of traffic on a network when the network is not operating near capacity. However, as a network nears capacity, the average cycle time increases with each train added to the network, as each
new train creates additional congestion. When the network is at capacity, adding another train to the network no longer adds to the traffic flow through the network; the new train may even cause so much delay that traffic flow decreases.

Figures 5-8 and 5-9 illustrate this interaction for the East and West coal distribution networks. Figure 5-8 is a graph of cycle time versus number of trains. For each network the figure displays the average cycle time as a function of the number of trains operating on the network. The graphs were created through multiple runs of UTRAIN. The simulation was run 10 times for each multiple of 5 trains (from 5 to 60 trains for the East, from 5 to 120 for the West). Each run represented one month of operations. The average cycle time from each run is plotted as a triangle. A third-order polynomial was fit to the data for each network, and is shown in the figure. For this set of runs, train capacity was held constant and track maintenance was assumed to have no effect on cycle time (this is not the case for the results presented in previous sections). Figure 5-9 is a graph of total monthly shipments for the East and West networks versus number of trains. The data in the figure is from the set of UTRAIN runs described above.

For the East network, the average cycle time begins to increase significantly for each train added when there are more than 40 trains in the network. Capacity is reached at approximately 60 trains. For the West network, cycle time begins to increase significantly for each train added when there are more than 85 trains in the network, and capacity is reached at approximately 115 trains.

Increasing train capacity essentially causes the curves in Figure 5-9 to shift upwards, as each train load of coal amounts to more net tonnage. If demand remains constant following an increase in train capacity, then the number of trains may be decreased. The factor by which the number of trains may be reduced depends upon the size of the
increase in train capacity, and upon how close the network is to capacity. For instance, if \( y \) is the number of monthly shipments for the West network (proportional to net tonnage), then:

\[
y = 16.2790 + 4.6850x + 0.0444x^2 - 0.0004x^3 \tag{1}
\]

where \( x \) is the number of standard train sets used in the network. If a new train is introduced that holds 20% more coal, then the effective number of shipments will be increased by 20%. Thus:

\[
y = 1.2(16.2790 + 4.6850z + 0.0444z^2 - 0.0004z^3) \\
y = 19.5348 + 5.6220z + 0.0533z^2 - 0.0005z^3 \tag{2}
\]

where \( z \) is the number of increased capacity (20% greater capacity) trains on the network.

For a given value of \( x \), the number of standard train sets, it is possible to solve for \( z \), the number of increased capacity train sets that will be required to meet the same demand. If the network is not close to capacity, then \( z \) should be approximately 20% smaller than \( x \); if there is no change in cycle time then switching to trains that carry 20% more coal should reduce the number of trains by 20%. For instance, if \( x=10 \), then (rounded to the nearest integer) \( z=8 \), representing a 20% reduction in the number of trains required.

However, if the network is operating near capacity, then a 20% increase in train capacity should reduce train requirements by more than 20%. For instance, if \( x=100 \), then \( z=73 \), a 27% reduction. This effect results from the fact that reducing the number
of trains improves the cycle time, further reducing the required number of trains. Thus, for congested networks increasing train capacity has a compound positive effect.

![Graph: Cycle Time versus Number of Trains]

**Figure 5-8.** Cycle Time versus Number of Trains
Figure 5-9. Shipments versus Number of Trains
If demand increases, then the situation is slightly different. Increasing train capacity by 20% can increase absolute network capacity by no more than 20%. However, if the goal is to increase traffic by a certain factor, then it may be more economical to increase traffic through increasing train capacity rather than increasing the number of trains. For instance, suppose there are 80 trains operating on the network, and there is a 10% increase in demand. According to (1), if \( x=80 \), \( y=470 \). To increase \( y \) by 10% to 517, \( x \) would have to be increased by 18% to 94. On the other hand, if trains with 20% more capacity were used, according to (2) only 72 trains would be required – a reduction of 10% in the number of trains resulting in 10% more tonnage being carried. Thus, particularly for congested networks, increasing train capacity can be an economical way to increase network capacity compared to adding more trains to the network.

Heavy axle load operations are a means of increasing train capacity, and thus may be used to help reap the cycle time and capacity benefits described above. However, heavy axle loads tend increase delays due to track maintenance, and for high density lines with large amounts of maintenance this provides a limit to potential cycle time improvements. This effect may be observed in the West network in Table 5-12. For cars with 2-axle trucks and 36-inch wheels, shifting from 33 ton axle loads to 36 ton axle loads results in an improvement in the cycle time from 5.41 to 5.35 days. However, a further shift from 36 tons to 39 tons results in an increase from 5.35 to 5.38 days.

5.5.4 Conclusions

Overall the optimal axle load for the cases analyzed is 36 tons. For the East network, given the assumptions made concerning equipment design, the greatest cost savings could be achieved using cars with 3-axle trucks operating at axle loads of 39 tons. However, such cars would be extremely long (over 70 feet long) and may not be feasible, given that tight, loop track configurations are used at many loading and unloading facilities. If long cars with 3-axle trucks are feasible, then their use could
result in savings of approximately 5% relative to the base. The maximum savings using cars with 2-axle trucks is comparable but lower. For 2-axle trucks operating with axle loads of 36 tons, the cost savings is 4% relative to the base.

For the West network, using cars with 3-axle trucks and axle loads of 36 tons would result in cost savings of just over 5%. However, as for the East network, the 3-axle cars would be very long (approximately 70 feet), and may not be feasible. Using cars with 2-axle trucks and axle loads of 36 tons would result in cost savings of 5%.

The results suggest that net train capacity is the critical parameter in achieving cost saving for unit coal train operations. Holding axle loads at 33 tons, moving from cars with the cross section of the 100-ton car to cars with the cross section of the 125-ton car increases net train capacity by 14%, and results in cost savings of 3 to 4%. In the latter case, the cars are shorter (45 feet rather than the standard 53 feet) but there are more cars per train, assuming length-limited trains. Lengthening cars can further increase the net train capacity. Longer cars result in heavier axle loads, but better utilize the limited train length. However, the extra savings from adjusting car length and axle load are less than the initial savings from increasing the cross section of the car.

Future research should be directed towards maximizing the cross section of coal cars, and towards quantifying the limiting parameters in car design. A case with a car that holds more coal per linear foot than the 125-ton car would likely outperform any of the cases analyzed in this study. The study assumes that it is feasible to adjust axle load by changing the car length, but changing car lengths would likely require changes to rotary dumpers and other components of loading and unloading facilities. If the cross section of coal cars can be increased, but car lengths are constrained to 53 feet, then the optimal axle load for unit coal train operations may be greater than 39 tons.
There are several important caveats to the study results. Much of the projected savings result from improvements in cycle times predicted using UTRAIN. For networks not operating near capacity there would still be cost savings from HAL operations, but the savings would be more modest because there would not be a significant improvement in cycle time.

Further, distributed power may be necessary to handle the heavier trains modeled in the study. In some cases, premium track components would have to be used; e.g., premium rail (340 Brinell) may be necessary on high-density lines in order to control defects. Bridge costs were not included in the study. Also, a number of assumptions were made concerning equipment design and costs; the assumptions made concerning 3-axle trucks are based on very limited data.

Finally, there are many complex issues relating to equipment ownership, pricing, and incentives for equipment utilization. Many electric utilities purchase their own equipment, and may not have incentives to pay for more expensive equipment that leads to operating savings for a railroad. A railroad may be able to cut costs through shifting to heavy axle operations, but cost savings through reduced cycle times and reduced line congestion may be difficult to quantify. Railroads and electric utilities will need to work together to realize the maximum savings from HAL operations.
CHAPTER 6: CONCLUSIONS

The following sections summarize the major conclusions of the preceding chapters. The final section recommends directions for further research.

6.1 Coal and the Unit Train

Unit coal train service is a large, highly-efficient and well-established service for U.S. railroads. However, meeting demand for additional capacity (especially in the Powder River Basin), further reducing costs of service and integrating unit train and scheduled operations present important challenges to the railroads. U.S. railroads will likely continue to face these issues in years to come.

A model or approach that could be used to analyze issues in operations of unit coal train networks would be a valuable tool for use by or for the U.S. railroads. A model or approach for analyzing unit coal train operations would need to address the following areas:

- **Large-scale networks**: Unit trains operate on networks with up to approximately 200 trains traveling to and from a set of up approximately 50 origins and 50 destinations.

- **Unscheduled Operations**: Whereas general merchandise and intermodal trains operate on a daily or weekly schedule, unit trains often are unscheduled, or cycle between a small set of origins and destination in a pattern that appears unscheduled compared to other traffic.

- **Medium Level of Detail**: The model or approach would need to have enough detail to examine individual train movements, address network effects, and predict a range of performance measures, including cycle times, equipment utilization, and track utilization.
• **General Framework:** Any model or approach should be applicable to the unit coal train operations of all North American railroads. The present research effort is not directed towards a particular network or railroad.

### 6.2 Literature Review and Review of Industry Practice

A detailed literature review was performed to identify approaches or models that have been used for analyzing unit coal train operations. Particular attention was given to models used for analyzing coal transportation and unit train network operations. MIT railroad research, academic research published between 1987 and 1996, and information obtained on industry practice in unit coal train operations were included in the review.

No general model or approach was identified that could readily be applied to analyzing a large-scale network with unscheduled operations at a medium level of detail. However, the available literature suggested the following results:

• The literature review included five examples of models that have been used for analyzing the operations of a unit train network at an appropriate level of detail. However, in each of these cases, the literature described only one application of each model. No author discussed how his or her model could be applied to a more general network, as required for general analysis of issues in unit coal train operations.

• In general, applying the simulation approaches used in the literature to a more general network model would be very difficult. The optimization models presented in the literature do not provide examples of approaches that could be used to predict detailed variables such as cycle times over a large-scale network.
• A number of commercially available railroad network models have been developed, requiring a medium level of detail and incorporating a combination of modeling techniques. However, the most powerful network models, such as SPM, ABM, and Multirail, cannot easily be used for evaluating unit train operations.

• Strategic planning of unit train operations at the major U.S. railroads, and tactical planning at railroads besides UP, is typically performed using manual methods.

6.3 Development of the Simulation Model

A computer simulation model, UTRAIN, was developed for analyzing operations of unit coal trains over a large-scale network. UTRAIN represents a complete unit coal train network. Individual trains move through the network, filling orders for shipment of coal between specified origins and destinations. Tracks on which trains travel are represented as arcs. Loading facilities, unloading facilities and other places where trains stop or where arcs meet are represented as nodes. The flow of the network may be interrupted by a number of events, including movement of other types of traffic over the network, track closure due to maintenance, or other occurrences. Running the model requires a set of input parameters for the trains, orders, arcs, nodes and events. Each model run produces output detailing train cycle times, equipment utilization, line utilization, average yard times, and other parameters of value to railroad planners.

6.4 Application of the Model to Heavy Axle Loads

UTRAIN was applied to study the effects of heavy axle load (HAL) operations on the costs of operating unit coal trains. Operating and maintenance costs were calculated for representative East and West coal distribution networks for a range of axle loads and operating scenarios. UTRAIN was used to determine the cycle time and capacity for each network, and was used to show how the cycle time and capacity vary as a function of axle load.
For each the East and West network, the following cases were considered:

- **Base Case**: 33 ton axle loads
- **2-Axle Trucks, 36-Inch Wheels**: 33, 36 and 39 ton axle loads
- **2-Axle Trucks, 38-Inch Wheels**: 39, 42 and 45 ton axle loads
- **3-Axle Trucks, 36-Inch Wheels**: 30, 33, 36 and 39 ton axle loads

For all cases, cars were assumed to be aluminum cars with advanced trucks. The base case represents operations with the standard 53-foot long 100-ton car. All other cases are based on cars of varying length, but the same height and width as the 125-ton car. Both the East and West networks were assumed to be length-limited. Demand was held constant for each network across all cases. Bridge maintenance costs were not included in the calculations.

For the East and West base cases, operations costs (measured in dollars per 1,000 net ton-miles) are approximately 27% lower than the costs projected for the HAL Phase III economic analysis [53], primarily as a result of the assumption that aluminum cars would be used. Track costs (excluding bridges) for the East and West base cases are approximately 27% higher than the costs projected for the HAL Phase III base case. Overall, costs for the East and West base cases are approximately 20% lower than the costs projected in the HAL Phase III analysis.

The results indicate that, compared to the base case, all other cases result in increased net train capacity and decreased cycle time. Together these effects result in reduced operating costs. However, heavy axle loads result in increased maintenance that tends to offset the savings in operating costs. Figure 6-1 summarizes the percentage savings for each case relative to the base case.
Overall the optimal axle load for the cases analyzed is 36 tons. For the East network, given the assumptions made concerning equipment design, the greatest cost savings could be achieved using cars with 3-axle trucks operating at axle loads of 39 tons. However, such cars would be extremely long (over 70 feet long) and may not be feasible. If long cars with 3-axle trucks are feasible, then their use could result in savings of approximately 5% relative to the base. The maximum savings using cars with 2-axle trucks is comparable but lower. For 2-axle trucks operating with axle loads of 36 tons, the cost savings is 4% relative to the base.

For the West network, using cars with 3-axle trucks and axle loads of 36 tons would result in cost savings of just over 5%. However, as for the East network, the 3-axle cars would be very long (approximately 70 feet), and may not be feasible. Using cars with 2-axle trucks and axle loads of 36 tons would result in cost savings of 5%.

The results suggest that net train capacity is the critical parameter in achieving cost saving for unit coal train operations. Holding axle loads at 33 tons, moving from cars with the cross section of the 100-ton car to cars with the cross section of the 125-ton car increases net train capacity by 14%, and results in cost savings of 3 to 4%. In the latter case, the cars are shorter (45 feet rather than the standard 53 feet) but there are more cars per train, assuming length-limited trains. Lengthening cars can further increase the net train capacity. Longer cars result in heavier axle loads, but better utilize the limited train length. However, the extra savings from adjusting car length and axle load are less than the initial savings from increasing the cross section of the car.
Figure 6-1. Summary of Cost Savings Relative to the Base Case
6.5 Recommendations for Further Research

This section recommends directions for further research. The research described in this thesis points to two directions, in particular, for future efforts: towards additional development of the UTRAIN model, and towards further research of heavy axle load operations. Specific recommendations for these areas are presented below.

Regarding UTRAIN, in its present form the model can be used as a research or consulting tool. An expert user should be able to construct input files for representing any general unit train network, and would likely use a spreadsheet to import, save and average the results of different model runs. However, development of a graphic user interface (for model input and animated display of results) would be indispensable for use of the model by casual or inexperienced users. Consideration should be given to developing a graphic user interface for the model.

Further, UTRAIN should be calibrated using data from an actual coal distribution network. The study described in this thesis concerned representative networks, purposefully constructed to be similar to, but not the same as actual U.S. railroad networks. A detailed calibration process should be performed before UTRAIN is used to predict the performance of an actual network.

UTRAIN provides an example of how a relatively straightforward model can be used to predict performance parameters at a medium level of detail for a complex railroad network. As railroad models become increasingly complex, using optimization methods, or handling large amounts of data in real time, there will likely be an important role for simulation models such as UTRAIN. Simulation models can be used to predict network performance in the short, medium or long-term, and can provide a critical supplement to other models that operate either in the short-term with a high
level of detail, or over the long-term with little detail. Further research in railroad operations research should consider what combination of models and approaches can best address the challenges in railroad operations.

Regarding heavy axle loads, further research should adopt the network framework used in this study. Previous research was directed towards study of individual coal lines. However, heavy axle load operations have different effects on high-quality high-density lines than on lower-quality low-density lines, and only through a network framework can the range of effects be quantified accurately.

The research indicates that a significant benefit of heavy axle load operations is the cycle time reduction for congested networks. Future research should explore the degree to which heavy axle load operations result in equipment savings and cycle time reductions.

A critical result is that net train capacity is a more important parameter than axle load for achieving cost savings. Axle loads should be seen as one component of the broader issue of optimizing equipment design. Future research should be directed towards maximizing the cross section of coal cars, and towards quantifying the limiting parameters in car design.
REFERENCES


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