CAR DESIGN FOR MORE PRODUCTIVE HEAVY-H/ L RAIL OPERATIONS:
INCREASING THE CAPACITY OF LENGTH-LIMITED TRAINS

by

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ABSTRACT

Improved car design can enhance the productivity of heavy-haul rail operations. Car design can increase train capacity in order to procure benefits from two broadly defined sources: increased load per linear foot and improved carrying efficiency (i.e. net-to-tare weight ratio). From a car design perspective, train capacity is a function of six components: axle load; number of axles per car; car cross-section; cross-section utilization; car spacing; and car net-to-tare. Considering all of these parameters provides opportunities for productivity enhancement beyond the traditional Heavy Axle Load (HAL) approach, wherein a tradeoff between operating cost benefits and increased track costs limits improvement.

The operating cost benefits and implementation costs associated with alternative car design were explored with respect to coal unit train operations using both rotary-dump bathtub gondola and open-top bottom-dump hopper car designs. The base case cars were established by modeling the best current industry practice – 53-foot long cars with aluminum bodies, improved suspension trucks and 36-ton axle loads. Analyses were performed over representative Eastern and Western U.S. coal distribution networks.

The most promising alternative gondola car design methodology entails maximizing the car cross-section by heightening the car to the limit established by the Center-Of-Gravity (COG), widening the car as much as clearances will permit and then shortening the car to maintain the same Gross Vehicle Weight (GVW). For each foot of additional height or width, operating cost benefits on the order of 2% and capacity benefits of 9% are achievable. Altogether, operating cost savings of more than 3-4% and network capacity benefits of more than 17% are feasible beyond the base gondola. The most promising hopper car design methodology is an articulated, longitudinal dog-leg door, manual-discharge concept. The combination of these design concepts improve operating costs and increase capacity by eliminating car spacing, improving the cross-section utilization, reducing car weight and car ownership costs. Overall, an articulated hopper car bound by current COG and clearance limits offers a 45% increase in capacity and 10-12% lower operating costs than the base hopper.

Optimal car design depends upon a tradeoff between the operating and capacity benefits and the implementation costs related to bridges, dumper modifications and clearances, all of which are very service and route-dependent. Four optimal car designs are suggested by the results: 1) a high/wide, dog-leg, automatic-discharge hopper – suitable for low distance and low volume service; 2) an articulated, dog-leg, manual-discharge hopper – suitable for a vast range of mid-distance and mid-volume service; 3) a higher axle load, 53-foot gondola – suitable for existing rotary-dump services where short distances and low volume cannot justify dumper modifications; and 4) a high/wide gondola – suitable for longer distance and higher volume service. Overall, improving car design without increasing axle loads appears to be a very cost-efficient and capacity-effective alternative for North American heavy-haul railroading.

ACKNOWLEDGEMENTS

> When the Grand Trunk was projected in 1852, it was to be the longest railway in the world. Later, it was characterized as the world's worst commercial failure. It was, in fact a pioneer – in design and management, in finance and in the economic interrelations of Britain, the United States and Canada. It was a pioneer, too, in that it gave Canadians one of their earliest experiences with "big business."
>
> A. W. Currie
> *The Grand Trunk Railway of Canada*

> This succinct analysis, by the author of what is unquestionably the best business history of the GTR yet written, sums up the seven-decade career of one of Canada's most interesting railway companies. Organized in 1853, and largely financed in Great Britain, its operations were dominated for more than 40 years by an absentee directorate in London which appointed Britons to manage operations in Canada. With the hiring of the American Charles M. Hays as general manager in 1896 the GTR's organization and operating practices underwent profound changes, and for the first time it became profitable. Hays died in the *Titanic* disaster of 1912, and, while his polices were continued, the GTR was soon hopelessly bankrupt. Its corporate demise came in 1923 when it was absorbed into the five-year-old Canadian National Railways.
>
> Omer Lavallee
> "The Grand Trunk Railway of Canada: An Overview",
> *Railroad History*, The Railway & Locomotive Historical Society

I find the preceding passage enchanting and exciting; not only because my great-grandfather, Alfred Chapman, was a locomotive engineer between Montreal and Toronto on the Grand Trunk Railway, and not only because it mentions the *Titanic*, which is enough to spark anyone's interest, but also because it serves as one of the many examples of a Canadian calamity wherein the embarrassing solution was to "import" American know-how. I would like to be an example of the opposite. I want to follow the steps of "The Empire Builder", J.J. Hill, by being a Canadian who changes the shape of American railroading, and in fact, the face of the whole world. With this as my ultimate goal, I am pleased to present the intriguing results and conclusions of my Master's thesis. This work might just alter the future direction of heavy-haul rail operations in North America. This thesis represents the perceived end to my formal education, completed on the dawn of my career in freight railroading – starting in operations, as a trainmaster for the first transcontinental, the Union Pacific Railroad.

I owe a great deal of gratitude, this thesis, all of my railroading research and experience, a lot of what I know and how I think, and the foothold of my career in the rail freight industry to one man – Carl Martland. Carl, thanks for *everything*.

I would like to thank all of my MIT friends, primarily the Logs and the Delts, especially Geoff Johnson, Kirk Seward, Seth Cooperman and Ryan Anderson. Thanks for all the fun. Thanks to my fellow graduate students and my two grad. school room-mates and friends, Cyrus Wadia and Chris Rodarte, for putting up with me during the highs and lows and listening to my "girl problems." Thanks also to Bob, Pretty Boy and Benny for all the good times in T.O. Thank-you to my long-time Trinity buds and friends from "God's Country," especially Christopher "Lawrence" Good. And a special thanks to my mentor and best friend, Billy Petro, for all the laughs, good times and for always being there for me. Bill, you're the best – I'm proud of you.

Most importantly I would like to thank my relatives and my family – Mom, Dad, Shelby and Paul. Thanks for always being there, supporting me and making me who I am today. I love you all very much.

I would like to dedicate this accomplishment – the biggest, scariest and final feat in completing my master's degree – to my father. I wish he were still alive to read my work. One of my fondest memories of him is walking together down the old Toronto, Grey & Bruce R/R right-of-way from Flesherton Sta. to Saugeen Jct. He taught me to get up early in the morning, make a day of it and work hard in order to excel. This work, as well as everything I do, is dedicated to him. I love you Dad and I'm proud to be your son.

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CHAPTER 1: INTRODUCTION

1.1 Purpose

This study seeks to identify effective methods for enhancing the productivity of heavy-haul rail operations through improved railcar design. Car design can be modified in order to maximize train capacity in such a way as to minimize total costs and maximize network capacity.

1.2 Motivation

The author, working along with Bill Robert and Carl Martland at the Massachusetts Institute of Technology's (MIT) Association of American Railroads (AAR) Affiliated Laboratory, conducted a study entitled, "Factors Influencing Optimal Axle Loads for Heavy Haul Operations" [1]. The results of that study suggested that increasing the net capacity of trains could attain benefits beyond the AAR's traditional Heavy Axle Load (HAL) approach.

The completed Phases I and II and the ongoing Phase III HAL analyses have almost exclusively focused on the track structure [2][3][4]. Motivation for the HAL research efforts has been to reduce the costs of heavy-haul railroading and, to a lesser extent, to increase track capacity. The traditional HAL approach entails focusing solely on increasing Gross Vehicle Weight (GVW) by increasing axle loads, in order to increase the net train capacity and thus decrease operating costs. Axle loads are clearly a major technological constraint on costs and capacity, but other factors can also be important in their effects on train configuration.

The primary detriment of the HAL approach is that increasing GVW by increasing axle load increases track costs and thereby decreases the value of the operating cost benefits. A broader, more systematic and better balanced approach to cost improvement and capacity enhancement than the traditional HAL

methodology was hypothesized as a better way to improve upon the best current operating practices. A more extensive approach that includes all of the parameters combining to define net train capacity could be far superior – mainly by investigating methods for increasing net train capacity without increasing axle loads or track costs.

Specifically, the Optimal Axle Load study suggests that redesigning railcars in order to maximize the car cross-section (height and width) and then adjusting car length to obtain the optimal axle load will lead to additional cost savings and capacity enhancement [1]. The intensive economic analysis of axle loads in the Optimal Axle Load study found that the benefits of heavier axle loads come from two sources. The first, and by far the largest, portion of the benefits comes from using cars with a greater linear load density (gross vehicle weight per foot of car length). Most of the operating benefits that arise from increasing axle loads relate to the number of trains that are run. Increasing linear loading increases the capacity of a train of fixed length, and thereby reduces the number of trains required to move the same net tonnage.

The second, much smaller benefit, occurs because higher axle loads allow the same net tonnage to be carried slightly more efficiently. Larger cars allow for an inherent increase in the ratio of net lading weight to car tare weight. This results in needing fewer trains *and* fewer cars to move the same net tonnage, since a larger portion of total gross train weight is comprised of lading. Thus, for a fixed car cross-section, the cars must be longer in order to accommodate the increased net capacity, and there are therefore fewer gaps in trains that are length-limited.

In other words, much of the benefits that have been quantified in the various HAL analyses could be achieved by increasing linear loading, which does not require increasing axle loads, by using higher, wider and *shorter* cars.

The current study extends beyond the HAL and Optimal Axle Load studies by identifying more of the factors, not just the size of the car cross-section and axle load, that affect net train capacity, and also by addressing the car design issues in greater detail.

1.3 Definitions

1.3.1 Heavy-Haul Rail Operations

Heavy-haul rail operations are defined best by Armstrong [5] as operations that require the transportation of major tonnages of goods. The goods characteristically have a relatively low marketable value. These facts lead to the use of high axle loads over a distribution network that has capacity closely tailored to the flow of the goods. Other traffic may or may not be present on the same route structure.

1.3.2 Total Cost

Total cost, for the purposes of this study, is defined as the sum of four cost components:

- Track costs
- Operations (transportation) costs
- Equipment costs
- Implementation costs
    - Clearance costs
    - Bridge costs
    - Unloading facility costs
    - Displaced locomotive power operating costs

This is not the true total cost – total logistics cost – since many cost components that comprise total logistics cost are omitted from the definition, such as fixed overhead costs, loading costs, inventory costs, et cetera. Logistics is the process of strategically managing the movement and storage of raw materials, in-process inventory and finished goods from point of origin to point of consumption [6]. Total logistics costs are a function of the characteristics of the shipper, the receiver, the commodity and the transportation options available [6]. In the definition of total costs used in this study, only the cost components that encompass the incremental benefit and cost changes of the alternative car designs are included.

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1.3.3 Network Capacity

There are many ways in which to define capacity. Capacity is not something that can be readily measured or observed [7]. Capacity limits may be based on a physical limit, service deterioration, rising resource costs, an inability to meet critical customer demand, or unacceptable risks associated with service collapse. Ultimately, the most appropriate definition of capacity depends upon the reasons for the analysis [7].

In this instance, since the analyses are performed over entire rail distribution networks, the best definition of capacity is network capacity. Network capacity is a function of two capacity components:

- Line capacity
- Terminal / yard capacity

The capacities of all of the individual line segments and terminals composing the network are encompassed in the definition of network capacity. Network capacity could be measured in many ways, including the number of trains per day, cars per week, Million Gross Tons (MGT) of traffic per year, and net tons of lading per year [8]. Network capacity, however, for the purposes of this study, is best defined in terms of average net train capacity as measured in net tons. Measuring network capacity in terms of net train capacity offers a broad and systematic approach to cost improvement and capacity enhancement (i.e. productivity). Net train capacity is the most appropriate measure of network capacity from a car design standpoint because it encompasses all the possible parameter changes in car design that effect total cost and network capacity.

1.4 Network Capacity Framework from a Vehicle Design Perspective

Network capacity can be decomposed into five different levels of detail, as depicted in Figure 1-1. These levels have a nested structure. The parameters composing each lower level interact in such a way as to form a higher level capacity-related vehicle design parameter.

Net train capacity defines network capacity at its most primary level, with respect to the purposes of this study. Net train capacity encompasses all of the train and vehicle assumptions and parameters that affect network capacity. Net train capacity is a function of two second-level parameters:

- Train length
- Net Linear Load (NLL) (also known as "train density")

The limit on train length (size) is set by one of two limits at a third level of capacity definition:

- Length
- Weight

The maximum allowable train length is usually constrained by yard track or passing siding lengths. Increasing yard or siding lengths is therefore a mechanism for increasing network capacity. This study focuses on length-limited trains, since the cost and capacity benefits that result from improved vehicle designs are much more acute for length-limited than for weight-limited trains.

The maximum allowable train weight is set either by maximum allowable drawbar force or locomotive pulling power. Maximum drawbar force for a given route is a function of the gross trailing tons behind the locomotives. The longitudinal train forces must not exceed a level large enough to pull a train apart or large enough to cause a derailment as the train accelerates, decelerates, or traverses over a series of grades. The drawbar forces can be reduced by using blocked cars (semi-permanently coupled cars by means of slackless couplers, fixed drawbars, or permanently-coupled cars by means of articulated joints) or by using displaced locomotive power (additional power placed anywhere but the head-end of a train – usually at a mid-train location). The locomotive consist must have enough power to pull the train up the ruling grade of a journey and provide enough braking capability to stop the train within the stopping distance dictated by the signal spacing.

The net linear load is a function of two third-level capacity parameters:

- Train net-to-gross (net weight as a percentage of total weight)
- Gross Linear Load (GLL) (also known as "track density")

For unit train operations, there is a loaded leg and an empty leg to the complete train cycle between origin and destination. The train net-to-gross can therefore be defined either over the complete equipment cycle or just for the loaded portion of the trip. The train net-to-gross under both definitions is further composed of two fourth-level parameters:

- Railcar net-to-tare
- Locomotive consist

A train is simply an arrangement of locomotives pulling cars. The net weight of the carloads plus the empty car weight plus the locomotive weight combine to form the train net-to-gross. The railcar net-to-gross would make a better and more direct measure of the carrying efficiency of the cars, but net-to-tare is a commonly cited measure in the industry that performs the same function. The railcar net-to-tare is affected by many factors such as the size of the car box, the size of the wheels, journals, and trucks, the materials used in the construction of the car, et cetera. The locomotive consist factors important in defining train net-to-gross are the total weight of the locomotive consist and the number of locomotives in relation to the number of freight cars.

The gross linear load is a function of two fourth-level capacity-related parameters:

- Gross vehicle weight
- Car length

The gross vehicle weight, is often thought of in terms of gross rail load, and is controlled by adjusting two fifth-level capacity-related parameters:

- Axle load
- Number of axles per car

Of course, increasing the axle loading has the detrimental effect of increasing track costs. The number of axles per car is a function of the number of trucks per car and the number of axles per truck.

The car length can be set by a number of constraints, such as the railcar unloading method. Given the gross vehicle weight and net railcar capacity, car length is a function of three fifth-level capacity-related parameters:

- Car cross-section
- Cross-section utilization
- Car spacing (length over couplers)

The car cross-section is measured in terms of the extreme car height above the top of rail and the extreme width (also called the loading gauge). Allowable clearances, the track gauge, and Center-Of-Gravity (COG) considerations restrict the car height and weight limits.

The car cross-section utilization is defined as the average cross-section of the lading calculated using the cubic capacity and extreme interior box length. It is quoted as a percent of the extreme car cross-section above the top of rail. The net cross-section is limited within the extreme cross-section by the clearance envelope limits (such as the minimum required space between the bottom of the car and the top of rail) and the area required for the structural car components.

Car spacing is defined in terms of the distance between the open coupler faces and the interior box length. Car spacing is the unproductive volume between cars that is empty of lading.

Increasing the car cross-section, improving the cross-section utilization, and decreasing car spacing are mechanisms that will all increase capacity.

With the formulation of this framework for envisioning network capacity from a vehicle design perspective, a very efficient and effective methodology exists for improving the productivity of heavy-haul rail operations in terms of cost and capacity.
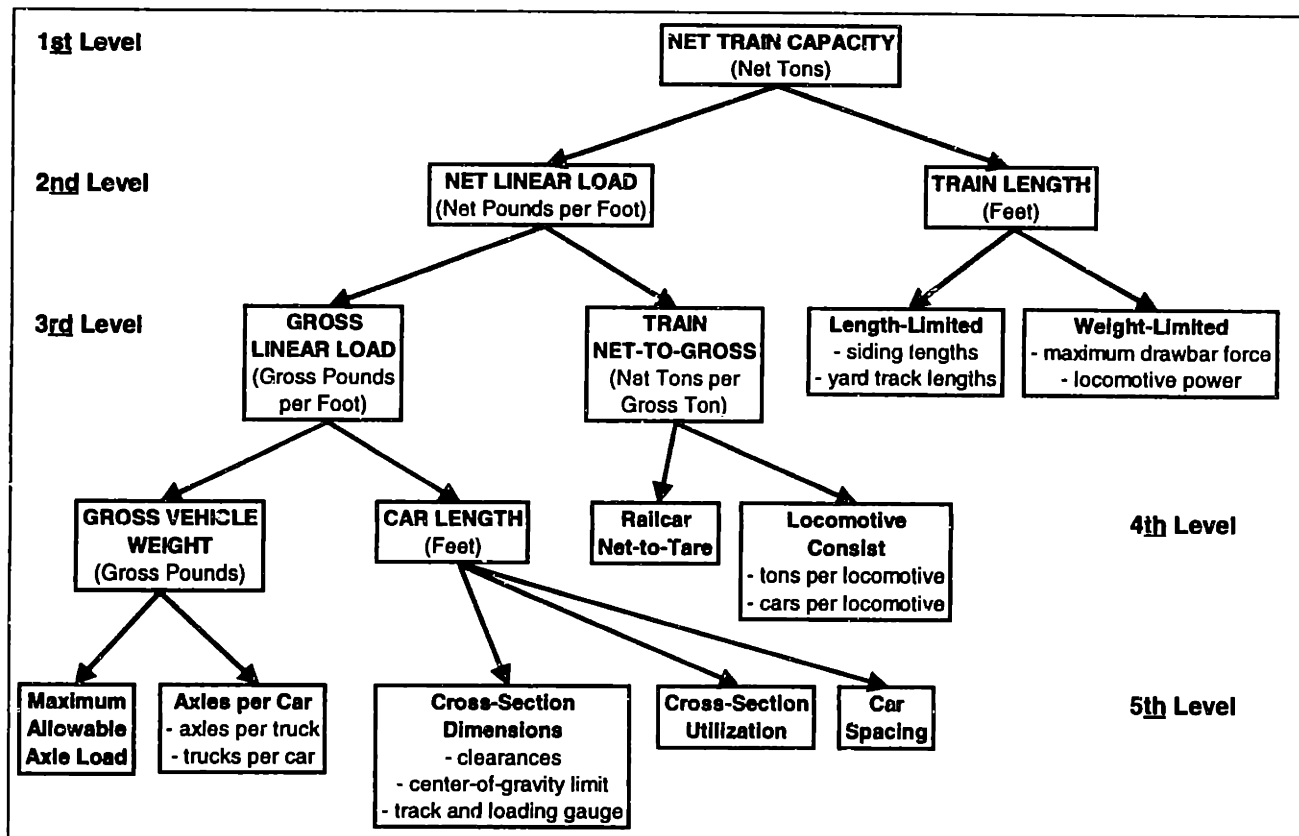
Figure 1-1: Network Capacity Framework for Car Design

1.5 Analysis Approach and Structure

Although the network capacity framework, as applied to vehicle design in order to reap operating cost and capacity benefits, could be extended to improve the transportation productivity of any commodity-type, the immediate ramifications are most apparent for bulk commodities. As a result, unit train transport of coal is investigated in this study.

1.5.1 The Importance of Coal

Coal consumption in the U.S. is at record levels and growing [9]. The largest market for coal is in sales to electric utilities. Over half of electricity generation in the U.S. is performed with coal, with electric utilities consuming approximately 940 million tons of coal per year. Transportation accounts for approximately one-third of the purchase price of coal. Over 60% of coal is transported by rail, with coal accounting for approximately 40% of the tonnage and 20% of the revenues of the rail industry. Over 85%

of the coal transported by rail is carried by means of unit train service. In short, coal unit train service is "big business" and an important part of the overall North American rail operation.

1.5.2 Unit Train Service Description

Unit train service is characterized by the shipment of bulk commodities in large blocks of cars or trainloads between a small set of origins and destinations [9]. Compared to general merchandise service, unit train service provides improved equipment cycle times and increased equipment utilization due to tailored and focused service, circumvention of terminal and switching operations, specially designed equipment, and high-speed specialized loading and unloading facilities. Unit train service therefore is able to offer reduced costs in comparison to other rail operations.

1.5.3 Extensions Beyond Previous Research

The current study extends beyond prior AAR work by considering:

- A broader range of alternative car designs
- The factors influencing optimal car design
- Implementation issues

The main themes of this study are two-fold:

1) To isolate and investigate the relevance of the car design factors that influence net train capacity.
2) To identify car design methodologies for simultaneously improving total costs and enhancing capacity.

1.5.3.1 Parametric Analysis

The best way to analyze a wide variety of car design alternatives and design methodologies is by implementing a parametric analysis approach. A parametric analysis entails isolating a single parameter and gauging the sensitivity of the results to changes in that parameter over a reasonable range. Simple car design methodologies were devised so that many alternative vehicles, modified from a base case, could be "constructed" and analyzed relatively quickly. The flexibility of such an approach allows for

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investigations of many more alternatives and design methodologies than otherwise would have been possible. The results offer sufficient accuracy in order to gauge the basic relative value of each alternative design methodology and parameter.

1.5.3.2 Optimal Car Design Methodology

As depicted in Figure 1-1 and outlined in Section 1.3, there are six parameters that govern network capacity from a car design perspective. Considering these factors in unison, therefore, encompasses the concept of optimal car design from a heavy-haul productivity perspective:

- Axle load
- Axles per car
- Cross-section dimensions
- Cross-section utilization
- Car spacing
- Car net-to-tare

These parameters were manipulated in order to construct alternative car designs under three basic methodologies:

- Higher, wider and shorter cars – cross-section dimensions
- Heavier cars – axle load
- 3-axle truck car – axles per car

Within the framework of these three basic alternative car design methodologies, other parameters and design characteristics were altered in order to identify the best approach to undertake for optimal car design.

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1.5.3.3 Implementation Issues

Implementation issues that would impede the adoption of any alternative car design are not directly incorporated into this analysis; however, they are identified and discussed at differing levels of detail. The relevance and magnitude of each issue is gauged. The implementation issues include:

- Clearances
- Bridges
- Unloading facility modifications
- Displaced power operating practices

Railcars are designed within certain dimensional limits – clearances. Allowable vehicle dimensions are a function of each specific route with limits typically imposed by tunnels, bridges, sharp curves and the proximity of other tracks, buildings or other structures. Expanding the maximum allowable cross-sectional vehicle dimensions, typically defined by the Plate C diagram, could impose a serious infrastructure cost penalty by requiring increased clearances.

Bridge costs increase with the loads placed upon the bridges. Increasing net train capacity through any method that subsequently raises either axle load or gross linear load will increase bridge costs. The increased loading could either exceed the design limits for bridges, mandating replacement, or could decrease the fatigue life of bridges, requiring replacement sooner than would otherwise be necessary.

Unloading facilities are specifically designed to accommodate a certain car design. Some unloading methods, such as rotary dumping, are very sensitive to the car geometry and weight. Specialized unloading equipment can be very expensive. Alterations to car design can impose substantial modification requirements and thus a significant expense upon an unloading facility.

Increases in net train capacity and subsequent increases in gross train weight beyond the current base case will almost certainly cause the length-limited trains assumed in this study to become weight-limited by exceeding maximum drawbar force limits as a result of their extreme gross weights. Maximum drawbar forces can be maintained at a safe level by placing locomotives in the middle of the train. Mid-train power operating practices are inherently more complicated as a result of the increased communication requirements between the mid-train locomotive units and the head-end controlling unit and also as a result of the difficulty inherent in inserting and removing units from the middle of a train.

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1.6 Thesis Structure

Chapter 2 of the thesis provides background information outlining recent U.S. and foreign experiences with car design as a method for improving the productivity of heavy-haul rail operations. The chapter describes recent North American research regarding vehicle design in relation to operational economics. The prior research that has led, either directly or indirectly, to this Optimal Car Design study is summarized. A selection of experiences in Canadian, Indian and Australian heavy-haul vehicle design are also recounted.

Chapter 3 provides descriptions of the alternative car designs derived and modeled in this optimal car design study. The chapter also describes the underlying assumptions and methodologies that were employed in contriving the alternative cars. The essential parameters and statistics of the alternative cars are outlined and compared to the base case cars. The intricacies involved in the parametric analysis design process are also described in detail.

Chapter 4 offers descriptions of the representative Eastern and Western U.S. coal distribution networks over which operations were modeled in this study. The key assumptions and parameters incorporated into the networks are summarized, as well as the differences between these networks and their respective counterparts that were used in the Optimal Axle Load study [1]. The ramifications of modeling operations over a network, versus over a mainline track segment, as in the HAL analyses [2][3][4], are also discussed.

Chapter 5 outlines the operating costing methodology employed in performing the economic assessments of the operating cost benefits of alternative car designs. Operating costs are the sum of direct track, transportation (operations) and equipment costs. The many assumptions that were incorporated into the cost component estimates are also outlined.

Chapter 6 discusses the implementation issues inherent in alternative car design for coal unit train operations. Background and qualitative descriptions of the major issues and incremental costs involved in implementing radically new car designs are described. Estimates of the costs are also provided.

Chapter 7 presents the results of the optimal car design study. The findings of the operating cost and capacity benefit investigation are outlined in great detail. The results of several operating cost sensitivity

analyses are also presented. Finally, the findings from the implementation issue investigations are compared to the operating benefit results.

Chapter 8 summarizes the major points from each of the preceding chapters and draws conclusions from all of the information discussed. The background and story-line leading to the Optimal Car Design study is outlined. The analysis methodologies employed in devising alternative car designs and modeling their economic performance are also outlined. The implementation issues are summarized. The results of the operating cost and capacity benefit analyses and the cost sensitivity analyses are also summarized. Finally, the issues and results are incorporated into a series of conclusions and optimal car designs are defined. Also, this chapter recommends directions for future research.

CHAPTER 2: BACKGROUND

For more than 150 years, inventors, engineers, financiers, and entrepreneurs have sought better technology for running longer, heavier, faster, and safer freight trains [10]. As a result of their activities, line performance, in terms of cost, capacity, travel time and trip reliability, has improved dramatically as evidenced by North American high density, heavy-haul rail operations. This chapter outlines recent U.S. and foreign experiences with vehicle design for increasing the productivity of heavy-haul rail operations. Recent North American research regarding vehicle design in relation to the economics of operations is also outlined.

2.1 Big John Hopper Case

The first recent technological push to improve the productivity of heavy-haul rail operations transpired in 1961 when the Southern Railroad attempted a transition to unit trains of 100-ton cars for grain transport in the celebrated "Big John Hopper Case" [11]. At that time, as well as today, the railroads competed fiercely with trucks for local and regional grain distribution and with barge lines for inter-regional grain movements. The rail competition with trucks focused mostly on service, while the competition with barge lines focused on costs.

The rail industry, lead by Southern's innovation, responded to the competition with two initiatives – one technological and one operational. The technological change was the development of larger cars specifically designed for grain transport. The operational change was the introduction of unit train service, designed to keep the cars out of yards, thereby reducing trip times and, more importantly, reducing equipment cycle times. The two changes were related since it was more important to keep the expensive new cars moving and in use than the older, much less valuable 40-foot boxcar equipment.

At the time, Southern believed that significant potential cost reductions could be achieved by increasing axle loads to enable the same tonnage to be handled in fewer, larger cars [12]. Utilizing the "Big John" hopper car in unit train service allowed Southern to propose a grain rate cut of 50% or more. Southern did not attempt an engineering analysis to support its case for higher axle loads. Research was not performed at the time to assess the impacts of the heavier cars on the track structure. The introduction of the new cars and new services were challenged by the barge competition for offering service at rates below cost [11]. The Interstate Commerce Commission subsequently suspended the rates in 1962 and the case dragged on for four years before Southern eventually won the right to quote the lower rates.

The Southern Railway attracted significant business, which forced the other railroads to follow suit in order to retain their share of the grain business [12]. Unfortunately, the track conditions were poor on the Southern and elsewhere, which caused extensive problems as a result of using the heavier cars. In the 1960's and 1970's, increasing axle load limits from 25 tons to 33 tons helped to precipitate a track quality crisis for many U.S. and Canadian railroads. It took twenty years for the rail industry to fully complete the transition from boxcars to jumbo hopper cars for hauling grain [11].

2.2 Heavy Axle Load Studies

The turmoil caused by the widespread introduction of the 100-ton car for grain and other bulk transport in the 1970's was not forgotten [12]. Despite dramatic track technological advances, the memory of the crisis was enough to limit further increases in axle loads for more than 20 years. Only when it became apparent that the railroad industry infrastructure was well able to handle the 100-ton car effectively, did the railroads seriously consider further axle load increases. The possibility that technology had changed sufficiently to allow increased economic efficiency in the transportation of bulk commodities by increasing axle loads above 33 tons was publicly raised by Australian representatives at the 1985 Heavy Haul Conference in Vancouver [2]. The basic motivation that provides impetus for heavier axle loads today is the growing belief on a part of the engineering community that higher axle loadings are feasible and the continuing belief that heavier axle loads lead to savings in operating costs.

Beginning in 1986, the Federal Railroad Administration (FRA) and the AAR began conducting extensive studies of the relative effects of cars with 33-ton and 39-ton axle loads (100-ton cars and 125-ton cars) at the Facility for Accelerated in-Service Testing (FAST) in Pueblo, Colorado [12]. Unlike the earlier experience, the push for heavier axle loads this time would be well grounded in engineering experience and supported by intensive research and analyzed in detail using engineering economic techniques.

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2.2.1 HAL Phase I

The FAST/HAL tests were designed to develop data on the relative deterioration rates of track components under 33-ton and 39-ton axle loads. The results of 160 MGT of 39-ton axle load traffic were documented in the Phase I tests. The FAST/HAL Ad Hoc Economic Review Committee reviewed the data from the FAST/HAL tests, from test sites on individual railroads and from laboratory tests, and translated the impact of HAL traffic into economic terms for rail bulk commodity (coal) transportation [2]. In some cases, where data from controlled tests was not available, expert opinion was used.

The Committee performed three activities. First, a life-cycle cost methodology was developed and calibrated. Second, estimates of the relative direct operating cost economics of providing unit train coal transportation were made for four "generic" operating scenarios:

- An "Eastern" route characterized by moderate grades and significant curvature
- A "Western" route characterized by moderate grades and less curvature
- A "mountain route" with extreme grades and curvature
- A "level route" with very little curvature or grades

Three conventional car designs were considered:

- 263,000-pound GVW (the "100-ton" car with 33-ton axle loads)
- 286,000-pound GVW (the "112-ton" car with 36-ton axle loads)
- 315,000-pound GVW (the "125-ton car with 39-ton axle loads)

The 286-kip car configuration was modeled as a 263-kip car loaded to 286 kips. Trains traveling each route were limited in one of two ways:

- Weight (drawbar force)
- Length (siding lengths loading or unloading loop, or other length)

This resulted in 16 evaluations of HAL equipment alternatives in two operating environments over four different route characteristics.

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The third action performed by the Committee was to conduct two case studies using the same methodology in order to evaluate actual operations on two railroads. This allowed the Committee's estimates to be compared to actual experiences with 263,000-pound equipment and to the estimates of the effects of HAL traffic.

The Committee drew three major conclusions [2]:

1) Although track deteriorates at an accelerated rate under HAL operations, the degradation of track components is not catastrophic; therefore, operating with increased axle loads is technically feasible.

2) Sufficient potential economic cost savings associated with increased axle loads exist under favorable conditions.

3) Certain areas of concern must be addressed to resolve the uncertainties of HAL operations and improve HAL economics.

The "generic" scenario results indicated that the 286-kip car total cost savings (including the impact on track costs) varied from 1.6% to 7% per net ton-mile, as compared to the 263-kip car "base case." The 286-kip car was superior to the 263-kip car in all of the cases considered. The 315-kip car had mixed results varying from a 3% disadvantage to a 5.2% advantage over the 263-kip car. In no case did the 315-kip option out-perform the 286-kip car. Importantly, none of these scenarios included any consideration of bridge upgrading or replacement cost. Length-limited operations were shown to gain greater advantage from increased axle loads than weight-limited operations because the greater capacity per unit of train length of the HAL cars could be used to increase the lading in the train.

The conclusions offered by the Committee were supplemented with a number of economic cautions [2]. The benefits of increased axle loads resulted principally from three sources:

- Increased net train loads due to increased net-to-tare ratios and increased net load per foot of train length
- Reduced equipment capital costs due to greater capacity per dollar of equipment ownership cost
- Reduced car and locomotive maintenance and other mileage-related costs

Wide variations in these benefits across car designs of the same GVW and axle load were noted. Therefore, specific equipment alternatives must be investigated. The economic results were highly route and service specific. Thus, individual railroads should analyze their own particular service alternatives. Bridge impacts must be carefully analyzed. These costs are highly site and service specific as they depend on the design and maintenance state of the individual bridges on each route under consideration. The analysis must also consider the entire infrastructure.

2.2.2 HAL Phase II

The purpose of Phase II of the FAST/HAL economic study was to update the Phase I analysis and conclusions based on the additional information available as a result of 300 MGT of 39-ton axle load traffic accumulated during the FAST/HAL Phase II tests completed in 1994 [3]. The new information included the FAST/HAL test results for new track component designs and maintenance procedures, the revenue experience on AAR member railroads, and the new theoretical models available concerning the performance of steel bridges and critical track components, such as turnouts, ballast, and ties. Phase II of the FAST/HAL testing was designed to evaluate components and maintenance practices that offered cost reductions in areas where the Phase I tests suggested potential improvements, such as rail field welds and turnouts. Phase II was also designed to better determine the life expectancy of longer-lived track components, such as ballast and rail. In short, the Phase II analysis differed from Phase I primarily in that the relative effects of HAL operations were gauged on an improved track structure and with consideration of bridges.

The Phase II economic studies used the same basic methodologies and many of the same tools employed in Phase I [3]. However, three significant changes were made with respect to these attributes:

- Changes in scope
- Changes in analytic tools
- Changes in relative prices of resources

Due to time and resource constraints, only the Eastern and Western "generic" studies were performed in Phase II. Further, the Committee and staff did not feel that the data collected from the extreme mountain and level routes added anything to the understanding of the economics of increasing axle loads. During the five years between the Phase I and II studies, there were several improvements in the analytical tools available to conduct the economic assessment. These new and upgraded tools were utilized to the

advantage of the Phase II analyses. Finally, account was taken for changes between Phases I and II in both the absolute and relative prices of the resources required to provide rail transportation as a result of inflationary pressures.

The Phase II test results indicated that specific cost components changed in their absolute and/or relative magnitude and importance [3]. Certain problem areas, such as turnouts and field welds, were improved. Overall, the FAST/HAL research and subsequent economic evaluations performed through the end of Phase II in 1995 confirmed the basic conclusions and recommendations reached at the end of Phase I. The operation of heavier a· ie loads (i.e. 39 tons) over well-maintained track that has good quality components and over bridges of sufficient strength is technically feasible.

The use of heavier cars and higher axle loads was deemed as a viable tool for achieving potentially significant total savings in cost for certain rail operations. Potential net benefits in the range of 2 – 6% (including bridge costs) were attained for the cases analyzed [3]. Depending on the route and operating scenario, the 315-kip car produced between a 0.9% increase and a 1.3% decrease in total direct operating costs when compared to 263-kip equipment. The 286-kip car was found to produce 1.7 – 6.5% savings in relation to the 263-kip car. The results were highly route and service specific, depending critically upon bridge characteristics, rail characteristics and maintenance, other track component characteristics, equipment characteristics and utilization polices, and operating constraints. While the 286-kip car was not directly modeled at FAST, the design still seemed to offer significant net benefits when compared to the 315-kip and 263-kip cars.

2.2.3 HAL Phase III

The primary objectives of the ongoing FAST/HAL Phase III testing and investigation are two-fold [4]:

1) To determine the ability of improved-suspension freight car trucks to reduce the adverse impacts of increased axle loads on the track structure.

2) To improve the economics of increasing axle loads.

The secondary objective of Phase III is to evaluate the economics of the use of improved-suspension trucks in heavy haul service.

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As of February 1998, 325 MGT of HAL traffic had been accumulated at FAST as a part of Phase III [4]. The Phase III study is essentially a continuation and update of the Phase II economic analysis with an emphasis placed on reporting the new findings provided from the additional data from the FAST/HAL Phase III tests. The basic methodology and analytical tools utilized in Phase III remain the same as those employed in the Phase II analysis.

As a result of the Phase III tests completed to date, specific cost component estimates have changed in their absolute and/or relative importance and certain problem areas, such as rail life in curves and rail corrugation, have been improved [4]. Overall, the FAST/HAL research and subsequent economic evaluations performed through the end of Phase III lead to a confirmation of the basic conclusions and recommendations reached at the end of Phases I and II with respect to HAL operations. This is because the benefits of improved-suspension trucks are applied to the base case as well as to the increased axle load cases. HAL operations are technically feasible. Potential net benefits in the range of 2 – 6% for some of the scenarios analyzed warrants a serious investigation of HAL operations as a means to increase productivity of specific routes or services; however, the results are highly route and service specific.

Overall, the improved-suspension trucks were shown to be economically effective in all four scenarios evaluated and for all three types of cars [4].

2.3 Optimal Axle Load Study

The Optimal Axle Load Study, conducted as part of the AAR's HAL research program, sought to identify the factors that influence optimal axle loads for bulk unit train operations [1]. The Optimal Axle Load study extended the prior AAR HAL economic analyses by considering:

- A broader range of axle loads
- Alternative car designs (higher capacity, varying length, different trucks)
- Effects of heavier trains on line capacity and equipment utilization
- Network operations, rather than operations on a single high density coal line

A broader range of axle loads was considered for two reasons [1]. First, it was thought possible for axle loads above 39-tons to provide extra benefits that could outweigh the added track and bridge costs. Just as the 286,000-pound car represents a standard 100-ton car filled to capacity, an overloaded standard 125-ton car might out-perform the 39-ton axle load 125-ton car. Second, it may make sense to load existing

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cars to their maximum physical capacity, even if the gross vehicle weight exceeds 286,000 pounds. More research was required to clarify the relationship between axle load, car design, operating benefits and incremental costs.

Alternative car designs allow greater flexibility in meeting capacity requirements [1]. If car length is not fixed, then train capacity can be increased with higher, wider and *shorter* cars without increasing axle loads. Once height or width limits are reached, higher car capacity can be achieved by lengthening the car and subsequently increasing axle loads.

If a network is near capacity, then operating fewer, but heavier trains has a compound effect on the number of train sets required in length-limited train operations [1]. First, with more net tons per train, fewer train sets are needed, assuming that cycle time remains constant. Second, with fewer trains operating on the network, delays diminish at bottlenecks, so that cycle times decline, which leads to a further reduction in train sets.

Finally, coal trains operate over networks that include lighter density branch lines serving mines and utilities as well as the high density mainlines [1]. The average track costs per net ton-mile on the light density lines are higher than on the high density lines and the HAL effects are also different. Analyzing the track costs over representative networks therefore provides a better estimate of the effects of HAL loads on track costs.

For the representative Eastern and Western coal distribution networks, the following cases were considered [1]:

- 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 of the cases, cars were assumed to have aluminum boxes and improved suspension trucks [1]. The base case represented operations with the standard 53-foot long 100-ton car. All other cases were based on cars of varying length, but the same height and width as the 125-ton car. The HAL III cases used steel cars with improved-suspension trucks. The 39-ton axle load HAL Phase III case used 38-inch diameter

wheels, as opposed to the 36-inch wheels for the other two lower axle loads. All of the alternative scenarios modeled assumed length-limited trains.

For the new East and West network base cases, operating costs were lower than the costs projected for the HAL Phase III economic analysis, primarily as a result of the assumption that aluminum cars were used [1]. Track costs (excluding bridges) for the East and West base cases were higher, which was predominantly due to the presence of low density lines leading from the coal mines and into the electric utilities. Overall, costs for the East and West base cases were approximately 20% lower than the costs projected in the HAL Phase III analysis.

Extending the analysis from coal lines to coal distribution networks tended to reduce the axle load effects on track maintenance costs [1]. Fixed maintenance costs for ties and routine maintenance tended to dominate on light density lines, while increases in deterioration rates for rail and turnouts were relatively less important because these components would still last for many years. The net effect was that track costs (excluding bridges) per net ton-mile varied roughly linearly over a wide range of axle loads (from 30 to 45 tons).

The results indicated that, compared to the base case, all other cases considered resulted in increased net train capacity and decreased cycle time [1]. Together these effects resulted in reduced operating costs. However, heavy axle loads resulted in increased maintenance that tended to offset the savings in operating costs.

Overall, the optimal axle load for the cases analyzed was approximately 36 tons, either with a shorter car with 2-axle trucks or a longer car with 3-axle trucks [1].

The results suggested that net train capacity was the critical parameter in achieving cost savings for unit train operations [1]. Holding axle loads at 33 tons, while increasing the cross-section from that of the 100-ton car to that of the 125-ton car increased net train capacity by 17% and resulted in cost savings of 3 – 4%. Increasing the cross-section while maintaining axle loads shortened the car from the standard 53 feet to 45 feet long. Therefore, there were more cars per train, assuming length-limited trains.

Stretching this car to 49 feet long increased axle loads to 36 tons [1]. Net train capacity was increased due to better utilization of the limited train length by reducing the number of "empty" gaps over the

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couplers since a train had fewer, longer cars. An additional 1% in cost savings and capacity relative to the base case was attained in this fashion.

Hence, the extra savings from adjusting car length and axle load were much less than the initial savings from increasing the cross-section of the car. More than 70% of the cost savings and more than 90% of the capacity benefits were achieved without increasing axle loads.

The optimal axle load study therefore concluded that redes._ ing cars in order to maximize the car cross-section (height and width) could allow additional operating benefits without any increase in axle loads [1].

Additional research was suggested concerning car design and performance, the ability of customers to use cars of different lengths and the role of car design in increasing network capacity [1]. A better understanding of equipment costs and operating benefits was felt to be required to make the best future strategic decisions concerning equipment acquisition, line capacity investment and operating cost reductions. The conclusions and recommendations of the Optimal Axle Load study led directly to the Optimal Car Design study within this thesis.

2.4 High Productivity Integral Train Project

In April 1984, the rail industry, through the AAR, announced the High Productivity Integral Train (HPIT) project at a public meeting to facilitate and promote the development of integral trains [13]. An integral train is an integrated set of load carrying and power units designed as a total system to provide a specific rail transportation service. This is different from a unit train, which is composed of conventional locomotives and freight cars that are employed as a unit.

From the perspective of productivity, the key aspect of integral trains was the possibility of dramatically reducing train operating costs in comparison to conventional unit train service and technology [14]. The potential for this productivity improvement stemmed from two basic mechanisms:

- Freedom from the design restrictions imposed by interchange standards
- High equipment utilization allowed by a dedicated service environment

Although the development of unit trains as a primary strategy for providing bulk commodity service was an attempt to obtain benefits from high equipment utilization, further benefits that could potentially be garnered from innovative equipment design in special purpose use were felt to exist [14]. The recognition of the untapped economic potential by equipment designs at the time was the motivation underlying the HPIT effort.

Unit train services in the early 1980's were provided by equipment designed to standards appropriate for free interchange service [14]. The requirements for free interchange service imposed a large number of restrictions on equipment design that were deemed unnecessary and undesirable in a dedicated service environment. Individually, some of the restrictions led to excessive weight, poor train dynamics and/or unnecessary complexity in equipment meant for dedicated train service. Collectively, the restrictions eliminated the potential for significant and rapid technological advancement. Such areas of potential design freedom included:

- Train slack and longitudinal component strength
- Brake and train control systems
- Improved suspension systems
- Low-tare power concepts

Unlike general merchandise service equipment, dedicated service equipment does not need the flexibility of being individually switched [14]. Thus, a large number of individual load-carrying units can be connected by lightweight, slack-free systems, such as articulated connectors or fixed drawbars. The weight and complexity of the car design could be reduced by eliminating slack and thus reducing the longitudinal buff and draft forces through the use of blocked cars. Longitudinal strength requirements could also be lowered below interchange standards.

The integral train concept allowed for the development of alternative brake systems that could be simpler and more reliable than the air-controlled, air-powered systems required for interchange service [14]. Also, the integral train environment may make distributed power throughout the train more desirable due to any reductions in longitudinal component strength.

The integral train environment frees the suspension system from the restrictions of standard coupler height and travel, allowing for the development of innovative suspension systems that could improve performance and reduce weight [14].

Power units could be integrated into the load-carrying units in such a way as to utilize the lading to provide the vertical load required for traction [14].

The AAR solicited for intermodal and bulk commodity integral train concept proposals from suppliers [13]. The cooperative industry program offered suppliers constructive technical and economic review of concept designs by committees of industry experts and AAR staff. These reviews were confidential between the committees and the potential suppliers and the final reviews were the property of the propositioning party. The economic performance objectives for HPIT trains called for a reduction in line-haul costs of 50% for intermodal trains and a line-haul cost reduction of 35% for bulk trains.

In addition, the AAR offered to provide testing of HPIT prototypes if those designs were felt by the committees to have economic and technical merit and unique features that required testing [14]. The results of the AAR-funded tests were publicly available.

Direct AAR participation in the HPIT project ended at another public meeting in June 1987 [15]. Supply firms submitted three bulk commodity and eight intermodal train concepts for consideration [16]. The economic analyses suggested possible intermodal train line-haul cost savings of up to 45% and total operating cost savings of up to 27% [17]. Bulk train line-haul cost savings of up to 22% were estimated, with up to 21% total operating cost savings.

Several technical innovations were suggested by the suppliers in their proposals, including [15]:

- New suspension systems
- Aerodynamic improvements
- Variety of slackless drawbars and couplers
- Integrated (or distributed) power across multiple load carrying units
- Microprocessor-based train line control systems

Overall, the HPIT project was not a complete success [15]. New technology was not introduced into the industry within the 1½-year goal of the project. However, HPIT was clearly a success in stimulating the development and introduction of "The Iron Highway", which is a new, radical design concept tested by the AAR. Several technological innovations were suggested in the proposed concepts and some technological spin-offs have subsequently occurred, including the Mark V Roadrailer and the concept of

125-ton trucks under articulation. Several of the integral train concepts were close to meeting the HPIT project's economic performance objectives. Also, economic analyses, particularly of double-stack container systems and aluminum cars for bulk service, were extremely helpful in encouraging the development of a new generation of rail transportation equipment.

2.5 Foreign Experiences

2.5.1 Canadian Experience

The Canadians have realized benefits to their bulk commodity business from advances in vehicle design. Some of the advances parallel the American experience, but some are along other fronts of the net train capacity framework that the U.S. has yet to exploit.

Heavy loading is one of Canadian National Railroad's (CN) key strategic cost initiatives [18]. In some regions in 1995, where the maximum GVW had been 263 kips for cars with four axles, the gross rail load was increased to 276 and 286 kips. Lightweight aluminum cars are beginning to replace heavier steel cars. The new cars weigh 10,000 pounds less than their steel counterparts, allowing this difference to be made up in additional loading before the maximum carload weight is reached.

The new 53-foot 1-inch long aluminum cars are also 5½ feet shorter than those normally used in Canada for coal service [18]. This permits unit trains to be extended from 100 to 110 cars without increasing the total train length, which is limited to that of passing tracks along the Western Canadian lines. With the shorter cars, the revenue of ten more units can be set against the train operating costs. CN claims that compounding the benefits of heavier loading limits with lighter cars can mean improvements in productivity of more than 20%. As of 1995, however, only one west-coast terminal was equipped to unload both the long and short cars, but others were considering adapting their facilities to handle the shorter cars.

2.5.2 Indian Railways Experience

The Indian Railways (IR) modified vehicle design in the early 1980's in order to improve productivity [19]. The height of railcars was elevated in order to increase net train capacity. The number of cars that could fit on the standard length passing sidings of the IR increased from 45 to 58 without increasing axle loads. These cars all had the same gross vehicle weight. This experience serves as an explicit example of

the benefits available from the recommendations suggested by the Optimal Axle Load study – increase train capacity by simultaneously increasing vehicle cross-section and decreasing vehicle length in order to maintain a constant level of axle loading. Currently, IR cannot go any higher or wider due to clearance limitations, so they are considering increasing train lengths and axle loads.

The maximum allowable axle load on IR is currently 22½ tons with gross linear loading of 5,200 pounds per foot [20]. The IR axle loads are only 2/3 that of most U.S. heavy-haul operations; however, the linear loading is comparable to U.S. 263-kip coal car operations. In an effort to improve operating costs and increase network capacity, IR is evaluating various options for heavier axle loads, including:

- 27½-ton axle loads (similar to U.S. 70-ton carload operations) with the same 5,200-pound per foot GLL
- 33-ton axle loads (equivalent to U.S. 100-ton carload operations) with a gross linear loading of 7,020 pounds per foot (almost 20% greater than proposed U.S. 125-ton carload operations)

Heavy-haul train lengths of 116 cars are also being considered, in place of the 58-car operations of today.

2.5.3 Australian Experience

The Australian's are reaping the benefits of coal car design development. The State Rail Authority of New South Wales (SRA) and Queensland Railways (QR) both expanded their fleets of bottom-dump railcars in the early 1990's [21]. Both acquisition programs were focused on improved operational efficiency through car design. Specialized engineering consideration of the structural configuration, material selection, geometric and operational principles of the discharge systems, slack reduction and aerodynamic geometry all led to the delivery of genuine efficiencies which improved coal transport in Australia.

As of 1987, QR was a regular purchaser of aluminum cars and the SRA was adding steel cars to its fleet [21]. Both companies shared a common philosophy dictating a goal to minimize car weight. This led to structural problems and even a few catastrophic incidents. While minimum mass was still a major objective, the need for absolute structural integrity was elevated on the design priority list after some costly experiences for both railways. Aluminum designs were especially susceptible to such occurrences. Steel designs generally avoided fatigue problems, but suffered from an inherent weight penalty and also from corrosion.

QR operates on a narrow 3-foot 6-inch track gauge, and therefore its bottom-dump hopper cars were much lighter than standard (4-foot 8½-inch) gauge North American cars in 1987 [21]. The hoppers operated by QR had a gross weight range from 138 to 176 kips, compared to the unrestricted 263-kip maximum typical of U.S. heavy-haul operations at the time. SRA operated on standard gauge track with car sizes ranging from 168 to 220 kips – also much lighter than the U.S.

One measure of improved efficiency is increased train density, referring to the payload per unit length of train [21]. One of QR's governing criteria for train capacity is the length of passing sidings on the system, so improvements in train density are particularly valuable in enhancing the efficiency of operations. The new heavier 198-kip VSNB cars purchased by QR in 1989 offered a 7% increase in train density beyond any other car design configuration on QR's system.

In addition to addressing the earlier car structural fatigue problems and providing benefits derived from increased train density, the VSNB cars reduced the amount of coal hang-up and were also the first "tandem pairs" operated in Queensland [21]. Discharge aperture geometry and center sill location reduced coal hang-up and contributed to a smoother unloading process and consequently improved unloading efficiency. Some of the VSNB cars were constructed in semi-permanently coupled pairs that shared brake equipment. The tandem coupling was accomplished by using solid drawbars and conventional draft gear. This technique provided further reductions in tare weight and capital cost and also offered some reduction in train slack action.

In 1991, the SRA began purchasing a new generation of cars in Australian service, classed as NHRH cars [21]. These cars are similar to the North American 100-ton car, in that they have a gross weight of 263 kips. The new cars had a train density 30% higher than the next best alternative at the SRA due to the significant car size increase and a subsequent improvement in the net-to-tare ratio. An automatic way-side operating system was also installed for these bottom-discharge cars. The cars are operated in semi-permanently coupled blocks of seven, using slack-free draw gear between cars. The reduced tare weight of the new cars is attributed to the new mechanical automatic door operating system, the use of slack-free draw gear connecting the cars with fixed drawbars, and conscious attention to every detail in the design process.

Early coal hopper cars in Australia used manually operated transverse opening doors [21]. To open the doors, people had to exert considerable effort near the edge of the coal dump bin, often while the train

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was in motion. After dumping, all of the doors were closed again manually. This mode of manual operation was slow, inefficient and dangerous. Car-mounted air operation was later introduced to ameliorate the situation. This arrangement worked very well at the expense of much increased capital and maintenance costs and increased car tare weight. Automated way-side door operation equipment was the next logical step.

Under the current automated door system, the air cylinder and all of the associated pneumatic equipment are eliminated from the car resulting in a very light and simple car-bound system [21]. At the unloading facility, an "opening" trip mechanism is located at track-side at the start of the unloading pit and a "closing" trip mechanism is located at the end of the pit. As the train travels through the dumping station, each car door is opened and closed automatically by interaction between the car unloading system and the wayside devices. The cars are automatically emptied in sequence.

The benefits from this automated unloading system are summarized as follows [21]:

- Decreased capital costs from eliminating all of the door-associated pneumatic equipment
- Decreased operating costs from automation at the unloading facility
- Decreased car maintenance cost from simplifying the car design
- Decreased car tare weight equating to both fuel savings and an equivalent increase in payload
- Increased reliability of door operations
- Increased safety during unloading operations

The other innovative feature of the new generation NHRH cars is the semi-permanent coupling of blocks of seven cars [21]. Coupling between the cars within a block is via a solid slack-free drawbar assembly. Conventional couplers and draft gears are used between car blocks. The advantages of the slack-free car blocks are reduced car weight and cost versus conventional coupler and draft gear arrangements and a significant reduction in run-in and run-out longitudinal train forces, thereby reducing fatigue damage to the car components.

CHAPTER 3: CAR DESIGN

This chapter describes the alternative car designs analyzed in this study and the underlying assumptions and methodologies that were employed in "constructing" these cars. Section 3.1 provides an overview of the alternative car designs that were devised under the net train capacity framework for car design. General descriptions of the alternative designs are providing, along with descriptions of some of the basic factors that were considered in devising the basic designs. Section 3.2 establishes the base gondola and hopper car designs, outlines the physical parameters of these cars and describes the processes undergone in formulating the base cases. Section 3.3 describes how the center-of-gravity height limits of the car designs was estimated. This is a very important parameter to the alternative high/wide car design methodology. Section 3.4 explicitly details the methodologies employed in deriving the alternative car design parameters by means of the parametric analysis approach. Section 3.5 offers qualitative descriptions and comparisons of key car design parameters across different design scenarios. The parameters include: car length; gross linear load; net linear load; net-to-tare ratio; and train capacity. Finally, Section 3.6 describes the assumptions that were used in building trains from the alternative car designs.

3.1 Overview of Alternative Car Designs

In the previous HAL analyses, three different sets of equipment parameters were evaluated:

- 100-ton car base case with axle loads of 33 tons
- 112-ton car, which was an overloaded 100-ton car with 36-ton axle loads
- 125-ton car with 39-ton axle loads

All of the cars were steel gondolas.

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The Optimal Axle Load study used an aluminum gondola car with 33-ton axle loads and improved-suspension trucks as the base (since the cars were aluminum they held approximately 112 tons of coal, but still had axle loads of 33 tons). For all of the alternative cases, the cars were aluminum with improved-suspension trucks, but the cross-section of the cars was equivalent to that of the 125-ton car. The car length was adjusted to meet a specified axle load. Thus, all cars were assumed to be fully loaded at every axle load (never under- or over-loaded).

In this study, all of the equipment scenarios considered were freight cars with aluminum boxes and improved suspension trucks. Statistics for all of the equipment scenarios modeled in this study are provided in Tables A-1 through A-10 located in Appendix A. The statistics include data describing the exterior and interior dimensions, weights, and related equipment design performance and efficiency ratings, such as gross and net linear load and net-to-tare ratio. Most of the statistics are depicted in two ways: stand-alone and in relation to the respective base car. Seven types of equipment were considered, for both rotary-dump bathtub gondolas and rapid-discharge open-top hoppers:

- Base Case
- Higher
- Wider
- Higher and Wider
- Maximum Dimension Car
- Heavier
- 3-Axle Truck Car

Two base cases were considered:

- Conventional rotary-dump bathtub gondola
- Rapid-discharge open-top hopper

The base gondola and hopper cases were modeled after actual cars for sale on the market. They both have a 286-kip gross vehicle weight and a 53 feet 1 inch extreme length. Standard coal cars are currently built almost exclusively to this length in order to provide flexibility in the car's unloading practice. Unit train rotary dumpers are manufactured to fit a single car (or sometimes, multiple cars) of this length for unloading purposes without having to uncouple the cars from the train as they are being unloaded. Section 6.3 provides more detail on coal car unloading practices.

3.1.1 Higher Alternatives

Alternative higher cases up to and beyond the center-of-gravity constraint were considered. The car width was kept the same in all of the alternatives. Keeping GVW, and thus the axle loading, the same across all alternatives meant that higher cars were necessarily shorter in order to hold roughly the same volume and weight of coal (excluding slight net-to-tare differences). Three higher gondola cases were considered:

- 1 Foot Up
- 2 Feet Up
- 3 Feet Up

The names are approximate in that the "1 Foot Up" car was not exactly 1 foot higher than the base case. The base gondola had an extreme height of 12.4 feet. The "1 Foot Up" gondola had an extreme height of 13.5 feet. The "2 Feet Up" gondola had an extreme height of 14.25 feet, which is the maximum height allowed above the top of rail within the Plate C clearance envelope for a full car width of 10 feet 8 inches. Clearance envelopes are discussed in detail in Section 6.1.3. "Plate C" is the name given to one of the definitions commonly used to describe the maximum allowable cross-sectional dimensions for railcars. The 14.25-foot extreme height was also felt to be around the COG height limit for a bathtub gondola car. The "3 Feet Up" case had an extreme height of 15.1 feet, which is the maximum height for which the Plate E clearance envelope has a full width of 10 feet 8 inches.

An ability to reach a height in excess of 15 feet, beyond the current COG limit, was imagined possible through two methods:

- Revision of the current 98-inch COG limit to a higher level
- Advanced-suspension trucks providing better rail car support on curves and unlevel track in order to prevent tipping

The revision of the current 98-inch center-of-gravity limit to a higher level is based on a suspicion that the limit was never set through an engineering analysis. The limit seems to more closely represent a rule-of-thumb that has persisted for many years. Through practical experience, it is known that 98 inches is in

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the proximity of a safe limit; however, it may be possible to raise the limit slightly without compromising operation safety.

Similar to the gondola analysis, three higher hopper cases were considered:

- 6 Inches Up
- 1 Foot Up
- 2 Feet Up

The names of these cases are also approximations of the additional height of each alternative car design beyond the base case. The base hopper car was 13.3 feet high. This is almost a foot higher than the gondola because the gondola's bathtub design provides more room for lading down low closer to the rail. The "6 Inches Up" case was 13.8 feet high, which was felt to be around the extreme height for a conventional hopper with transverse doors at its COG height limit. The "1 Foot Up" hopper case was 14.25 feet in extreme height, which was felt to resemble the COG-constrained maximum height for a hopper car with longitudinal doors. Longitudinal-door design closely resembles a bathtub-type design. The "2 Foot Higher" hopper case was 15.1 feet high, and assumed feasible only with a longitudinal-door design and advanced-suspension trucks.

3.1.2 Wider Alternatives

The wider alternative cases, beyond the current 10 foot 8 inch clearance limit of Plates C and E, were devised keeping the extreme car heights at their respective levels. As in the higher cases, to keep the GVW at a constant level meant that wider cars of the same height were necessarily shorter in length. Three alternative wider cases were considered for both the gondola and hopper cars:

- 6 Inches Out
- 1 Foot Out
- 2 Feet Out

For both car-types, the "6 Inches Out" case had an extreme width of 11 feet 2 inches, the "1 Foot Out" case had an extreme car width of 11 feet 8 inches and the "2 Feet Out" case had an extreme width of 12 feet 8 inches.

3.1.3 Higher and Wider Alternatives

In addition to the higher only and wider only alternative car designs, several alternative higher *and* wider alternative combinations were modeled for both car-types. As with the higher and the wider alternatives, the car length decreased as the car cross-section increased, while holding GVW and axle loading at a constant level across all scenarios. Five higher and wider gondola alternatives were considered. These alternatives were simply combinations of the former higher only and wider only car designs:

- 2 Feet Up and 6 Inches Out
- 2 Feet Up and 1 Foot Out
- 2 Feet Up and 2 Feet Out
- 3 Feet Up and 1 Foot Out
- 3 Feet Up and 2 Feet Out

The first three alternatives listed assume that the car is at a COG-constrained maximum height (under current standards), and challenge horizontal clearance limits to varying degrees. The last two options listed have a COG-enhanced maximum height and varying widths beyond the current clearance limit.

Three higher and wider hopper alternatives were considered:

- 1 Foot Up and 6 Inches Out
- 1 Foot Up and 1 Foot Out
- 2 Feet Up and 2 Feet Out

All three designs had longitudinal doors. The first two listed were assumed to be at a COG-constrained maximum height and challenge the Plate width to differing degrees. The third design alternative is a much more "radical" departure from the norm, challenging the COG limit as well as clearances to a much greater degree.

3.1.4 Maximum Dimension Car

The Maximum Dimension Car is a shorter car that still grosses 286 kips, but has a height as high as possible subject to the 98-inch COG constraint and the width limited by Plate C (10.7 feet). In other

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words, it is the 36-ton axle load car design that maximizes the available cross-sectional dimensions within the currently established limits. The Maximum Dimension hopper car was assumed to have longitudinal doors, so that its extreme height was the same as the Maximum Dimension gondola – 14.25 feet.

Both Maximum Dimension car designs hugged the Plate C diagram, while complying with Plate C height and width clearances. The cross-section utilization of both designs was improved, assuming such innovations as interior car box posts (as opposed to exterior posts) that vertically stiffen the car box and also assuming that the net cross-section around the trucks and longitudinal support members (i.e. the center sill) could be improved.

3.1.5 Heavier Car Alternatives

Two heavier car designs were considered for both the gondola and hopper car-types:

- 315-kip GVW (39-ton axle loads)
- 336-kip GVW (42-ton axle loads)

Both heavier car designs had dimensions hugging the Plate C diagram limits and were kept at the industry standard extreme length over coupler pulling faces of 53 feet 1 inch in order to maintain compatibility with existing unit train rotary dumpers (See Section 6.3 for more information on coal car unloading techniques). The extra capacity of each car was attained through additional box height.

The extreme heights of the 315-kip and 336-kip gondola cars were 13.5 feet and 14.1 feet respectively. The extreme heights of the hopper cars depended upon whether or not the cars had transverse or longitudinal doors. The longitudinal-door cars had heights similar, but slightly higher, than the respective gondolas, while the 315-kip and 336-kip transverse door cars had heights of 14.3 and 14.9 feet respectively. Notice that both transverse-door hoppers have heights in excess of the COG limit. The 336-kip transverse-door hopper car's height also exceeds the Plate C clearance diagram limit for a car of 10 feet 8 inches width.

3.1.6 3-Axle Truck Car

A 3-axle truck car with 36-ton axle loads was devised for both gondola and hopper car designs. These cars had a 419-kip GVW and were limited in cross-section by Plate C and COG considerations. Both

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gondola and hopper 3-axle truck cars were on the order of 70 feet long. Due to the long distance between truck centers (in excess of 46 feet 3 inches), the car width for the entire clearance outline was reduced to compensate for the increased swing-out at the center of the car on curves, as dictated by Plate C-1 (see Section 6.1.3 for more detail). Both 3-axle truck cars had widths around 10.1 feet, which is a 6-inch reduction from the Plate C maximum.

The 3-axle truck hopper had longitudinal doors. The transverse door design was not technically feasible – the car would have to be infinitely narrow as governed by the Plate C-1 curving width requirement, due to the relatively inefficient cross-section utilization characteristics of the design, the low maximum height as governed by the COG limit and the increased car tare weight due to the increase in length.

3.2 Establishment of the Base Cases

The basic equipment parameters used for this study were based on actual existing car designs from "The Car and Locomotive Cyclopedia of American Practices" [22] and from "The Official Railway Equipment Register" [23]. Data was also provided by the AAR in a spreadsheet entitled "3AXLE.WK1," dated March 1997. The data in this spreadsheet was previously utilized in the Optimal Axle Load study. The "Car Cyclopedia" contains a wide selection of modern cars currently manufactured for the rail market. The "Equipment Register" contains information on equipment in service.

Bathtub gondolas and open-top hoppers designed for the shipment of coal were examined and an "average" or "median" car of each type was chosen to serve as the base gondola and base hopper case. These two "median" base cars were chosen from a selection of "eligible" car designs meeting the base car description. The choice was based on having "average" cubic capacity and net-to-tare ratio characteristics.

Table 3-1 summarizes the relevant data of both the gondola and hopper base car designs. The gondola car has an extreme length over the coupling faces of 53 feet 1 inch, as already mentioned, and the hopper car is ½ inch shorter. The length over the strikers is on the order of 50 feet 5 inches for both cars, meaning that there is about 2 feet 7 inches between the strikers and the coupler pulling faces.

Both cars have an identical 40 foot 6 inch distance between truck centers and an extreme width of 10 feet 7 15/16 inches. This width is 1/16 inch shy of the maximum allowable width for the AAR's Plate C equipment diagram for limited interchange service at the specified truck center distance [24].

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Table 3-1: Base Case Gondola and Hopper Equipment Characteristics

Parameter	Bathtub Gondola	Open-Top Hopper
Exterior Dimensions (ft):		
Length over Coupler Pulling Faces	53.08	53.04
Length over Strikers	50.46	50.42
Length between Truck Centers	40.50	40.50
Extreme Width	10.66	10.66
Extreme Height	12.44	13.27
Interior Dimensions (ft):		
Length	47.73	47.25
Width	9.91	10.11
Cubic Capacity (cu ft):		
Level Full	4,400	4,200
with 10" Average Heap	4,790	4,598
Weights (lbs):		
Gross Rail Load	286,000	286,000
Load Limit	243,000	235,500
Light Weight	43,000	50,500

The extreme height of the bathtub gondola is 12 feet 5¼ inches, which is 10 inches lower than the hopper's height of 13 feet 3¼ inches. The gondola is lower, even though it holds 200 cubic feet more lading when fully loaded to a level even to the top and has an inside width about 2½ inches narrower than the hopper, with the sides of both car boxes are perfectly vertical. The additional capacity of the gondola car comes from 6 extra inches of maximum interior length and from the greater cross-section utilization inherent in the bathtub design. The lading extends down deeper, between the trucks, closer to the top of the rails in a bathtub design.

The base gondola is also equipped with one rotary coupler for unit train rotary dumping purposes. Note that only one rotary coupler is required between any two cars for unloading purposes. Thus, only one rotary coupler is needed per car, if all the cars have their single rotary coupler facing the same direction within the train. The other coupler on the car is conventional in design.

Figure 3-1, compliments of Robert [9], depicts a typical gondola car for coal. Note that this illustration depicts a flat-bottomed gondola, not a bathtub design.

The hopper car, due to its bottom-dump unloading characteristics, inherently is a less efficient design with respect to car volume utilization. The base car is a quintuple-hopper, having five individual hoppers

along its length. The unloading hoppers are each equipped with automatic rapid-discharge doors oriented in a transverse fashion across the width of the car. The doors open and close mechanically by means of car-mounted machinery. This car is also equipped with one rotary coupler and one conventional coupler.

Figure 3-2, also compliments of Robert [9], depicts a typical hopper car for coal. Note that this illustration depicts a quadruple-hopper car, not a quintuple-hopper car.

The gross rail load is the maximum permissible weight of a loaded freight car in interchange service based on the size of the axle used. The load limit is a measure of car capacity equal to the maximum amount of lading that can be carried by a car. It is the difference between the gross rail load and the light weight. The light weight, or tare (weight of the empty car) for the base hopper is 7,500 pounds heavier than the gondola due to the extra material and more heavy-duty material required to fabricate the hopper dump and door system and the car-mounted machinery necessary to operate the doors automatically.

The relationship between the cubic capacity and the load limit of the base cars indicates that the gondola is optimally designed to haul coal with a density of 51-55 pounds / cubic foot. The actual value depends on whether the car is fully loaded and heaped to an average height of 10 inches or just fully loaded level to the top. Coal with a higher density will not be able to fill the car full before the car reaches it's maximum axle loading. The corresponding values for the hopper car are 51-56 pounds / cubic foot.
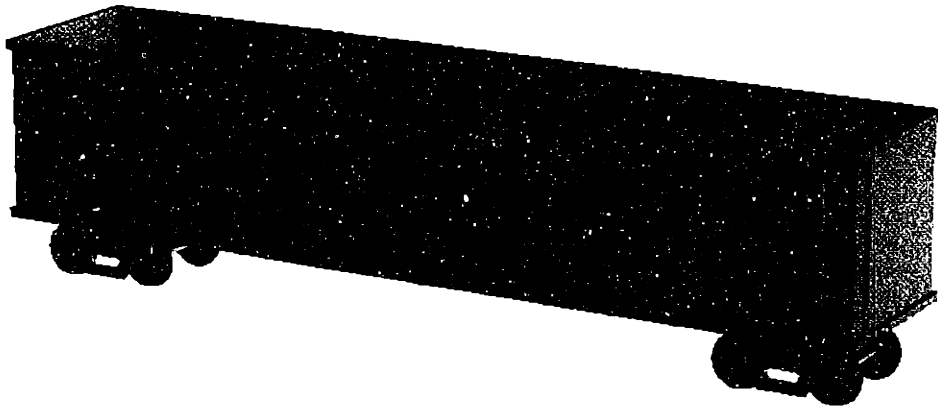
Figure 3-1: Typical Gondola Car
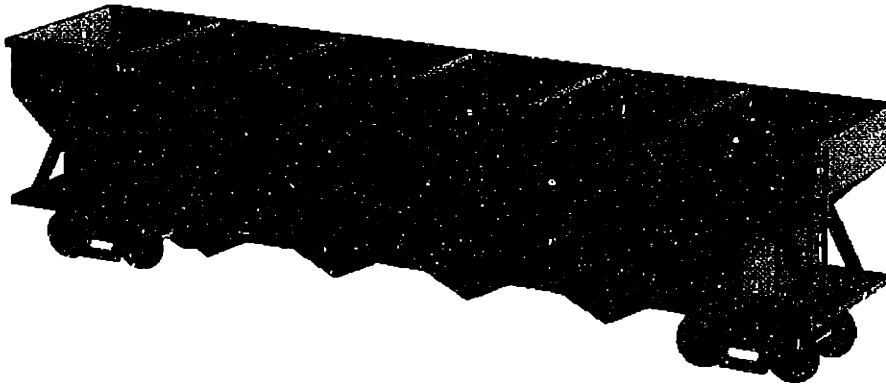
Figure 3-2: Typical Hopper Car

3.3 Establishment of the Rail Car Center-Of-Gravity Height Limit

A rough estimate of the maximum extreme height achievable subject to the 98-inch COG limit was calculated from data in the "Car Cyclopedia" [22]. The exact COG-limited height for a car depends on the car's design; however, by knowing the COG of similarly designed cars an estimate of the COG-limited height can be estimated. Some of the car descriptions in the "Car Cyclopedia" contained information pertaining to the COG of the car when loaded with or without coal heaped above the box. The COG data was not available for the two specific base cases modeled the COG data of similar rotary-dump bathtub gondolas and rapid-discharge hopper cars was utilized, i.e. cars made of aluminum and that had 36-ton axle loads.

difference between the COG, assuming heaped coal, and the 98-inch COG-limit was calculated for each comparable car for which this data was known. This difference was then doubled and added to the extreme height of the car to attain a rough estimate of the COG-limited extreme car height. This method overestimates the maximum extreme height due to doubling the difference when the bottom half of a loaded car is lighter than the top half since there is empty space between the bottom of the car and the top of rail. Thus, the maximum height estimate was rounded down on the order of ¼ foot. A mean value for the COG-limited extreme height was used from the range of values supplied by the estimates from the similar car designs.

3.4 Car Design Methodology

The values presented in Tables 3-1 and 3-2 were applied under a reasonable and uniform car design methodology in order to construct a range of alternative equipment design scenarios in a parametric fashion. A parametric approach was chosen for the analysis in order to provide flexibility and ease to the car design process so that the economics of a large number of scenarios could be evaluated quickly. A parametric analysis is sufficient for portraying the order of magnitude of the economic and capacity benefits, if any, of alternative equipment designs over a reasonable range for each key parameter. The car design methodology is discussed in the following sections.

The spreadsheet provided by the AAR contained information on truck weights that was used in devising alternative car designs. Table 3-2 summarizes the relevant data on truck types from the spreadsheet. As indicated in the table, a 2-axle truck with 36-inch diameter wheels weighs 9,200 pounds. This is the truck

found on all of the cars in this study, except the 3-axle truck cars, 336-kip cars and one variation of the 315-kip car. The 263 and 286-kip cars of the prior HAL analyses used this truck-type [2][3][4]. Improved, advanced and conventional 3-piece truck designs were all assumed to weigh the same in this study.

A 2-axle truck with 38-inch wheels weighs 11,019 pounds. This is the truck found on the 315-kip car in the prior HAL analyses, but was not the norm on 315-kip cars in this study [2][3][4]. The economic performance of the 315-kip car is very sensitive to the truck and wheel size and weight assumptions. In the previous Optimal Axle Load study, the maximum acceptable axle load for 36-inch wheels was assumed to be no more than 39 tons [1]. This assumption was carried over to this analysis. There are concerns over wheel/rail contact, bearing and thermal braking stresses for 36-inch wheels under 39-ton axle loads; however, no detailed engineering analyses of the practical axle load for 36-inch wheels has yet been identified.

Table 3-2: Truck Weights

Truck Type		Weight
# Axles / Truck	Wheel Diameter (inches)	(lbs)
2	36	9,200
2	38	11,019
3	33	16,005
3	36	17,460
3	38	19,230

The 3-axle truck with 36-inch wheels weighs 17,640 pounds. This was the 3-axle truck assumed on the 419-kip 6-axle car.

3.4.1 High/Wide Car Design

The parameters of the higher, wider, and the higher and wider alternative freight cars were devised assuming that the car boxes have perfectly vertical sides along the length, which is true of both base cases. Knowing the cubic capacity and the maximum interior box length and width, the "average" inside height was calculated. The alternative case extreme heights and widths, in excess of the base cases, were already discussed in Section 3.1 and are summarized in Tables A-1 through A-10 of Appendix A.

The gondola and hopper car box base "thickness'" (i.e. the difference between the maximum interior and extreme dimensions of height and width) were assumed to remain unchanged for all alternative car designs. Therefore, any additional exterior height or width equated to an equivalent interior box height or width.

The alternative interior box width and average height were used to calculate the new required maximum interior box length, keeping the cubic capacity of the box the same as for the respective base case. A new extreme length was furnished, assuming that the distance from the inside edge of the car box to the coupler face remained the same as in the respective base case for all alternatives.

The next phase in the design of an alternative car involved an iterative process. Even though the interim shorter car obtained from the process described in the preceding paragraphs had the same cubic capacity as the base car, it was felt that it would have a lower tare weight. The heaviest components of a car are longitudinally oriented. Specifically, the center sill is the heaviest single car component. The center sill acts as a beam supporting the car between the trucks and also acts as a connector holding the car together, transferring the tensile and compressive train dynamic forces between the couplers. Thus, the base car body weight (which is the car tare weight less the truck weight) was adjusted proportionally by the difference between the interim car's length and the base car length.

The decrease in car length and subsequent decrease in car body and tare weight allowed for an increase in car net weight, in order to keep the car gross weight and axle loading at a constant level. Since the interior box height and width were assumed to be fixed, the increased weight and volume of lading necessarily increased the box length. At this new length a new car tare weight was calculated, and the process was repeated. This repetition continued until equilibrium between car length, tare weight and cubic capacity was reached.

An interesting aspect of the fixed car cross-section assumption was that an improved net-to-tare ratio increased car length, as opposed to decreasing car length. This may seem counter-intuitive at first glance, but makes sense, if one considers that an increase in car length by an increased net-to-tare ratio means a lower gross linear load for the same net linear load.

This car length / car weight methodology has a major short-coming in that it furnishes an optimistically low car body weight for the new alternative car, since the car body weight will not exactly reduce linearly with the car length. The presence of other, unmodified, heavy components, such as the couplers and draft

system, and the extra material required for the increased box height and/or width will lessen the beneficial impact of the decrease in length on the car body weight. Therefore, in order to account for the non-linear reduction in car weight that can not be calculated without an in-depth and specific car design for each alternative considered, a mid-point value between the optimistic and conservative car tare weight estimates was utilized.

The optimistic car tare weight assumed that the car body weight varied linearly with the extreme car length. The conservative car tare weight assumed that the car weight did not change from the respective base case. Thus, the tare weight used had a net-to-tare ratio that was an average of the optimistic and conservative case net-to-tare ratios. The extreme car length was calculated using this average net-to-tare estimate.

3.4.2 Maximum Dimension Car Design

The Maximum Dimension car was designed in a similar fashion to the high/wide cars; however, a further parameter that was manipulated when designing the Maximum Dimension car was cross-section utilization. For the purposes of this study, the cross-section utilization was defined as the ratio of the net cross-section (described in terms of the interior box width and average height) over the extreme car cross-section (described in terms of extreme width and extreme height above the top of rail). This definition of utilization was chosen instead of the percentage of the clearance envelope that was utilized because many of the car designs exceeded the existing clearance width constraints. The biggest drawback with the current definition of utilization is that increases in height improve the utilization of a basic car design much more than increases in width. This is because the empty gap between the rails and the bottom of the car increases with width, but not with height.

The cross-section utilization of typical 286-kip bathtub gondola cars is in the range of 68 – 72% [22]. Values of 59 – 65% are more typical for 286-kip rapid-discharge transverse-door hopper cars. The Burlington Northern Santa Fe (BNSF) Railway's "Trough Train" has a cross-section utilization of 72%. The "Trough Train" was designed with the intent of maximizing equipment efficiencies such as cross-section utilization. The "Trough Train" is an articulated, longitudinal dog-leg door design and has a relatively low extreme height due to lower 33-ton axle loads. Thus, for a higher car design intent on maximizing cross-section utilization, a utilization rating of 75% is not unreasonable. The cross-section utilization of the Maximum Dimension car designs (for both the bathtub gondola and the longitudinal-

door hopper) was fixed at 75%. This is about 3½ % better than the basic gondola of the same exterior dimensions and 5% better for the longitudinal-door hopper.

Adjusting a car's cross-section utilization increases the net cross-section of the car. This was achieved in the parametric modeling framework by assuming an increase in the average inside box height. Increasing the net cross-section necessarily requires a shortening of the box length, in order to keep the total box volume (and axle loading) the same. But, shortening the car length also lowers the assumed net weight of the car, requiring an increase in car length in order to accommodate the extra allowable net tonnage. Thus, the iterative process described for the high/wide car design must again be undertaken in order to find an equilibrium length between car length and car tare. The overall effect of improving the car cross-section utilization is to shorten the required car length, while increasing the capacity of the car design.

3.4.3 Heavier Axle Load Car Design

Cars with higher gross vehicle weights were significantly different in design from the base car to require a unique methodology for calculating a tare weight estimation. Components must be strengthened in order to withstand the additional stresses imposed by heavier loadings. The center sill and axle journals must especially be enhanced in order to endure under greater forces. In order to compensate for the stiffening and strengthening of car components under higher net capacities, the tare weight of the car body was increased using a simplistic methodology that yielded results believed to be realistic.

The weight of the trucks was first removed from the tare weight of the respective base car in order to furnish the base car body weight. The car body weight of the heavier alternative was then calculated by increasing the base body weight by a factor of one-half the ratio of the heavy alternative's GVW over the base car's GVW. The base car GVW was 286 kips in both the gondola and hopper cases. An example of this procedure is as follows: the 315-kip car has a GVW ratio of 1.10 over the 286-kip car (315/286), meaning that the 315-kip car body weighs 5% (1/2 x 1.10) more than the 286-kip car body. This new car body weight was used to construct a new tare weight value for the heavier alternative car at a 53.1-foot length. Finally, the height of the base car was adjusted in order to accommodate the increase in coal carrying capacity.

This method resulted in a 53.1-foot 315-kip gondola car with a height of 13.5 feet and car body weight of 25,840 pounds. The 125-ton base aluminum car of the Optimal Axle Load study had a car body weight of

25,870 pounds [1]. This value was based on an actual existing car design. The close proximity of the estimated value to a real value validated this car tare weight estimation methodology.

Calculating the parameters of any heavier car designs with increased cross-sections was formulated using the same iterative "average" net-to-tare methodology as for the 36-ton axle load high/wide alternatives.

3.4.4 3-Axle Truck Car Design

Increasing the car capacity and GVW significantly without increasing axle loads can be accomplished by increasing the number of axles. A car with six axles (two 3-axle trucks) and 36-ton axle loads similar to the 286-kip car has a GVW of 419 kips. The 6-axle car is necessarily much longer than its 4-axle counterpart in order to hold the extra volume of lading.

The car body weight was not adjusted for the difference in GVW over the base case as in the heavier car alternatives. The car body weight was calculated using the same iterative car length / net-to-tare ratio approach as in the high/wide design methodology. When lengthening a car, this approach increases the car body weight. One technical difference between the iterative methodology as applied to 3-axle truck cars versus 2-axle truck cars was that the base case net-to-tare ratio used in calculating the "average" net-to-tare weight for the final car design tare weight assumption was the net-to-tare of the respective base car on heavier 3-axle trucks.

3.4.5 Longitudinal-Door Hoppers

The longitudinal dog-leg door hopper design was assumed to have a cross-section utilization improvement of 10% beyond a transverse-door hopper of the same extreme cross-sectional dimensions. The base transverse-door hopper has a utilization rating of 63%. The 53-foot long dog-leg hopper, being 10% better, thus has a 67% utilization. This rating is slightly worse than the low-end of the bathtub gondola utilization range, which was deemed reasonable.

The base hopper tare weight was 7,500 pounds heavier than the base gondola. Changing from a transverse door configuration to a longitudinal door configuration on the hopper was assumed to drop the weight of the car by 3,000 pounds. Less material was felt to be required with the dog-leg design than the quintuple-hopper configuration, thus promoting the weight savings. This 3,000 pounds of tare weight was removed from the car body weight before adjustments were made to the car weight as a result of any

length changes. Within the "average" net-to-tare iteration procedure used in calculating the car weight and length, the lighter 53-foot dog-leg car body weight was used in the calculation. All alternative longitudinal-door hopper designs used this modified iterative procedure in calculating net-to-tare and car length.

3.4.6 Manual-Discharge Hoppers

The rapid-discharge equipment that automatically operates the doors on a hopper car was estimated to contribute 1,500 pounds to the base hopper car tare weight. This meant that the tare weight of a manual dog-leg hopper that was 53 feet in length was only 3,000 pounds heavier than the base bathtub gondola. Alternative manual-dump hopper car tare weights were estimated using the same modified iterative procedure described for the longitudinal door hopper.

3.4.7 Fixed Drawbars

A fixed drawbar connection was assumed to weigh 1,500 pounds less than a conventional coupling system, as in the study by Little and Smith entitled "Evaluation of Power Distribution, Coupling Systems, and Braking Equipment Alternatives" [25]. As in the cases of the longitudinal-door and manual-dump hoppers, this tare weight benefit was applied to the car body before any alternative design length adjustments were made according to the iterative car length / net-to-tare methodology. Similarly, this weight improvement was also factored into the "average" net-to-tare calculation.

In order for this parametric analysis to remain as generic as possible and to avoid making detailed and specific assumptions that could create a false impression upon the results, all of the connections between the cars on a train were assumed to be of the same type. In reality, blocks on the order of 5-10 cars would be permanently coupled by fixed drawbars and these car blocks would be joined with conventional couplers. The specific assumption of the number of cars within a block was felt to be a secondary detail for the purposes of this study. So, in effect, the effects of fixed drawbars on the economics and productivity of coal unit train operations were overstated due to the assumption that there were no conventional couplers.

3.4.8 Articulated Hoppers

Very little data was readily available from which to base articulated car designs, so a range of assumptions were made in order to gauge the effectiveness and efficiency of such a design concept in relation to the other car types. The "Evaluation of Power Distribution, Coupling Systems, and Braking Equipment Alternatives" study did not discern between fixed drawbars and articulated joints [25]. Both alternatives were treated in the same fashion with respect to cost benefits and drawbacks and weight savings. Thus, as in the fixed drawbar case, an articulated joint was assumed to weigh 1,500 pounds less than a conventional coupling system. This reduction in tare weight was replaced with extra lading as in the dog-leg, manual dump and fixed drawbar cases, in order to maintain a constant gross vehicle weight and axle loads. The extreme car length for each articulated scenario was first calculated using the iterative car length / net-to-tare methodology and "average" net-to-tare assumption, adjusting for the scenario's improved net weight over the base hopper car.

Articulated car designs were assumed to have a great benefit over more conventional cars – an articulated car, such as the BNSF's "Trough Train," is loaded as one continuous car. There are not any gaps over the articulated joints. The volume of a car and train is therefore much better utilized. The train is more or less one continuous hopper trough, even over the joints. Therefore, extra lading can fit within a "car length" for two reasons:

1) The space, which is usually empty above the couplers, is filled with lading.
2) The empty space at the ends of the car box due to the heaping of coal is now filled with lading since the lading extends beyond the traditional box length.

The second point deserves some clarification. When a car is filled with coal, the coal heaps at the top naturally, like a pile of dirt. The angle of repose for coal lies between 25 and 35 degrees [26]. Since coal cars are subject to vibration while moving, the lower angle of repose was chosen as more feasible, as in "Burlington Northern's Assessment of the Economics of High Capacity / Heavy Axle Load Cars" [26]. Since an articulated car is loaded as a continuous trough without a physical barrier (the box ends) between each section of the articulated car, the volume traditionally lost to heaping at the ends of each car can be filled with lading. Using simple geometric techniques, assuming an angle of repose of 25 degrees, an interior car width of 10.1 feet and a triangular/pyramidal heap, it was found that there was an additional 47 cubic feet available for lading for each articulated "car" section length. Assuming a density of 50

pounds per cubic foot for coal, the elimination of car-end heaping furnished room for an additional 1.2 tons of coal per articulated car section length.

Since the axle loading was kept at 36 tons, both factors that contributed to providing extra volume utilization within articulated cars necessarily shortened the truck spacing and thus the articulated car section length. The extra volume due to heaping was assumed to directly improve the net-to-tare ratio by adding the net tonnage to the existing car. The cross-section utilization was then increased so that the car length was shortened until the car's length-adjusted net-to-tare ratio matched the ratio set directly by adding the net tonnage. Finally, the space between the assumed interior box length and the extreme length over the couplers was eliminated from the extreme length in order to account for the articulated joints replacing the conventional coupling system.

As in the case of fixed drawbars, all of the connections between the cars on a train were assumed to be the same type, in order for the parametric analysis to remain generic and in order to avoid making detailed or specific assumptions that could alter the true results. The BNSF's "Trough Train" is composed of articulated units with the same number of axles as 6½ 2-axle truck cars. The specific assumption of the number of cars within an articulated unit was felt to be a secondary detail for the purposes of this study. The results solely attempted to gauge the relative impact of articulation on car design economics. As a result of the full-articulation assumption, the economic impact of articulation was overstated.

3.5 Equipment Description

Figures 3-3 to 3-7 show how the basic equipment parameters and statistics vary across the basic gondola scenarios considered in this study. The information charted in Figures 3-3 to 3-7 can be found in tabular form in Tables A-1 to A-10 of Appendix A.

Figure 3-3 is a graph of car length for the scenarios. The base gondola is 53.1 feet long. The heavier 39-ton and 42-ton axle load cars are also 53.1 feet long in order to remain compatible with conventional unit train rotary dumpers. The maximum dimension car is 44.3 feet long, 1.3 feet shorter than the 2-foot up car, which has almost identical extreme cross-section dimensions. The 3-axle truck car has a length of 69.3 feet. Raising the height of the gondola car to the COG-limit and widening 6 inches beyond the Plate C clearance limits shortens the car 9.4 feet from the base to 43.7 feet long. Increasing the height on the order of 3 feet and increasing the width by 2 feet simultaneously shortens the car more than 16 feet to 36.8 feet long.

Figure 3-4 is a plot of freight car gross linear load by gondola scenario. Since all the cars but the last three on the chart are 2-axle truck 36-ton axle load vehicles, the results are exactly reverse of the previous car length chart. For a fixed GVW, the shorter the car, the higher the gross weight per foot of car length. The base case has a GLL of 5,390 pounds per foot. The 39-ton axle load car has a 10% higher GLL of 5,930 pounds per linear foot while the 42-ton axle load car's GLL is 17% greater at 6,330. The 3-axle truck car has a GLL 15% higher than the base at 6,190 pounds per foot, chiefly attributable to its larger cross-section over the base. A higher gross linear load imposes a heavier loading on bridges. A gondola with a cross-section 3 feet higher and 2 feet wider has a GLL of 7,780 pounds per foot, which is just under the 8,000-pound per foot maximum design load recommended by the American Railway Engineering and Maintenance-of-way Association for rail bridge design since 1967. Bridge loading and bridge issues are discussed in detail in Section 6.2.

Figure 3-5 plots freight car net linear load across the gondola scenarios. The chart is very similar to the gross linear load chart, varying only by the difference in net-to-tare. Freight car net-to-tare is charted in Figure 3-6 for the gondola scenarios. The values of NLL are of course lower than the respective gross values since the net weight is a component of the gross weight. The higher and wider cars are shorter and have better net-to-tare ratios than the base. Thus, the percentage increase in NLL for these cars over the base is greater than the percentage increase in the GLL.

The net-to-tare ratios of all the cases considered in Figure 3-6 are relatively high since they are based on such an efficient car – an aluminum, 36-ton axle load, bathtub gondola design. In the HAL Phase III analysis, the ratio was 3.4 for the 100-ton car, 3.8 for the 112-ton (overloaded 100-ton) car, and 3.6 for the 125-ton car [4]. The base gondola of this study has a ratio of 5.65. The 39-ton axle load car has a very high net-to-tare (6.1), even better than the 42-ton axle load car because it was assumed to have 36-inch diameter wheels, whereas the 42-ton car has 38-inch wheels. The 3-axle truck car's net-to-tare is better than the base, but not as high as many of the other alternatives due to the 3-axle truck weight penalty and the car body length weight penalty.

Figure 3-7 is a graph of train capacity by gondola scenario. It almost exactly resembles the NLL chart since trains are assumed to be length-limited. Minor deviations are due to slightly different train lengths since there must be an integral number of cars per train resulting in a total length less than the finite maximum allowable length. This graph was included in order to demonstrate the magnitude of the tonnage hauled in a single train and the relative differences across scenarios. Net train capacity was

found to be the critical factor in achieving savings in the "Optimal Axle Load Study" [1]. Train capacity was also felt to best encompass the concept of network capacity (both line and terminal), as affected by the alternative equipment designs. In the length-limited train case, an increase in the net capacity per train will result in a direct reduction in the number of trains required to move the same volume of goods, and thus will reduce the required run-thru yard space required due to the reduction in the number of trains. In both the length and weight-limited train cases, less marshalling yard and empty car storage space will be required as a result of shorter cars.
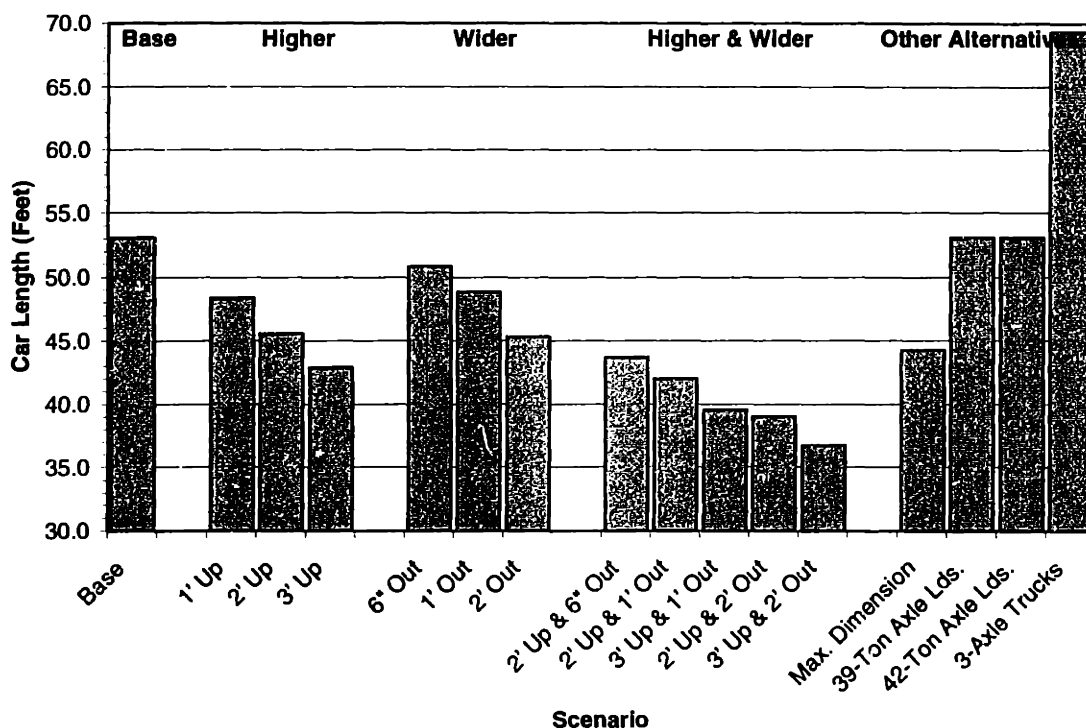
Figure 3-3: Gondola Car Length by Scenario
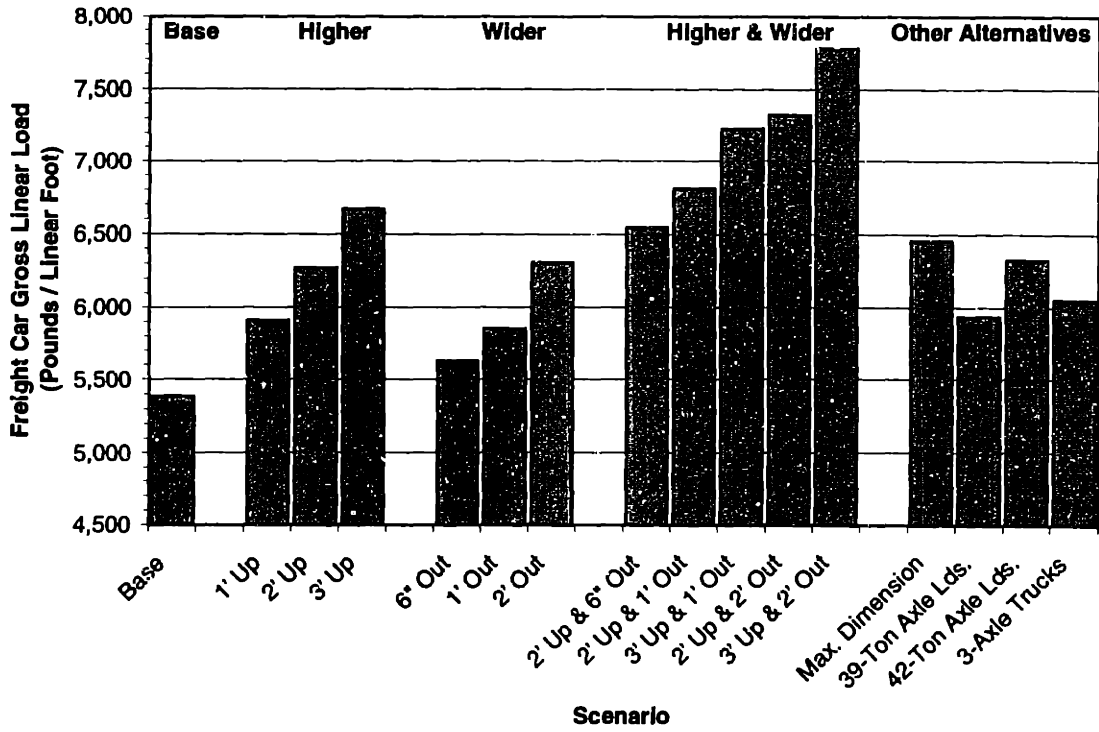
Figure 3-4: Gondola Car Gross Linear Load by Scenario
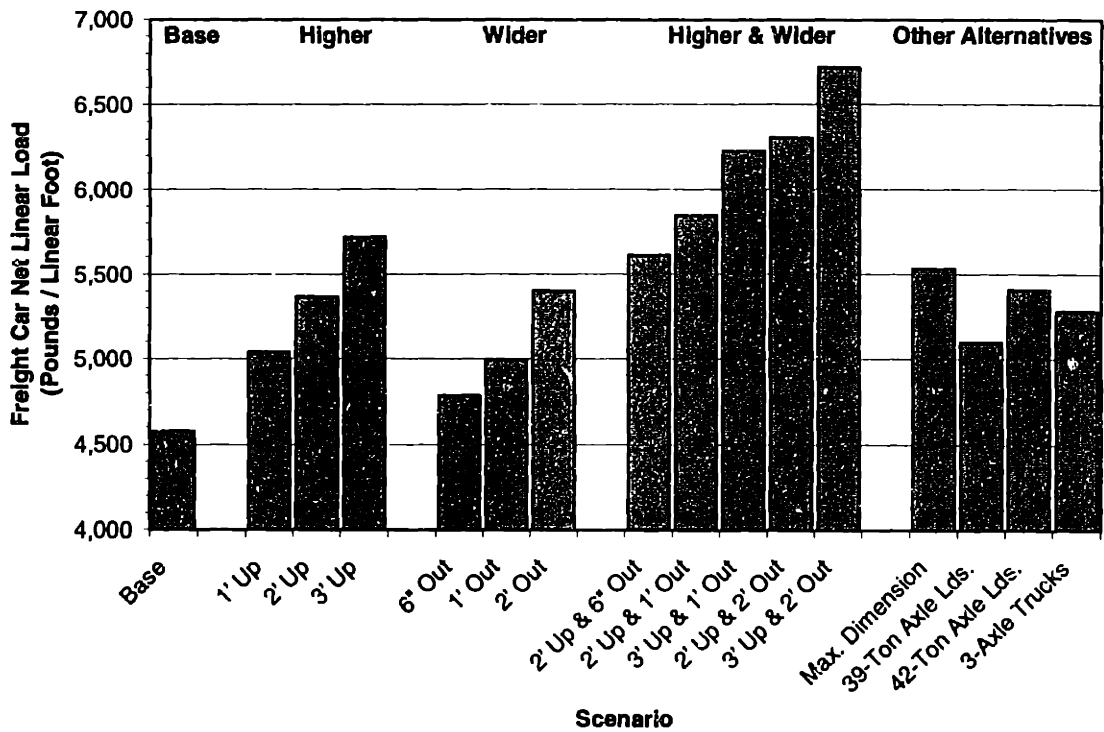
Figure 3-5: Gondola Car Net Linear Load by Scenario

66
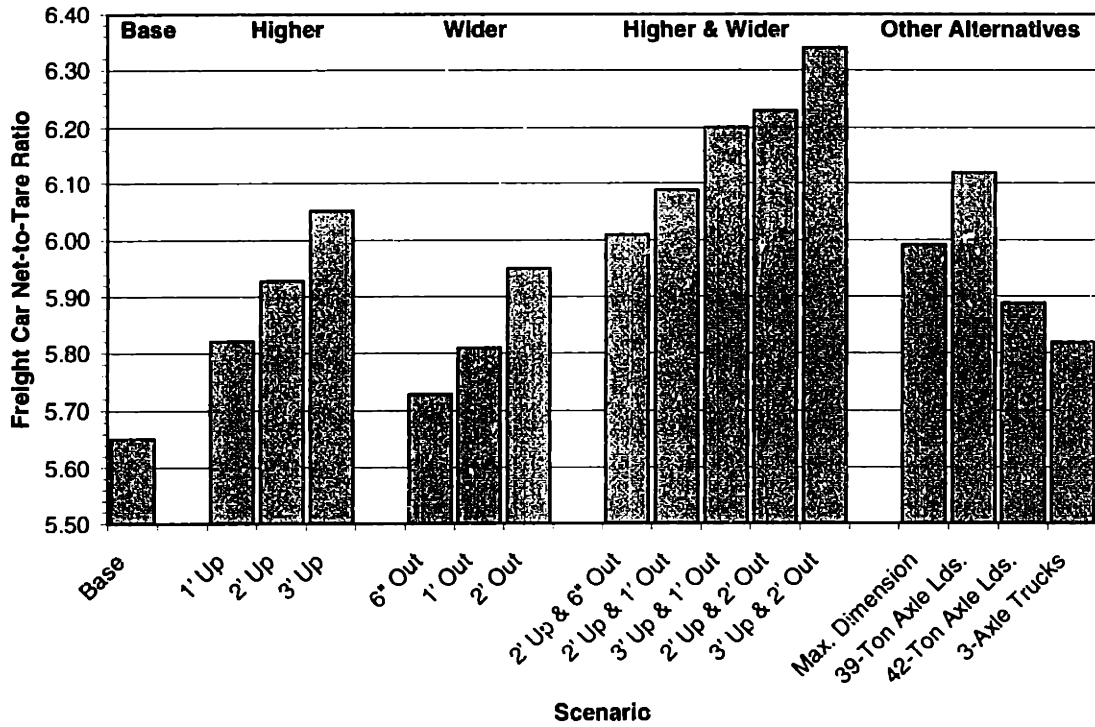
Figure 3-6: Gondola Car Net-to-Tare Ratio by Scenario
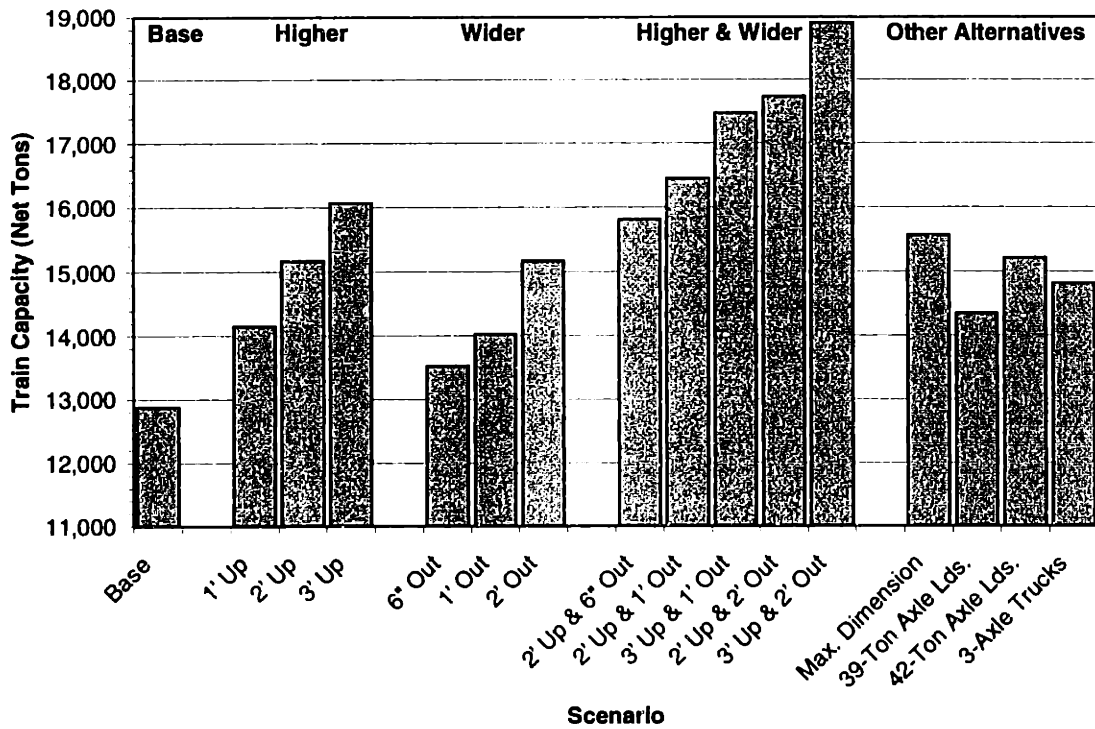
Figure 3-7: Gondola Car Train Capacity by Scenario

Appendix B has the same graphs as Figures 3-3 to 3-7 for other scenarios. Car length, car GLL, car NLL, car net-to-tare, and train capacity graphs for the 39-ton axle load gondola scenarios, the transverse and longitudinal-door hopper car scenarios, the manual-discharge hopper car scenarios and the articulated hopper car scenarios. These figures may be compared to the gondola scenario figures in order to identify the basic characteristic and parametric differences between the car types.

Figures B-1 to B-5 of Appendix B illustrate the differences between the 39-ton axle load alternative scenarios to the 36-ton scenarios. Typically, the 39-ton axle load cars are longer for the same cross-section since they hold more lading. These cars also have a slightly higher GLL and an even higher NLL due to higher net-to-tares for the same cross-section. The better net-to-tare ratios of the 39-ton axle load equipment stems from the assumption of the same truck and wheel set as the 36-ton cars and the carrying efficiencies inherent with a larger box for a given length. As a result the train capacity of the 39-ton scenarios is somewhat higher than the respective 36-ton scenarios.

The key characteristics of the transverse and longitudinal-door hoppers are summarized in Figures B-6 to B-10 of Appendix B. The characteristics are graphed with respect to the base gondola in order to help depict the relative magnitude of the hopper alternatives with respect to the gondola alternatives. The alternative hopper cars are shorter than the respective alternative gondola cars of the same cross-section since the hopper cars have higher tare weights and thus a lower volume of lading for a fixed GVW. Since the hopper cars are somewhat shorter for a given cross-section and GVW, the GLL is somewhat higher for the hopper alternatives than the respective gondola alternatives.

Due to the much lower net-to-tare of the hopper cars, the NLL is lower for all scenarios than the respective gondola. A NLL and net-to-tare benefit is apparent for the longitudinal-door hopper cars versus the transverse-door hoppers. The net-to-tare of a longitudinal-door design is on the order of 0.25 – 0.3 better than the respective transverse-door design. The NLL is especially enhanced by the longitudinal-door design when the length is not fixed at 53.1 feet. The train capacity of the hopper scenarios resembles the NLL chart.

The key characteristics of the manual-discharge hopper designs are summarized in Figures B-11 to B-15 of Appendix B. Again, the statistics are depicted in relation to the base gondola car for comparative purposes. The manual-dump hoppers are slightly longer than the rapid-discharge hoppers due to an improved net-to-tare for the manual-dump cars requiring more length to fit the increased volume of lading, given the same cross-section and GVW. The manual-dump cars are shorter than the gondolas, all

other things being equal, since the gondola cars have a superior net-to-tare. Since the manual-dump cars are shorter than the gondolas, they have a higher GLL, but they have a lower GLL than the rapid-discharge hoppers, since the rapid-discharge cars are shorter.

The NLL of the manual-discharge hoppers is only minutely better than the rapid-discharge hoppers. Since the net cross-section remains unchanged between the two types of hoppers, given the extreme dimensions, the relative manual-discharge net-to-tare improvement serves to lower the GLL while maintaining the NLL. The gondola NLL is higher than the rapid-discharge NLL since the gondola net-to-tare and cross-section utilization are better. The same holds true for train capacity. The manual-dump hopper designs have net-to-tare ratios on the order of 0.2 better than the respective rapid-discharge designs. A manual-discharge dog-leg design 1 foot higher and 1 foot wider than the base hopper has approximately the same net-to-tare ratio as the base gondola car.

Figures B-16 through B-19 of Appendix B depict the characteristics of the articulated hopper car designs. A chart for car length was not included since the definition of a car is not as relevant to an articulated design. "Cars" are composed of multiple sections or boxes. The articulation design innovation enables the hopper car to out-perform the bathtub gondola, in some respects. The GLL of the base hopper car cross-section can be increased by over 30% by switching to an articulated, manual-dump, longitudinal-door design. The GLL of such a car design is on the order of 7,100 pounds per foot. The Maximum Dimension articulated design is estimated to have a GLL on the order of 7,600 pounds per foot, almost 20% greater than the maximum dimension gondola. The "1 Foot Up and 1 Foot Out" articulated design approaches the modern bridge limit of 8,000 pounds per foot; while the "2 Feet Up and 2 Feet Out" design exceeds the limit by over 1,100 pounds per foot.

The NLL of the articulated designs are also superior to the gondolas. The articulated manual-dump longitudinal-door design has a NLL (and train capacity) higher than the "2 Feet Out and 1 Foot Up" gondola. The "2 Feet Up and 2 Feet Out" articulated design a train capacity of 22,200 tons – more than a 75% increase from the base hopper case. The net-to-tare ratios of the articulated designs are also, not surprisingly, better than the respective gondola designs.

3.6 Train Description

As has already been outlined, the limits on train size for most North American bulk train services is set by one of two limits:

- Length
- Weight

For the most part, this study was concerned only with length-limited trains since most of the productivity benefits resulting from alternative car design are much more acute in the length-limited case. Some account, however, was taken for weight-limited scenarios, for comparative purposes.

All of the trains considered in this study had a locomotive consist of 5 units. Each unit was assumed to weigh 200 tons and have a length of 69 feet. This resembled the train assumptions made in the prior HAL economic evaluation scenarios [4]. In the HAL analyses, the number of locomotives in the consists varied somewhat, but five units was the average consist size. For the most part, all of the locomotive units were assumed to be assembled as head-end power; however, the implementation sensitivity analyses regarding displaced power assumed that three units remained at the head-end and two units were reoriented as mid-train power.

The base case trains, with 53 foot 1 inch long cars had 106 cars, as in the HAL analysis [4]. This meant that the base trains had a length of 5,972 feet. As a result, a maximum train length of 6,000 feet was used for the length-limited train cases throughout this study. The loaded base case trains had a trailing weight of 15,158 tons. As a result, a maximum train weight of 16,000 tons was used for the weight-limited train cases throughout this study.

Of course, the alternative car designs changed the number of cars that could be accommodated within a train. Thus, the gross weight and length of each train varied slightly from the base, but remained under the limits of either weight or length as stated above.

A sensitivity analysis was performed on the parameter of car spacing. Adjusting the distances between the car boxes affected the number of cars and thus the weight of a length-limited train. Car spacing affects the length of weight-limited trains.

CHAPTER 4: COAL DISTRIBUTION NETWORKS

This chapter describes the two rail networks analyzed in the study:

- East
- West

A typical Eastern and a typical Western U.S. coal distribution network. Operations were analyzed for both networks using many scenarios as discussed in Chapter 3.

The parameters for the networks that were used are based upon networks developed for a previous MIT study for the AAR that investigated the factors that influence optimal axle loads for heavy-haul rail operations [1]. The Eastern and Western networks in the prior study were developed based on discussions with representatives of U.S. railroads, and on previous work performed for the AAR [27]. 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 4.1 describes the East network and the modifications made to the East network since the last study, and Section 4.2 describes the West network with a similar account of the differences between the parameters assumed in this study versus the prior study. Section 4.3 discusses the ramifications of changing the East and West network parameters from the prior Optimal Axle Load study. Finally, Section 4.4 discusses the effects of the network modeling approach and the presence of other traffic on track costs with respect to the track costs attained in the HAL analyses.

4.1 Eastern Coal Distribution Network

4.1.1 Description of Parameters

Figure 4-1 depicts the Eastern coal distribution network. The dark circles at the center of the network represent locations where coal is loaded onto trains. Loaded trains are routed in one of three directions, depending on the originating location (traffic is evenly distributed in each direction). The flows over the network are designed so that a loaded train leaving a #2-type segment will always traverse across a #3-type segment before entering a #4-type segment. In other words, all loaded trains take a long route to their destination branch in the network. Each train passes through a run-thru facility where its power is inspected and fueled, the train is inspected, and bad orders are removed. Trains unload coal at the light-colored triangles at the edge of the network. After unloading they are routed back towards the center of the network. They again pass through the run-thru facility and back to the loading area, and the cycle is repeated.

There is a total of 2400 miles of track in the Eastern coal distribution network. The trip from each loading to every unloading facility is 360 miles, and the cycle time is typically 3.6 days. Trains operate at a speed of 35 miles per hour, but often must slow down or stop for train meets or due to line congestion. In the gondola base case, there is 90 MGT of coal traffic across the network annually. A total of 46 coal train sets operate at any one time over the network in the gondola car base case, resulting in 59.6 MNT of coal shipped annually. This level of net tonnage is held constant across all of the scenarios investigated, however, the number of train sets required to move that level of coal tonnage and thus the level of gross tonnage, will vary depending upon the net-to-tare ratio of the scenario considered. 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 track per day (about 20 MGT per track 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, regardless of the unloading method (rotary dump or bottom dump). At run-thru facilities there is space for 4 trains, but service may occur simultaneously on no more than 2 trains. 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.

Table 4-1 summarizes key operating parameters for the East network. The table shows the number of segments of each type in the network, individual segment length, track type (single or double), total track miles, and the gross annual traffic in MGT both for coal trains and other traffic by type of track segment. There are 9 different types of track segments, as labeled in Figure 4-1. Segment 1 is a spur line to a loading facility. Segments 2 and 3 are heavily used by coal trains, but not by other traffic. Segments 1 – 3 are imagined to be located somewhere deep in the Appalachian mountains where most of the Eastern coal is mined. Segments 4 – 7 are main line segments similar to the East coal route in previous HAL analyses. Each of these segments is heavily used by coal trains and other traffic. Segment 8 is a less heavily used branch line used only for coal, and Segment 9 is a spur leading to an unloading facility. Except for Segments 5 and 6, all track segments are single track.

Table 4-1: Operating Parameters for the East Network

Parameter	Value by Track Segment								
	1	2	3	4	5	6	7	8	9
Number in Network	12	6	3	6	3	3	6	12	24
Length (miles)	10	20	40	20	80	80	80	20	10
Track Type (single / double)	1	1	1	1	2	2	1	1	1
Total Track Mileage (miles)	120	120	120	120	480	480	480	240	240
Annual Coal Traffic (MGT)	7.5	15.0	30.0	15.0	30.0	30.0	15.0	7.5	3.8
Annual Other Traffic (MGT)	0.0	0.0	0.0	20.0	40.0	40.0	20.0	0.0	0.0
Total Annual Traffic (MGT)	7.5	15.0	30.0	35.0	70.0	70.0	35.0	7.5	3.8

Table 4-2 summarizes the distribution of track by degree of curvature. Table 4-3 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 increasingly been used, especially on high-density lines. Premium rail (greater than 300 BHN) may be used on curves. Table 4-4 lists the number of turnouts per mile by track segment and type of turnout. Table 4-5 summarizes the ballast section quality as either good or bad (as defined in the HAL analyses) by track segment.

Table 4-2: Distribution of Track Curvature for the East Network

Track Curvature (degrees)	Percent by Track Segment								
	1	2	3	4	5	6	7	8	9
0	50%	60%	68%	68%	68%	68%	60%	60%	55%
2	20%	18%	18%	18%	18%	18%	18%	18%	20%
4	15%	12%	10%	10%	10%	10%	12%	12%	15%
6	10%	8%	4%	4%	4%	4%	8%	8%	8%
8	5%	2%	0%	0%	0%	0%	2%	2%	2%

Table 4-3: Distribution of Track Metallurgy for the East Network

Curvature (degrees)	Metallurgy (BHN)	Percent of Given Curvature with Specified Metallurgy by Track Segment								
		1	2	3	4	5	6	7	8	9
0	270	100%	50%	40%	40%	40%	40%	40%	100%	100%
	300	0%	50%	60%	60%	60%	60%	60%	0%	0%
2	270	100%	50%	25%	25%	25%	25%	25%	100%	100%
	300	0%	50%	75%	75%	75%	75%	75%	0%	0%
4	300	100%	0%	0%	0%	0%	0%	0%	100%	100%
	340	0%	100%	100%	100%	100%	100%	100%	0%	0%
6	340	100%	100%	100%	100%	100%	100%	100%	100%	100%
	370	0%	0%	0%	0%	0%	0%	0%	0%	0%
8	340	100%	100%	100%	100%	100%	100%	100%	100%	100%
	370	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 4-4: Distribution of Turnouts for the East Network

Turnout Type	Turnout Spacing by Tack Segment (turnouts / mile)								
	1	2	3	4	5	6	7	8	9
Standard #16	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Standard #20	0.00	0.50	0.00	0.00	0.00	0.00	0.70	0.70	0.00
Premium #20	0.00	0.00	0.50	0.50	0.50	0.50	0.00	0.00	0.00
Total	0.80	0.50	0.50	0.50	0.50	0.50	0.70	0.70	1.00

Table 4-5: Distribution of Ballast Quality for the East Network

Ballast Section Quality	Percent by Track Segment								
	1	2	3	4	5	6	7	8	9
Good	70%	80%	90%	90%	90%	90%	80%	80%	70%
Poor	30%	20%	10%	10%	10%	10%	20%	20%	30%

The track parameters for the mainlines are identical to those used for the HAL routes, but on lower density lines the track (especially rail metallurgy, turnout-type, and ballast section) 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.

All of the segments are assumed to have grades similar to the typical East route from the AAR HAL analyses [2][3][4]. Segments 1 – 4 should have steeper grades than the other segments because of the mountainous geography that they are assumed to traverse; however, variations in gradient were not incorporated into the analysis since TEM/RECAP [28] was not directly utilized. The transportation cost results of the HAL III study were extrapolated to attain the transportation cost results of this study. Unless otherwise specified, the values used in modeling the networks (such as train lengths, locomotives per train, grinding policy, defect limit, and so forth) are the same as those used in the AAR HAL Phase III analysis for length-limited trains of the same axle loading [4].

Figure 4-1: East Coal Distribution Network

4.1.2 Summary of Network Modifications from Optimal Axle Load Study

The Eastern network was modified slightly from the prior study in order to more closely match the Eastern U.S. reality and East HAL route assumptions. Higher levels of other traffic were added to the network, so that the tonnage levels and commodity mixes would more closely match reality in the Eastern U.S. Also, double track segments were added and removed to tailor the traffic density on the mainline segments so that they more closely matched the East HAL route tonnage level of 30 MGT. Finally, the mainline rail metallurgy was changed on some segments in order to more closely resemble the East HAL route assumptions.

A summary of all the specific changes is as follows:

- 20 MGT of other traffic added to Segment 4 (formerly there was not any other traffic)
- 20 MGT of other traffic added to Segments 5 and 6 (there already was 20 MGT of other traffic on these segments)
- Double track on Segment 3 downscaled to single track
- Single track of Segments 5 and 6 expanded to double track
- Rail metallurgy improved on Segment 7 to 60% 300 BHN / 40% 270 BHN on tangent track (from 50% / 50%) and 75% 300 BHN / 25% 270 BHN on low-radius (2-degree) curves (from 50% / 50%) in order to reflect the East HAL route metallurgy assumptions at the appropriate tonnage level

4.2 Western Coal Distribution Network

4.2.1 Description of Parameters

Figure 4-2 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 dark circles at the top of the network, pass through the large run-thru facility at the center of the network, through one of the 4 smaller run-thru facilities, and then are unloaded at one of the light-colored triangles at the bottom of the schematic. After unloading, trains are routed back along the same path and the cycle is repeated.

There is a total of 4,200 miles of track in the Western coal distribution network. The trip from each loading to every unloading facility is 1300 miles, and the cycle time is typically 5.6 days. Trains operate at a speed of 35 miles per hour, but often must slow down or stop for train meets or due to line congestion. Congestion is worst near the large run-thru facility. In the gondola base case, there is 120 MGT of coal traffic across the network annually. A total of 95 coal train sets operate at any one time over the network in the gondola car base case, resulting in 79.5 MNT of coal shipped annually. This level of net tonnage is held constant across all of the scenarios investigated, however, the number of train sets required to move that level of coal tonnage and thus the level of gross tonnage, will vary depending upon the net-to-tare ratio of the scenario considered. 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 track per day (about 20 MGT per track 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, regardless of the unloading method (rotary dump or bottom dump). At the large run-thru facility there is space for 14 trains, but service may occur simultaneously on no more than 8 trains. At each of the 4 smaller facilities there is space for 8 trains, but service may occur simultaneously on no more than 4 trains. 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 somewhat congested, more congested than the East network, but the number of coal trains operating on the network could be increased by approximately 10% before the network would reach 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 the cycle times of the remaining trains.

Table 4-6 summarizes key operating parameters for the West network. The table shows the number of segments of each type in the network, individual segment length, track type (single or double), total track miles, and the gross annual traffic in MGT both for coal trains and other traffic by type of track segment. There are 10 different types of track segments, as indicated in Figure 4-2. Segment 1 is a spur line to a loading facility. Segment 2 is a branch line used exclusively by coal trains. Segments 3, 4 and 5 are main

line segments similar to the West coal route in previous HAL analyses. Segments 6 – 8 are main lines, but carry a greater proportion of other types of traffic. Segment 9 is a branch lines assumed to be located on the Eastern edge of the West network with relatively little traffic. Segment 10 is a spur leading to an unloading facility. Except for Segments 4 and 5, all track segments are single track.

Table 4-7 summarizes the distribution of track by degree of curvature. Table 4-8 summarizes the distribution of track metallurgy by track segment and degree of curvature. Table 4-9 lists the number of turnouts per mile by track segment and type of turnout. Table 4-10 summarizes the ballast section quality as either good or bad (as defined in the HAL analyses) by track segment.

Table 4-6: Operating Parameters for the West Network

Parameter	Value by Track Segment									
	1	2	3	4	5	6	7	8	9	10
Number In Network	8	4	2	1	1	2	4	8	16	32
Length (miles)	10	50	140	300	300	300	130	130	30	10
Track Type (single / double)	1	1	1	2	2	1	1	1	1	1
Total Track Mileage (miles)	80	200	280	600	600	600	520	1040	480	320
Annual Coal Traffic (MGT)	15.0	30.0	60.0	120.0	120.0	60.0	30.0	15.0	7.5	3.8
Annual Other Traffic (MGT)	0.0	0.0	0.0	40.0	40.0	20.0	20.0	20.0	0.0	0.0
Total Annual Traffic (MGT)	15.0	30.0	60.0	160.0	160.0	80.0	50.0	35.0	7.5	3.8

Table 4-7: Distribution of Track Curvature for the West Network

Track Curvature (degrees)	Percent by Track Segment									
	1	2	3	4	5	6	7	8	9	10
0	65%	68%	83%	83%	83%	83%	75%	75%	68%	60%
2	20%	18%	16%	16%	16%	16%	15%	15%	18%	18%
4	10%	10%	1%	1%	1%	1%	7%	7%	10%	12%
6	5%	4%	0%	0%	0%	0%	3%	3%	4%	8%
8	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%

Table 4-8: Distribution of Track Metallurgy for the West Network

Curvature (degrees)	Metallurgy (BHN)	Percent of Given Curvature with Specified Metallurgy by Track Segment									
		1	2	3	4	5	6	7	8	9	10
0	270	100%	40%	0%	0%	0%	0%	0%	40%	100%	100%
	300	0%	60%	100%	100%	100%	100%	100%	60%	0%	0%
2	270	100%	25%	0%	0%	0%	0%	0%	25%	100%	100%
	300	0%	75%	100%	100%	100%	100%	100%	75%	0%	0%
4	300	100%	0%	0%	0%	0%	0%	0%	0%	100%	100%
	340	0%	100%	100%	100%	100%	100%	100%	100%	0%	0%
6	340	100%	100%	0%	0%	0%	0%	50%	50%	100%	100%
	370	0%	0%	100%	100%	100%	100%	50%	50%	0%	0%
8	340	100%	100%	0%	0%	0%	0%	50%	100%	100%	100%
	370	0%	0%	100%	100%	100%	100%	50%	0%	0%	0%

Table 4-9: Distribution of Turnouts for the West Network

Turnout Type	Turnout Spacing by Tack Segment (turnouts / mile)									
	1	2	3	4	5	6	7	8	9	10
Standard #16	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Standard #20	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.70	0.00
Premium #20	0.00	0.00	0.50	0.25	0.25	0.25	0.50	0.50	0.00	0.00
Total	0.80	0.50	0.50	0.25	0.25	0.25	0.50	0.50	0.70	1.00

Table 4-10: Distribution of Ballast Quality for the West Network

Ballast Section Quality	Percent by Track Segment									
	1	2	3	4	5	6	7	8	9	10
Good	80%	90%	90%	90%	90%	90%	90%	80%	70%	70%
Poor	20%	10%	10%	10%	10%	10%	10%	20%	30%	30%

The track parameters for the mainlines are identical to those used for the HAL routes, but on lower density lines the track (especially rail metallurgy, turnout-type, and ballast section) is of lower quality, and there are more curves and turnouts.

All of the segments are assumed to have grades similar to the typical West route from the AAR HAL analyses [2][3][4]. Variations in gradient from the HAL analyses were not incorporated into this study since TEM/RECAP [28] was not directly utilized. The transportation cost results of the HAL III study were extrapolated to attain the transportation cost results of this study. Unless otherwise specified, the values used in modeling the networks (such as train lengths, locomotives per train, grinding policy, defect limit, and so forth) are the same as those used in the AAR HAL Phase III analysis for length-limited trains of the same axle loading [4].
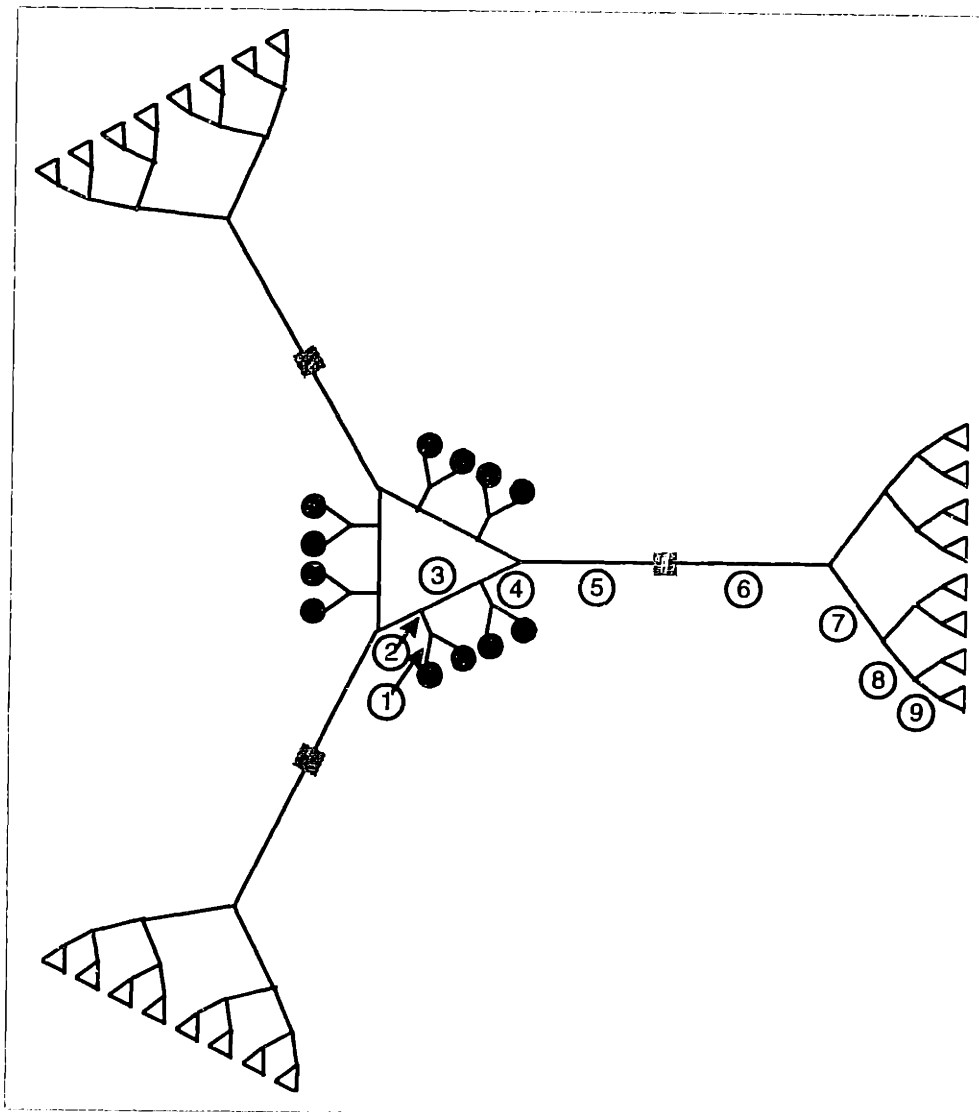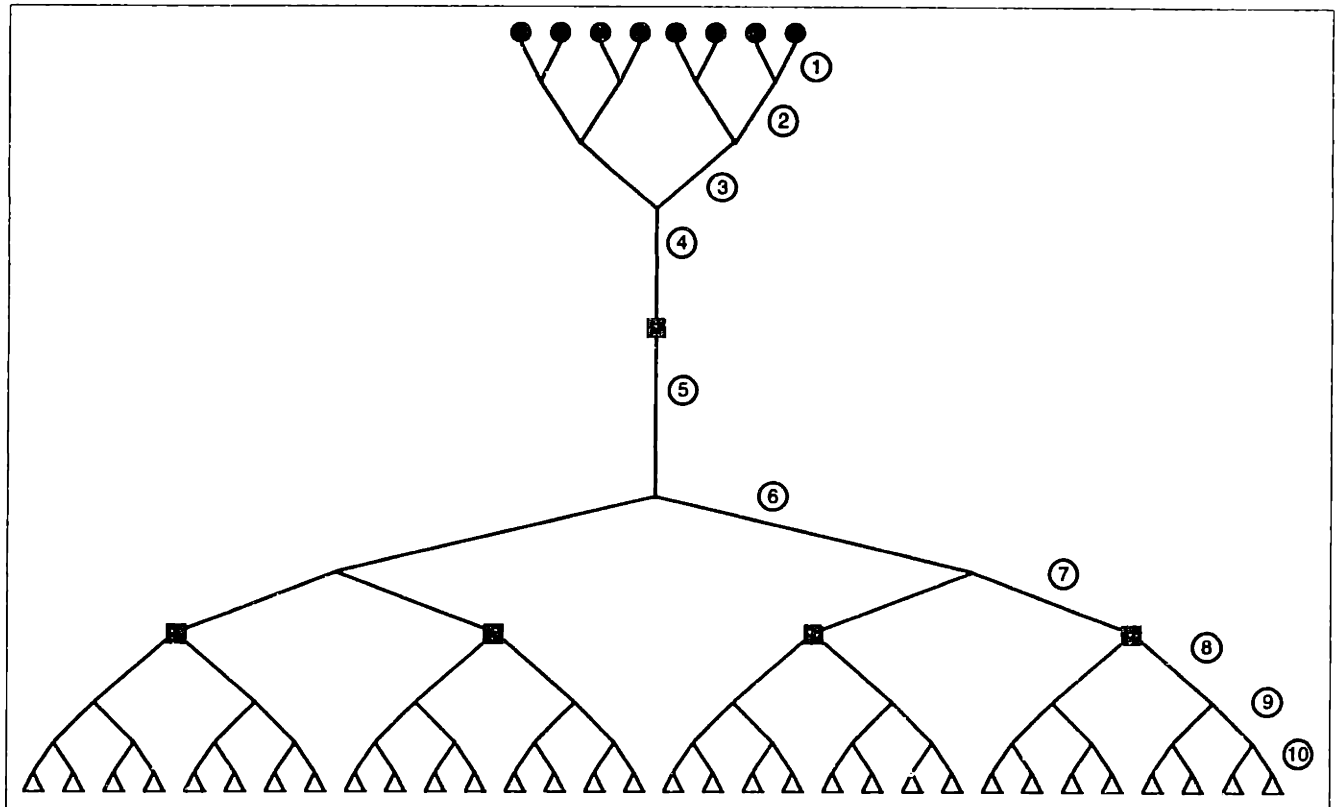
Figure 4-2: West Coal Distribution Network

4.2.2 Network Modifications since Optimal Axle Load Study

The Western network was modified slightly from the prior study in order to more closely match the Western U.S. reality and West HAL route assumptions. Higher levels of other traffic were added to the network, so that the tonnage levels and commodity mixes would more closely match reality in the Western U.S. Mainline rail metallurgy was also changed on some segments in order to more closely resemble the East and West HAL route assumptions. A summary of all the specific changes is as follows:

- 20 MGT of other traffic added to Segment 8 (formerly there was not any other traffic).

- 20 MGT of other traffic added to Segments 4 and 5 (there already was 20 MGT of other traffic on these segments).

- Rail metallurgy improved on Segment 7 to more closely match the West HAL assumptions since the tonnage level of 50 MGT is significantly higher than the 30 MGT of the East HAL route. These changes prompted substantial steady-state track cost savings, especially due to rail fatigue at axle loadings above 36 tons:

  - Tangent track – 100% 300 BHN from 60% 300 BHN / 40% 270 BHN

- Low-curves – 100% 300 BHN from 75% BHN / 25% 270 BHN
- Medium-curves – 100% 340 BHN from 100% 300 BHN
- High-curves – 50% 370 BHN / 50% 340 BHN from 100% 340 BHN

- Rail metallurgy improved on Segment 8 to more closely match the East HAL assumptions since the tonnage level of 35 MGT is very close to the 30 MGT of the East HAL route:

  - Tangent track – 60% 300 BHN & 40% 270 BHN from all 270 BHN
  - Low-curves – 75% 300 BHN & 25% 270 BHN from 50% 300 BHN & 50% 270 BHN
  - Medium-curves – 100% 340 BHN from 50% 340 BHN & 50% 300 BHN

4.3 Ramifications of Changing the Network Structure from the Optimal Axle Load Study

The Eastern and Western coal distribution networks were modified slightly from the prior Optimal Axle Load study in order to more closely match real American networks and the HAL route assumptions. Higher levels of other traffic were added, the total gross tonnage levels modified, and rail metallurgy improved on some segments in order to achieve these ends.

As a result of these network parameter modifications, the results of this study are not directly comparable to the results of the prior "Optimal Axle Load" Study. The magnitudes of the quantitative cost results will be different for an identical modeling scenario. Although, the qualitative trends in the results of the prior study should still apply to the modified networks.

Many of the railcar vehicle parameters have been modified since the prior study, as well as the train-makeup description. In modeling track costs, the other traffic is handled in a much more explicit fashion in this study. The other traffic is now modeled as having a different axle load distribution from the coal traffic (a major improvement over the prior analysis) and the track cost allocation to coal traffic versus other traffic has been improved. Also, the base case between the two studies is different. The base case for the "Optimal Axle Load Study" was an aluminum gondola car with 33-ton axle loads. The base case for this study is an aluminum gondola car with 36-ton axle loads, reflecting the current best practice. The present base case train is heavier with a better railcar net-to-tare ratio. The number of trainloads per year needed to haul the same base gross tonnage has dropped by over 10%. But, the train net-to-gross ratio (net as a percent of total weight) has dropped slightly due to a locomotive consist assumption change –

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this study assumes 5 200-ton locomotive units in accordance with many of the HAL scenarios, while the prior analysis assumed 3 220-ton locomotive units. As a result, the level of net tonnage dropped almost 3% from the prior analysis for the base case, for the same total gross tonnage.

The gross tonnage level (measured in MGT) was held the same across both studies (90 MGT/year in the east and 120 MGT/year in the west). Matching the gross tonnage levels enabled aligning the gross tonnage of individual track segments in the network more closely to the HAL routes and track component type and maintenance practice assumptions. Track maintenance requirements and costs are proportional to gross tonnage, not net tonnage; the track assumptions could thus be more readily aligned. The gross tonnage levels are easier to relate to and match to reality since this data is more readily available from the railroads. From these base MGT and MNT levels, the MNT is held constant across all scenarios, adjusting the gross traffic volume to accommodate for varying vehicle and train assumptions.

Overall, since there are so many differences in many of the assumptions and parameters regarding vehicles and trains between this Optimal Car Design and the prior Optimal Axle Load study, the details of the results of the two studies are not comparable. The conclusions of the two studies, however, should be comparable.

4.4 Effects of the Network Modeling Approach and Presence of Other Traffic on Track Costs

All other things being equal, the effect on track costs of modeling over a distribution network versus a mainline route is to lower the level of average total cost per mile, but raise the level of average total cost per ton-mile (either gross or net ton-miles). The low-density track segments near the loading and unloading facilities cost less to maintain on a per mile basis because of the lower demands placed upon the track structure. These same low-density track segments cost significantly more than a mainline track segment on a per ton-mile basis due to the presence of high fixed costs and thus a strong component of economies of traffic density in a typical railroad track cost structure. The low-density segments near the loading and unloading facilities in the networks thus raise the average cost per ton-mile above the mainline costs.

The presence of other traffic on the network has the opposite effect on total average track costs. The presence of other traffic in addition to the already present coal traffic inherently raises the gross tonnage

level and thus raises the track cost per mile. However, since the average axle load of the other traffic is lighter than for the coal bulk traffic, if the total gross tonnage is kept constant by eliminating coal tonnage while adding other tonnage, the total average cost per mile will decrease. Due to the other traffic's lighter average axle load, regardless of whether or not the gross tonnage is kept constant or increasing, in the presence of economies of traffic density, the total cost per gross ton-mile will drop with the addition of other traffic or by replacing coal traffic with other traffic. The total cost per net ton-mile will almost certainly decrease for these same reasons if the total net tonnage is increased by adding other traffic, but could conceivably rise if the tonnage is kept constant. Without the extra cost savings boost from economies-of-density, if the net-to-tare ratio of the other traffic mix is poor enough, the fact that the average axle load of this traffic is lower than the coal traffic may not be enough to compensate for the lower level of net tonnage carried for the same amount of gross tonnage.
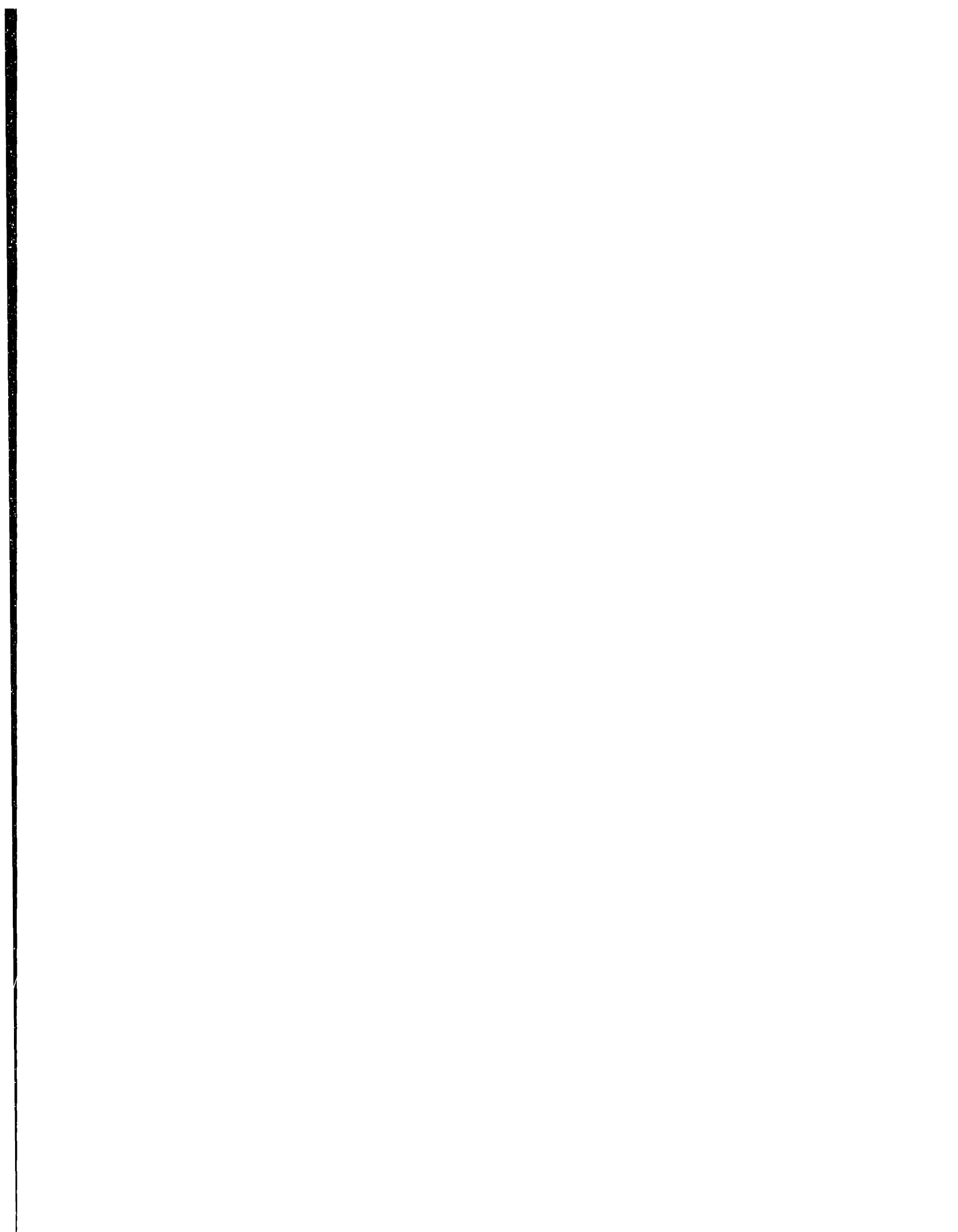
CHAPTER 5: OPERATING COSTING METHODOLOGY

This section describes the operating costing methodology used for the study. Section 5.1 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 5.2 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 5.3 describes the cost model used to calculate the combined operating and maintenance costs for each case.

5.1 Track Cost Analysis

The analysis of track maintenance requirements was performed using the AAR TRACS model [29] and a variation of the HALTRACK spreadsheet model [30] 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.

5.1.1 TRACS Model Background

The TRACS (Total Right-Of-Way Analysis and Costing System) model was developed at MIT for the AAR [29]. TRACS 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 [31]. 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.

Track accounts for approximately 15% of rail freight expense in North America [31]. Increasing competition within the rail industry, increasing traffic density, rising axle loads, more durable track component materials, and innovations in inspection and maintenance techniques have created a need for rail engineering officials to attain greater knowledge concerning the mechanisms of track deterioration, the options for maintenance techniques, and the characteristics of new track materials all within an economic context.

TRACS relates railroad track and traffic characteristics to the maintenance activities and associated costs of maintaining the track structure [32]. TRACS is primarily directed toward the objectives of service specific cost analysis and the assessment of alternative technologies and service plans; however, the TRACS framework also supports maintenance planning alternative assessment. TRACS differs from other track maintenance planning tools in that some of the underlying deterioration models are developed from basic engineering principals to be "causally" correct rather than being relatively simple statistical extrapolations of recent experience. TRACS can thus be used for consideration of technological and operating alternatives outside the range of current experience with greater confidence.

TRACS is a fundamental tool in the continuing effort to translate the technical characteristics of new equipment designs and new track materials into economic terms. TRACS can be used to set maintenance standards, predict maintenance requirements under existing traffic, or determine the incremental costs of operating specific equipment over a specified route. TRACS can predict the long-term track maintenance implications of a particular service on a life-cycle cost basis, or it can estimate maintenance requirements and costs on a short-term basis from site-specific data of track condition.

TRACS was developed as an integral part of the AAR's research program. This had several important implications for its design. TRACS did not have to stand alone, but instead was built upon and complemented by other AAR tools and techniques already available or under development. The goal of TRACS was to provide a useful tool for industry managers linking the engineering and economic issues, therefore the model combines engineering models with life-cycle costing techniques to provide a versatile tool for infrastructure management [31]. This versatile model is user-friendly and can be used by people at various levels of an organization in various departments to address a wide range of problems.

Physical deterioration relationships are central to the development of any life-cycle costing and maintenance planning tools. The rates at which track components deteriorate, which have been studied extensively by the AAR Track Research Program, are functions of route, track, and traffic characteristics.

TRACS includes causal rather than statistical models to allow consideration of a wide range of technological options. This is a critical difference between TRACS and several other maintenance planning models currently under development.

A focus on life-cycle costing is another essential feature of TRACS. Life cycle costing provides a way to balance the high costs of installing new components, the costs of multi-year maintenance cycles, and the costs of routine maintenance. By looking at all of the relevant costs, it is possible to compare alternative scenarios using such financial concepts as net present value (NPV) and equivalent uniform annual cost (EUAC).

The TRACS framework has been built as a modular structure so that it can quickly be modified to incorporate new deterioration models as new information becomes available. At this time, causal models for rail, both wear and fatigue, and ties have been incorporated within TRACS, and simple, empirical models for ballast and turnouts have been included. In the future, TRACS will also include causal deterioration modules for ballast, turnouts, and perhaps bridges.

The extensive knowledge base within TRACS includes technical information about track components, parameters for calibrated deterioration relationships, and a detailed framework for specifying the costs and policies related to track maintenance and renewal.

5.1.2 Role of TRACS in the Analysis

Similar to the approach followed in the previous HAL analyses, TRACS was used to project component lives for rail and ties in this study. Component lives for turnouts were projected using a least-squares regression modeling technique calibrated to the results of the AAR's Turnout Model [33] from the HAL Phase III economic analysis [4]. 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 [4][30].

The assumptions listed in the Chapter 4 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 mainline 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.

5.1.3 Procedure for Modeling Traffic within TRACS

Within TRACS, traffic is defined on three levels:

- Individual vehicles
- Trains composed of an assortment of vehicles
- Traffic mixes composed of an assortment of trains

The base case gondola train was modeled as 5 locomotives and 106 gondola cars, as in the HAL analyses. The locomotives each weighed 200 tons, modeled with 3-axle trucks and 33-ton axle loads. Loaded gondola cars had 35.75-ton axle loads (286-kip GVW) on 2-axle trucks and empty cars had 5.375-ton axle loads (43-kip tare weight) on 2-axle trucks. For different scenarios, base cases at 33, 39 and 43-ton axle loads were also executed. All of the 36-ton scenario results were extrapolated from the 36-ton gondola base case. The same is subsequently true for the other base case axle loads.

Unlike the prior "Optimal Axle Load" Study, the other traffic present in the network was modeled explicitly within TRACS. The other traffic had significantly different axle load distributions from the unit coal trains. There were two different other traffic trains: Eastern and Western. The axle load distributions for these two traffic-types (modeled as individual generic trains) came from the HAL Phase I analysis [2]. As part of the HAL Phase I analysis, the AAR conducted 2 case studies where the AAR and the Ad Hoc FAST/HAL Economic Committee used their methodology to work closely with 2 member railroads to analyze specific proposed HAL services. One of the railroads was in the East, while the other was in the West. Table 5-1 summarizes the characteristics of the two "other traffic" distributions.

Table 5-1: Other Network Traffic Axle Load Distributions and Net-to-Gross Ratios

Axle Load (tons)	East "Other Traffic" Mix		West "Other Traffic" Mix	
	Percent Distribution by Weight	Carload Distribution to Nearest Integer Car	Percent Distribution by Weight	Carload Distribution to Nearest Integer Car
8.0	22.0%	46	11.5%	33
12.5	12.8%	17	0.0%	0
20.0	35.0%	29	1.7%	2
27.0	22.2%	14	74.6%	65
30.0	8.1%	3	12.3%	6
Total	100.0%	109	100.0%	106
Equivalent Axle Load (tons)	18.8		25.1	
Total Case Net Tonnage (MNT)		9.1		5.5
Total Case Gross Tonnage (MGT)		21.0		8.6
Net-to-Gross Ratio		0.431		0.635

The 30-ton axle loads were assumed to be 180-ton locomotives on 3-axle trucks. From the characteristics of the "other traffic" axle load distributions it appears that both mixes are composed of general merchandise and intermodal freight. The Western mix is heavier than the Eastern. This is probably due to the presence of more double-stack intermodal freight or bulk agricultural commodities (such as grain) in the mix. The equivalent axle load in the West is more than 6 tons, or 1/3, higher than the equivalent axle load in the East, assuming a damage factor exponent of 1.0. The lighter density characteristics of the Eastern traffic also accounts for its much lower net-to-gross ratio when compared to the West.

The traffic mixes used in TRACS to model the Eastern and Western gondola base cases were modified as appropriate to account for the presence of other traffic. The generic (or average) other traffic trains constructed by the carload distributions presented above in Table 5-1, were mixed in accordingly with loaded and unloaded 36-ton base case gondola coal trains to get the correct gross tonnage traffic mix for the segment being modeled.

5.1.4 Procedure for Obtaining Rail Wear Lives from TRACS

Generic East and West routes were set up within TRACS to attain the rail wear lives for input into the HALTRACK spreadsheet. Both routes were set up following the assumptions and parameters already outlined for the Eastern and Western coal distribution networks. Wherever possible, these parameters and assumptions were made consistent with the previous HAL analyses, especially the most recent HAL Phase III analysis. This section details how the HAL III analysis was conducted and the actions taken to apply the same approach to the current study.

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In accordance with these guidelines, the head wear limit was set at 0.56" and the gauge face wear limit was set at 0.5", exactly as in the HAL analyses. Within TRACS, the defect limit was set to 99 defects/mile/year to ensure that the rail would fail due to wear, since the HALTRACK spreadsheet incorporated the PHOENIX model rail fatigue calculations [34].

The procedure used to set up the traffic files that were used for this study were previously outlined in section 5.1.3. Once the traffic files have been adjusted and the right traffic file linked to the route file, the gross traffic level had to be adjusted. The gross traffic level must necessarily match the traffic level for the appropriate specific track segment being modeled within the network and the correct traffic scenario. Finally, the level of rail grinding must be adjusted in accordance with the level of gross tonnage for the scenario.

In order to obtain the rail wear lives in HAL Phase III, the Phase II wear lives from TRACS were used with the Phase II grinding assumptions, and then adjusted according to the results of the FAST/HAL Phase III test results in Pueblo within the HALTRACK spreadsheet model. For segments in the network with under 50 MGT of gross traffic, the East HAL Phase II base level grinding assumptions were utilized. These assumptions were 0.01" / 100 MGT on tangent track and 2-degree curves, and 0.02" / 100 MGT on curves of 4-degree curvature or more. For segments with 50 MGT of gross traffic or more, the West HAL II base grinding assumptions of 0.02" / 100 MGT on tangent track and 2-degree curves, and 0.04" / 100 MGT on steeper curves were utilized. The level of base grinding was felt to be more a function of tonnage than anything else, explaining the shift from the 30 MGT East line to the 80 MGT West line HAL II assumptions with increasing tonnage.

The TRACS model was calibrated to the HAL results. The most representative results were obtained when rail lubrication was at the following levels: none on tangent track, 10 pounds / mile / MGT / year on 2-degree curves, and 25 pounds / mile / MGT / year on steeper curves. The rail weight was assumed to be 132 pounds per yard on all segments, regardless of the traffic level, on tangent track and 2-degree curves. The rail weight was assumed to be 136 pounds per yard on curves tighter than 2-degrees, regardless of the tonnage level. The assumed weight of rail did not have a very large effect on rail wear life when tested.

TRACS was only run for the gondola base cases at each axle load studied in this analysis. All other scenarios used the rail wear lives (in MGT) of the base case at the respective axle load. This was not a large source of error. The HAL analyses found that rail wear life, in MGT, is largely independent of axle load and traffic volume. Doubling the traffic volume will halve the wear life in terms of years, but not

affect the wear life in terms of MGT. Small deviations in axle loads also do not affect wear life appreciably. For example, when the other traffic with its significantly lower equivalent axle loads was modeled explicitly, as opposed to being modeled as additional coal traffic, the wear life on tangent and 2-degree curves did not increase at all. These two types of curvature compose by far most of the Eastern and Western network track miles.

The HALTRACK spreadsheet accounts for deviations in gross tonnage due to a change in net-to-tare across scenarios, given rail life in MGT. The spreadsheet also updates fatigue life given changes in the tonnage level and net-to-tare ratio. As the net-to-tare ratio improves, the equivalent axle load decreases since the loaded cars weigh the same, but the empty cars weigh less and the proportion of loads to empties remains unchanged in unit train operations. This drop in axle load, however, will not improve the rail wear life. So, overall, it is reasonable to assume that the rail wear life, in MGT, holds across all of the scenarios with the same fully-loaded freight car axle loading.

5.1.5 Procedure for Obtaining Average Tie Lives from TRACS

The tie module of TRACS was used to obtain the average tie lives for this study. The average tie lives were translated into economic costs using the HALTRACK spreadsheet, assuming that program ties are replaced at a constant annual rate on each route and spot ties are a constant percentage of program ties on all degrees of curvature and at all levels of traffic volume. The average tie spacing was assumed at 20 inches and spot ties were assumed to comprise of 10% of the total ties replaced, as in Phase III. In accordance with the Phase III findings, premium fastenings were not used on curves as they were in the Phase II analysis. The Eastern network was modeled as a medium decay zone and the Western network was modeled as a low decay zone, just as in the HAL analyses. These decay zone definitions are of a geographic / environmental decay factor used by the Tie Model within TRACS.

The TRACS tie module average tie life results were calibrated as closely as possible to the HAL III results, holding as many of the assumptions as constant and consistent as possible. Six cut spikes were assumed per tie (3 per tie plate), and 8" X 14" tie plates were assumed everywhere, regardless of tonnage or curvature. These assumptions seemed to generate consistent results with the HAL III analysis when the parameters of Table 5-2 were utilized. The levels of superelevation and track speeds on curves were obtained from the FRA track standards handbook [35]. The speed of coal trains on tangent track and 2-degree curves was aligned with the speed assumptions of the UTRAIN model in order to promote a

consistent analysis. The higher speeds of the other traffic was designed to more closely resemble the actual speeds of general merchandise and intermodal trains in reality.

The tie module was run for every case that the rail wear module was executed. Hence, only the Eastern and Western coal network gondola base cases at 33, 36, 39 and 43-ton axle loads were explicitly modeled with TRACS. From the results of the HAL analyses and from investigations using the TRACS model, average tie life (in years) is not largely affected by changes in tonnage or axle load. Large changes in axle loads will have a significant impact on tie life on steep curves, but minor fluctuations in the equivalent axle load over a network comprised mostly of tangent track and gentle curves will have little overall affect on the bottom line cost or average tie life across the network. The level of gross tonnage has only a second-order effect on tie life. For example, doubling the tonnage of the Eastern gondola base case from 15 MGT/year to 30 MGT/year only drops the average tie life on tangent track 8%, from 35.3 years to 32.4 years. There is more than a factor of 10 between changes in the two variables. Therefore, for small variations of MGT across alternative scenarios in relation to the base case, due to fluctuations in the net-to-tare ratio, keeping the average tie life constant in terms of years is not a large source of error.

Table 5-2: TRACS Tie Model Assumptions

Curvature (degrees)	Speed Limit (mph)		Superelevation (inches)
	Coal Traffic	Other Traffic	
0	35	60	0.0
2	35	50	2.0
4	35	45	4.0
6	25	35	5.5
8	15	25	5.5

5.1.6 Procedure for Obtaining Turnout Costs

The turnout costs in this study are obtained by means of a regression technique developed by Bill Robert as a way to simplify the AAR Turnout Model [33] results for use in the coal network Optimal Axle Load study [1]. The same technique was used to calibrate a simple regression costing model from the HAL Phase III results.

Three types of turnouts were modeled in the HAL III analysis and this study:

- Standard #16

- Standard #20
- Premium #20

The cost components from the AAR's Turnout Cost Model were combined into 3 different categories for incorporation in the regression technique:

- Installation Costs
- Major Maintenance Costs
- Routine Maintenance Costs

The installation costs are the same in this study as in the HAL analysis. The major maintenance activities of this study encompass the following maintenance activities of the HAL analysis: hand grinding the points, hand grinding the frog, welding the frog, replacing the straight switch point, replacing the curved switch point, replacing the frog, undercutting, production grinding, surfacing and replacing switch ties. The routine maintenance activities of this study encompass the following maintenance activities of the Turnout Model: lubrication, point adjustment, bolt tightening and guard rail adjustment.

The regression model was developed by considering the total turnout lifecycle costs using the turnout model results, the total maintenance activities over the life of the turnout and the turnout activity costs. The installation costs and routine maintenance costs were assumed to remain constant over the life of a turnout, regardless of axle load or traffic volume. However, turnout life was felt to vary most closely with axle load and traffic volume and thus a regression analysis was performed identifying how turnout life varied with these two parameters in the HAL analysis. Equation 5.1 describes the relationship between turnout life and axle load and traffic volume in relation to a base case, as defined by the regression analysis. Table 5-3 outlines the principal input parameter values found to best fit into the regression analysis modeled by Equations 5.1 and 5.2.

$$T_1 = T_0 \left(\frac{A_1}{A_0}\right)^{C_1} \left(\frac{M_1}{M_0}\right)^{C_2} \tag{1}$$

$$MM_1 = MM_0 + C_3 \left(\frac{M_1}{M_0} - 1\right) \tag{2}$$

Where:

T_1 = Predicted Turnout Life for Scenario [MGT]

T_0 = Base Case Turnout Life [MGT]

A_1 = Scenario Equivalent Axle Load [Tons]

A_0 = Base case Equivalent Axle Load [Tons]

M_1 = Scenario Gross Tonnage Level [Annual MGT]

M_0 = Base Case Gross Tonnage Level [Annual MGT]

MM_1 = Predicted Major Maintenance EUAC over Life of Turnout

MM_0 = Base Case Major Maintenance EUAC over Life of Turnout

C_1, C_2 = Damage Factor Exponents

C_3 = Gross Traffic Multiplier

Table 5-3: Turnout Regression Cost Model Parameters

Parameter	Standard #16	Standard #20	Premium #20
Base Axle Load (tons)	28.5	28.5	28.5
Base Traffic (MGT)	80	80	80
T_0	605.6	756.6	986.4
C_1	-0.48	-0.46	-1.31
C_2	0.23	0.22	0.25
C_3	$11,381	$10,945	$25,228

C_1 and C_2 represent Damage Factor Exponents (DFE's). The DFE approach in this case entails utilizing an equation that estimates the life of a track component given the base life at a base axle load and tonnage level and the exponents to which the life varies with respect to the ratio of the actual scenario axle load and tonnage level over the base case axle load and tonnage level. The base case was chosen as the 33-ton axle load, 80 MGT HAL Phase III case.

As axle load increases, turnout life decreases, thereby increasing the EUAC of the installation and routine maintenance costs. Interestingly though, an increase in annual tonnage was found to increase the life of a turnout in terms of tonnage, according to the regression model. This result may seem somewhat peculiar at first, but suggests that turnouts decay over time due to environmental factors. A higher level of tonnage means that a turnout will not be exposed to the environment for as long a time before expiring due to usage. Thus, it may be expected to last somewhat longer in terms of tonnage exposure. This tonnage/environmental factor is not as evident as the axle load factor over the range of tonnage and axle loads considered.

Major maintenance costs were felt to vary most closely with traffic volume. As the traffic volume increases, the major maintenance cost increases over the life of the turnout. This makes sense since as traffic volume increases, the life of the turnout in years will decrease, and assuming that the same number of major maintenance activities are performed over the life of the turnout, the same work is completed in less time, and thus the EUAC increases. This relationship is captured in Equation 5.2. C_3 is a damage factor multiplier. It is a unit cost applied to the proportional change in gross traffic volume. The magnitude of this multiplier is much higher for the premium turnout because it's major components and maintenance requirements are much more expensive than for conventional turnouts, but they are replaced and performed less frequently. Note that the Premium #20 turnout's life is much longer than the Standard #20 turnout, all other things being equal, and the Standard #20 turnout lasts much longer than the Standard #16 turnout.

Overall, the results obtained from the regression model match reasonably well with the HAL III results. This should not be surprising since the regression model was developed based upon the HAL results as the only data points.

5.1.7 Track Cost Result Measurement

A focus on life-cycle costing is an essential feature of this analysis. Life cycle costing provides a way to balance the high costs of installing new components, the costs of multi-year maintenance cycles, and the costs of routine maintenance. By looking at all of the relevant costs, it is possible to compare alternative scenarios using such financial concepts as net present value (NPV) and equivalent uniform annual cost (EUAC). This analysis, as in the HAL analyses, assumes steady-state conditions. The ages of all components are assumed to be uniformly distributed and at steady-state. The track work is thus spread out evenly over time. Therefore, the discount rate for EUAC calculations is not a factor.

The track costs are calculated in terms of EUAC / mile at a first level in this analysis. These EUAC / mile calculations are converted to EUAC / 1000 NTM. The cost per net ton-mile calculations are further decomposed into EUAC per 1000 NTM of "total traffic" (coal plus other tonnage) and EUAC per 1000 NTM of "coal traffic only". The cost per 1000 NTM of "total traffic" was used to get the *average* track cost for all traffic (coal and other) for the base cases.

The track cost for scenarios that differed from the base cases were measured in terms of *incremental* track costs. Since only the coal traffic was modified between any two scenarios, any change in track costs was solely due to the changes in the coal traffic operations. All of the change in track costs should therefore be allocated to the coal traffic. The *difference* between the cost per 1000 NTM of the "coal traffic only" cases therefore captures the total track cost *change*. Therefore, the *differential* between the "coal-only" cost allocation for a specific scenario and the "coal-only" cost allocation of the respective base case was used to calculate the appropriate cost per 1000 NTM of "total traffic" for the alternative scenario. This was accomplished by adding the "coal-only" cost allocated *differential* to the base case *average* track cost value.

The fixed cost and variable cost components of total track costs are extremely difficult to separate. Although calculating track costs per 1000 NTM of total traffic and then equating that value to the cost per net ton of both coal and other traffic is incorrect, this method is much easier than any other alternative. Separating the variable costs of coal versus other traffic and allocating the fixed costs appropriately presents a seemingly insurmountable task laden with many arbitrary cost allocations. Since the equivalent axle load of the coal traffic is higher than the other traffic, this method will underestimate the total costs attributable to coal. However, this method will furnish a result much closer to the "right" value than allocating all of the cost to coal. For these reasons, the total traffic allocation method is used for the base cases and the coal-only allocation differential is utilized to calculate the incremental track costs for each alternative scenario.

5.1.8 UTRAIN Track Maintenance Input Requirements

Given track maintenance requirements, annual hours of track closure were determined in the same manner as that described by Robert and Martland [36]. 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

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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.

5.2 Operating 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 the TRACS model and HALTRACK spreadsheet model approach, as described in Section 5.1. Operating and equipment costs were determined using unit costs from the HAL Phase III economic analysis [37][38] in a similar fashion to the prior Optimal Axle Load study. The cycle time applied in calculating the equipment costs was determined using UTRAIN. An exception to using the HAL results directly was for equipment ownership costs, which are based on the underlying HAL Phase III assumptions [39] and costing technique, the prior Optimal Axle Load study and other material furnished by the AAR. Operating costs are defined here as the sum of train crew costs and fuel costs. Equipment costs are considered as the sum of locomotive ownership and maintenance costs and car ownership and maintenance costs. The total variable cost, excluding bridges, is the sum of the track maintenance, operating and equipment costs. Fixed costs were not considered in this study.

In previous HAL analyses, operating (i.e. non-track) costs were calculated for the following categories: train crews, locomotive ownership, locomotive maintenance, car ownership, car maintenance, and fuel. These same cost categories were used in this analysis. The basic approach of this study was to use unit costs derived from the East and West 112-ton car length-limited cases for all of the respective Eastern and Western network cases. Specific HAL III parameters, such as train consist, vehicle characteristics, cycle time, traffic volume, et cetera, were used in constructing the unit costs. The unit costs were defined in different terms for each cost component; each unit cost was defined in terms of a cost-driving parameter that was felt to have the most direct impact on the cost category under consideration. For example, fuel costs were felt to vary most directly (and in a linear fashion) with gross ton-miles, ceteris paribus. Using the fuel cost per net ton-mile results of the East and West 36-ton HAL Phase III cases and the percentage of gross tons that net tonnage represented in the 36-ton HAL cases, the implicit East and West HAL III fuel cost per gross ton-mile could be calculated.

The 36-ton length-limited HAL III cases are the most closely related cases to the alternatives considered in this study. Hence, the East and West 36-ton length-limited cases were used to determine the unit costs unless otherwise noted. This even applies to the 39-ton and 42-ton axle load cases, adjusted accordingly

with respect to car costs, in order to remain consistent throughout the analysis. The weight-limited sensitivity analysis cases of course use the weight-limited results, and the historica. AL comparison of course uses the respective HAL results for each case. The following paragraphs detail the specific assumptions made in applying the unit costs for each category from the HAL Phase III analysis.

5.2.1 Operating Costs

5.2.1.1 Train Crew Costs

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 [37][38], in the same fashion as the "Optimal Axle Load Study". Crew costs are almost invariant with train size and weight; therefore, the crew cost per net ton-mile is minimized by maximizing the net load per train [2]. The limits on train size for most North American bulk train services is set either by maximum allowable drawbar force or by maximum allowable train length due to yard track and passing siding lengths. Car size (axle load and length) can effect crew cost per net ton-mile in both situations although the effect is larger in the length-limited situation.

5.2.1.2 Fuel Costs

Fuel costs were assumed to vary as a function of gross ton-miles. The fuel cost per gross ton-mile was calculated from the HAL Phase III data [37][38] in the same fashion as in the "Optimal Axle Load Study". In bulk train service, the primary determinant of fuel consumption per net ton-mile on a given route is the gross train weight per net ton [2]. Holding other factors constant, the higher the net-to-tare ratio, the less fuel consumption per net ton-mile. Fuel costs therefore improve only with the train net-to-tare ratio, and not with a decrease in the number of trains. An alternative with a fewer number of trains hauling more net tonnage each with the same overall net-to-tare ratio will have the same total gross tonnage hauled over the same network mileage. In other words, the alternative gross ton-mile level will equal the base level.

5.2.2 Equipment Costs

5.2.2.1 UTRAIN Analysis

The analysis of network operations, in order to attain cycle time estimates for the equipment ownership costs, was performed using UTRAIN. UTRAIN [9] 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.

5.2.2.1.1 UTRAIN Background

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. UTRAIN is designed to simulate the operations of a unit coal train network and test the effects of different operating scenarios and control strategies. A simulation model is a very powerful tool.

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. The input parameters required for running the model include information regarding the trains, orders, arcs, nodes and events. Running the model provides output detailing train cycle times, equipment utilization, line utilization, and average yard times.

UTRAIN, as a modeling approach that can be used to analyze issues in operations of unit coal train networks, addresses the issues of: large-scale networks, unscheduled operations, medium level of detail, and a general framework. Unit trains operate on networks with many trains traveling to and from many origins and destinations. 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 destinations in a pattern that appears unscheduled compared to other traffic. The modeling approach needed 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. The

modeling approach also needed to be applicable to the unit coal train operations of all North American railroads.

5.2.2.1.2 Role of UTRAIN in the Analysis

For this study, UTRAIN was used to determine the cycle time and equipment requirements for meeting demand for each case studied. The base case cycle time was 3.6 days for the Eastern case and 5.6 days for the Western case. These cycles are consistent with recent experience based upon discussions with officials at several railroads. These cycles are faster than what was used in the prior HAL analyses [37][38]. These analyses used an average velocity of 6 mph in the East and 12 mph in the West in order to calculate car and locomotive ownership costs in terms of dollars per 1000 net-ton miles. These average velocities imply average cycle times of 5.0 days in the East and 9.0 days in the West over the coal networks assumed in this study.

These cycles are also somewhat faster than what was used as the base case in the "Optimal Axle Load Study". The average cycle times of 3.8 days in the East and 5.8 days in the West were used in that study. The cycle times dropped due to a major reduction in the number of trains assumed to be required to haul the base case amount of coal. The level of other traffic was increased substantially and the train net-to-tare ratio worsened slightly – two factors that will increase average cycle times – however, the carrying capacity of a single train (the net weight of a train) increased 8% and the level of gross tonnage remained the same. As a result of the constant gross tonnage assumption across base cases, the differential in the base case net tonnage levels compensates for the drop in train net-to-tare. Also, more significantly, the number of trains required to move the base tonnage level of coal dropped 10% between the two cases due to a switch to 286-kip cars from 263-kip cars for a length-limited train. This major reduction in the number of trains alleviated some of the congestion on the network and thus improved the overall average cycle time.

5.2.2.2 Locomotive Ownership Costs

Locomotive Ownership costs were assumed to vary as a function of the number of locomotive consist-days, which is somewhat different from the prior "Optimal Axle Load Study". The locomotive ownership cost per consist-day was calculated from HAL Phase III data for the East and West 286-kip car cases [37][38]. The prior study assumed locomotive ownership costs to vary as a function of the number of train-days. This approach implicitly assumed that the number of locomotives per train was the same for

that study as the previous HAL analyses. The current approach circumvents this problem and presents a more realistic appraisal of estimated locomotive ownership costs.

Locomotive requirements are proportional to the trailing tons for a specific bulk service over a given route. As in the case of fuel, locomotive costs per net ton-mile are favorably effected by increases in the net-to-tare ratio of the equipment. In order to account for the different power requirements of trains with differing trailing tonnage, the base locomotive consist-day cost was adjusted for the specific loaded train trailing weight of each scenario by a "horsepower multiplier". The incorporation of this multiplier into the analysis had the effect of maintaining a constant level of horsepower per trailing ton across all of the alternative scenarios considered.

A constant level of horsepower per trailing ton is required in order to keep the train handling characteristics constant across all scenarios for comparison purposes. A train with a lower horsepower per ton rating will not be able to accelerate as quickly as a train with a higher rating. This has an adverse effect on line capacity. Since one of the major benefits of the alternative scenarios being considered in this study was their capacity boost, it was deemed desirable to avoid adversely affecting capacity. A simple and generic way to do this was through the use of a horsepower multiplier. The use of the multiplier made it possible to crudely account for increased costs due to the need for more power without identifying how this power would come about. Additional power can come from the use of larger locomotives or more locomotives. The horsepower multiplier provides a generic unbiased approach to calculating a train's power costs without necessarily optimizing the locomotive consist for each scenario, given the multitude of variables affecting this optimization process, such as gradients, curvature, trailing weight, siding lengths, car lengths, locomotive type, locomotive age, operating speed, et cetera.

Use of a multiplier avoids the possibility of possibly artificially making one scenario appear more beneficial than another because its locomotive consist is better optimized for the operating environment and requirements. The base consist is composed of 5 units at the head-end each weighing 200 tons. This resembles three of the six HAL scenarios modeled. One concern highlighted in the prior Optimal Axle Load study was that distributed power might be necessary to handle the heavier trains modeled in that study. This same concern is of relevance in the present study and was addressed with a sensitivity analysis. Section 6.4 describes the concept and motivation for using displaced power and the specific assumptions and methodology used in this study to incorporate a displaced power cost sensitivity analysis.

The multiplier was defined assuming a captive locomotive fleet; the locomotives used on the coal trains in every scenario were assumed to cycle exclusively in the coal service. Thus, the multiplier was defined as a specific scenario's loaded train trailing tonnage in relation to the gondola base case loaded train trailing tonnage. Only the loaded portion of the trips was considered, since power requirements are limited by that portion of the train cycle.

5.2.2.3 Locomotive Maintenance Costs

Locomotive Maintenance costs were assumed to vary as a function of the number of locomotive consist-miles. The locomotive maintenance cost per train mile was calculated from HAL Phase III data [37][38]. The "horsepower multiplier" was also applied to the locomotive maintenance costs. Implementing the multiplier assumes reasonably that larger and/or a greater number of locomotives will cost more to maintain.

This technique is an improvement upon the prior Optimal Axle Load study technique wherein locomotive maintenance costs were assumed to vary as a function of train-miles, implicitly assuming that the size and number of locomotives per train is the same for all scenarios as in the previous HAL study. As a result, the locomotive maintenance costs (as well as the locomotive ownership costs) will not decrease with the number of train sets, as in the previous Optimal Axle Load study. Since the amount of coal hauled across all scenarios is constant, an increase in the capacity per train is off-set by a corresponding decrease in the number of train sets. But an increase in the capacity per train results in a similar increase in trailing tonnage per train, so that the greater power requirement per train (horsepower multiplier) will eliminate any cost benefit from the need for fewer trains. An improvement in railcar, and therefore train, net-to-tare will, however, result in lower locomotive maintenance costs (and locomotive ownership costs) per net-ton miles, since less trailing tonnage (gross tonnage) would be required to move the same amount of goods.

5.2.2.4 Car Ownership Costs

Car Ownership costs were assumed to vary as a function of car-type, box surface area, truck-type, wheel size and coupling system. 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 [4]. In this study, the same approach was used, similar to the Optimal Axle Load study, expect that in the prior study car length played a key role in estimating the car ownership cost for alternative car designs, as opposed to the box surface area. This was a reasonable assumption in the prior analysis since the railcar

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box cross-section remained the same size across all alternatives, whereas in this study, the cross-section as well as the length of the box changes across alternatives.

The car ownership EUAC calculations were based on NPV valuations of investment cash flows in individual cars. The discount rate was assumed to be 10%. A major car rebuild was assumed to be undertaken in year 15 of the car's existence at a cost of $5000, regardless of car-type or characteristics. Car life expectancy was set at 25 years, at which time the car was scrapped. The scrap value of a car depended on the weight of the car body and the weight of the trucks. The trucks were assumed to be mostly made of steel worth $100 / ton, while the car body was assumed to be mostly made from aluminum with a scrap value of $500 / ton. These assumptions are based on the calculations of the "Optimal Axle Load Study".

Car utilization was assumed at 95%, regardless of the scenario considered. Of course the equipment ownership cost per net ton-mile of service depends on the annual utilization of the equipment, with equipment ownership cost being higher for lower utilization levels. All of the above assumptions were kept constant across all of the scenarios considered so that no one car-type would have an unnecessary ownership cost advantage over another.

5.2.2.4.1 Basic Freight Car Purchase Price

The car costs were based on information attained from the AAR [40] and the previous "Optimal Axle Load Study" [1]. The purchase price of a basic 53-foot 100-ton bathtub gondola car was $48,000. A 112-ton gondola was assumed at $49,000 and a 125-ton gondola was $55,000. Basic hopper car purchase costs were $2,000 higher than the equivalent gondola car, accounting for the extra material and labor required to manufacture the bottom-dump doors. Hence, a conventional 53-foot 100-ton open-top hopper was assumed to cost $50,000, while the 112-ton and 125-ton hoppers cost $51,000 and $57,000 to purchase respectively.

38-inch wheels carried a $3,000 premium over 36-inch wheels, and 3-axle trucks carried a $9,000 premium over the conventional 3-piece 2-axle truck. Improved trucks were assumed on all cars as suggested by the HAL Phase III results, unless otherwise noted, at an incremental cost of $2000 per car. This cost magnitude was suggested by the AAR [41]. Advanced suspension, used on cars with a center-of-gravity thought to be above 98 inches, was estimated to cost an additional $4,000 above the base car cost, i.e. twice as much as improved suspension.

5.2.2.4.2 Manual-Discharge Hoppers

An increment of $8,000 above the basic hopper car cost was required for a rapid-discharge unloading system, to account for the additional equipment that must necessarily be fixed onto the car to open and close the doors automatically. The manual-discharge door system is therefore $8,000 less per car.

5.2.2.4.3 Blocked Cars – Fixed Drawbars and Articulated Joints

In cases where blocked cars were used, two factors were taken into account, affecting car ownership costs:

- Car maintenance availability costs
- Car capital costs

The magnitude of the car maintenance availability costs was derived in terms of dollars per car-day from the results of the study conducted by Little and Smith, entitled "Evaluation of Power Distribution, Coupling Systems, and Braking Equipment Alternatives" [25]. Within that study, as with this investigation, costs were assumed to be the same for blocked cars joined by means of fixed drawbars or articulated connections.

Availability costs are incurred whenever one car requires shopping for maintenance because the entire block of cars must be removed from service. To accommodate for such conditions, either additional shop space will be required to quickly return the cars to service, or additional cars will be required to cover the loss of the original cars to the shop.

The estimate for this portion of the operating costs in the Little study [25] is based on the per diem car hire rate, the number of cars in use, and the mean miles between failures for typical cars. A critical assumption for the economics of blocked cars is how reliable they are relative to conventional cars. It is assumed that blocks of cars might be somewhat more reliable than conventional cars due to the reductions in the number of components in the draft system and due to the reductions in the train action forces. In the Little study [25], it was therefore assumed that *each car* is only 67% as likely to fail as a conventional car, although *each failure* causes an entire block of cars to be removed from service. This was consistent

with discussions with managers of a double-stack fleet. In that study, a block of coal cars was assumed to be composed of 10 individual cars.

The additional car maintenance availability cost was found to increase car ownership costs per car-day approximately 9%.

Car capital costs are reduced in cases where blocks of cars are used. Fixed drawbars and articulated connectors are lighter and less complicated than a conventional coupling system. The costs of slackless drawbars and articulated joints for the blocked car configurations of this study are based on estimates of the material and installation of one of these systems versus conventional couplers, as obtained from Little's study [25]. The installed cost for one drawbar or articulated connection system is assumed to be $2,200, while the cost for couplers, draft gears, and other conventional components was $2,910, for a net savings of $710 per car. The installed cost of the slackless drawbar or articulated connection was assumed to be composed of $1,000 for materials and $1,200 for 16 hours of labor. The savings of $710 per car were applied to the base purchase price of the car.

5.2.2.4.4 Car Box Surface Area Adjustment

The purchase price of the car, adjusted for the type of car as outlined above, was further adjusted for the box surface area. The maximum interior length and width and cubic capacity were known for each scenario. Thus, the average interior height could be calculated. The purchase price of the car was adjusted proportionally by the interior box surface area in relation to a base car. The four base cars considered were the 53-foot 112-ton gondola, 53-foot 112-ton hopper, 53-foot 125-ton gondola and 53-foot 125-ton hopper. Interior box dimensions were used as opposed to exterior in order to accommodate changes in cross-section utilization. The extreme exterior dimensions of the cars considered in the cross-section utilization sensitivity analysis did not change, but the interior box dimensions did in order to accommodate more lading in a given cross-section. The average inside height was adjusted to account for changes in the level of cross-section utilization.

A cube is the most efficient 6-sided vessel with respect to minimal surface area. Therefore the higher, wider and thus shorter a car is, the less surface area is required to contain the lading. Also, as the length of a car decreases, its net-to-tare ratio will most likely improve, even holding gross vehicle weight constant, since additional height and width of an aluminum box weighs much less than the heavy longitudinal support structure forgone that supports the car structure. Due to this net-to-tare improvement

the total number of cars required to move the same amount of lading is constant. In other words, the reduction in the number of trains required for a service more than compensates for the increase in the number of cars per train, assuming that the net-to-tare ratio improves. Thus, overall, equipment ownership costs will improve with alternative shorter freight cars.

5.2.2.5 Car Maintenance Costs

Car Maintenance costs were assumed to vary as a function of axle load, the number of car-miles, truck type and coupling system, which is slightly different from the prior Optimal Axle Load study. The prior study assumed car maintenance costs to vary as a function of axle load and car-miles only. The base 36-ton gondola car maintenance cost per car-mile was calculated from HAL Phase III data [37][38] using the East and West 286-kip car cases for the respective Eastern and Western coal networks.

The largest components of car maintenance costs include wheels, trucks, brakes and the coupling system and draft gear [41]. Since adjusting the car length does not in itself affect any of these car components, changes in car length were assumed to not affect the car maintenance cost per net ton-mile. The maintenance cost 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 assuming a linear relationship between car maintenance costs per net ton-mile and maximum allowable axle load.

Costs for cars with 3-axle trucks were assumed to be 50% higher than costs for cars with 2-axle trucks. Trucks with 38-inch wheels were assumed to have the same maintenance cost per net ton-mile as 36-inch wheels due to a lack of better data depicting otherwise. Alternatives using cars with advanced suspension truck systems beyond the improved suspension trucks of the base gondola case were assumed to have identical car maintenance requirements and costs per net ton-mile given a lack of information supporting the contrary. Another shortcoming of this analysis due to the lack of equipment costing data is that the car maintenance cost per car-mile for a hopper car was assumed the same as a gondola car. The added complexity of a hopper car with all of its additional equipment and moving parts should make it a more expensive car-type to maintain. This is especially true for automatic rapid-discharge hopper car design.

5.2.2.5.1 Blocked Cars – Fixed Drawbars and Articulated Joints

The use of blocked cars (i.e., permanently-coupled cars) is another approach currently in use to eliminate the slack inherent in a train of typical freight cars. The major to the use of such devices, such as fixed

drawbars and articulated joints, is that the block of cars moves as one unit. With the use of blocked cars, the effective number of cars in a train is reduced. This change has the effect of reducing the accelerations and forces seen by the cars. Car maintenance costs are therefore affected favorably by the decreased demands placed upon the freight car longitudinal load environment. The results of the "Evaluation of Power Distribution, Coupling Systems, and Braking Equipment Alternatives" study conducted by Little and Smith [25] were used to derive the car maintenance cost savings in terms of dollars per car-mile for both fixed drawbars and articulated joints. Their study did not discern between the two types of blocked car designs.

Operating savings that may accrue due to maintenance reductions were broken into two parts in the prior study [25]:

- Savings due to components that have longer maintenance intervals due to the reduced force environment
- Savings due to the use of slackless drawbars or articulated joints in lieu of a conventional coupling system

In the first category of car maintenance savings, the force reduction is reflected in extensions in the life of certain components of the draft system: sills, couplers, and draft gears. More specifically, the characteristic life of each component is predicted to grow based upon the relative improvement in the force environment over the base conventional coupler case. In the case of the car sill, the characteristic life was represented by the interval between successive repairs to the sill.

In the second category of car maintenance savings, the reductions in maintenance spending due to the use of blocked cars were captured. When cars are permanently coupled with slackless drawbars or articulated connectors, the number of components in the draft system is effectively reduced. Hence, fewer couplers and draft gears (which are the components that require significant maintenance attention) need to be maintained. Savings are based on the number of repairs that were likely to occur had the base conventional coupler case been in force but were avoided due to the use of a permanent coupling system.

The savings due to removed parts were found to be more than an order of magnitude greater than the savings due to reduced forces. In all, the savings were found to reduce car maintenance costs per car-mile by approximately 16%.

CHAPTER 6: IMPLEMENTATION ISSUES

There are some serious implementation issues that must be investigated and resolved before any alternative car designs can be adopted. Depending on the nature of a specific alternative design, the incremental costs associated with the practical implementation of the new equipment must be weighed against the incremental operating benefits offered by that equipment in order to gauge total costs. Four major implementation issues are identified and discussed, including:

- Clearances
- Bridges
- Loading and unloading facility modifications
- Displaced power operating practices

Within this chapter, the implementation issues are outlined and explained and their impact on costs is discussed and estimated. The relative importance of each impediment to the implementation of optimal car design is included in Chapter 7, by means of implementation cost comparisons with benefit estimates. These issues are very route and site specific and highly dependent upon the exact equipment parameters. This discussion and investigation serves only as a rough indicator of the practical implementation issues involved in a search for a more optimal car design. Further analysis of these issues is a certain necessity for more specific definitions of "optimal car design."

6.1 Clearances

6.1.1 Overview

Clearance limits dictate the height and width of railroad equipment. Allowable vehicle cross-sectional dimensions are a function of the territory that the equipment will operate over. Limits are typically

imposed by parallel track centers, tunnels, bridges, sharp curves, and the proximity of buildings and other fixed structures to the right-of-way. Higher clearances increase track capacity, since more tonnage can fit on a track of a given length. Higher clearances also improve efficiency and productivity by allowing increases in net train capacity and thereby lowering operating costs.

Two important dichotomies exist which must be recognized in order to fully understand the railroad clearance vehicle design issues:

- Infrastructure (engineering) clearance limits versus vehicle (mechanical) clearance limits
- Minimum physical clearance standards and limits versus actual existing physical clearances

The maximum railcar dimensions must fit within the mechanical clearance requirements which, in turn, must fit within the right-of-way clearance dimensions. Moving rail vehicles are subject to dynamic forces and safety concerns, therefore the maximum dimensions of a car must fit within a dynamic clearance envelope that provides considerable buffers to account for the dynamic forces inherent in a railroad operating environment and for operational safety. Reducing dynamic movements or the required tolerances between the static and dynamic vehicle clearance envelopes and the vehicle and infrastructure clearance requirements are two ways of increasing vehicle cross-section dimensions without affecting way-side infrastructure.

Current clearance practices and standards do not necessarily dictate the reality of the railroad operating environment. Railroads have been constructed in North America since early in the 19th century. The clearance standards that existed at the time of the construction of many lines were much more restrictive than the current practices. Older facilities, structures and right-of-ways are strewn with many obstructions to the use of higher or wider rail equipment.

Railroads maintain tables of clearances for lines. Many routes can accommodate "high / wide loads" to varying degrees. With the widespread implementation of double-stack intermodal train operations since the mid-1980's, vertical clearances are now quite well-known across the U.S. rail network; however, horizontal clearances are often far from detailed, up-to-date or accurate in many cases, given the Herculean task of maintaining such a database. A detailed inventory of horizontal clearances would necessarily be needed for areas where increased vehicle widths (increased loading gauges) were under consideration.

Methods for improving clearances include [42]:

- Lowering the track
- Raising overhead bridges or replacing bridge components
- Realigning track
- Modifying the track superelevation on curves
- Trimming or removing rock cuts
- Relocating lateral obstructions, such as signals, signs, train sheds, hand rails, et cetera
- Stabilizing the roadbed
- Rebuilding or modifying an obstruction
- Completely removing an obstruction

The methods actually utilized for improving clearances, of course, depend on the extent of the improvement and the economics of the alternatives for each specific instance. The economic implications of improving clearances can be very profound and are very site and route specific.

6.1.2 Engineering Clearance Background

The clearance diagrams for fixed obstructions generally provide for 18 feet of width and 23 feet of height, as dictated in the American Railway Engineering Association's (AREA) (now called the American Railway Engineering and Maintenance-of-way Association, or AREMA) "Manual for Railway Engineering" [42]. These clearances are for tangent track and new construction. Clearances for reconstruction work or for alteration depend upon existing physical conditions, but are improved to meet the requirements for new construction where reasonably possible. Near or on curved track sections, the lateral clearance each side of the track centerline is increased in order to compensate for railcar over-hang. In some instances, state laws or individual railroads require greater clearances than the AREMA recommended minimums. Separate clearance diagrams are provided for tangent track, bridges, tunnels, double-track tunnels, side tracks and industrial spurs.

There are many legal clearance requirements for individual states that are more restrictive than the AREMA clearance standards [42]. Legal minimum mainline track centers (the distance between the centerlines of two adjacent tracks) vary from 13 feet to 15 feet. A minimum of 13 feet exists in Canada,

Connecticut, Massachusetts and Rhode Island. Track centers as narrow as 11 feet 6 inches exist in Nevada and Utah for team tracks in pairs and unloading tracks at platforms. Minimum vertical clearances range from 18 feet to 23 feet 6 inches above the top of rail. The most restrictive instances are 18 feet in Rhode Island, 20 feet 9 inches in Oregon and 21 feet in New Hampshire, North Dakota and Ohio. Building doors and within buildings, 17 – 18-foot vertical clearance minimums are commonplace. Horizontal clearance minimums range from 8 feet to 8 feet 6 inches from the centerline of track, except in Texas where a minimum of 7 feet 6 inches is allowable through bridges. Building doors and within buildings, a horizontal clearance minimum of 7 feet is common. Other clearance considerations include platforms, signals, poles, mail cranes, icing docks, ore and coal loading docks and cattle chutes.

6.1.3 Mechanical Clearance Diagram Background

Over the years the rail industry has recognized the need for increased clearance envelopes, since higher, wider and shorter cars are more economical to operate [43]. The industry has moved on from the initial Plate B clearance envelope by adding Plates C, E and F. Today, cars are built and operated that exceed even these clearance limits, such as double-stack container cars, which correspond to a Plate H diagram for the most part.

The Plate B equipment diagram for unrestricted interchange service was first adopted by the industry in 1948 [43]. This diagram was intended to limit the size of equipment being manufactured so as to avoid interference with any existing or new fixed obstructions in the rail system. In 1963 the industry recognized that many of the previous fixed obstructions had been removed and/or were only a small percent of the total U.S. railroad right-of-ways. The industry therefore decided to provide a larger clearance envelope. At this time, railroads were identified where some interference to this less restrictive diagram existed. It was found that ninety-five percent of the total track mileage could accommodate vehicles built to this enlarged Plate C equipment diagram.

Figure 6-1 depicts the Plate C equipment diagram for limited interchange service as taken from the AAR Mechanical Division's "Manual of Standards and Recommended Practices" [24]. The following major changes were made from Plate B in the establishment of the Plate C diagram [43]:

- Height increase to 15 feet 6 inches from 15 feet 1 inch
- Criteria for reducing the vehicle width, either at the center or at the end overhang, established at 46-foot 3-inch versus 41-foot 3-inch truck centers

The results of these modifications allowed for the construction of higher and wider cars, and thus provided improved economies and productivity.

The basic principle behind reducing the extreme width for vehicles with truck centers in excess of a certain distance is to limit the swing-out that occurs on a curve for a particular clearance envelope [43]. Plates B-1 and C-1 define the maximum allowable car width given the truck center spacing that both respective Plates are able to accommodate. Beyond a certain base car truck center distance, the 10-foot 8-inch maximum car width must be reduced so that the base car has the maximum allowable swing-out for that particular clearance envelope. For example, in the Plate C diagram, a car with a 46-foot 3-inch truck center will swing-out 7¼ inches on a 13-degree curve. For cars designed to this clearance diagram with truck centers less than 46 feet 3 inches, no reduction is required. For truck centers over 46 feet 3 inches, width reductions are required so that the maximum swing-out of 7¼ inches is not exceeded.

With the introduction of hi-cube boxcars for automotive service and cars to haul lightweight appliances in the 1960's, additional Plate diagrams were developed [43]. At first these cars were manufactured with an understanding that they exceeded Plate C and were handled on interline agreements. Eventually Plate E was developed for these cars, which changed the conventional Plate C equipment diagram in the following ways:

- Height increased to 15 feet 9 inches versus 15 feet 6 inches for Plate C
- Upper corners of the diagram were flattened out considerably and the central portion at the top of the diagram was modified

These changes accommodated higher cars. In 1974, Plate F was adopted with the incorporation of the following changes [43]:

- 17-foot height versus 15 feet 9 inches for Plate E and 15 feet 6 inches for Plate C
- Further modifications to the upper corners in order to avoid some critical fixed obstructions

Both Plates E and F retained the Plate C width requirements.

Since 1974 a major significant change came with the introduction of double-stack intermodal train service. Double-stack container cars far exceed Plate F both in height and at the lower corners. Plate H

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was devised as the equipment diagram for double-stack container cars in controlled interchange and other limited interchange service [24]. The following major characteristics differentiate Plate H from the previous Plate diagrams:

- Extreme height of 20 feet 2 inches
- Extreme width of 9 feet 11 inches versus 10 feet 8 inches
- Much more "full" corners at extremities

Note that most of the modifications to Plate C have dealt with height. No adjustments to the clearance diagrams have challenged the extreme width constraint of 10 feet 8 inches.

6.1.4 Alternative Car Design Issues

In recent times, emphasis has been placed on increasing vertical clearances to accommodate such vehicles as tri-level auto racks and double-stack container trains. Modifications to bridges and tunnels for additional height allowances has become more and more expensive with increasing height. Trying to increase vertical clearances above 22 feet would bring about a whole new order of magnitude of expense, since most bridges and tunnels were built to the standard height clearance around 22 feet which has existed most of the 20th century [44]. With respect to coal, however, car height is not so much a clearance issue, as it is a center-of-gravity issue, due to its high density characteristics on the order of 55 pounds per cubic foot [45].

Increasing vehicle width poses as an intriguing, yet potentially complicated and expensive, proposition. If the inside width of an auto-carrying car were twelve feet or more, many autos could be shipped two-abreast, doubling the capacity of auto-haul rail cars [44]. More economical coal and grain cars could be built, since the frame would not have to span such a great distance between trucks for a given capacity. Greater width could also allow centers-of-gravity to be lower, which provides an improved ride performance.

Wider loading gauges beyond the current 10-foot 8-inch Plate C limit are technically feasible. The new cars for the English Channel Tunnel Shuttle have an exterior width of 13 feet 1½ inches and operate at speeds in excess of 80 miles per hour on standard gauge track [44]. In South Africa, trains run on narrow gauge track, but the loading gauge is wider than in Britain, where standard track gauge is used [46]. Railways with gauges narrower than standard use equipment much wider in proportion to their track

gauge than in North America. Equipment three times and more as wide as the gauge is common on such lines, and was common on U.S. and Mexican narrow gauge lines when they existed [44]. Three times standard 4 feet 8½-inch track gauge is a 14-foot 1½-inch loading gauge.

Very few bridges or tunnels have horizontal dimensions less than 14 feet, with most being about 16 feet [44]. Three major horizontal clearance problems do exist with respect to coal traffic:

- Track centers
- Loading and unloading facilities

Track centers are probably the most important impediment to the use of wider cars. While track centers under 13 feet are relatively unusual, 13-foot 6-inch and 14-foot track centers are common [44]. Most new construction involves track centers of at least 15 feet.

Vertical clearance issues for coal cars might exist at loading and unloading facilities, and certainly exist for rotary dumpers for any extensions outside of Plate C.

In the mountainous coal-producing Appalachian region, NS has many small tunnels and extensive stretches of 13-foot track centers that could seriously hinder any but the most incremental car width increases [47]. Any proposed width increases could cause "ultimate havoc" on CSX's entire rail system [48], as claimed by one individual. Maximum clearance is at best 15 feet between track centers and often is 14 feet and even less. Some adjacent passing and storage tracks are located only 12 feet from mainline track center. Most loading facilities on CSX were designed with an 8-foot horizontal clearance from the centerline of track as the standard. Despite these apparent obstacles to increasing loading gauge, most of both NS's and CSX's systems allow for a loading gauge of 11 feet before it is required of a customer to alert the respective Clearance Bureau [49][47]. This is 4 inches more horizontal clearance than is allowable under Plate C restrictions.

Overall, it appears that it may be possible to increase loading gauge incrementally on the order of ½ foot without incurring any line clearance costs. Increases of 1 foot or even 1½ feet may be possible with little expenditure in many instances. An issue with wider cars may exist at the loading or especially at the unloading sites.

PLATE C

EQUIPMENT DIAGRAM
FOR LIMITED INTERCHANGE SERVICE

Standard

S-2028-91

Adopted 1963, Revised, 1965, 1966, 1967, 1991

UNRESTRICTED ON ALL ROADS EXCEPT ON CERTAIN ROUTES, FOR SPECIFIC RESTRICTED AREAS ON SUCH ROADS SEE "RAILWAY LINE CLEARANCES".

LIGHT CAR CONDITIONS

CARS MAY BE CONSTRUCTED TO AN EXTREME WIDTH OF 10'-8" AND TO THE OTHER LIMITS OF THIS DIAGRAM WHEN TRUCK CENTERS DO NOT EXCEED 46'-3" AND WHEN, WITH TRUCK CENTERS OF 46'-3", THE SWINGOUT AT ENDS OF CAR DOES NOT EXCEED THE SWINGOUT AT CENTER OF CAR ON A 13° CURVE; A CAR TO THESE DIMENSIONS IS DEFINED AS THE BASE CAR.

WHEN TRUCK CENTERS EXCEED 46'-3", CAR WIDTH FOR ENTIRE CLEARANCE OUTLINE SHALL BE REDUCED TO COMPENSATE FOR THE INCREASED SWINGOUT AT CENTER AND/OR ENDS OF CAR ON A 13° CURVE SO THAT THE WIDTH OF CAR SHALL NOT PROJECT BEYOND THE CENTER OF TRACK MORE THAN THE BASE CAR.

MAXIMUM CAR WIDTHS FOR VARIOUS TRUCK CENTERS, AT CENTER OF CAR, ARE SHOWN ON PLATE C-1. MAXIMUM CAR WIDTH AT LOCATIONS OTHER THAN CENTER OF CAR ARE SHOWN ON PLATE D.

CARS WITH RAIL LOADS IN EXCESS OF 65,750 LBS. PER AXLE CANNOT BE OPERATED IN UNRESTRICTED INTERCHANGE. HOWEVER, THEY MAY BE PERMITTED UNDER CONTROLLED CONDITIONS WHERE SPECIAL AGREEMENT HAS BEEN REACHED BETWEEN PARTICIPATING RAILROADS TO SO HANDLE.

THE 2-3/4" ABOVE TOP OF RAIL IS ABSOLUTE MINIMUM UNDER ANY AND ALL CONDITIONS OF LADING, OPERATION, AND MAINTENANCE.

Figure 6-1: Plate C Equipment Diagram for Limited Interchange Service

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6.2 Bridges

6.2.1 Overview

Railway bridges are a critical link in the U.S. rail network. Maintenance and replacement of railroad bridges costs millions of dollars each year in direct expenses related to repair, restoration and replacement of bridges, as well as, indirect costs resulting from disruption of transportation services [50]. There are more than 100,000 bridges in the U.S. and Canada combined, with 1,270 miles of track on these bridges. This number includes multiple tracks on the same structure.

Railway bridges may be classified under four categories corresponding to the principal material of construction [51]:

- Steel
- Timber
- Masonry
- Concrete

The majority of the structures are steel bridges, which make up 58% of the total track mileage located on bridges [50]. Steel bridge types include pinned trusses, riveted trusses, plate girders, deck girders and through rolled beam trestles. 28% of the bridge track mileage is made of timber. Timber structures are primarily of a trestle design. The remaining 14% of all bridges are masonry and concrete. These types of bridges can be arches, rigid-frame, slab bridges or concrete girders in design.

Steel structures comprise the most significant portion of the North American railroad infrastructure and have therefore been the subject of many recent studies. There are over 600,000 linear feet of steel truss railway bridges alone in the United States [50]. Most of these were built more than 70 years ago. There are also tens of thousands of girder bridges, many of which were built near the turn of the century.

In studying the impacts of alternative car designs on bridges and the bridge cost ramifications, it is important to note that bridges can be a very complicated part of a costing analysis. There are many different kinds and lengths of bridges, bridges last a long time and the replacement costs of bridges are high [53].

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A bridge may last 100 years or more (the oldest railroad bridge in the U.S. is a stone masonry structure in Baltimore that was built in 1829), depending upon its design and the traffic it carries [53]. If a bridge is to carry heavier loads, it may need to be replaced earlier, or it may need more frequent replacement of certain bridge components. Some bridges might be in good condition, but are operating at or near their maximum load rating. Before increasing the size and weight of railcars or trains, it would be necessary to replace these bridges.

The key to an alternative car design analysis is to identify the *incremental* costs associated with intensified loading [53]. A marginally safe bridge may need to be replaced immediately in order to accommodate higher loadings, but it may need to be replaced very soon in the future anyway without any vehicle design modifications. The entire cost of this type of replacement should not be attributed solely to the alternative vehicle design. Only the difference in the net present value between immediate replacement and deferred replacement should be attributed to the new railcar design.

6.2.2 Bridge Loading

The excellent safety record of railroad bridges in the U.S. is attributable to the conservative design of late 19th century and early 20th century bridges, which were designed for steam locomotives [51]. By 1940, a steam locomotive and tender combined, weighed about 440 kips, with individual driving wheel axle loads on the order of 70 kips. An impact factor was used in the design of these bridges to account for the "hammer blow effect", arising from the reciprocating parts of a steam locomotive. At times this impact factor gave dynamic loads almost twice as great as the static loads. Diesel-electric locomotives, which brought an end to the steam era beginning in the 1930's, do not have a hammer blow effect.

The current concern for accelerated bridge deterioration, however, is caused by the steady increase in the magnitude of axle loads and linear loading levels resulting from the use of higher capacity cars [51]. Whereas, at the turn of the 20th century, the average capacity of freight cars was merely 25 net tons, the use of 100-ton cars is common today, with a push to introduce heavier cars of up to 125-ton capacity. Moreover, the average number of cars per train has also increased from about 30 in 1900 to on the order of 90+ today. There has clearly been an increase in the magnitude and frequency of load applications on bridges, with a shift from locomotive-dominant to car-dominant loading. The cumulative effect of these repeated loads raises concerns about the faster deterioration of these bridges. The phenomenon of

strength loss due to cyclic loading, at intensities that might be well below the load carrying capacity of a bridge, is called "fatigue."

During the late 19th century, a rapid increase in locomotive loading and the multitude of design specifications used by various railroads necessitated some standardization [51]. In the 1880's, Theodore Cooper, who was a prominent consulting engineer, recommended a system of axle loads representing the heaviest double-headed locomotive of that time, followed by a uniform load, as a standard for live loading specification. The total weight of each locomotive and tender was 213 kips with four driving axles spaced at 5 feet, weighing 30 kips each, followed by a uniform load of 3 kips per foot. This became known as the Cooper E-30 loading – standard live load for railway bridge design as specified by the AREA (now AREMA).

Over the years, this loading was increased by the AREA in order to account for increasing axle loads, and currently stands at E-80, as depicted in Figure 6-2. During the 1956 AREA meeting there was a discussion about reducing the design standards from the E-72 standard of the time to E-50 or E-60 on the basis of the reduced weights of diesel locomotives [51]. Since certain specialized equipment, such as snow plows, wreck cranes and pile drivers were rated higher, the recommended design loading was maintained and eventually increased to E-80 in 1967, where it remains today. Many new bridges are built to higher live load standards than E-80 today.

To put the E-80 live load in a better perspective, each of the locomotives is approximately 53 feet long and weighs 568 kips, with a wheel base of 48 feet. In other words, two Cooper E-80 locomotive units have a total mass of 1136 kips distributed over 104 feet. In comparison, a modern six-axle diesel locomotive weighs 440 kips over an extreme length of 69 feet with 73-kip axle loads as compared to the 80 kips of the Cooper E-80 loading. Similarly, the uniform load of 8 kips per foot could be represented by a train of 39-foot long 315-kip cars, a linear loading of 8,000 pound per foot, which is almost 50% greater than the load induced by standard 53-foot long 286-kip cars. Therefore, the Cooper train (E-80) calls for a much more highly concentrated load compared to the heaviest diesel locomotives and cars in service today.

Within the AAR's Mechanical Division "Manual of Standards and Recommended Practices," [24] there exist weight and axle spacing criteria for cars intended for unrestricted interchange service. Currently, cars are not to be constructed to either dimensions or weights that produce Cooper ratings in excess of E-

66 for 8-foot spans, E-64 for 10-foot spans or E-60 for 12-foot to 400-foot spans. This is due to the fact that many pre-Cooper E-80 bridges still exist across the U.S. railroad network.
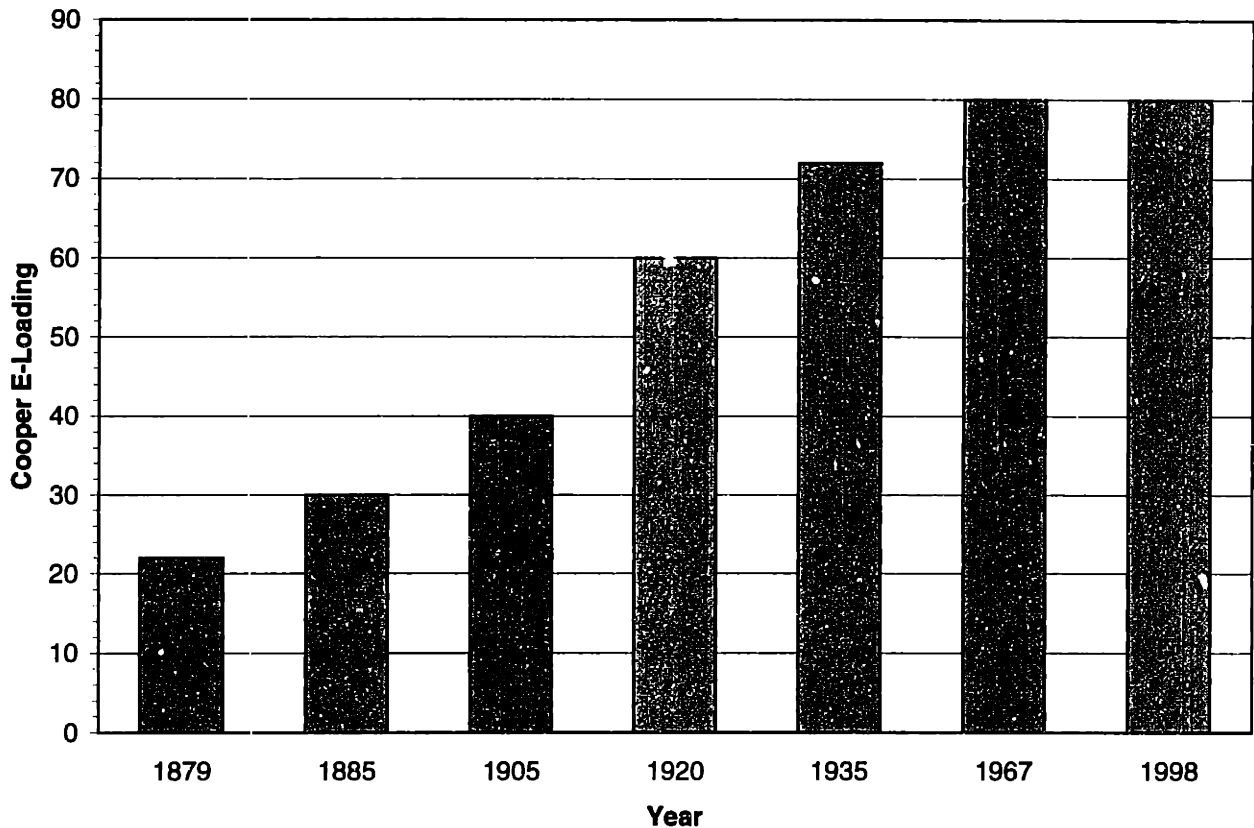
Figure 6-2: AREA / AREMA Recommended Live Load for Bridge Design

6.2.3 HAL Phase II Bridge Analysis

In the AAR's HAL Phase II study, a representative set of bridges was identified by bridge engineers in order to represent the major U.S. and Canadian railroad systems [53]. The AAR's bridge experts selected and analyzed 30 of the bridges to determine the effects of HAL operations on the fatigue lives of major bridge components. Three coal unit train types were modeled [50]:

- 100-ton car unit train with 33-ton axle loads for the loaded cars and a train gross linear load of 5,000 pounds per foot

- 112-ton car unit train with 36-ton axle loads for the loaded cars and a train GLL of 5,400 pounds per foot

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- 125-ton car unit train with 39-ton axle loads for the loaded cars and a train GLL of 5,500 pounds per foot.

The 100-ton and 112-ton car lengths were 53 feet 1 inch and the 125-ton car was assumed to be 57 feet 6 inches long. That is why the GLL of the 125-ton car train is not much higher than the 112-ton car train. The results of this bridge fatigue analysis were then used to estimate the bridge costs for the HAL routes, taking into account the number of bridges of each type (i.e. the absolute number and relative distribution) on each route.

Three types of bridges were found to be potential problems with respect to increasing railcar axle loads [53]:

- Old bridges crossing major rivers
- Pin-connected steel truss bridges
- Old, short steel bridges

The most costly potential problem was related to old bridges that cross major rivers [53]. These bridges could each cost $100 million or more to replace. These bridges appeared to be capable of handling 36-ton axle loads, although some strengthening could be required. More precautions and remedial actions would be necessary for 39-ton axle loads.

Pin-connected steel truss bridges were felt to be a potential safety problem due to the difficulty involved in detecting cracks in the pins [53]. These bridges tend to be older and inspection is very difficult. If a pin breaks, the unfortunate consequence is that the bridge will fail. The general opinion of the bridge engineers involved in the HAL analysis was that these bridges needed to be replaced to handle higher 36 or 39-ton axle loadings. Fortunately, there are not too many of these bridges left in service today.

The problem with short bridges is that they undergo a complete load / unload cycle with every passing car [53]. This accelerates the deterioration of the bridge. Longer bridges will always have one or more wheel set on the bridge, so that an entire train only counts as one single fatigue cycle. This may not be true for individual bridge components, but is certainly true for the entire structure. In recent years, short bridges have generally been made of prestressed concrete members that have been designed to withstand very heavy axle loadings. Therefore, there was not believed to be a problem with younger shorter bridges, only with older ones.

6.2.4 Alternative Car Design Cost Impact

Two factors affect the fatigue life of bridges [52]:

- Axle load
- Axle spacing

The HAL study, which was a pure axle load study, also resulted in linear loading increases. The results of the HAL analysis, however, cannot simply be interpolated or extrapolated in order to determine the effects of pure increases in linear loads [52]. The predicted increases in the fatigue rates of the HAL study were a function of axle loads, not a function of load per linear foot (axle spacing). These two factors affect bridge fatigue very differently. Changing the axle spacing changes the moment and shear forces generated on the bridge span, and therefore change the carrying capacity of the bridge. Closer axle spacing will intensify the rate of fatigue.

Due to the inherent complexity of the bridge issue, an independent analysis of the ramifications of alternative car designs on bridges was not undertaken. Instead, the results of the HAL analysis were applied to the Eastern and Western coal distribution networks in order to determine the benefits of alternative car design. This was done in order to gauge the relative magnitude of the incremental HAL bridge effects in relation to the incremental benefits of alternative car design. Even though the results obtained from axle load increases are not directly applicable to the expected results from axle spacing decreases, this exercise at least gives an idea of the relative magnitude of the bridge problem. One notable bridge expert suspects that a decrease in the axle spacing of cars will not pose as serious an issue as an equivalent increase in the axle load of cars [52].

The bridge cost results of the HAL Phase III analysis were quoted in terms of dollars per 1000 net ton miles [37][38]. These cost values were adjusted to a cost per mile basis, using the HAL III assumptions [30]. Since the base case hopper and gondola cars of this alternative vehicle design study have 36-ton axle loads, the incremental cost differential between 36-ton and 39-ton axle loads was taken from the HAL results to represent the incremental cost of interest. This cost differential represents a 10% axle load increase. 5% of the incremental bridge cost in the East was for timber bridge work and 95% was for steel bridges. 32% of the incremental bridge cost in the West was attributable to timber bridges, with the

remainder being for steel structures [37][38]. This great difference between the East and West is due to the fact that bridge costs are highly route and regional-specific.

The average cost per mile estimates for both the East and the West were applied across the respective networks and adjusted for the total network traffic level in terms of net ton miles. The East HAL route carried 30 MGT of traffic per year, while the West HAL route carried 80 MGT. Most of the trackage in the distribution networks has a line density below the respective HAL route. This might result in lower average bridge costs on lower density lines, since bridge work that does not need to occur immediately may be further deferred. A very conservative approach was taken; however, in that the average bridge cost was kept constant across all line segments within a network, regardless of traffic density. In the most extreme case, safety concerns might require bridge upgrades for linear load increases regardless of the level of traffic density. Also, many of the alternative car designs exceed the maximum design loads of bridges built before 1920 or so.

The incremental bridge cost estimates attained for the Eastern and Western coal distribution networks for a 10% axle load increase from the base case were:

- $0.160 / 1000 NTM in the East
- $0.114 / 1000 NTM in the West

If the incremental costs are the same for increasing axle loads as they are for decreasing axle spacing, these incremental costs would apply for a 10% car GLL increase, from 5,390 pounds per foot to 5,930 pounds per foot (a Cooper E-59 rating). This estimate is felt to be quite conservative and could actually be much lower.

6.3 Loading and Unloading Facilities

6.3.1 Overview

Rail equipment is inherently intimate with the loading and unloading operations to which it is subjected. The loading and unloading facilities where the activities are performed are specially designed to accommodate the running equipment in an efficient and productive manner. Changing the dimensions of coal cars could require modifications to existing coal loading and unloading facilities. Major alterations to many rotary-dump unloading facilities would be required at a fairly considerable expense. A study by

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Robert for the AAR, entitled "Coal Rail Car Size Constraints at U.S. Electric Utilities," identified the effects of potential changes in coal rail car dimensions on U.S. electric utilities' coal unloading facilities [54]. Robert interviewed dumper manufacturers and surveyed electric utilities in order to compile the information for the study. His conclusions are outlined and utilized here in order to estimate the implementation costs in relation to the incremental benefits of alternative car designs.

6.3.2 Loading Facility Background

Loading facilities have been designed to load unit coal trains quickly and efficiently. The state-of-the-art facilities load trains at a rate of 3,000 – 4,000 tons per hour based on technology developed in the 1950's and 1960's [9]. In the Western U.S., especially in the Powder River Basin of Wyoming and Montana, most loading facilities can handle an entire 100+-car train at once, loading the train in motion in 3 - 4 hours. At older facilities, primarily in the more mountainous Appalachian region of West Virginia and Kentucky in the Eastern U.S., fewer cars can be handled at once, and loading typically requires 20 – 24 hours.

Figure 6-3, compliments of Robert [9], depicts a typical coal loading facility. After coal is mined it is placed in a silo that regulates the flow of the raw mine run into a processing facility. After processing, the coal is moved by means of conveyor belts and possibly a stacking tower to either an open storage pile or enclosed storage silos. The coal is moved again by belts to a surge bin for weighing and flow regulation. Ultimately, the coal is loaded into trains through a chute from the surge bin above.
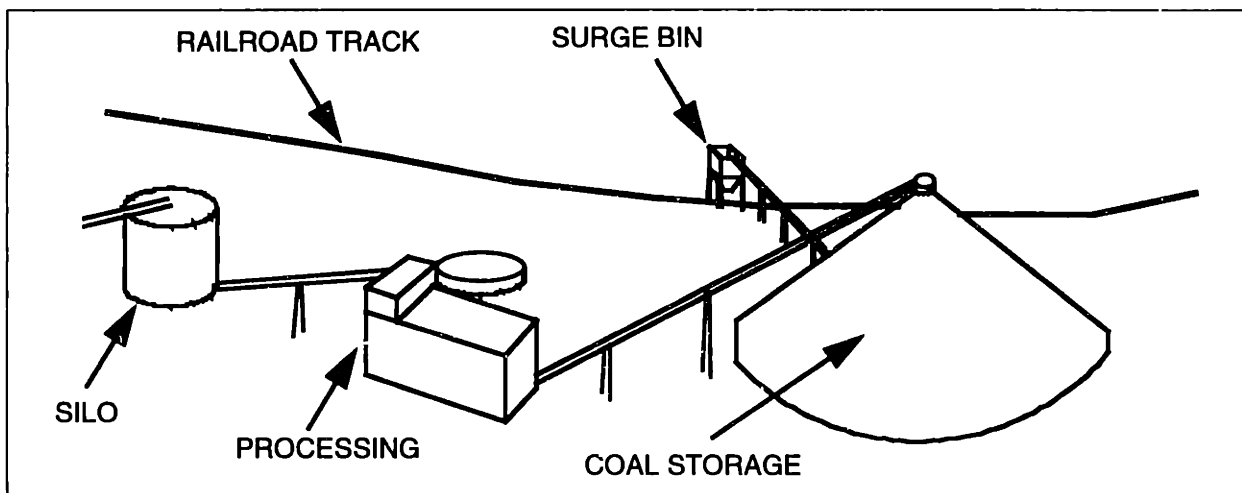
Figure 6-3: Typical Unit Coal Train Loading Facility

6.3.3 Unloading Facility Background

The two basic techniques for unloading coal trains are:

- Bottom dumping
- Rotary dumping

In bottom dumping, the discharge doors on the bottom of the hopper cars are opened as the cars pass over a pit or hopper bin while in motion. Alternatively, the train may pass over a trestle, dumping the coal from the cars onto a conveyor belt below. Only hopper cars may be bottom dumped.

In rotary dumping, gondola or hopper cars are rotated either one at a time or in groups, at an angle of up to 180 degrees, unloading through the top of the car into a pit or hopper. There must be at least one rotary coupler between each pair of cars in order to rotate them in this fashion.

There are two techniques used for rotary dumping:

- Random car
- Unit train

When a random car dumper is used, individual cars are decoupled from the train and positioned into the dumper. After cars are dumped, they pass through the other side of the dumper and are recoupled to the train.

When a unit train dumper is used, cars are not decoupled. Instead, each car is equipped with one or two rotary couplers, and can be dumped without the need for decoupling them from the rest of the train.

Typically, unloading hopper cars moving on a trestle requires 30 seconds per car, a rate of approximately 12,000 tons per hour [9]. If hopper cars are unloaded over a hopper bin, then the unloading rate is usually limited by the "takeaway" system. Typical values are 3,000 – 4,000 tons per hour. Unit train rotary dumping typically requires approximately 2 minutes per car, a rate on the order of 3,000 tons per hour. Typically, the practical unloading rate of a random car dumper is 3 – 4 minutes per car, or approximately 1,500 – 2,000 tons per hour [54].

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 can be a major issue in bottom dumping. It is less of a problem with rotary dumping, so this technique is often preferred in colder climates. Thawing is possible by either attaching steam hoses to specially equipped cars for the purpose of running steam through the coal, or by passing the cars through thaw sheds. Each car typically requires on the order of 90 seconds in a thaw shed, equating to about 20 extra minutes for a typical train [9].

Figure 6-4, compliments of Robert [9], depicts a typical unit train rotary-dump unloading facility. Once dumped, the coal falls into a hopper bin and is carried to a storage pile using conveyor belts via a stacking tower. Note also the tight loop track that the train progresses around, as it is unloaded in preparation for the return back to a loading origin point.
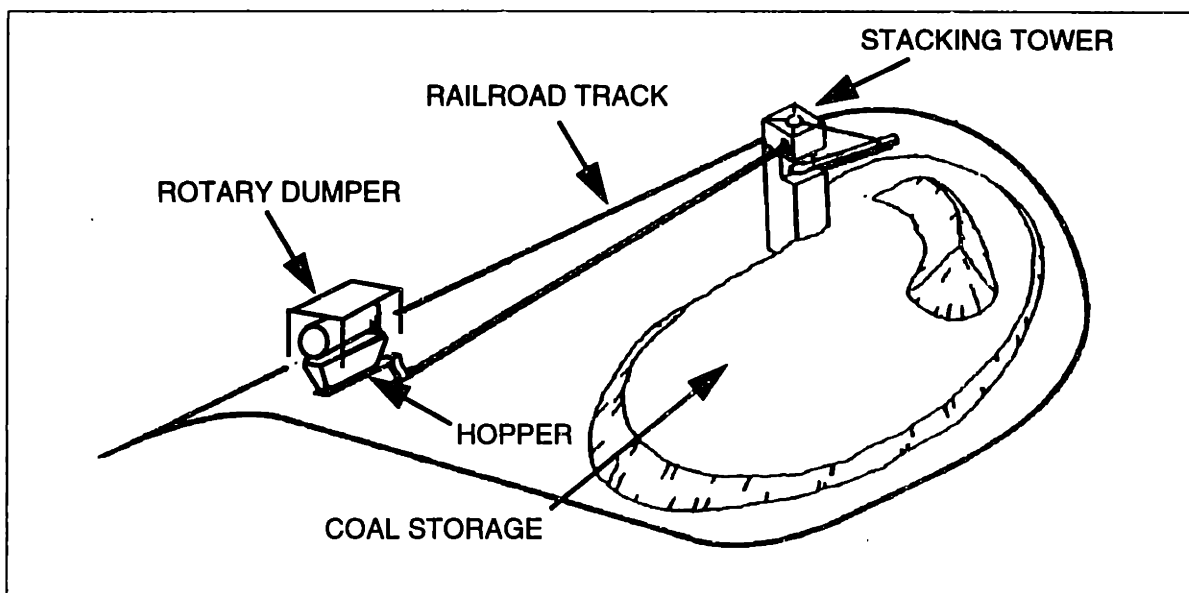
Figure 6-4: Typical Unit Coal Train Unloading Facility

6.3.4 Loading Facility Issues

The cost implications of changing coal car dimensions for loading facilities are very minor. The most likely problematic issue would arise with clearances at the facility. All existing facilities should have been built to at least Plate B standards, with most likely corresponding to the Plate C or E clearance envelope. If any major alteration cost issues were to arise, they would most likely involve height clearances for the surge bin and coal chute.

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6.3.5 Bottom-Dump Unloading Facility Issues

Robert concluded that bottom-dump facilities are not particularly sensitive to car dimensions, and to a first approximation, changes in car dimensions would have only modest cost implications to these facilities [54]. There might be issues with thaw sheds. Typically, thaw sheds are built to accommodate a certain number of cars. Higher or longer cars may not fit into the sheds. If the coal is dumped into a pit, significantly longer or shorter cars may require changes to the pit dimensions. For facilities using loop tracks, there is also a limit to how much longer cars could be in order to negotiate the extreme curvature and remain within clearance limits. For car designs with an extreme increase in linear loading, trestle structural integrity may also be an issue.

Based on Robert's information, an increase in cross-section or reduction in car length is not expected to have significant cost implications for a typical bottom-dump facility [54]. This assumes that the car cross-section would fit within the Plate C clearance envelope and that any reduction in car length would be on the order of 15% or less. An increase in car length would be limited to the allowable car dimensions as governed by typical loop tracks and would require the lengthening of thaw sheds at a typical facility, costing on the order of $0.1 million.

6.3.6 Rotary-Dump Unloading Facility Issues

Robert concluded that both random car and unit train dumpers are sensitive to increases in car length [54]. Random car dumpers are moderately sensitive to reductions in car length and are not particularly sensitive to increases in car cross-section within the clearance envelope. Unit train dumpers, however, are sensitive to both length reductions and cross-section increases.

The essential issue with rotary dumping facilities is that the barrel of the dumper is designed for cars of fixed dimensions [54]. The barrel is the apparatus that rotates the cars. Depending on the type of dumper and the extent of car dimension changes, a change in car dimensions could necessitate:

- Modifications to the car positioning system
- Modifications to the clamps on the dumper barrel
- Modification or replacement of the barrel
- Foundation work to accommodate a longer barrel

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In addition, the issues with thaw sheds and loop tracks are similar to those of bottom-dump facilities, although rotary-dump facilities are less likely to need thaw sheds.

The alteration costs are very scenario and site specific; however, Robert drew some general conclusions regarding the order-of-magnitude of the costs for modifications to typical rotary-dump facilities. These costs are summarized in Table 6-1.

Table 6-1: Cost Estimates for Changes to Typical Rotary-Dump Facilities

Car Dimension Change	Cost by Rotary Dumper Type ($ Million)	
	Random Car	Unit Train
Increase Cross-Section	$0.0	$0.3
Decrease Car Length	$0.3	$2.0
Increase Car Length	$3.0	$3.0

The costs outlined in Table 6-1 are based on approximate costs for basic changes made to typical rotary-dump facilities as provided by the manufacturers and electric utilities [54]:

- Upgrading a facility designed for 263-kip cars to handle 286-kip cars by modifying the car positioning system and car clamps = $0.2 – 0.3 million
- Rebuilding an existing facility by replacing the drive system, barrel, car positioning system and car clamps = $1.5 – 2 million
- New rotary dumper, excluding foundation work = $5 – 6 million
- New rotary dumper, including foundation work = $7 – 8 million

The effects of changing car dimensions are very different between random car and unit train dumpers [54]. Random car dumpers can usually accommodate cars of varying height and width, up to a specified clearance envelope, typically Plate C. If the car weight is increased significantly, the drive system may need to be upgraded or replaced. Decreasing car length may require changes to the facility's positioning system, but the dumper barrel of a random car dumper is typically able to handle shorter cars. Increasing car length would require significant changes to random car dumpers, as it is not feasible to allow cars to be dumped with ends extruding from the dumper barrel. At a minimum, the barrel would need to be lengthened or replaced. Typically, foundation work would be required to increase the length of the pit underneath the dumper.

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Unit train dumpers, in contrast to random car dumpers, can accommodate cars with different cross-sections only with changes to the clamps that hold the cars in place as the barrel rotates [54]. Increasing or decreasing car length would certainly require changes to the dumper barrel and positioning system, since cars are not decoupled for unloading. The barrel must necessarily match the length of the car. Additional work would be required to correct for the fact that the shorter barrel would be smaller than the span of the pit, in the case of a car length decrease. This could be compensated for by building a structure to span part of the pit or by filling in part of the pit.

6.3.7 Alternative Car Design Cost Impact

Using the modification cost estimates derived by Robert [54], approximate unloading facility implementation costs were constructed for the representative Eastern and Western coal distribution networks. The implementation costs do not include estimates of operating or maintenance costs, costs of upgrading the track structure to accommodate heavier trains or higher axle loads, or the costs of new equipment. In calculating the Equivalent Uniform Annual Cost (EUAC), a discount rate of 10% was used and an expected design life of 15 years was applied to any incremental modifications. The concept of EUAC amortizes the incremental capital costs involved in modifying unloading facilities with attention to the "time value of money."

The unloading facility implementation costs are quoted in terms of EUAC per 1000 net ton miles in order to establish a meaningful comparison to the operating cost benefits. In order to construct the cost estimates in this manner, it was necessary to convert the absolute dollar values into net ton-mile terms.

The approximate magnitudes of the modifications for each type of unloading facility (i.e. bottom-dump, random car rotary-dump and unit train rotary-dump) were used to calculate the total cost for modifying the entire U.S. rail system. The number of facilities of each type in 1995, as attained from Robert's work [54], was applied to the individual facility modification costs. The facilities are broken down by region (i.e. East versus West) in order to match up to the coal distribution network assumptions applied in the modeling and calculations of alternative car design benefits.

In total, 265 plants existed in the U.S. in 1995, as summarized in Table 6-2. Of these, 162 were located in the East and 103 plants were located in the West. Approximately half of the plants used bottom dumping and half used rotary dumping. In the table, plants that use both rotary dumping and bottom dumping are

classified under rotary dumping. Over half of the plants in the East that use rotary dumping use random car dumpers, while fewer than one-third of the plants in the West that use rotary dumping use random car dumpers.

Table 6-2: Region and Unloading Method for U.S. Utility Plants

Unloading Method	Region		
	East	West	Total
Number of Utility Plants			
Bottom Dump	72	56	128
Rotary Dump - Random Car	52	5	57
Rotary Dump - Unit Train	33	39	72
Unspecified	5	3	8
Total	162	103	265
Percentage of Utilities			
Bottom Dump	44%	54%	48%
Rotary Dump - Random Car	32%	5%	22%
Rotary Dump - Unit Train	20%	38%	27%
Unspecified	3%	3%	3%
Total	100%	100%	100%

These total Eastern and Western U.S. network costs were then amortized in terms of the EUAC assumptions and normalized for the actual volume of coal delivered in the U.S. in 1995, as attained from Robert's work [54]. The volumes were again classified as either East or West. Further, the volumes were classified by unloading method (i.e. dumper type). The classified volumes of coal delivered are summarized in Table 6-3.

Table 6-3: U.S. Electric Utility Coal Deliveries by Unloading Method

Unloading Method	Region		
	East	West	Total
Volume of Coal Delivered (Million Tons)			
Bottom Dump	88.6	94.0	182.6
Rotary Dump - Random Car	66.4	5.0	71.4
Rotary Dump - Unit Train	83.5	138.3	221.8
Unspecified	1.4	4.4	5.8
Total	239.9	241.7	481.6
Percentage of Coal Delivered			
Bottom Dump	37%	39%	38%
Rotary Dump - Random Car	28%	2%	15%
Rotary Dump - Unit Train	35%	57%	46%
Unspecified	1%	2%	1%
Total	100%	100%	100%

In 1995, 799 million tons of coal were delivered to electric utilities [54]. Rail had approximately 60% of the modal share, or about 482 million tons of coal. This table only includes coal delivered to electric utilities, and does not include the coal that was delivered to the utility by another mode but was carried by rail on an earlier portion of the trip. Interesting of note is the fact that 46% of all coal deliveries, in terms of tonnage, were made to plants with unit train rotary dumpers, whereas only 27% of the plants are equipped with this unloading method. Overall, 46% of the coal unloaded at U.S. electric utilities by rail is unloaded using unit train rotary dumping, 38% is unloaded using bottom dumping and 15% is unloaded using random car rotary dumpers. The West is much more dependent on unit train rotary dumpers than the East.

Finally, the U.S. dumper modification costs quoted as EUAC values per ton of coal by region and unloading method were normalized for the average length of haul as dictated by region (East versus West). In calculating the value of the benefits from modifying car design, an average length of haul of 360 miles was used for the Eastern network and 1,300 miles was used for the Western network. Table 6-4 summarizes the estimated implementation costs per 1000 net ton miles for modifying unloading facilities by dumper-type and by East versus West.

Table 6-4: Estimated Costs for Changing Car Dimensions by Region and Unloading Method

Unloading Method	Costs by Region ($/1000NTM)	
	East	West
High/Wide Alternatives		
Bottom Dump	$0.00	$0.00
Rotary Dump - Random Car	$0.09	$0.03
Rotary Dump - Unit Train	$0.33	$0.07
3-Axle Trucks		
Bottom Dump	$0.00	$0.00
Rotary Dump - Random Car	$0.86	$0.30
Rotary Dump - Unit Train	$0.48	$0.09

The high/wide alternatives reflect increases in the car cross-section with the Plate C clearance envelope and subsequently reducing car length in order to maintain GVW. The 3-axle truck alternative represents a longer car with two 3-axle trucks.

The 3-axle truck rotary-dump alternatives cost more than the respective high/wide alternatives because lengthening railcars involves lengthening the barrel and pit of rotary dump facilities. This involves extensive foundation work.

The West costs are only a fraction of the respective East costs due to two facts:

- Average length of haul in the West was assumed to be 3½ times farther than in the East
- Volume of coal delivered to the average Western utility is greater than in the East

The costs outlined in Table 6-4 are average costs. The actual values will vary greatly depending upon the exact modifications required at a specific facility, the volume of coal handled by that facility and the average length of haul.

6.4 Displaced Locomotive Power

6.4.1 Overview

Train size is set by one of two limits:

- Length
- Weight

The maximum allowable train weight, as set by maximum allowable drawbar force, is a function of route characteristics and the gross trailing tons behind the locomotives. The longitudinal train forces must not exceed the level large enough to pull a train apart or large enough to cause a derailment as the train accelerates, decelerates, or traverses over a series of curves or grades.

The drawbar forces can be reduced by using displaced locomotive power (additional power placed anywhere but the head-end of a train – usually at a mid-train location). The use of helper locomotives is not unusual in North American railroad practice [25]. Traditional use of such locomotives generally finds them placed at the rear of trains, commonly referred to as "pusher" units. Pushers are often used to help trains negotiate steep grades, and are often removed once the rugged terrain has been passed.

Two other forms of displaced power operations exist: additional units may be placed near the middle of a train, called "mid-train" units; or in an even more unorthodox approach, the locomotives can be evenly distributing throughout the train, called "distributed" power. Displaced power operations were modeled as mid-train power configurations in this study, since this method is the most often utilized technique for

long-distance displaced power operations, and is generally accepted as the most conventional and economical long-distance displaced power configuration.

Displaced power operations will likely be required for fixed-length unit coal trains composed of cars of any of the proposed alternative equipment designs, due to the increased trailing weights (capacity) of trains with these cars. Individual railroads use different maximum drawbar limits, typically 350 – 375 kips, which result in trains of 9,000 – 12,000 trailing tons with head-end power only [2]. The base case trains of this study have a gross trailing weight of 15,158 tons, in accordance with the HAL Phase III analysis [4]. These trains were assumed to utilize pusher power in both the East and West and were also assumed to incorporate some additional helper operations in the West, as in the HAL III analysis. Further increases in train weight were expected to require intensifying the displaced power operations by removing one of the head-end units and the pusher unit and replacing them with two mid-train units, thus keeping the total number of locomotives the same.

6.4.2 Alternative Car Design Cost Impact

In order to simplify the incremental cost impact analysis and to provide a conservative cost estimate, it was assumed that the base case trains were operated absent any displaced power. The incremental benefits and costs of mid-train power were fully applied to the cost results assuming that the base case used head-end power only.

The benefits of displaced power operations are three-fold, and they stem from a reduction in longitudinal buff and draft forces [25]:

- Lower car maintenance costs
- Increased maximum allowable weight-limited train size
- Improved train handling performance

The costs associated with displaced power operations include [25]:

- Locomotive capital costs from installing the necessary remote control equipment
- Equipment ownership costs (both car and locomotive) from increased cycle times

The results of the "Evaluation of Power Distribution, Coupling Systems, and Braking Equipment Alternatives" study conducted by Little and Smith [25] were used to derive the car maintenance cost savings from displaced power operations. These cost savings are a direct result of reduced draft system component wear and increased fatigue life of the draft system and car body structure [55]. Overall, these improvements were found to reduce car maintenance costs only on the order of 1%.

Since this study was concerned with length-limited trains, the benefits from increased train size were not included. The benefits from improved train handling performance were also not explicitly modeled, since these benefits are very cost subjective.

Displaced power train configuration requires some form of remote control system for the locomotives not located at the head end. Locomotive capital costs were added to the locomotive ownership costs in order to account for equipping locomotive units with radio control equipment. All of the locomotives were retrofitted with the equipment in order to provide full operational flexibility with respect to displaced power operations – any unit could be placed mid-train. In accordance with the aforementioned "Evaluation of Power Distribution, Coupling Systems, and Braking Equipment Alternatives" study [25], the cost of this equipment was assumed to be $12,000 per unit with 10 years of economic life. A discount rate of 10% was applied in the EUAC calculations. The concept of EUAC amortizes the incremental capital costs, attending to the notion of the "time value of money." This additional cost raised locomotive ownership costs on the order of 1%.

Equipment ownership costs are increased for both locomotives and cars due to increased cycle times in displaced power operations. The productivity of equipment is reduced because the time to construct and disassemble trains in a terminal is increased if locomotives are placed in the middle of a train. Whenever a mid-train locomotive requires servicing, the train must be pulled apart and the unit replaced.

In accordance with the UTRAIN unit coal train network model's [9] assumptions, a locomotive unit was assumed to have a 20% chance of requiring maintenance servicing. By utilizing simple probability and statistics techniques, it was further calculated that one or both of the mid-train locomotive units would require servicing 36% of the time. Hence, 36% of the time a run-thru coal unit train would need to be broken apart in order to access the mid-train power for servicing. It was assumed that ½ hour would be needed to swap mid-train power units (either one or both), as in the "Evaluation of Power Distribution, Coupling Systems, and Braking Equipment Alternatives" study [25].

The overall effect of the reductions in equipment productivity due to displaced power operations was to raise cycle time, and therefore both locomotive and car ownership costs, 0.4% in the East and 0.6% in the West. The relative rise in the West was greater than in the East, even though the cycle was longer in the West, because the number of run-thru terminal operations per equipment cycle was twice as great in the West as the East (4 versus 2).

The overall effect of instituting displaced power operations was estimated as a cost increase as follows:

- $0.035 / 1000 NTM in the East
- $0.017 / 1000 NTM in the West

The increase is higher in the East than in the West because equipment costs comprise a larger portion of total costs in the East.

CHAPTER 7: RESULTS

Chapter 7 details the result findings of the operating cost and capacity benefit analyses. Section 7.1 provides a comparison of the cost performance of the base gondola and hopper cases to the HAL cars. Section 7.2 presents the operating cost and capacity benefits of the gondola cars in relation to the base gondola. Section 7.3 presents the operating cost and capacity benefits of the hopper cars in relation to the base hopper. The findings of the transverse and longitudinal-door, automatic and manual-discharge, and articulated hopper car design methodologies are all included in this section. Section 7.4 presents the results of several operating cost sensitivity analyses. Finally, the findings from the implementation issue investigations are compared to the operating benefit results in Section 7.5.

The figures pertaining solely to operating cost benefits depict the results primarily in terms of absolute dollars. The vertical axes are measured in terms of absolute dollars. Percentage improvements over the respective base cases are provided in a secondary fashion. The cost results are displayed in this manner in these figures in order to facilitate comparison to the implementation costs derived in Chapter 6 and also to portray the actual magnitude of the estimated benefits given the generic cost and network assumptions.

The costs calculated in the operational analyses are the sum of track, transportation and equipment costs. Bridge costs and other implementation costs are not directly included in the result findings of this chapter. These costs, discussed in Chapter 6 and Section 7.5 of this chapter, were not subject to the same level of analysis and investigation and were therefore kept separate from the operating cost benefits.

Cost, as depicted in the result figures and discussed in the result findings, is defined in terms of Equivalent Uniform Annual Cost per 1000 Net Ton-Miles. The costs are based in terms of EUAC in order to smooth the value of capital investments over time in order to enable fair comparison with the steady stream of operating expenditures and the steady-state track cost analysis. The concept of EUAC

also captures the accounting principle of the "time value of money." A dollar today is worth more than a dollar tomorrow because today's dollar may be invested in order to be worth more than $1 tomorrow.

The costs are quoted in terms of net ton-miles because this unit normalizes the results so that they best capture cost and productivity changes for comparison across scenarios. Also, this unit relates directly to the cost per shipment from the perspective of the ultimate customer. For coal and many bulk commodities the shipper is substantially indifferent to the number of cars involved in the movement. The shipper's only concern is to move a large quantity of commodity between two points. Thus the value of the service (i.e. the revenue potential) is not effected by vehicle design. Alternative car designs are of value only to the extent that they reduce the cost of providing this service on a net ton-mile basis [2].

Capacity, as depicted in the result figures and discussed in the result findings, is defined in terms of net train capacity. Net train capacity is the key measure for network capacity, from the perspective of this study. Changes all of the car design parameters that effect network capacity are effectively measured by net train capacity. Net train capacity also differentiates between the effects of length-limited versus weight-limited trains on capacity. In the weight-limited case, if an increase in net linear load is solely due to an increase in gross linear load and not from net-to-tare at all, the net train capacity will remain unchanged.

The results of the operating cost analyses are best summarized on cost-capacity space diagrams. These diagrams depict the operating cost benefits in relation to the capacity benefits of a scenario in order to garner a better appreciation of the overall attractiveness of that scenario in relation to the base case and other alternative car designs. The best overall result summary would stem from a cost-capacity diagram depicting total incremental cost (operating plus implementation costs) versus incremental capacity. Observing the cost-capacity tradeoff in this fashion, one could choose the best alternative according to the objective of the investigation and one's preferences. The tradeoff between cost and capacity benefits could be played against the need for capacity, knowing the cost of other capacity improvement options in relation to the tested scenarios. This study did not investigate the high/wide car design methodology implementation issues to enough detail in order to feasibly illustrate the results in so thorough a fashion. The results of such an approach would be very case specific, since so many costs and parameters are intimately linked to the characteristics of the specific network and car types under consideration.

7.1 Base Gondola and Hopper Cost Performance versus HAL Analyses

An important aspect of this study to consider when evaluating the results is that the results are quoted in relation to an extremely efficient base case by modern standards. Operations with the aluminum, 36-ton axle load, bathtub gondola car are significantly enhanced beyond any of the prior HAL analysis scenarios. Figure 7-1 depicts this finding. This figure puts the operating cost results of this study into perspective with respect to the prior HAL Phase II and Phase III economic evaluation findings. The alternative car designs investigated throughout this study are much more cost efficient and capacity effective than any of the HAL equipment types.

Both the length-limited and weight-limited base gondola cases have drastically lower operating costs than the HAL Phase II base case. The HAL II base case is a steel, 33-ton axle load gondola car. The comparisons illustrated in Figure 7-1 were derived by holding the length and weight-limit assumptions of the HAL II base case across all of the cases portrayed. The results of all of the scenarios depicted in Figure 7-1 were derived by running the analyses over the networks assumed for this study in order to promote an equitable comparison. As many assumptions as possible were matched to the respective original analysis. The cost results of each respective original analysis were utilized to derive costs for the network scenarios depicted in Figure 7-1 by estimating unit costs and applying simple cost-drivers, much in the same fashion as the cost calculations were performed in this analysis. Note also that bridge costs have been omitted from the HAL scenarios since bridges were not directly modeled in this study.

In the East, operations with the base gondola are 17.6% cheaper in the length-limited case and 14.6% less expensive in the weight-limited case. In the West, the cost savings are 17.2% and 14.4% for the length and weight-limited cases respectively. These dramatic operating cost improvements in both the length and weight-limited cases are due to a substantial increase in car capacity and the methods employed in attaining this additional capacity. The HAL II base car has a load limit of 203,300 pounds whereas the base gondola of this study has a capacity of 243,000 pounds. This is almost a 20% capacity increase. The increase in car capacity is due to:

- Reduced car tare weight (improved net-to-tare ratio)
- Increased gross rail load / axle loads

The increase in car capacity brought about by these two mechanisms enabled a reduction in the number of trains required to move a fixed level of coal in unit train service. The effects are more pronounced in the length-limited case since the weight-limited case does not benefit from increased axle loads without a reduction in tare – larger cars that each weigh more only result in trains of the same gross trailing weight with fewer cars each. The reduction in the number of trains required for a service brought about by the gross and tare mechanisms explained above directly equate to fewer train-miles, car-miles, gross ton-miles, car-days, and locomotive-days, thus reducing operating costs. Increasing the gross rail load will increase track costs, ceteris paribus, but the improvement in car net-to-tare made possible by moving to a heavier car may reduce total track costs if the net-to-tare improvement enables a significant enough drop in gross ton-miles.

Total operating costs were found to decline with the introduction of improved suspension trucks in lieu of the standard 3-piece truck. The track and equipment maintenance cost improvements brought about by the improved truck improved the total economic picture beyond the incremental increase in equipment ownership cost.

The base hopper car operating cost improvement is not as great as the gondola car cost improvement in relation to the HAL II base case. In the East, the base hopper operating costs are 11.8% lower in the length-limited case and 8.6% lower in the weight-limited case. In the West, the base hopper costs are 12.4% better in the length-limited case and 9.4% better in the weight-limited case than the HAL II base case. There is about a 6% difference in the gondola versus hopper cost improvement levels in relation to the HAL II base in the East and a 5% difference in the West. The gondola car has a lower tare weight than the hopper car. It is therefore able to carry more coal and thus operations with the gondola car require fewer train and carloads to move the same volume total of coal. The improved net-to-tare also implies a lighter empty train requiring less fuel to move. Also, the hopper car costs more to purchase due to its heavier and more complicated design involving the unloading doors and the automatic rapid-discharge equipment.

The results of running the HAL analyses over the network configurations are very similar to the mainline analysis results actually conducted. The basic conclusions are the same: 36-ton axle loadings are preferred to 33-ton and 39-ton axle loadings, the benefits are much greater for the length-limited case, and improved-suspension trucks make economic sense [2][3][4]. However, the magnitudes of the operating cost results are slightly different, especially with respect to 39-ton axle loads, although the order-of-magnitude of the cost results is unchanged.

The HAL Phase III analysis conclusions remain unchanged. The basic conclusion is that 36-ton axle loads are the most attractive, although the relative axle load effect of the 39-ton case versus the 33-ton case is less severe when improved-suspension trucks are used. The relative axle load effect of 36-ton versus 33-ton axle loads remains unchanged for the most part, but the base case cost level is improved by switching to improved trucks. The track and fuel cost savings more than compensate for the increased truck costs, in all cases.

Three cases from the Optimal Axle Load study are included for comparative purposes to both the HAL analyses and the current car design study. The Optimal Axle Load study scenarios exhibit a vast improvement in operating costs beyond the traditional HAL analyses. This dramatic cost improvement stems from the relative benefits of aluminum versus steel cars. Cars made of aluminum have a much reduced tare in comparison to steel cars. This tare reduction is answered with a net increase, thus maintaining gross weight. The resulting dramatic net-to-tare improvement lowers transportation costs since the number of train-miles and gross ton-miles to perform a service are reduced. Track costs are reduced since the gross ton-miles per mile of track are reduced. Equipment costs are also reduced, even though the cost per car has increased, since the number of car-miles, train-miles, and car and locomotive-days are all reduced.

The 33-ton case encompassed in the Optimal Axle Load study scenarios of Figure 7-1 is the base case of that study. The 39-ton axle load case is actually the 53-foot 125-ton car upon which all of the alternatives in the Optimal Axle Load study are based. The 36-ton Optimal Axle Load case has the same cross-section as the 125-ton car and is thus shorter than 53 feet. The results in Figure 7-1 do not depict the 36-ton Optimal Axle Load case as attractive compared to the 39-ton case as in the actual Optimal Axle Load study. This is due to the fact that the beneficial network cycle time effect of the 36-ton versus the 39-ton case as dictated by the UTRAIN analysis in the Optimal Axle Load study was not included here [1]. The adverse effects of track maintenance on cycle time when comparing the 36 and 39-ton axle load cases are not modeled in this figure.

Figure 7-1 shows the cost benefits due to technological progression on three fronts:

- Equipment axle load
- Equipment suspension system
- Equipment weight

The recommendation of HAL Phase II, to increase axle loads to 36-tons from 33-tons, reduces operating costs by 6.5% and 5.5% in the East and West length-limited cases respectively and by 2.9% and 1.9% in the East and West weight-limited cases respectively. The HAL Phase III recommendation, to increase axle loads to 36-tons from 33-tons and to replace conventional 3-piece trucks with improved-suspension trucks, reduces operating costs by 9.5% and 9.4% in the East and West length-limited cases respectively and by 6% and 5.9% in the East and West weight-limited cases respectively. A further recommendation, to follow the HAL III recommendation but also to replace steel cars with aluminum cars, reduces costs from the HAL Phase II base case by over 17% in both the East and West length-limited cases and by over 14% in both the East and West weight-limited cases.

By comparing the appropriate results of Figure 7-1, it is possible to decompose the contribution of each technological innovation (HAL, trucks and aluminum cars) to operating cost savings. Improved-suspension trucks reduce operating costs on the order of 3% in the East and 4% in the West for both length and weight-limited cases. Increasing axle loads reduces operating costs 6½% in the East and 5½% in the West length-limited cases and 3% in the East and 2% in the West weight-limited cases. Finally, and most strikingly, aluminum cars reduce operating costs on the order of 8% in all cases.
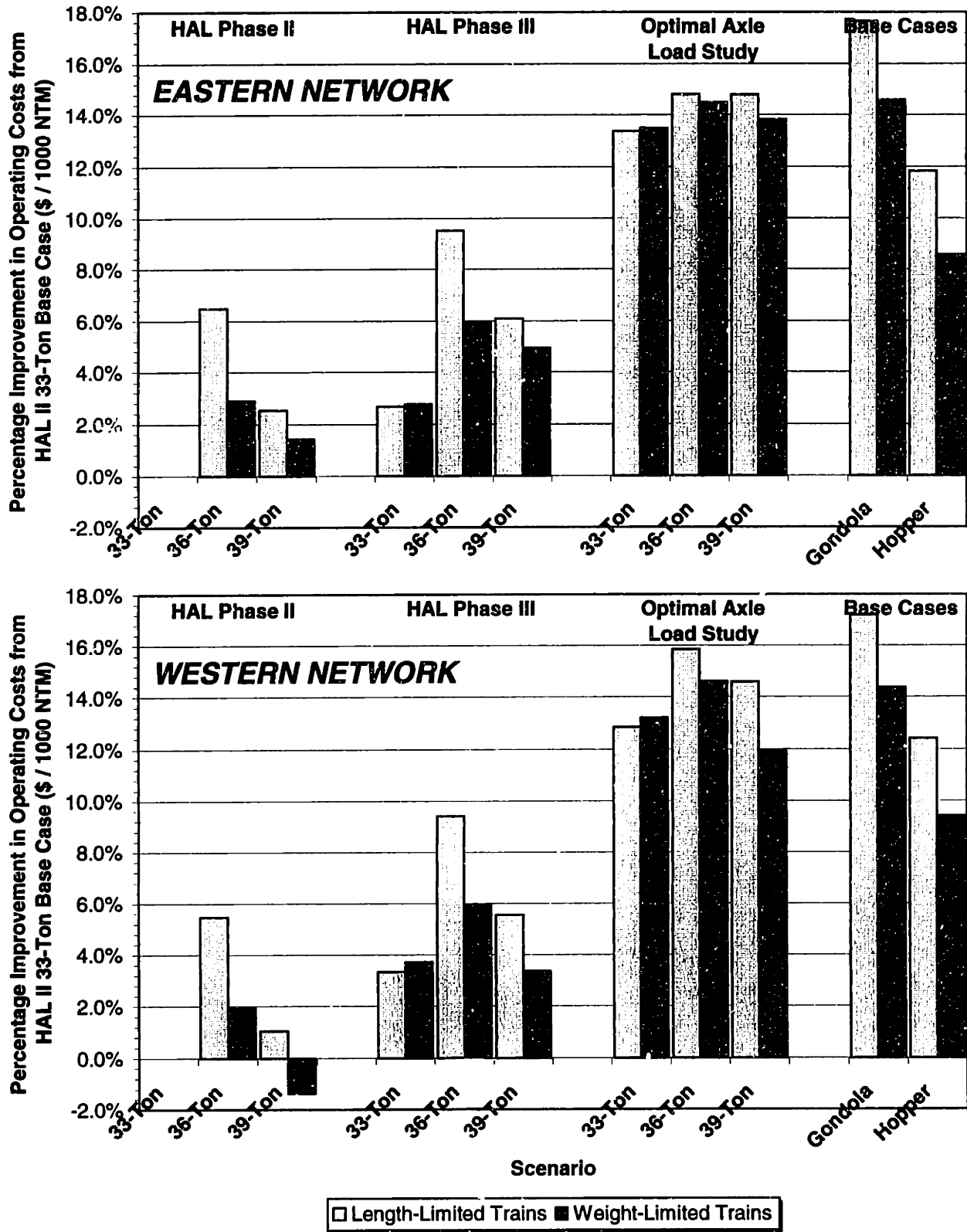
Figure 7-1: HAL Operating Cost Comparison to Base Cases

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7.2 Gondola Scenarios

7.2.1 Basic Alternative Design Concepts

7.2.1.1 Operating Cost Benefit Comparison

Figure 7-2 depicts the operating cost savings of the alternative gondola scenarios versus the base gondola for both the Eastern and Western networks. The most striking result prevalent from this chart is the magnitude of the cost savings. The high/wide cost benefits range from 1-6% in the East and 1-8% in the West, for the alternatives considered. The savings increase with the size of the cross-section considered. Another immediately apparent result from the chart is that the absolute magnitudes of the high/wide cost savings are very similar for the East and West, however, the magnitudes relative to the base cases are much different. This is due to the fact that the Western Gondola base case total operating cost is 29% lower than the Eastern case. The cost, in terms of dollars per 1000 NTM, of the base is lower in the West due to:

- Higher average traffic density on tracks
- Higher level of tonnage
- Longer average haul between origin and destination
- Better average track component quality (especially with respect to rail hardness)
- Lower number of turnouts per mile of track
- Less severe climate (prolonging tie life)
- Better quality ballast and subgrade on branch lines

The operating cost benefits from increasing gondola car height are on the order of 2% per foot in the East, until the COG-limit is reached, whereupon the benefits drop to approximately 1% per foot of added height over the base for the range of cross-sections analyzed. This drop is due to the increased car cost from advanced suspension trucks. In the West, the benefits are about 2% per foot, dropping to 1 2/3% per foot. The added truck cost is not as significant in the West because car ownership is not as great a portion of total operating costs in the West.

The operating cost benefits from increasing gondola car width beyond the base case are on the order of 2% per foot in the East and the West, being somewhat higher in the West. The benefits from increasing

car width are greater than from increasing car height, with the difference being slightly more pronounced in the East. This result is attributable to the differences in height increase versus width increase on the car ownership costs, despite the fact that an increment of added height adds 6% more to car volume than an increment of width, if length is kept constant. The car ownership costs are assumed to vary as a function of car box surface area in this study. Adding an increment of height increases the surface area of the four box walls, whereas an increment of width only increases the surface area of two walls and the floor of the box. Total operating costs are more sensitive to this surface area differential assumption than the slight difference in incremental car cross-section changes resulting from width versus height. Also, increasing the height above the COG-limit at two feet higher than the base height increases car ownership costs with the incremental cost of advanced trucks.

The "3 Feet Up and 2 Feet Out" case, with its 15.1-foot height and 12.7-foot width, boasts 6.2% savings in the East and 8.3% savings in the West, which is the best of all the scenarios considered. This scenario also provides a very attractive capacity boost, as will be discussed in conjunction with Figure 7-6; however, these results should be taken with some skepticism. The extremely large dimensions offer a sizeable capacity increase, but also intensify the gross linear loading to a level of 7,780 pounds per foot, 44% over the base, as a result. This loading magnitude could easily increase bridge implementation costs beyond the operating benefits and may not even be feasible due to bridge loading complications. The horizontal clearance improvement costs could also be quite extreme for increasing car width by two feet, especially if track center distance is an issue at this car width.

A more reasonable range of attractive higher/wider alternatives include the "Maximum Dimension" car, the "2-Foot Up" case, the "2-Foot Up and 6-Inch Out" case, and the "2-Foot Up and 1-Foot Out" case. The benefits of these cases range from 2.8-4.6% in the East and 3.9-5.9% in the West. The "Maximum Dimension" case falls between the "2-Foot Up" and the "2-Foot Up and 6-Inch Out" cases with respect to the level of savings.

Increasing car height above the COG-limit from the 2-Foot cases to the 3-Foot cases is neither an attractive option in the West at first glance nor especially in the East with respect to operating cost savings. The graph suggests that costs may be reduced more effectively by increasing car width after the COG-limit constraint has been tightened. The overall attractiveness of the highest options cannot be fully judged by this figure, since many other unconsidered variables play a part in that judgement. The increase in height does substantially increase capacity, on the order of 8-9%, as depicted in Figure 7-6.

Also, clearance implementation issues and costs may make wider alternatives a very unpopular option for increasing capacity and decreasing operating costs.

The 39-ton axle load scenarios suggest modest operating cost benefits of 1.5% in the East and 0.7% in the West, but these do not include bridge costs. The bridge costs, discussed in Section 6.2, are enough to overturn the result, making the 39-ton cases more costly than the 36-ton base cases, as in the prior HAL studies. Nevertheless, the operating cost benefits are more substantial for the 39-ton case in relation to the 36-ton case in this study than in the HAL analyses for two reasons:

1) The 39-ton cars in this study are assumed to have lighter 36-inch diameter wheels, as opposed to the heavier 38-inch wheels of the HAL analyses. Therefore, the net-to-tare ratio of the 39-ton car is assumed to be higher than the 36-ton car, in contrast to the HAL analyses.

2) The HAL effect on track costs was found to be less significant over a network than on a mainline due to two reasons. First, ties comprise a major cost component. Tie lives also do not deteriorate much from increased axle loads. Tie life is also not very sensitive to tonnage. Thus, on low-density track, ties compose the largest component of track costs. Since much of the network is low-density track, the overall average HAL effect is reduced. Second, rail fatigue was found to be a major issue in increasing axle loads, escalating rail cost, which is typically the highest cost-component of track. Rail fatigue is less likely to be an issue on low density track since the defect rate is less likely to reach a relay threshold. Less traffic equates to fewer defects, all other things being equal.

The attractiveness, if any, of the 39-ton axle load option stems from the fact that a significant capacity boost may be garnered without suffering large implementation cost penalties from clearance modifications or from unit train rotary dumper modifications.

The 42-ton axle load alternative is not an attractive option. The operating benefits are extremely low in the East case, at 0.6%, and slightly negative in the West. Even with the lack of dumper implementation costs, the fact that there are additional bridge costs significantly beyond the 39-ton bridge costs is enough conviction to conclude that the higher/wider option is a better method for increasing capacity without a incurring expenditures, and possibly even reducing total costs.

The 3-axle truck car is also not an attractive option. This option decreases operating costs 0.9% in the East and 2.4% in the West. The benefits are greater in the West since the car ownership cost penalty is

not as significant in the West in relation to the transportation cost efficiencies. The magnitudes of these cost savings may easily be surpassed by increasing the height to the COG (also the Plate-C) limit, or just by increasing the cross-section in general. Also, there is a much larger rotary dumper cost penalty required for lengthening cars as would be required in the 3-axle case, as opposed to shortening the cars as in the higher/wider cases.

EASTERN NETWORK

Scenario values (top chart):
- 1' Up: 1.8%
- 2' Up: 2.8%
- 3' Up: 3.1%
- 6" Out: 1.1%
- 1' Out: 2.0%
- 2' Out: 3.7%
- 2' Up & 6" Out: 3.8%
- 2' Up & 1' Out: 4.6%
- 3' Up & 1' Out: 4.8%
- 2' Up & 2' Out: 6.1%
- 3' Up & 2' Out: 6.2%
- Max. Dimension: 3.3%
- 39-Ton Axle Lds.: 1.5%
- 42-Ton Axle Lds.: 0.6%
- 3-Axle Trucks: 0.9%

WESTERN NETWORK

Scenario values (bottom chart):
- 1' Up: 2.3%
- 2' Up: 3.9%
- 3' Up: 4.7%
- 6" Out: 1.3%
- 1' Out: 2.4%
- 2' Out: 4.4%
- 2' Up & 6" Out: 4.9%
- 2' Up & 1' Out: 5.9%
- 3' Up & 1' Out: 6.7%
- 2' Up & 2' Out: 7.6%
- 3' Up & 2' Out: 8.3%
- Max. Dimension: 4.4%
- 39-Ton Axle Lds.: 0.7%
- 42-Ton Axle Lds.: -0.1%
- 3-Axle Trucks: 2.4%
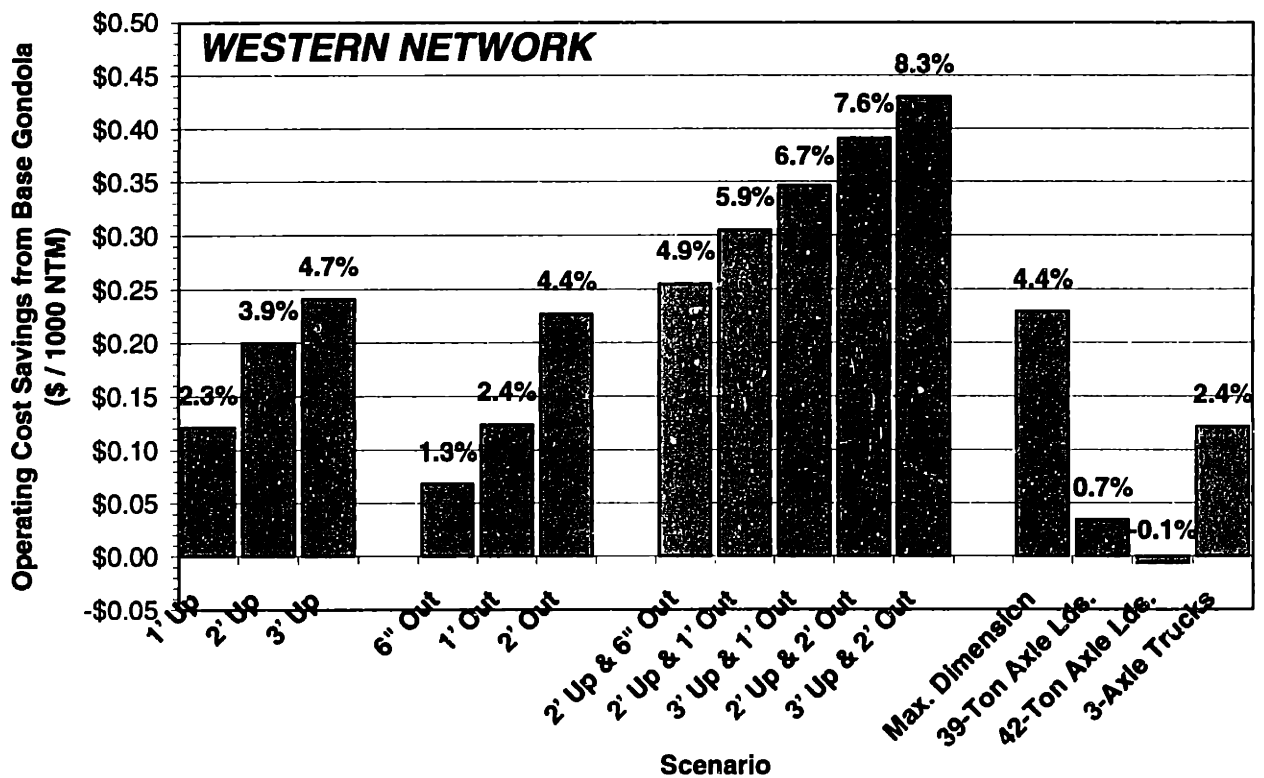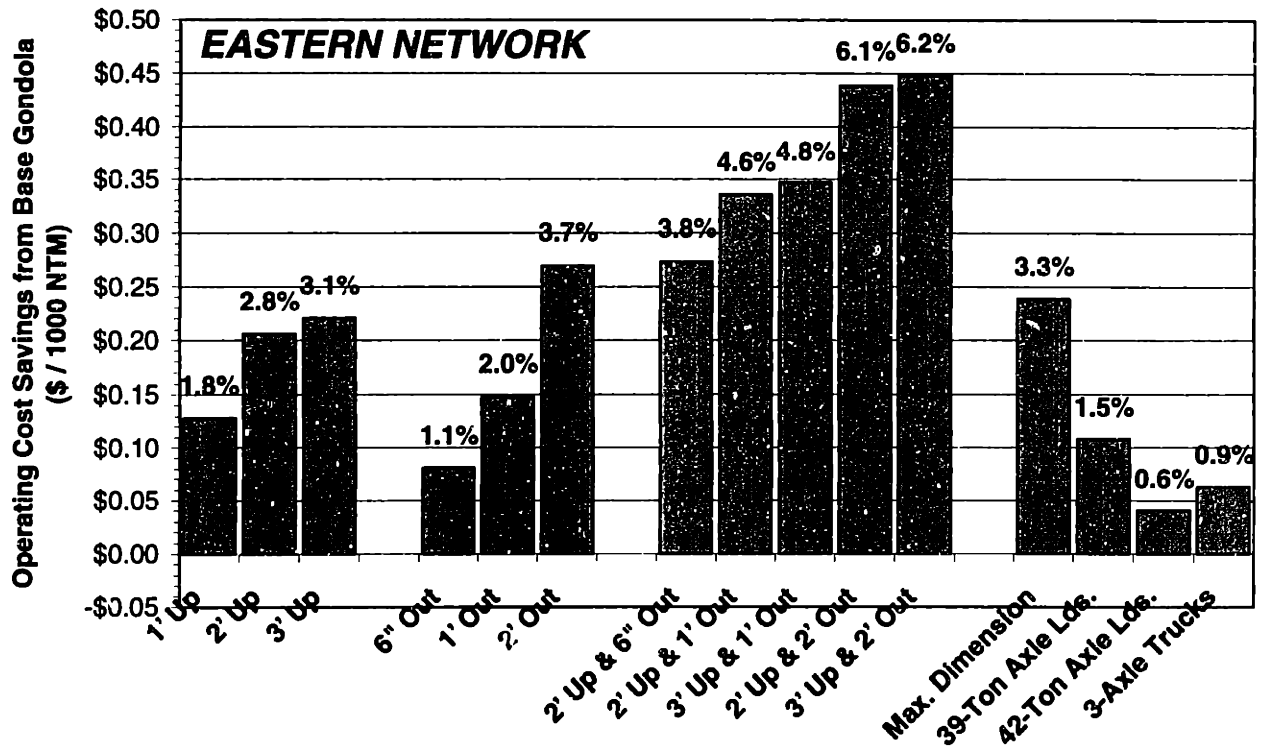
Scenario

% Cost Savings from Base Gondola

Figure 7-2: Gondola Scenario Operating Cost Savings

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7.2.1.2 Operating Cost Benefit Decomposition

The operating cost improvements of the alternative gondola car design scenarios depend on the relative size of each operating cost component and the affects of changes in vehicle design to each individual component. Figure 7-3 provides a breakdown of where the operating cost benefits originate. The "other equipment" category includes locomotive ownership, locomotive maintenance, and car maintenance costs.

Crew cost savings are the primary source of operating cost benefits. The crew costs decrease directly with the reduction in train-miles characteristic of the alternative cases. The level of train-miles declines since the number of trains required to move a fixed tonnage of coal drops as the net capacity of a train increases. The larger the train capacity, the higher the NLL for the length-limited case, and the higher the crew cost savings.

In the East, the next largest contributor to total operating cost savings is from car ownership costs. In the West, it is either car ownership or fuel costs, depending upon the scenario. Car ownership costs improve for the high/wide cases since the shorter cars are closer to cubes in shape than longer cars with smaller cross-sections. Also, shortening a car by holding the car capacity constant and increasing the cross-section improves the net-to-tare ratio, due to the reduction in the weight from the relatively heavy longitudinal components on the underside of the car. Improving the net-to-tare ratio, while holding the total gross weight constant, means that the total number of cars required to move a fixed tonnage of coal can be reduced. Thus, the trains are the same length, they have more cars each, but there are fewer trains in total. The overall result is a reduction in the total number of cars in the fleet. The reduction in the number of cars reduces the car ownership costs.

This net-to-tare improvement that reduced the number of cars required in the fleet subsequently reduces the number of car-miles, and also reduces the number of gross tons per mile, locomotive-days, and locomotive-miles by the same token. The net-to-tare improvement reduces the number of trains required to move a set volume of coal, holding the loaded coal train gross weight constant, thus reducing all of these statistics, even accounting for the locomotive multiplier assumption. The track, locomotive ownership, and locomotive and car maintenance costs are therefore all affected to the same extent.

The fuel cost savings are greater than the savings prompted solely by the net-to-tare ratio improvements. The fuel costs decline directly with a reduction in gross ton-miles. A reduction in train-miles due to an

improvement in net-to-tare will, of course, reduce the gross ton-mileage and thus fuel expense of a scenario. However, a further reduction in gross ton-miles is attributable to the net-to-tare improvement, thus compounding the fuel savings benefits – the empty train is lighter with an improved net-to-tare. Therefore, the gross ton-mileage accumulated on the empty return leg of the cycle is lower.

Evident in Figure 7-3, is the fact that the higher axle load cases increase track costs, regardless of the reduction in gross tonnage. This should not be a surprise, as the phenomenon is well documented from the FAST/HAL analysis results [2][3][4]. Logically, increasing the loading and forces exerted upon the track structure will increase the track costs. These track cost increases reduce the overall operating benefits collected from the transportation and other cost components.

The higher axle load and 3-axle truck scenarios also do not benefit from improved car ownership costs – often the second-largest contributor to total operating savings. In fact, in all of the cases, there is an incremental car ownership expense with respect to these alternative car designs. The heavier axle load cars must be made sturdier in order to accommodate more lading safely. The increased material inherent in their design increases the cost of the cars. The 3-axle truck car must also be strengthened longitudinally on account of its increased length. The increased weight of the 42-ton and 3-axle cars due to their heavier truck and/or wheel assemblies also hinders the net-to-tare ratios of these cars.

There is a net-to-tare weight benefit over the base case with both the 42-ton and 3-axle truck designs, however, the high/wide design approach is a more efficient fashion with which to improve net-to-tare. The 42-ton axle load car improves net-to-tare by filling up a given length of car with more lading by increasing car height. The 3-axle truck car improves net-to-tare more by lengthening the cars to reduce the number of cars in a set length of train. This, in turn, reduces the number of gaps empty of lading between cars in a train. The high/wide concept improves net-to-tare by increasing car cross-section, thereby decreasing car length and reducing the length of heavy longitudinal car components on the bottom of the car.

The cost variation between incremental height or width increases, as was described previously in Section 7.2.1.1, is also apparent in Figure 7-3. An increment of height improves costs more than an increment of width with one exception – car ownership. An increment of height increases the car cross-section more effectively than an increment of width, thereby shortening the car to a greater extent, since the car box width is greater than the average box height. However, the car ownership costs decrease much more rapidly with an increase in width because of width versus height effects on the car box surface area

adjustment factor in car ownership calculations. The overall effect is that operating costs decrease more rapidly with width than with height increases.

The effect of advancing car height above the COG-limit is also very apparent in Figure 7-3. Car ownership costs are affected detrimentally due to the incremental cost of an advanced suspension system in order to exceed the COG-limit. In the "3-Foot Up" versus "2-Foot Up" cases, this increment is large enough to revert the overall car ownership benefit from the base case into a cost in both the East and West.
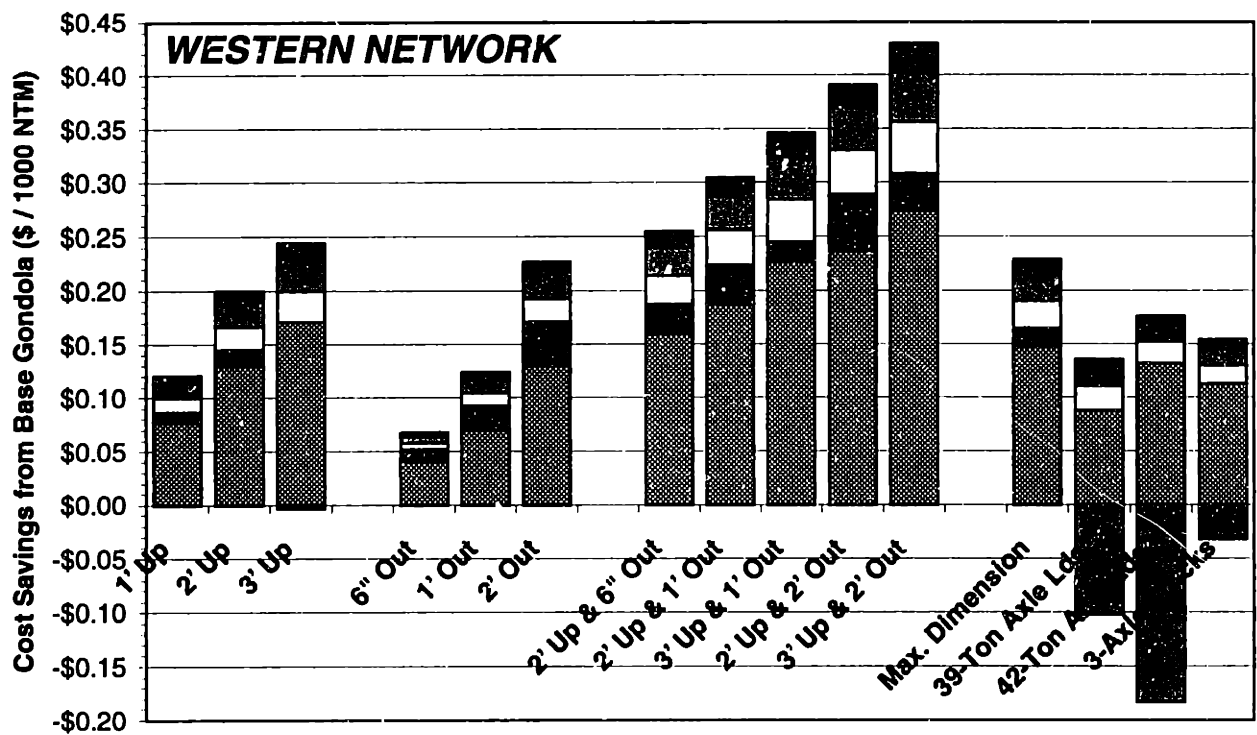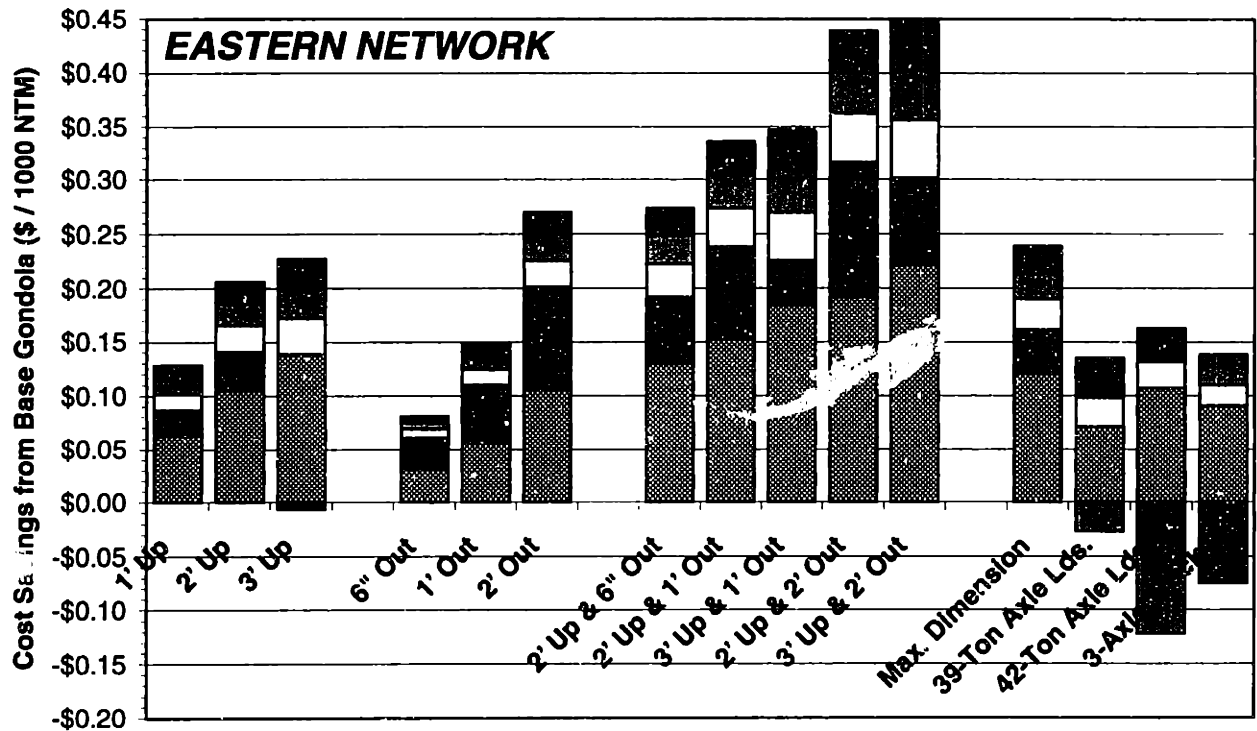
Figure 7-3: Gondola Scenario Operating Cost Savings Decomposition

The operating cost improvements of the alternative gondola car design scenarios depend on the relative size of each operating cost component and the effects of changes in vehicle design to each individual component. Figures 7-4 and 7-5 describe where the operating cost component savings described in Figure 7-3 originate. Figure 7-3 illustrates the decomposition of the Eastern and Western network gondola base case costs by operating component. Figure 7-4 shows the relative changes of each cost component from the base case across the alternative scenarios for both networks. These results are grouped by track, transportation, and equipment cost categories in order to simplify the presentation of the findings.

In the East, locomotive ownership costs comprise the largest single cost component with about ¼ of total operating cost. Track costs and car ownership both account for about 20% of total operating costs each. Crew and fuel costs (i.e. transportation costs) are next in importance at 10% and 13%, respectively. The smallest cost components are car and locomotive maintenance, both contributing 6% to total operating costs. Overall, in the East, track accounts for 20% of total operating costs, transportation accounts for 23%, and equipment accounts for 57%.

In the West, the cost levels are more evenly distributed. Track costs comprise the largest single component with 22% of the total. Locomotive ownership, crew, and fuel costs comprise a second tier of costs, each ranging between 16% and 17% of total operating costs. Car ownership costs are next in importance, with 11% of the total. Finally, again both car and locomotive maintenance contribute the least in a fairly equal fashion, with 8 – 9% each. The high fixed car and locomotive ownership costs are not as important to total operating costs because the variable transportation, and equipment and track maintenance costs are much higher in the West versus the East. The total volume of traffic is higher in the West. Also, the average length of haul is assumed to be on the order of 3½ times farther in the West than in the East.

Figure 7-5 convincingly illustrates the relative effects of the alternative car designs on the different components of operating cost. In most of the cases, the transportation costs are most dramatically affected. The percentage change in transportation costs dwarfs the percentage change in equipment costs in every case and dwarfs the percentage change in track costs in all cases but the heavier axle load scenarios. For the high/wide alternatives the relative change in transportation costs is on the order of 5 times larger than the relative change in track and equipment costs. This is because all of the cost components are equally affected by the beneficial effects of alternative car design net-to-tare improvements, but the transportation costs are also very sensitive to the reduction in train-miles though

the elimination of train-starts made possible by increasing train capacity. Crew costs are the only cost component affected in this fashion. The fuel costs are also more sensitive to the car design concepts because of the compound effect that net-to-tare improvements have on the level of gross ton-miles.

In the West, track costs are typically more effected by alternative car design than equipment costs. This is because track costs are more sensitive to relative changes in traffic volume in the West than in the East. The average level of traffic volume is higher in the West. Thus, a set relative change in net-to-tare will have more of an effect on the absolute tonnage level in the West because track costs are related to traffic volume in a non-linear fashion. The non-linearity is accountable to economies-of-traffic density in railroad track costs [56]. The presence of a large fixed cost component in total track costs means that a given percentage change in traffic volume will have more of an effect on the level of track costs at a higher level of traffic than at a lower level of traffic. Also, rail fatigue is more sensitive to relative changes in traffic volume at high traffic volumes, since rail relay defect limit thresholds are defined in terms of defects per mile per year. The level of defects is more constant with respect to tonnage than with time. Thus, a higher level of tonnage over a fixed time interval will equate to a higher defect rate. As a result, changes in the rail cost component of track costs are larger in the West.

Figure 7-5 explicitly demonstrates the potential of the high/wide car design concept versus the traditional HAL approach. The high/wide concept improves transportation and equipment costs and enhances capacity without the negative effects on the track structure and thus without suffering the inherent track cost ramifications. Going even further, the high/wide concept actually reduces track costs. This observation, of course, results when bridges are excluded from consideration.

Track costs increase about 2% in the East for the 39-ton axle load case and about 8½% in the West, excluding bridges. The track cost increases for the 42-ton axle load scenarios are estimated on the order of 6% in the East and 14% in the West, three times higher in the East and almost twice as high in the West as the 39-ton axle load scenario.

The larger the cross-section of a scenario, the shorter the assumed car length, the greater the train capacity, and thus the greater the relative changes in the cost benefits for the high/wide scenarios. The transportation cost improvements range from 8 to 17% in the East progressing from the "2-Foot Up" case to the "3-Foot Up and 2-Foot Out" case. In the West the improvements range from 9 to 19% for the same alternative designs. Track and equipment cost benefits range from 1% to 3% in the East and from 1% to 4% in the West for these same two alternatives.

EASTERN NETWORK

Car Maintenance
6%

Track
20%

Car Ownership
19%

Crew
10%

Locomotive
Maintenance
6%

Fuel
13%

Locomotive
Ownership
26%

WESTERN NETWORK

Car Maintenance
8%

Track
22%

Car Ownership
11%

Locomotive
Maintenance
9%

Crew
17%

Locomotive
Ownership
17%

Fuel
16%
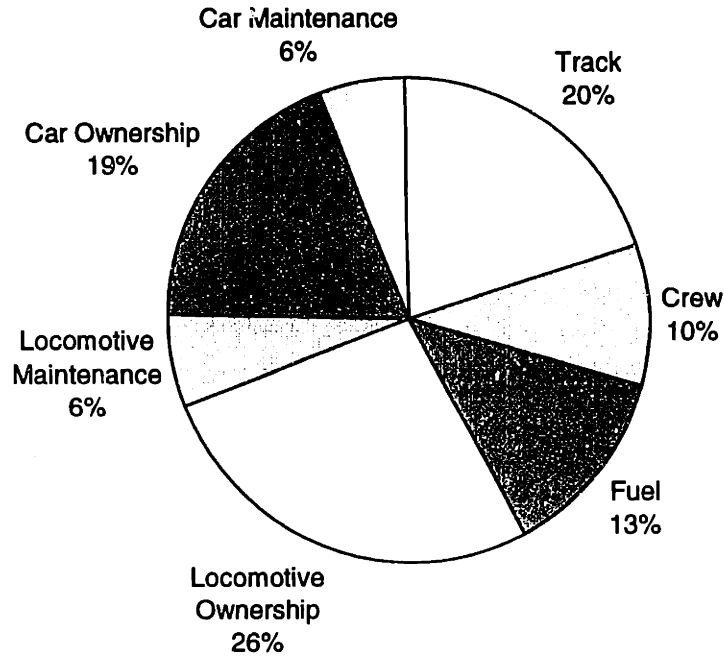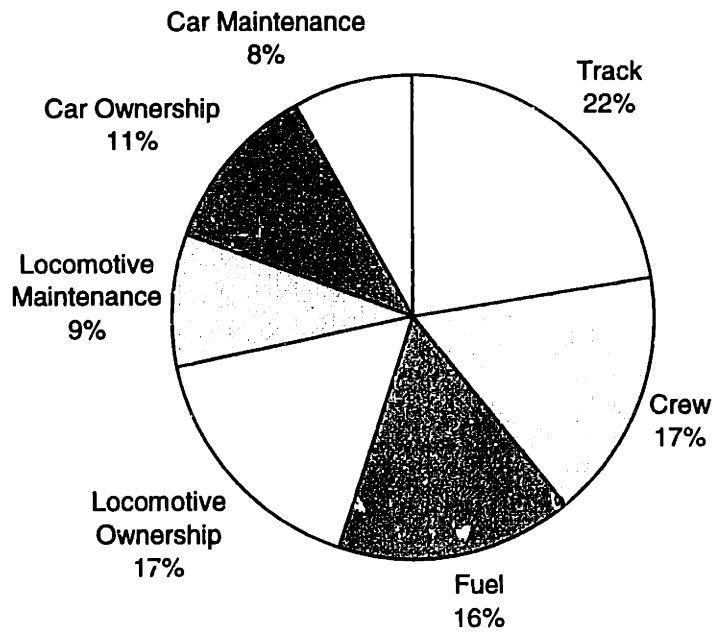
Figure 7-4: Base Gondola Case Operating Cost Decomposition
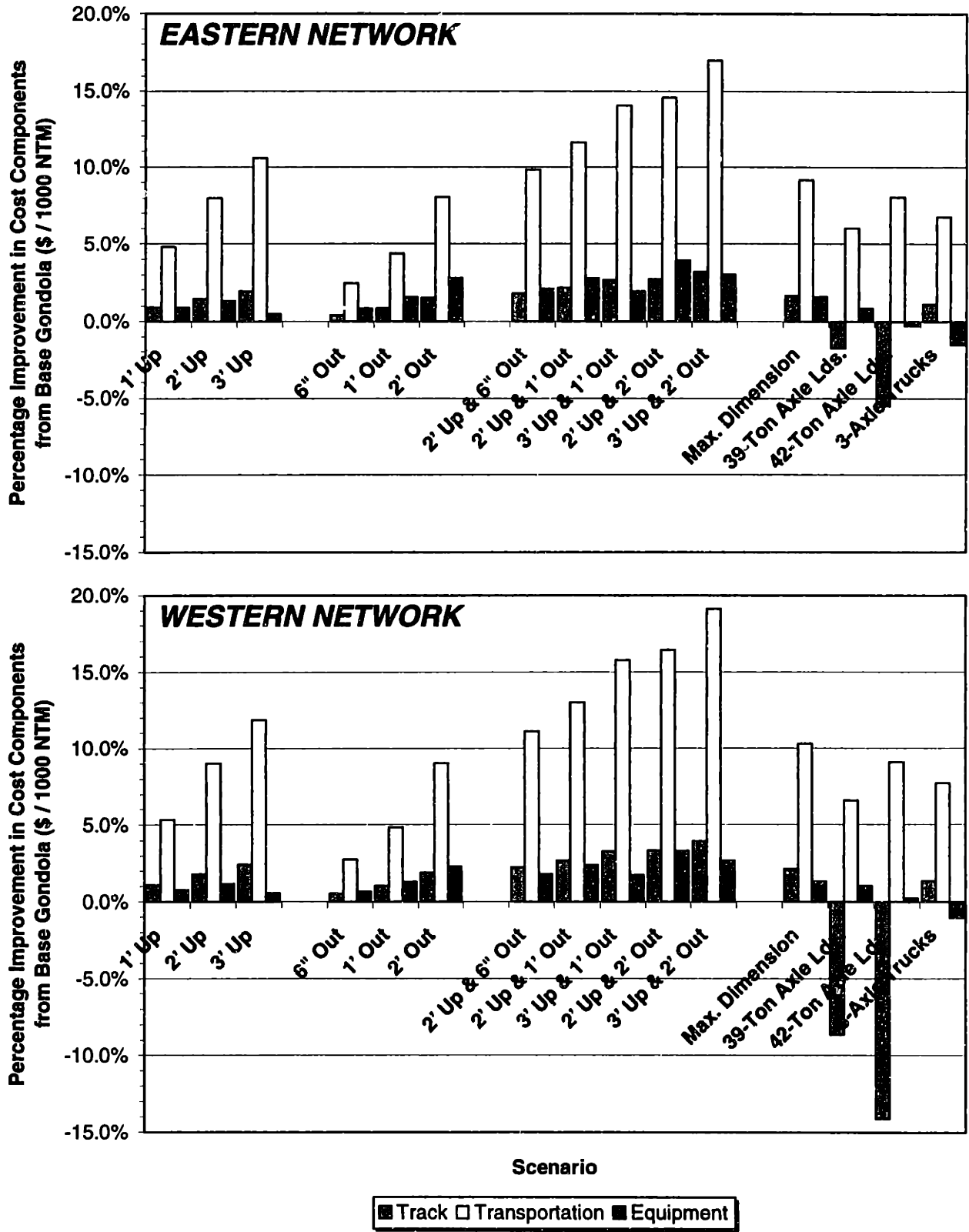
Figure 7-5: Gondola Scenario Operating Component Relative Cost Changes

7.2.1.3 Operating Cost and Capacity Benefit Comparison

Figure 7-6 offers an operating cost versus capacity benefit comparison for the alternative gondola scenarios versus the gondola base case. The most striking observation from these results is that increases in capacity are matched with decreases in cost. Excluding implementation cost issues, capacity comes with a cost benefit. Even when including these additional costs, many of the alternative car designs will provide additional cost savings from the base case. This is contrary to most capacity enhancement alternatives, such as increasing train locomotive power, increasing siding lengths, double and triple tracking, improving track quality, adding or improving signal systems and communications, or implementing Advanced Train Control Systems [57].

On this graph it is generally desirable to be located high and to the right. This is the region of the highest cost and capacity benefits. There is no doubt that advancing along the vertical axis is beneficial since this represents lower operating costs for the same net train capacity. This assumes that the level capacity level has not remained constant despite a tradeoff amongst the components comprising train capacity, i.e. the implementation costs have not changed. Advancing along the horizontal axis may not be beneficial depending upon the implementation cost implications. For example, a flat horizontal movement out to the right of Figure 7-6 would most likely be accomplished by increasing GLL. The cost savings are the same for this move, but the bridge costs will increase total costs as dictated by the physical condition of the bridges and the loading imposed upon them by the scenario considered.

Interestingly, due to the assumptions and methodology assigned in designing the parameters for the alternative scenarios, the alternatives follow a relatively tight band across cost-capacity space, extending into an improved cost and capacity region from the origin (base case). Also, the incremental capacity benefits of each alternative are similar for both networks. This is because train capacity is dependent upon the car design and train make-up assumptions, neither of which are affected by the network assumption.

The position of the 3-axle truck and 42-ton axle load scenarios on the East graph illustrate the relative lack of attractiveness of these options. Both of these options lie well below the bandwidth established by the rest of the alternatives. The same holds true for the 39-ton and 42-ton axle load cases and the 3-axle truck case in the West. These options offer less operating cost savings for the same relative capacity boost as the other alternatives.

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Importantly, one should not completely discount the 39-ton axle load case when other aspects are considered. This alternative does not have much or any rotary dumper cost implementation implications and it does offer an 11% capacity boost over the 36-ton base case. The only implementation costs would be for bridge impacts and possibly for instituting mid-train power operations. This could, therefore, be a relatively attractive option for increasing capacity in some instances.

The capacity benefits reach 47% with the extreme "3-Foot Higher and 2-Foot Wider" case. More modest high/wide alternative scenario capacity increases include: 18% for the "2-Foot Up" case, 21% for the "Maximum Dimension" case, 23% for the "2-Foot Up and 6-Inch Out" case, and 28% for the "2 Foot Up and 1 Foot Out" case. Overall, these "modest" high/wide car design scenarios provide for quite significant increases in capacity.

EASTERN NETWORK

Percentage Improvement in Operating Costs from Base Gondola ($ / 1000 NTM)

9.0%
8.0%
7.0%
6.0% — 3' Up & 2' Out, 2' Up & 2' Out
5.0% — 3' Up & 1' Out, 2' Up & 1' Out
4.0% — 2' Out, 2' Up & 6" Out, Maximum Dimension
3.0% — 2' Up, 3' Up
2.0% — 1' Out, 1' Up
1.0% — 6" Out, 39-Ton Axle Loads, 3-Axle Trucks, 42-Ton Axle Loads
0.0% — Base
-1.0%

0.0% 5.0% 10.0% 15.0% 20.0% 25.0% 30.0% 35.0% 40.0% 45.0% 50.0%

WESTERN NETWORK

Percentage Improvement in Operating Costs from Base Gondola ($ / 1000 NTM)

9.0%
8.0% — 3' Up & 2' Out
7.0% — 2' Up & 2' Out, 3' Up & 1' Out
6.0% — 2' Up & 1' Out
5.0% — 2' Up & 6" Out, 3' Up
4.0% — 2' Out, Maximum Dimension, 2' Up
3.0%
2.0% — 1' Out, 1' Up, 3-Axle Trucks
1.0% — 6" Out, 39-Ton Axle Loads, 42-Ton Axle Loads
0.0% — Base
-1.0%

0.0% 5.0% 10.0% 15.0% 20.0% 25.0% 30.0% 35.0% 40.0% 45.0% 50.0%

Percentage Increase in Train Capacity from Base Gondola
(Net Tonnage per Train)

X Higher and/or Wider + Other Alternatives

Figure 7-6: Gondola Scenario Operating Cost Savings versus Capacity

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7.2.2 39-Ton Axle Load Alternative Gondolas

The gondola scenario analysis indicated that the 39-ton axle load car design (with 36-inch diameter wheels) has higher operating cost savings than the base 36-ton axle load car. Even though this finding excludes bridge costs, which when considered do invert the result, it came as a surprise. Therefore, a 39-ton axle load high/wide car design investigation was undertaken in order to gauge the effectiveness of 39-ton axle loads versus 36-ton axle loads with respect to car designs with varying lengths. The result findings are summarized in Figure 7-7. The 39-ton axle load alternative results are quoted with respect to the 36-ton base gondola car and with respect to the respective 36-ton axle load alternatives of the same dimensions.

High/wide car design train capacity can be improved on the order of 2% by increasing axle loads to 39 tons from 36 tons. This is because, for a fixed car cross-section, the 39-ton axle load car designs are longer than the 36-ton car designs. Thus, there are fewer cars in a length-limited train with the higher axle loads and fewer gaps empty of lading located between cars. In the East, the operating cost benefits of the 39-ton cars are typically about the same to about 0.2% less than the equivalent 36-ton case. The cost improvements in transportation and other cost components by going to the higher axle loading are met with an equivalent or greater combined increase in track and car ownership costs.

In the West, the cost comparison results are more erratic. The high/wide 39-ton axle load cases generally offer about 1½% less cost improvement than the equivalent 36-ton case. However, in the "2-Foot Up and 1-Foot Out" case, the 39-ton car design showed a 0.1% cost improvement over the 36-ton design, but in the "2-Foot Up and 2-Foot Out" case, the 36-ton car design exhibits a 3½% cost improvement beyond the 39-ton case from the base. Even though the transportation cost benefits are greater in the West, the track cost increase is also greater, thereby decreasing total operating cost benefits in relation to the equivalent 36-ton axle load case.

The operating cost benefits quoted in Figure 7-7, of course, do not include bridge costs, which will serve to hinder the 39-ton axle load cases even further. Since, in most cases the 39-ton high/wide scenarios offer lower operating cost benefits than the equivalent 36-ton case, even excluding bridge costs, and because the incremental capacity benefit of the 39-ton versus the 36-ton scenarios is relatively minor, advancing to 39-ton axle loads is not recommended for high/wide car design. 39-ton axle loads might be an attractive option only if the economic implications of changing the 53-foot rotary dumper unloading constraint are overwhelming and additional system capacity is required.

The HAL analyses assumed heavier 38-inch diameter wheels and associated truck and axle components with the 125-ton car. The operating costs were found to be 0.6% higher in the East and 1.2% higher in the West for this car design than the base case. This cost differential from the 39-ton axle load car with 36-inch diameter wheels assumed for this analysis is due to two factors:

1) A 38-inch wheel set costs more in car ownership than a 36-inch wheel set.
2) A 38-inch wheel set weighs 1,800 pounds more than a 36-inch wheel set, thus reducing operating cost benefits stemming from net-to-tare benefits since each car holds less lading.

If it is necessary to use the larger wheels on the 53-foot 125-ton car, then the 10% capacity boost that this car design offers is less attractive in comparison to other capacity enhancing options.
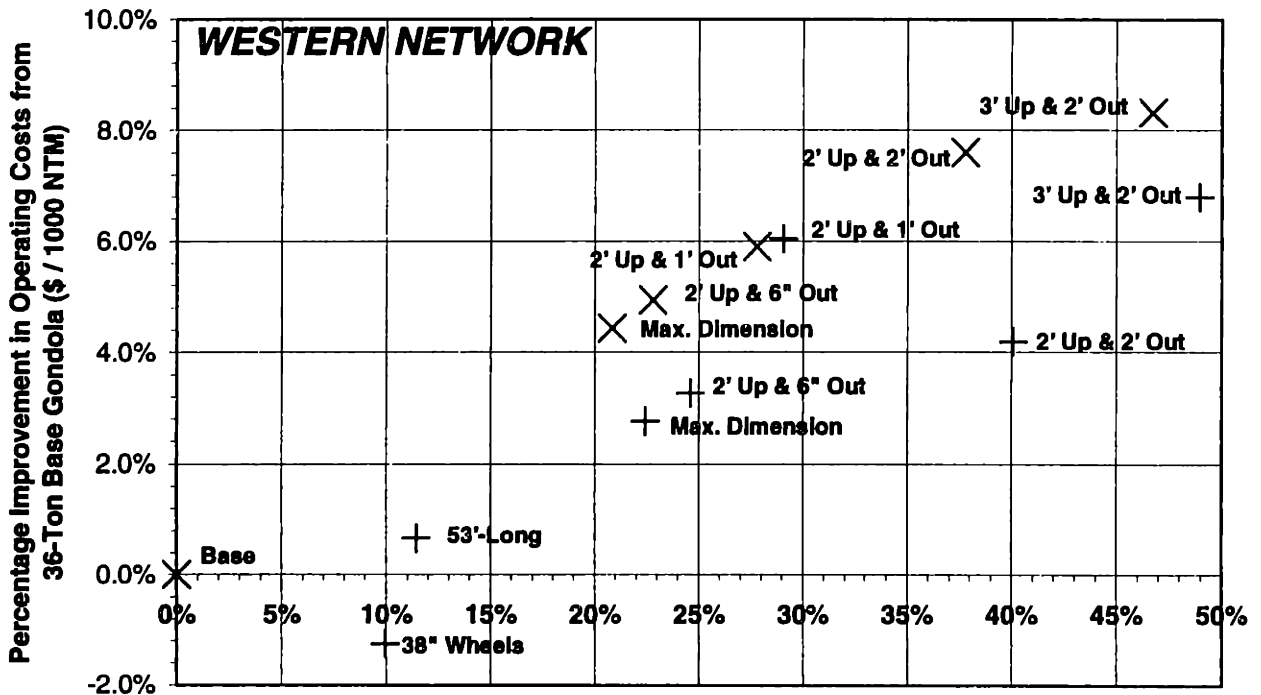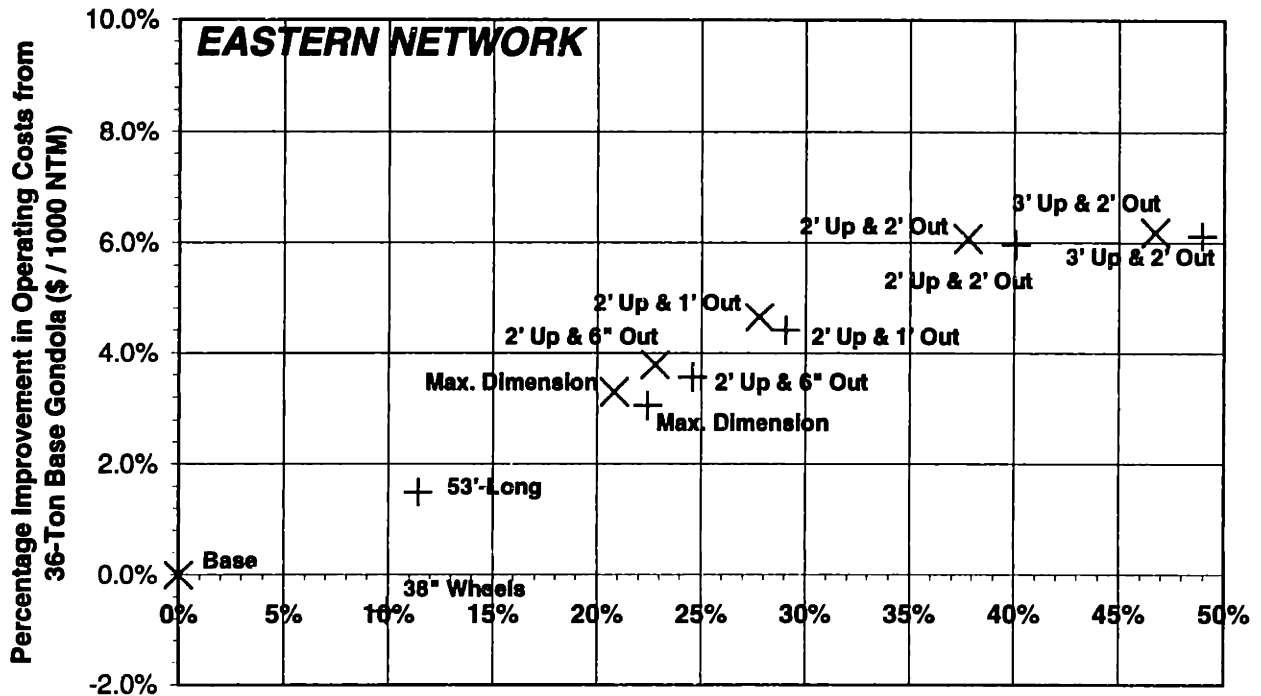
Figure 7-7: Gondola Scenario 36 - Ton versus 39 - Ton Axle Load Operating Cost Savings versus Capacity

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7.3 Hopper Scenarios

7.3.1 Basic Alternative Design Concepts

7.3.1.1 Operating Cost Benefit Comparison

A similar investigation to the gondola scenario analysis was conducted for the basic hopper car alternatives. High/wide, maximum dimension, heavier axle load and 3-axle truck alternative car design methodologies were applied to the base hopper car for both the Eastern and Western coal distribution networks. The operating cost benefit results of this investigation are portrayed in Figure 7-8. The benefits are quoted with respect to the base hopper car case. The base gondola case is also shown as a horizontal line across the bar chart, as this car design is more similar to the prior HAL analyses. The base gondola case is 6.6% more operating cost efficient in the East and 5.5% more efficient in the West than the base hopper case.

The base hopper is not as operating cost efficient as the base gondola for two reasons:

> 1) The gondola car has a lower tare weight than the hopper car.
> 2) The hopper car has higher car ownership costs than the gondola car.

The base gondola tare weight is 43,000 pounds. The base hopper tare weight is 53,500 pounds. The fact that the gondola car has a lower tare means that it is able to carry more coal for the same total gross weight. Thus, operations with the gondola car require fewer train and carloads to move the same volume total of coal. The greater hopper car ownership costs stem from a higher purchase price due to the heavier and more complicated hopper design which involves unloading doors and automatic rapid-discharge equipment. The car ownership costs are 23% higher for the base hopper case in the East and West than the base gondola.

Five results are readily apparent from viewing Figure 7-8:

> 1) All of the scenarios investigated exhibit operating cost savings over the base hopper.
> 2) The greater the car cross-section is increased, the further operating costs are decreased.
> 3) Only the most extreme hopper car cross-section increases can reduce operating costs to a level comparable to the base gondola case in the East.

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4) All alternative car designs are more cost efficient with respect to the base hopper in the West than in the East.

5) Longitudinal-door car design reduces operating costs beyond transverse-door car design, especially for high/wide car alternatives without a fixed length constraint.

The operating cost savings of the high/wide hopper car designs range from 4.1% for the "1 Foot Up" case to 7.5% for the "2-Foot Up and 2-Foot Out" case over the base hopper in the East. In the West, these same two cases offer savings of 5.2% and 9.8%, respectively, over the base. The Maximum Dimension car provides 4.8% savings in the East and 6.3% in the West.

The 3-axle truck car design has operating cost savings of 3.7% in the East and 4.9% in the West over the base case, which is better than this car design methodology fared in the gondola investigation. The 3-axle truck car design is relatively more effective as a hopper alternative than a gondola alternative due to the hopper scenario assumption of longitudinal doors and the associated benefits that this type of door design offers over the base hopper case.

The higher axle load scenarios are not attractive alternatives with respect to operating cost benefits in comparison to the other car design methodologies. This is especially true considering that there is not any unloading implementation cost for hopper cars since these cars do not need to be rotary dumped in order to be unloaded.

In all of the scenarios, the West benefits are larger in relation to the base than the East benefits. This is because the transportation costs comprise a larger portion of total operating costs in the West than in the East, as in the gondola analysis. This can be seen by analyzing Figure 7-10.

Longitudinal-door car design improves the operating costs of the base case by 1.1% in the East and 1.3% in the West. The base case assumes transverse doors. This operating cost benefit arises despite the fact that the car length is held constant at 53.1 feet. The operating cost improvements of the heavier axle load alternatives are even more dramatic by shifting to longitudinal doors. In all of these cases, the costs improve about 1½%, while holding the car length constant at 53.1 feet. The longitudinal-door car design was assumed to decrease car tare by 3,000 pounds. The fixed car length benefits cited above result from the consequent net-to-tare improvements and net weight increases.

The benefits from longitudinal-door design are even more profound when car length is not fixed. The longitudinal-door design improves cross-section utilization by reaching lower in the Plate diagram towards the rails. Increasing the volume of lading close to the rails increases the COG-limit allowing the car to reach a more extreme height before reaching the upper limit. Thus, a longitudinal-door car design may ultimately be higher than a transverse-door car design and can be higher before needing to install advanced-suspension trucks. Both the improved net-to-tare and cross-section utilization factors act to enable a shorter car design than would otherwise be possible with transverse doors for a given extreme car cross-section and gross weight. Therefore, more cars are able to fit in the length-limited train, increasing train capacity and decreasing train-miles. The crew costs are therefore reduced substantially.

The "6-Inch Up" transverse-door car design offers a 2% operating cost benefit per foot of additional height beyond the base in the East and about a 2½% benefit per additional foot in the West. The "1 Foot Up" longitudinal-door car design provides about a 4% operating cost benefit per foot of additional height beyond the base in the East and about a 5% benefit per additional foot in the West. The longitudinal-door car design doubles the operating cost benefit over the transverse-door benefits for high/wide alternative car design up to the COG-limit.
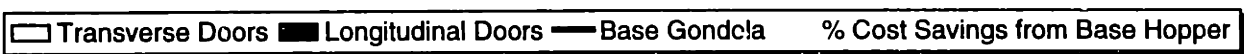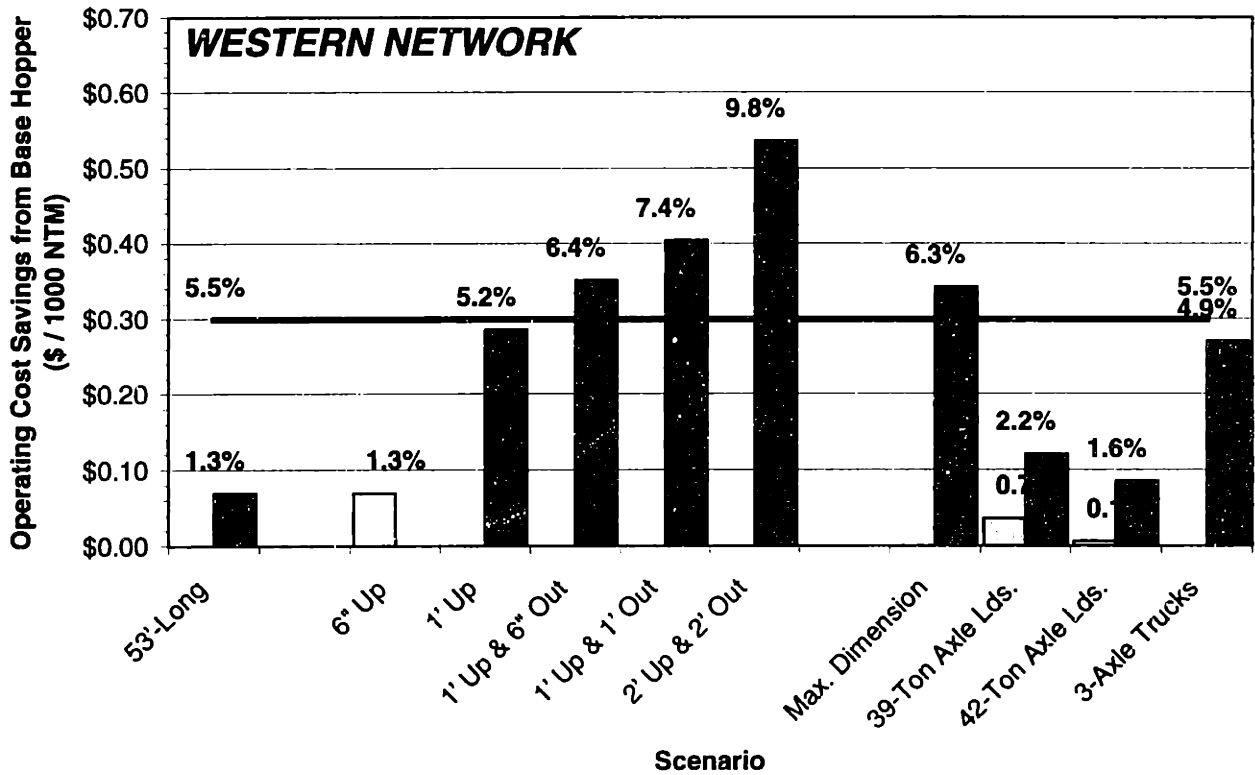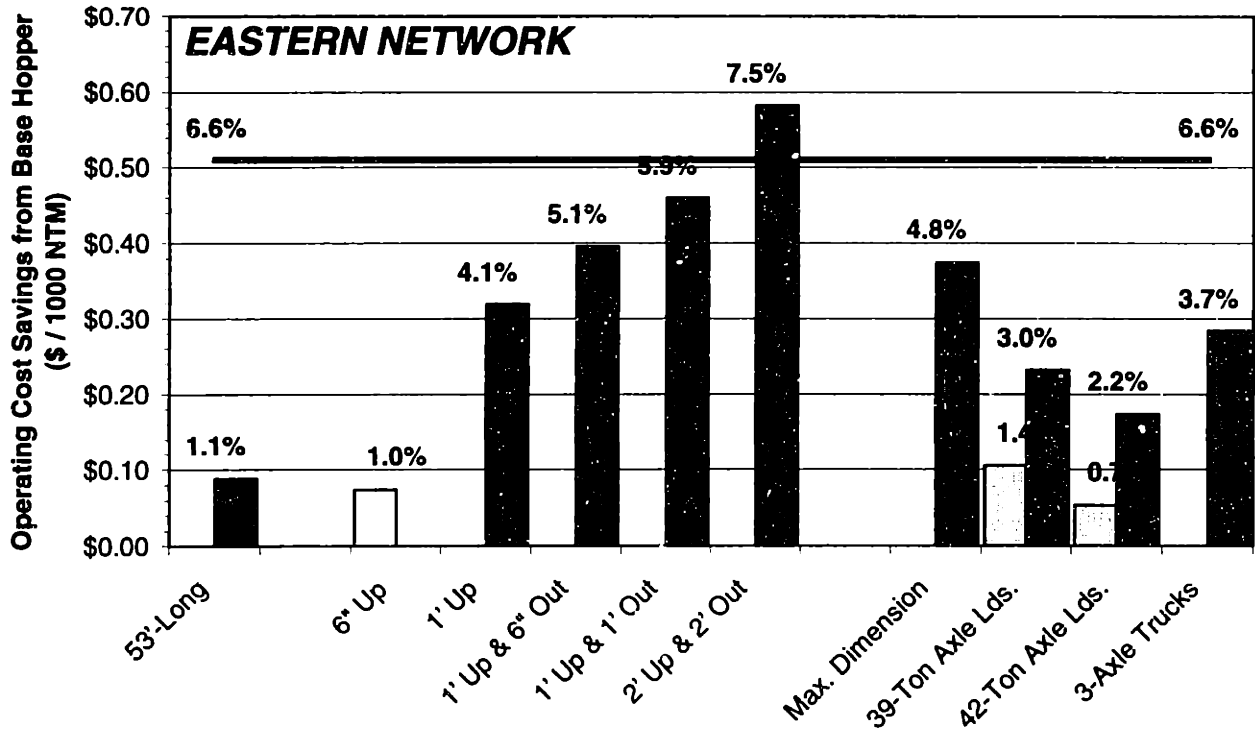
Figure 7-8: Hopper Scenario Operating Cost Savings

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7.3.1.2 Operating Cost Benefit Decomposition

Figure 7-9 depicts the changes in operating costs from the base case by cost component for the alternative hopper scenarios. As in the gondola scenario investigation, the majority of the cost benefits originate from crew cost savings. In the East, the second largest contributor to cost benefits is car ownership savings, as in the gondola analysis. In the West, the fuel cost savings are larger than the car ownership savings, contrary to the gondola analysis. This difference is due to two reasons:

1) Fuel costs are much larger with respect to car ownership costs in the West than in the East, as depicted in Figure 7-10.

2) There is a dramatic net-to-tare improvement brought about by longitudinal-door car design that affects fuel costs more than car ownership costs.

The dramatic net-to-tare improvements attributable to the benefits of longitudinal-door car design over transverse-door car design have a pronounced effect on fuel, track and other equipment costs. Thus, the relative benefits attributable to these cost components decreases the overall total share that crew cost savings have of total benefits. The net-to-tare benefit affects crew costs also, but due to the much smaller portion that crew costs compose of total operating costs in comparison to the sum of the other cost components, crew costs improve relatively less. As can be seen in Figure 7-10, in the East, crew costs compose of 9% of total costs while locomotive ownership and maintenance, car maintenance, track, and fuel costs sum to 69% of the total. In the West, the proportions are 16% and 71%, respectively.

The effect of the longitudinal dog-leg door design on car ownership costs is also beneficial, as demonstrated in Figure 7-9. The "53-foot dog-leg" case exhibits car ownership benefits from the base case, as do the 39 and 42-ton axle load dog-leg designs in relation to the respective transverse-door design. The car ownership benefit between the "1 Foot Up" case and the "6-Inch Up" case is also more drastic than is evidenced in the other high/wide alternative designs, which all have longitudinal doors.

Figure 7-10 illustrates the cost decomposition of the base hopper scenario by cost component for both the East and West cases. In the East, the locomotive ownership costs are the largest component, as in the gondola case, with 25% of total operating costs. The increased car ownership expense of the base hopper car relative to the base gondola increases car ownership costs enough in the East for this cost component to overtake track costs as the second-largest contributor to the total. The other cost components of the East case are mainly the same for the hopper base as for the gondola base – track costs exceed fuel costs

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which exceed crew costs which exceed car and locomotive maintenance costs which are about evenly matched.

In the West, the hopper operating cost decomposition is almost identical to the gondola cost decomposition. The rankings are virtually identical: track costs followed by a close grouping of crew, fuel, and locomotive ownership costs, followed by car ownership costs, and finally car and locomotive maintenance trailing the rest in an equal fashion. The only significant cost proportion change is the increase in car ownership versus the East.
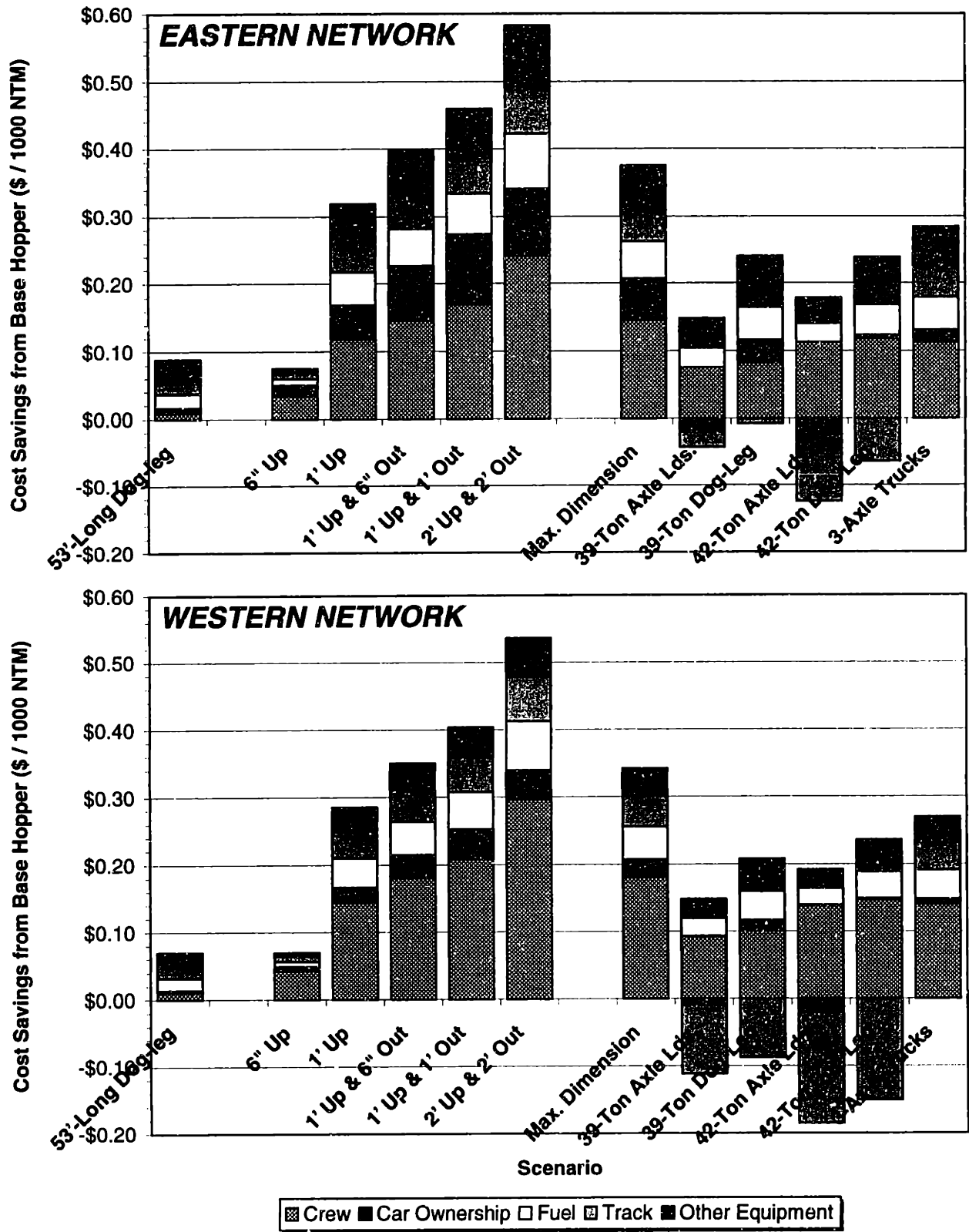
Figure 7-9: Hopper Scenario Operating Cost Savings Decomposition

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EASTERN NETWORK

Car Maintenance
6%

Track
19%

Car Ownership
22%

Crew
9%

Locomotive
Maintenance
6%

Fuel
13%

Locomotive
Ownership
25%

WESTERN NETWORK

Car Maintenance
8%

Track
22%

Car Ownership
13%

Locomotive
Maintenance
9%

Crew
16%

Locomotive
Ownership
16%

Fuel
16%
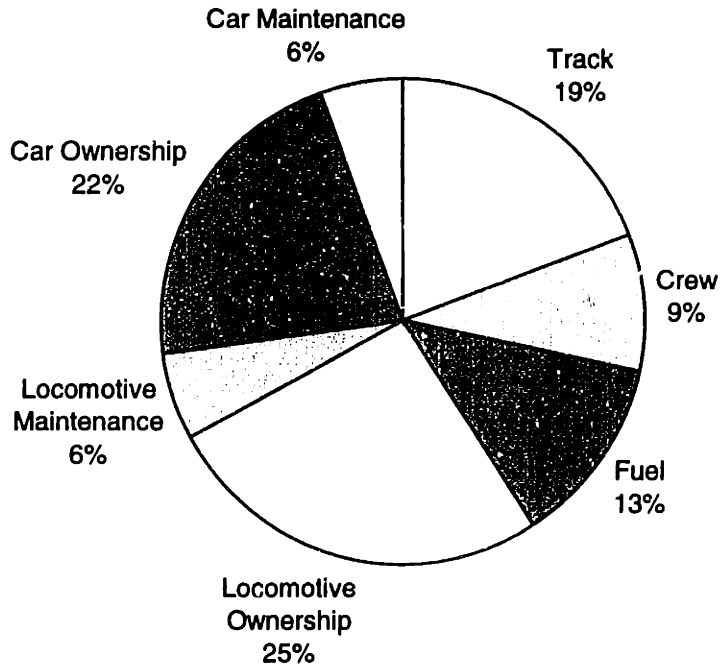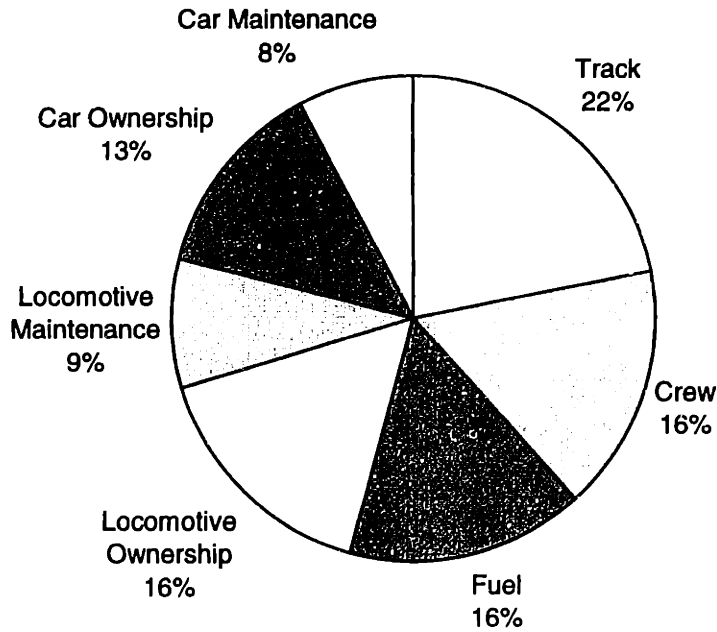
Figure 7-10: Base Hopper Case Operating Cost Decomposition

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7.3.1.3 Operating Cost and Capacity Benefit Comparison

The incremental cost and capacity benefits of each alternative car design over the base hopper case in both the East and West are summarized in Figure 7-11. The position of the base gondola with respect to the base hopper and hopper alternatives in cost-capacity space is also illustrated in the figure. The cost dimension results of this figure were summarized in the preceding Section 7.3.1.1.

The 53-foot dog-leg hopper design improves cost and capacity somewhat over the base hopper, but the design still does not even come close to comparing to the base gondola. The "6-Inch Up" transverse-door scenario has about the same level of operating costs as the 53-foot dog-leg design scenario, but has 5% more capacity than the base hopper, which exceeds the 3% premium of the base gondola case. In all three 53-foot long scenarios (base, 39-ton and 42-ton axle loads), a capacity boost of approximately 1% is apparent by switching to a longitudinal dog-leg door design from a transverse-door design.

Doubling the added height increment from the "6-Inch Up" to the "1-Foot Up" case should be expected to approximately double the capacity benefit, as was generally observed in the gondola scenario analysis. This, however, was not the case. Doubling the height increment provided a quadrupling of the capacity increment – double the expected result. This enhanced capacity benefit is due to the tare and cross-section utilization benefits of longitudinal doors over transverse doors. A longitudinal-door hopper car design provides double the incremental train capacity of a transverse-door design for the length-limited case when considering high/wide alternative car designs up to the COG-limit.

The "1-Foot Up" car design, which couples the COG-restricted height limit, offers a 19% incremental capacity boost over the base hopper case. The Maximum Dimension and "1-Foot Up and 6-Inch Out" cases both promote capacity 26% above the base case. The "1-Foot Up and 1-Foot Out" car design increases capacity 31%. At the most extreme cross-section investigated, the "2-Foot Up and 2-Foot Out" case, a capacity benefit of 50% is boasted.

An interesting difference of the hopper car analysis versus the results of the gondola analysis is that the 3-axle truck and 39-ton axle load cases are either on or very close to the bandwidth cost-capacity benefit path established by the high/wide car design methodology. This is made possible by the benefits of the longitudinal-door car design in relation to the base hopper. Both of these alternative options offer a significant capacity boost – 12 % in the case of the 39-ton axle load car and 18% for the 3-axle truck car. And both of these alternative options provide operating cost savings – 3% and 2% for the 39-ton axle load

car in the East and West respectively, and 4½% and 5% for the 3-axle truck car in the East and West respectively. Since these alternatives are hopper car designs, they are also not hindered by rotary dumper unloading implementation costs. Despite all of these attractions for these two hopper car designs, it is still apparent from Figure 7-11 that much more substantial operating cost and capacity benefits are relatively available by pursuing the high/wide car design methodology, as in the gondola case.
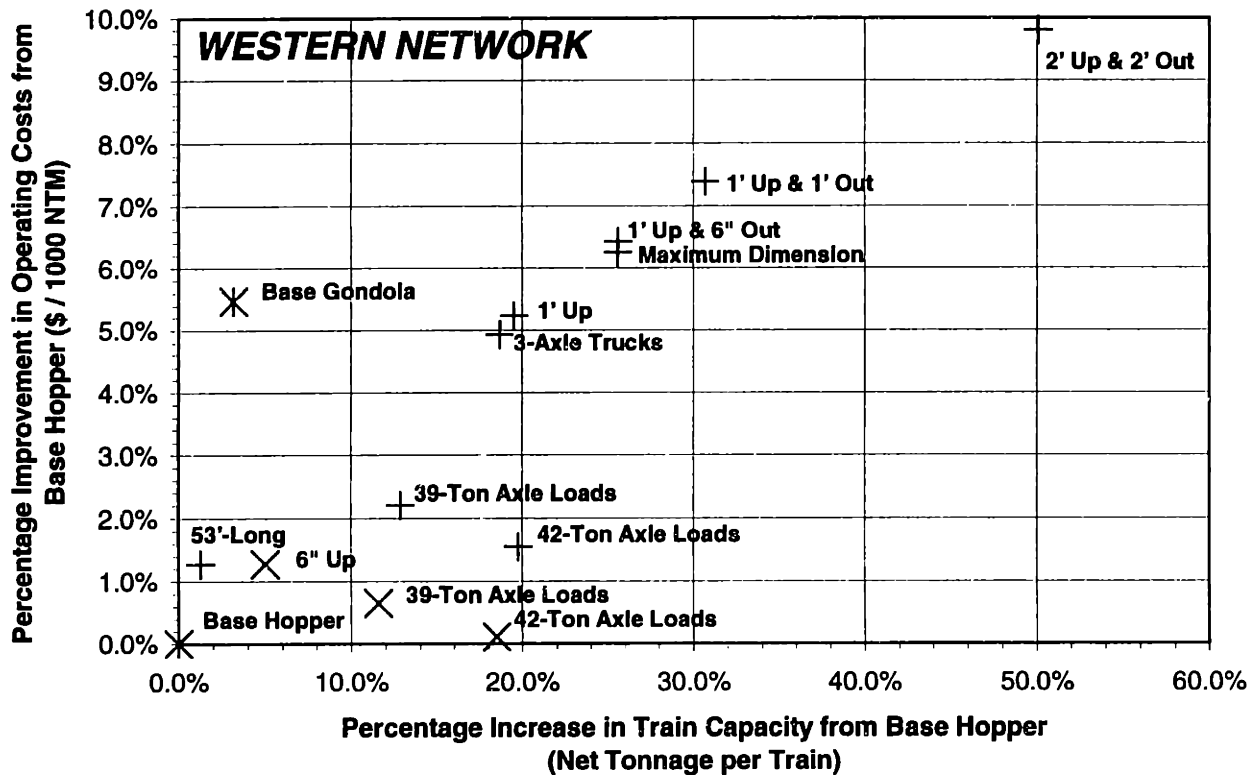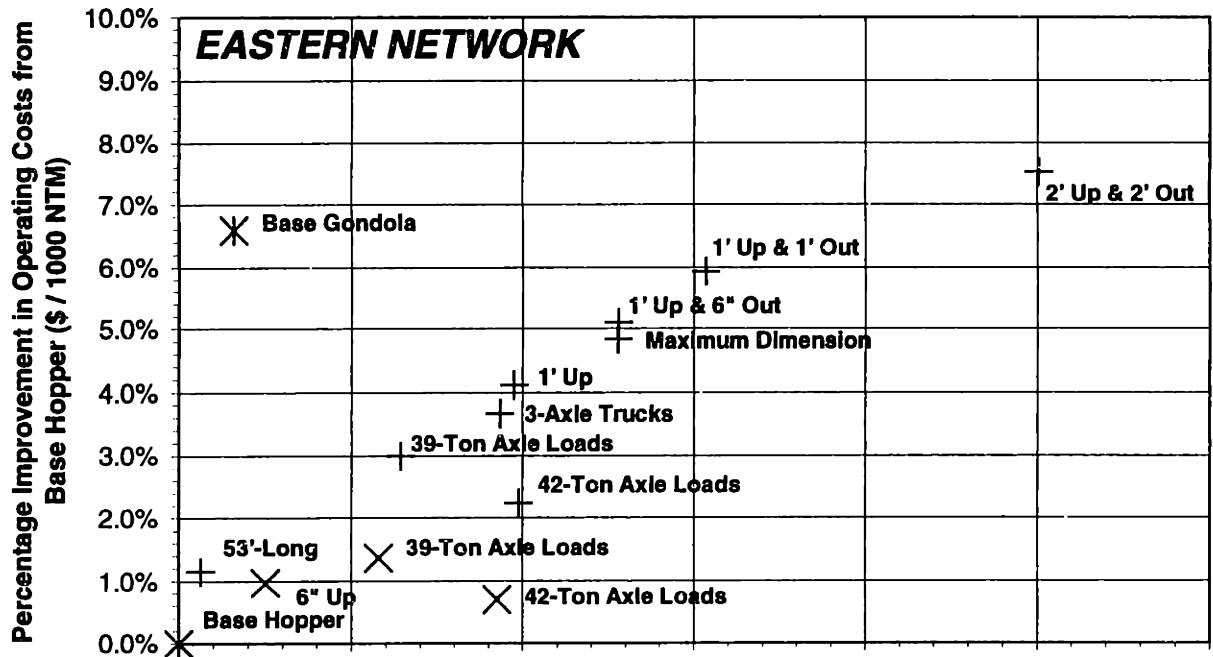
Figure 7-11: Hopper Scenario Operating Cost Savings versus Capacity

7.3.2 Manual-Discharge Hoppers

7.3.2.1 Operating Cost Benefit Comparison

The longitudinal dog-leg door design is one way to improve hopper car cost efficiency and capacity effectiveness. Another way to improve upon the base hopper design is to remove the automatic rapid-discharge equipment. The machinery that opens and closes the bottom-dump doors on a rapid-discharge hopper car is very costly and heavy. Removing this equipment improves line-haul operating costs in two ways:

- Reduced car ownership cost
- Reduced car tare

The automatic door operating equipment was assumed to cost an $8,000 premium above a manual-discharge bottom-dump door system. The equipment was also assumed to weigh 1,500 pounds. Removing this equipment from the cars was used as a method for increasing the car net capacity.

The major drawback to removing the unloading automation equipment from the cars is that the cars must be unloaded in a different fashion. There are two alternative unloading mechanisms for bottom-dump hoppers. Either wayside equipment must be installed that springs the doors open for unloading and shuts them again as the cars pass by or the doors must be opened and closed manually by personnel at the unloading site. The costs of instituting either of these unloading methods must be weighed against the improved line-haul operating costs from removing the automatic-dump equipment. The results of this sort of economic analysis will be very case specific. The manual-discharge design will appear more attractive for cases with higher levels of tonnage or longer average lengths of haul in which the line-haul operating costs are a more significant portion of the total cost.

Figure 7-12 displays the operating cost benefits of manual-discharge hopper car design with respect to the automatic rapid-discharge base hopper and in relation to the base gondola car. All of the alternatives depicted in this figure are dog-leg by design, except the very first case, entitled "Manual Discharge". This case shows that there is a 3.4% operating cost benefit in the East and a 2.3% benefit in the West, by switching from an automatic to manual-discharge 53-foot hopper car design. Combining the dog-leg design changes with the manual-discharge changes, while fixing the car length at 53 feet, further escalates the operating cost benefits to 4.5% in the East and 3.6% in the West.

For all of the high/wide and the 39-ton axle load alternatives, the operating cost benefits of the manual-discharge design are uniformly 3% in the East and 2% in the West over the subsequent rapid-discharge design. The benefits are larger in the East than in the West because they primarily stem from reduced car ownership costs and car ownership costs constitute 22% of total operating costs in the East and only 13% in the West.

The benefits of the manual-discharge approach are less for the 3-axle truck scenarios – only 2% in the East and 1½% in the West over the automatic-discharge design. This is because the car ownership cost savings were kept at a constant level over all of the alternative scenarios, regardless of car length. The 3-axle truck car is a much longer car than all of the other alternatives, thus these scenarios have fewer cars in a length-limited train, and there are therefore less total savings per train and overall.

The 42-ton axle load alternative was omitted from the manual-discharge analysis on account of its apparent undesirability in relation to the other alternative car designs from the results of the basic hopper and gondola car design investigations.

The operating cost savings of the high/wide alternatives in the East range from 7.3% for the "1-Foot Up" case to 10.6% for the extreme "2-Foot Up and 2-Foot Out" case. The Maximum Dimension car boasts operating cost benefits of 8%. All of these cases exceed the savings exhibited by the base gondola over the base hopper car. Combining the manual-discharge and dog-leg design innovations almost manages to enable the 39-ton axle load and 3-axle truck alternatives fare as well as the base gondola, from an operating cost standpoint. In the West, the high/wide alternatives all exceed the operating cost benefits of the base gondola in relation to the base hopper. At the modest end of the spectrum, the "1-Foot Up" case exhibits savings of 7.5%, while at the other extreme side of the high/wide car design cost benefit range, the "2-Foot Up and 2-Foot Out" case evinces savings of 11.9%. The Maximum Dimension car design portrays benefits of 8.3%. In the West, the 3-axle truck car design actually has operating benefits exceeding the base gondola car.
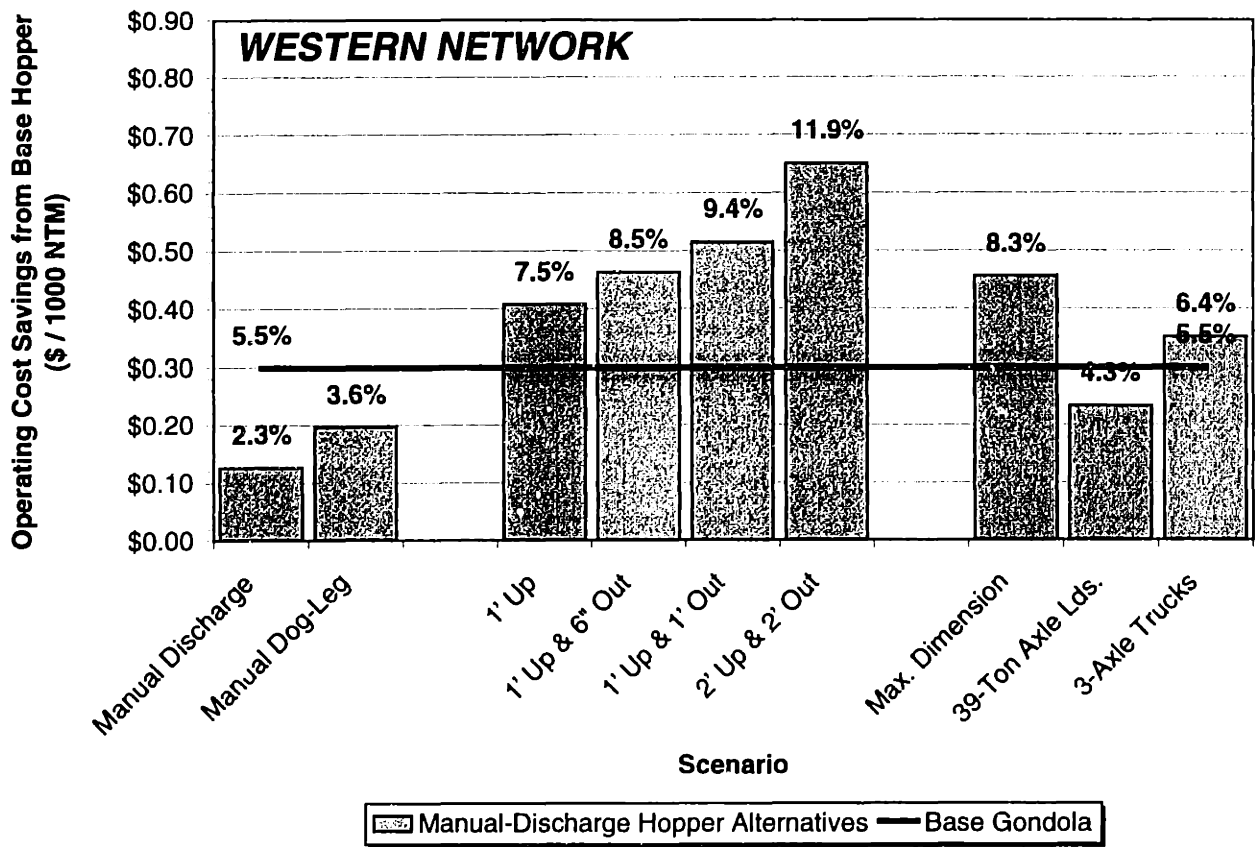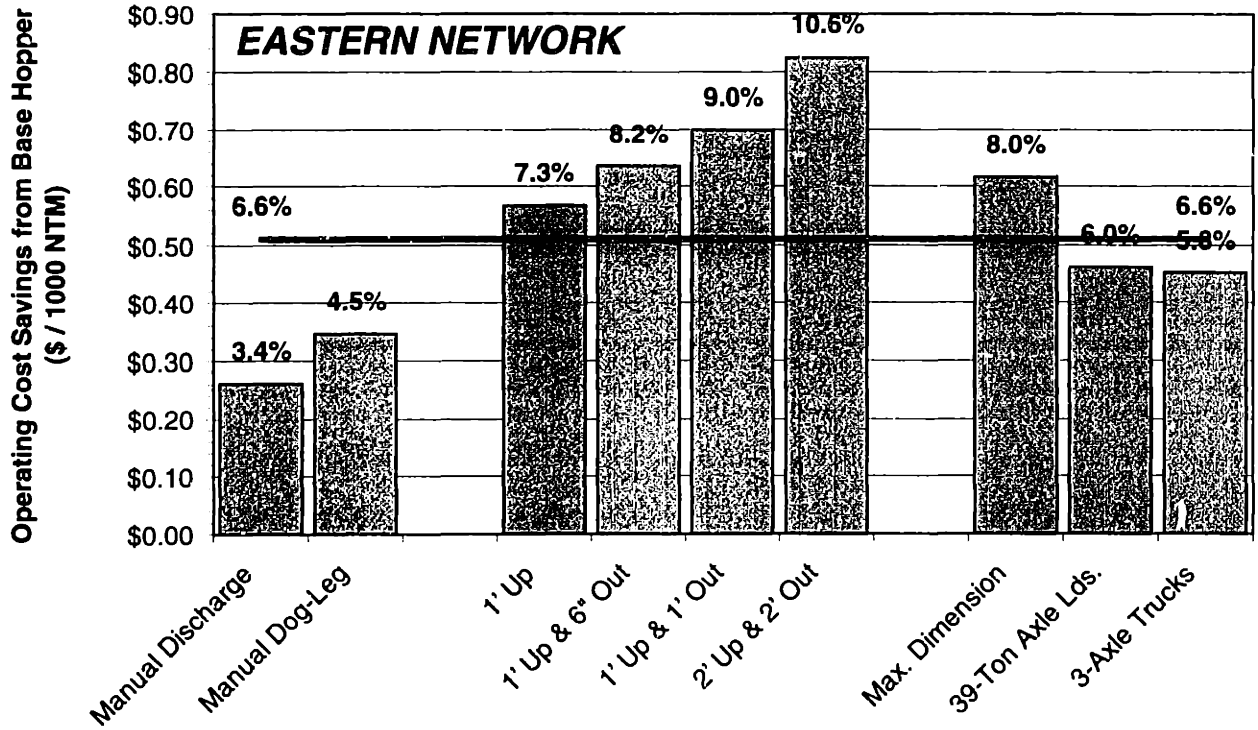
Figure 7-12: Automatic versus Manual-Discharge Hopper Scenario Operating Cost Savings

7.3.2.2 Operating Cost and Capacity Benefit Comparison

Figure 7-13 depicts the alternative manual-discharge hopper car design results in cost-capacity benefit space for both the East and West. The benefits are quoted in terms of percent improvement over the base hopper case. The results are also displayed in relation to the base gondola and the corresponding automatic rapid-discharge car designs for comparative purposes.

The uniform operating cost benefit boost between the manual and automatic-discharge car designs is readily apparent across all of the alternative car designs. This is evident in the figure from the two parallel alternative design bandwidths that cross cost-capacity space – the manual-discharge designs are located above the rapid-discharge designs.

The other striking result from Figure 7-13 is that the manual-discharge car design does not have a very significant impact on capacity. Almost all of the benefits of this design methodology are cost related. The manual-discharge car design increases train capacity between 0% and 2% above the subsequent rapid-discharge car design for all of the alternative scenarios considered.
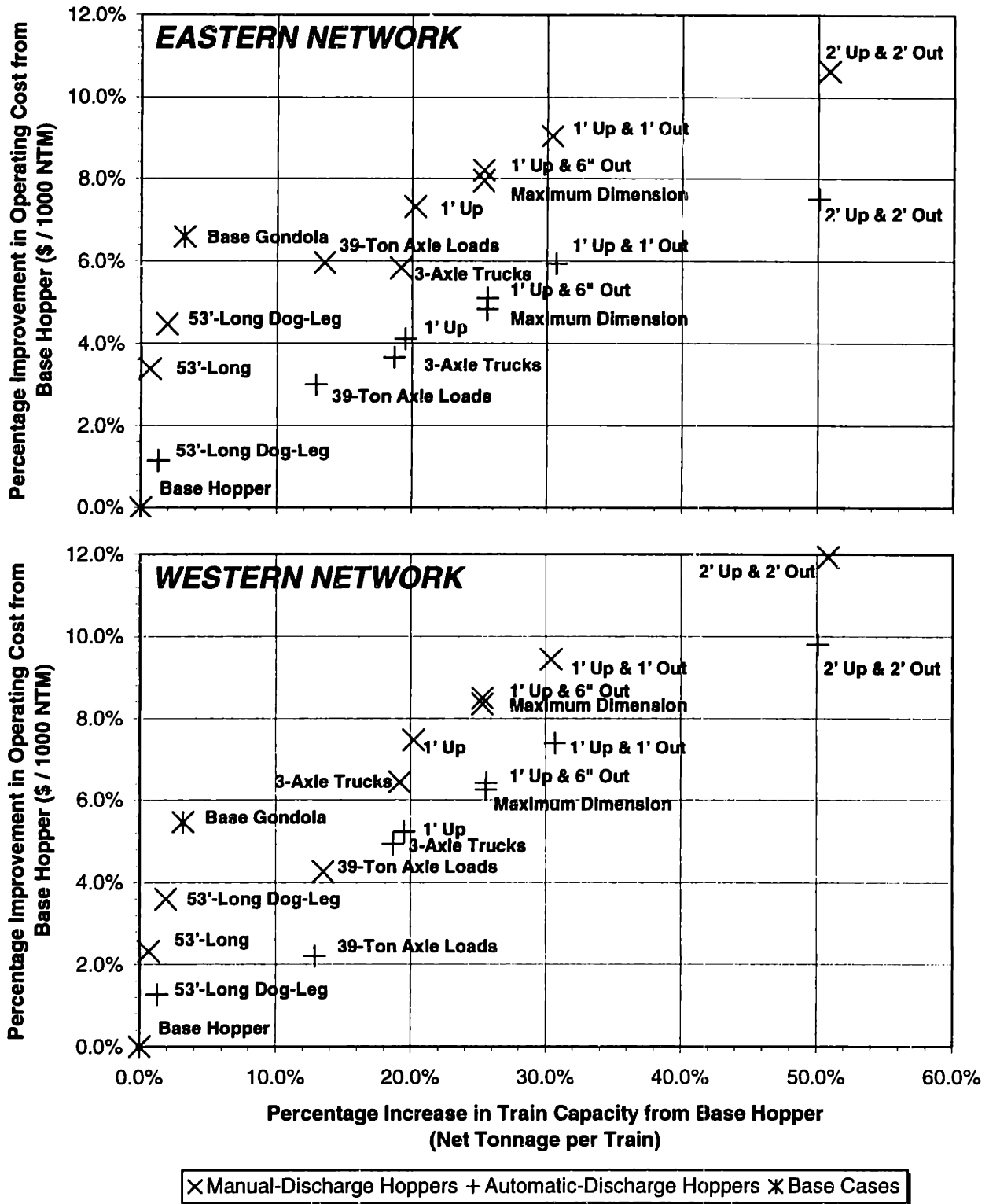
Figure 7-13: Automatic versus Manual-Discharge Hopper Scenario Operating Cost Savings versus Capacity

7.3.3 Articulated Hoppers

7.3.3.1 Operating Cost Benefit Comparison

The articulated car design offers vastly superior operating cost benefits and capacity enhancements beyond the base hopper car than any other alternative hopper design concept. The improvements are especially acute when applied on the base hopper extreme cross-section – without advancing to the high/wide design methodology. Articulating the base hopper car decreases operating costs 3.8% in the East and 5.5% in the West, as can be seen in Figure 7-14.

The benefits of articulation are compounded by combining this design concept with the longitudinal dog-leg door design. The articulated dog-leg base hopper car exhibits operating cost savings of 5.9% in the East and 8.7% in the West. These are 4.8% and 7.4% greater benefits from the base hopper than the stand-alone longitudinal-door design.

Adding the manual-discharge design idea to the dog-leg approach does not change the increment of improvement from incorporating the articulated design concept on the base case, but it does further escalate operating savings to 9.2% in the East and 11% in the West.

The hopper car operating costs can be improved beyond the base gondola cost level by keeping the base hopper extreme cross-section. Both the dog-leg and manual-discharge design concepts must be combined with the articulation in order for the hopper to improve upon the base gondola car cost level in the East, but the articulated design approach is enough to surpass the cost level of the base gondola in the West.

The operating cost benefits of the articulated hopper car design concept stem from four factors:

- Decreased car spacing
- Decreased tare
- Improved cross-section utilization
- Reduced car maintenance expenses

By articulating hopper cars, the distance between the coupler faces and the inside edge of the car box is essentially eliminated from each car. The cars are joined together by an articulated joint, thus eliminating the empty space over the couplers and the conventional coupling system. This amounts to 5.7 feet in the

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base hopper car instance. The cars are shortened substantially in actual fact in order to maintain the original axle loadings, since cars effectively share trucks under an articulated design. However, the car bodies may be extended over the articulated joints, thus effectively expanding the length available for lading. Individual cars are transformed into individual sections, or segments, of an articulated car.

The weight of an articulated joint is 1,500 pounds lighter than a conventional coupling system. This means that, for each pair of couplers that are eliminated, approximately 1,500 pounds of extra lading can be placed in the car – the amount of lading will actually be lower than 1,500 pounds since the car box must necessarily be expanded, or the car lengthened, in order to accommodate the extra lading.

Extra lading may also fit into a car section due to the fact that the long articulated car may be loaded as a single, long trough. The volume conventionally lost to the heaping of coal at the ends of each individual car is captured in an articulated car (except for the extreme ends of the articulated car). The gained volume of coal acts effectively as an improvement in cross-section utilization.

Buff and draft forces are reduced throughout a train by utilizing articulated cars. Also, coupling systems and the related components are high maintenance cost items for railroad equipment. Both of these factors work to reduce the maintenance costs of articulated cars. This maintenance cost benefit, however, was approximately equaled by a subsequent rise in car ownership costs as a result of reduced car availability. If one of the sections of an articulated car is bad-ordered, then the whole string of articulated cars must be removed from service for repair.

The end result of all of these benefits is a massive increase in length-limited train capacity and an equivalent reduction in the number of trains required to transport a specified volume of product. The reduced number of car-miles from the net-to-tare and utilization improvements and the greatly reduced number of train-miles from all of the improvements, especially the car spacing reduction, promote operating cost benefits for the hopper-based car design to a much higher level than the other alternative car design concepts. The operating cost benefits are more pronounced in the West than the East because most of the benefits emanate from transportation costs, which are a larger portion of total operating costs in the West.

All of the alternative car designs illustrated in Figure 7-14 are manual-discharge, longitudinal-door hoppers, except the "Articulated Base" and "Dog-Leg" scenarios. For the high/wide alternatives, articulation advances operating cost benefits an additional 2½ – 3% in the East and 4 – 4½% in the West

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beyond the basic manual-discharge dog-leg door benefit level. The benefits range from 10% in the East and 12.1% in the West for the "1 Foot Up" case to 13.4% in the East and 16.1% in the West for the "2-Foot Up and 2-Foot Out" case. One caveat of the "2-Foot Up and 2-Foot Out" case is that it has a gross linear load of 9,120 pounds per foot. This extreme level exceeds the design loads of even the most modern bridges; therefore this scenario is not practicably feasible.

The Maximum Dimension alternative furnishes cost savings of 10.4% in the East and 12.7% in the West. The 39-ton axle load alternative's savings over the base hopper are identical in the East and West at 10.3%. This level of benefits in relation to the high/wide alternatives is much higher than the 39-ton designs under any other car design investigations. The relative attractiveness (excluding the bridge impact, of course) of the articulated, 39-ton axle load hopper car design is mainly a peculiarity attributable to the parametric car design methodology. The longitudinal-door 39-ton car design does have an extreme height above the base hopper car, benefiting it in terms of increased train capacity, but the car ownership costs also benefited the articulated heavier axle load car design in relation to 36-ton axle load designs. This would probably not be the case in reality and is an unfortunate result of the articulated car design methodology exercised in this study. The 39-ton axle load scenario is therefore not as attractive a design option as the other 36-ton axle load alternatives.
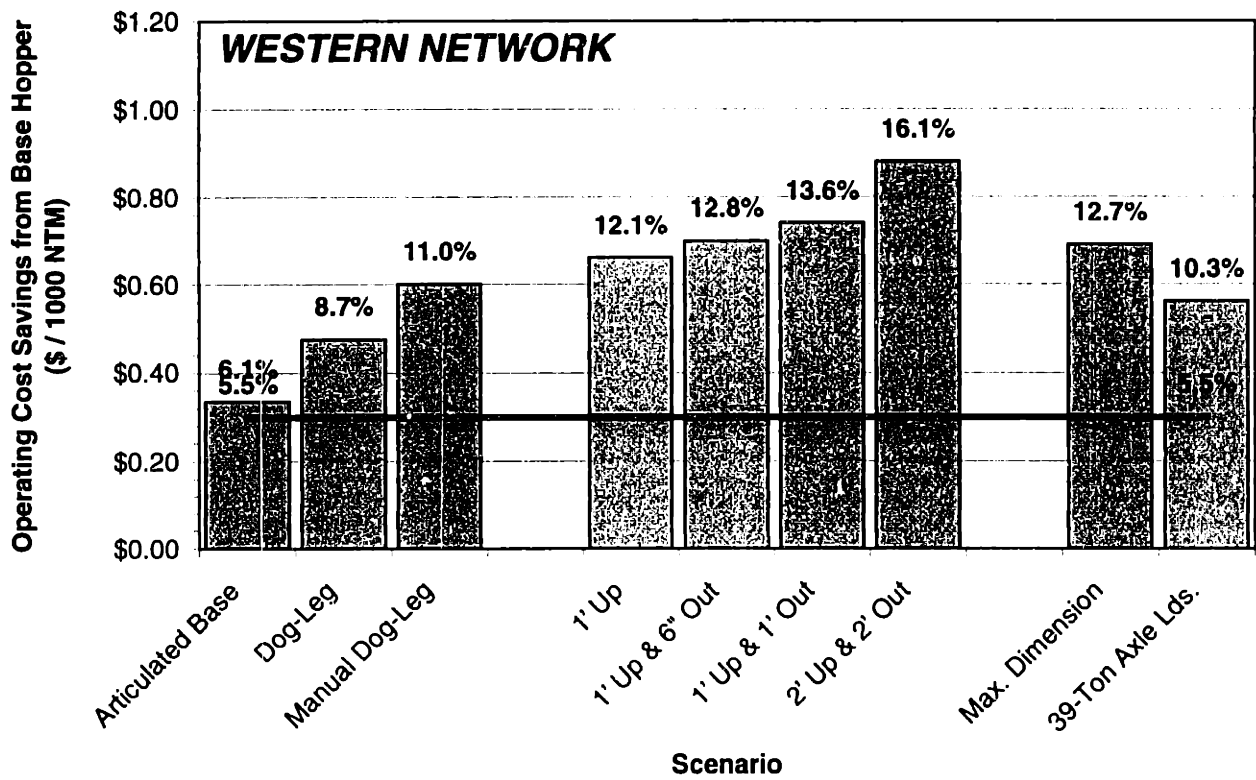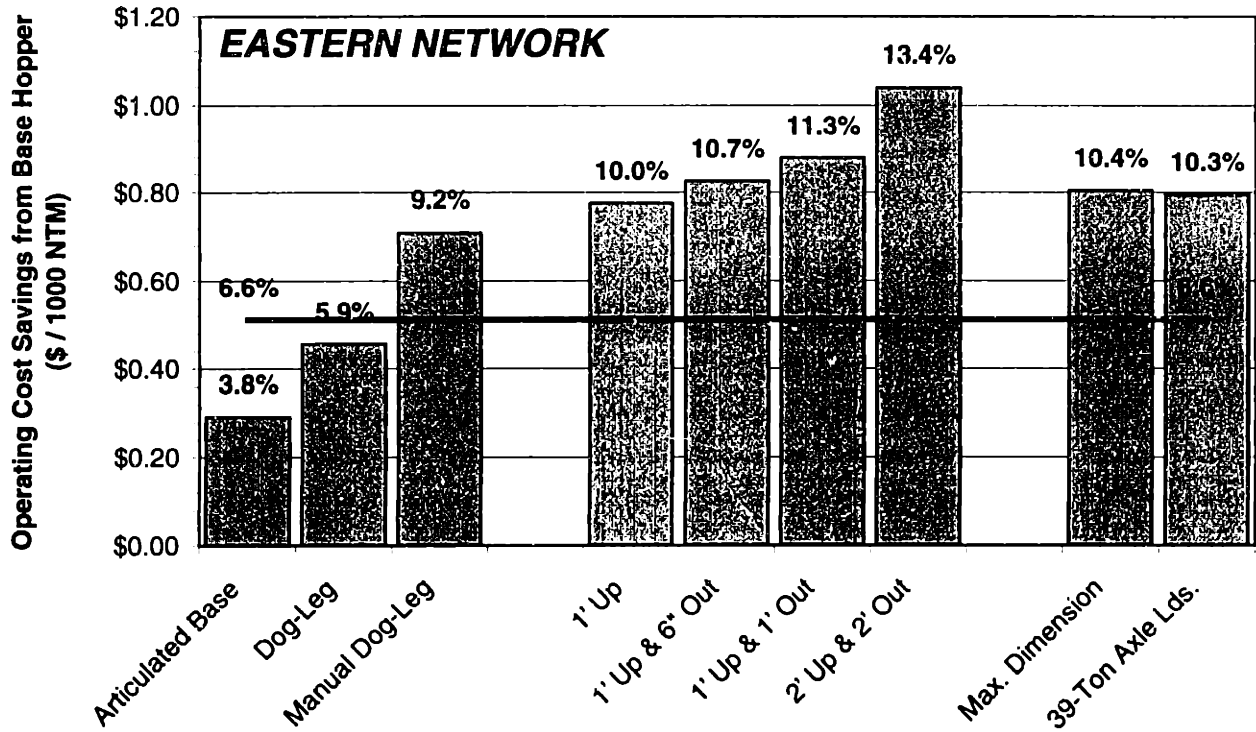
Figure 7-14: Articulated Hopper Scenario Operating Cost Savings

7.3.3.2 Operating Cost and Capacity Benefit Comparison

The cost benefits of the articulated hopper car design are striking; however, the capacity benefits are even more extraordinary. Figure 7-15 illustrates the cost savings and capacity enhancements of the articulated car design options investigated in relation to the base hopper car for both the Eastern and Western coal distribution networks. The cost and capacity results of the automatic and manual-discharge car design alternatives are also displayed on this graph for purposes of comparison to the articulated designs. It is extremely important to notice the difference in the horizontal axis scale of Figure 7-15 in comparison to the other cost-capacity diagrams. The maximum value is much higher in Figure 7-15. The vertical axis of Figure 7-15 is also more extensive than any of the other cost-capacity charts in presented thus far.

There are three especially notable results that may be observed from Figure 7-15:

1) The extraordinary capacity boost offered by the articulated design concept over every other design of the same cross-section.

2) The impressive increment of cost savings offered by the articulated design concept over the automatic and manual-discharge hopper car designs of the same cross-section.

3) The extreme improvement that is possible on the base cross-section by combining the manual-discharge and longitudinal-door design techniques with the articulated design concept.

Articulating the base hopper car boosts train capacity 26%. This capacity increase is comparable to the level capable of the Maximum Dimension and "1-Foot Up and 6-Inch Out" automatic and manual-discharge hopper car designs.

Incorporating the dog-leg door design improves capacity a further 10%, to a level 36% higher than the base hopper. This level of capacity is situated between the "1-Foot Up and 1-Foot Out" and "2-Foot Up and 2-Foot Out" automatic and rapid discharge hopper car designs. The cost level of the articulated dog-leg hopper car design in the East is slightly below the base gondola car and equal with the "1-Foot Up and 1-Foot Out" rapid-discharge hopper and the 39-ton axle load manual-discharge alternative. In the West, the level of cost benefits is situated between the "1-Foot Up and 1-Foot Out" and "2-Foot Up and 2-Foot Out" rapid-discharge scenarios and the "1-Foot Up and 6-Inch Out" and "1-Foot Up and 1-Foot Out" manual-discharge alternatives.

Adding the manual-discharge design option to the articulated, dog-leg, base hopper car increases capacity a slight 1% to 37%, but improves the level of cost savings much more significantly. The level of savings improve so that, in both the East and West, the articulated base car exceeds the benefits of any of the rapid-discharge car designs and lies between the "1-Foot Up and 1-Foot Out" and "2-Foot Up and 2-Foot Out" manual-discharge scenarios. This is a very attractive position for a modified base case in cost-capacity space.

The articulated car design concept is capable of increasing train capacity on the order of 80% above the base hopper for the most extreme cross-section considered. A capacity increase on the order of only 50% is possible with non-articulated concepts. This capacity enhancement does come with a major drawback – increased gross linear loading. The extreme high/wide articulated car design, "2 Feet Up and 2 Feet Out", offers a train capacity 79% greater than the base hopper, but at a gross linear load of 9,120 pounds per foot. As already mentioned in the previous section, this exceeds the 8,000-pound per foot design load of modern bridges, as recommended by AREMA, and is therefore not practically feasible. This linear loading is 69% greater than the base hopper value of 5,390 pound per foot. The increase is less than the train capacity increase due to the improved net-to-tare of the articulated design over the base. The increase in net linear load equals the increase in train capacity at 79%.

The "1-Foot Up" articulated car design offers a capacity increase of 45% over the base hopper and a GLL of 7,480 pounds per foot. The articulated Maximum Dimension scenario offers a 49% capacity boost over the base hopper, which is comparable to the most extreme high/wide design alternatives of the automatic and manual-discharge hopper cars. The amazing fact is that this level of capacity is possible without exceeding the bounds of Plate C. The "1-Foot Up and 1-Foot Out" articulated design offers approximately the same capacity as the Maximum Dimension design. The GLL of these options is around 7,660 pounds per foot. There will be a capacity and operating cost benefits tradeoff with bridge costs that merits a much more detailed investigation of the promising articulated hopper design concept.
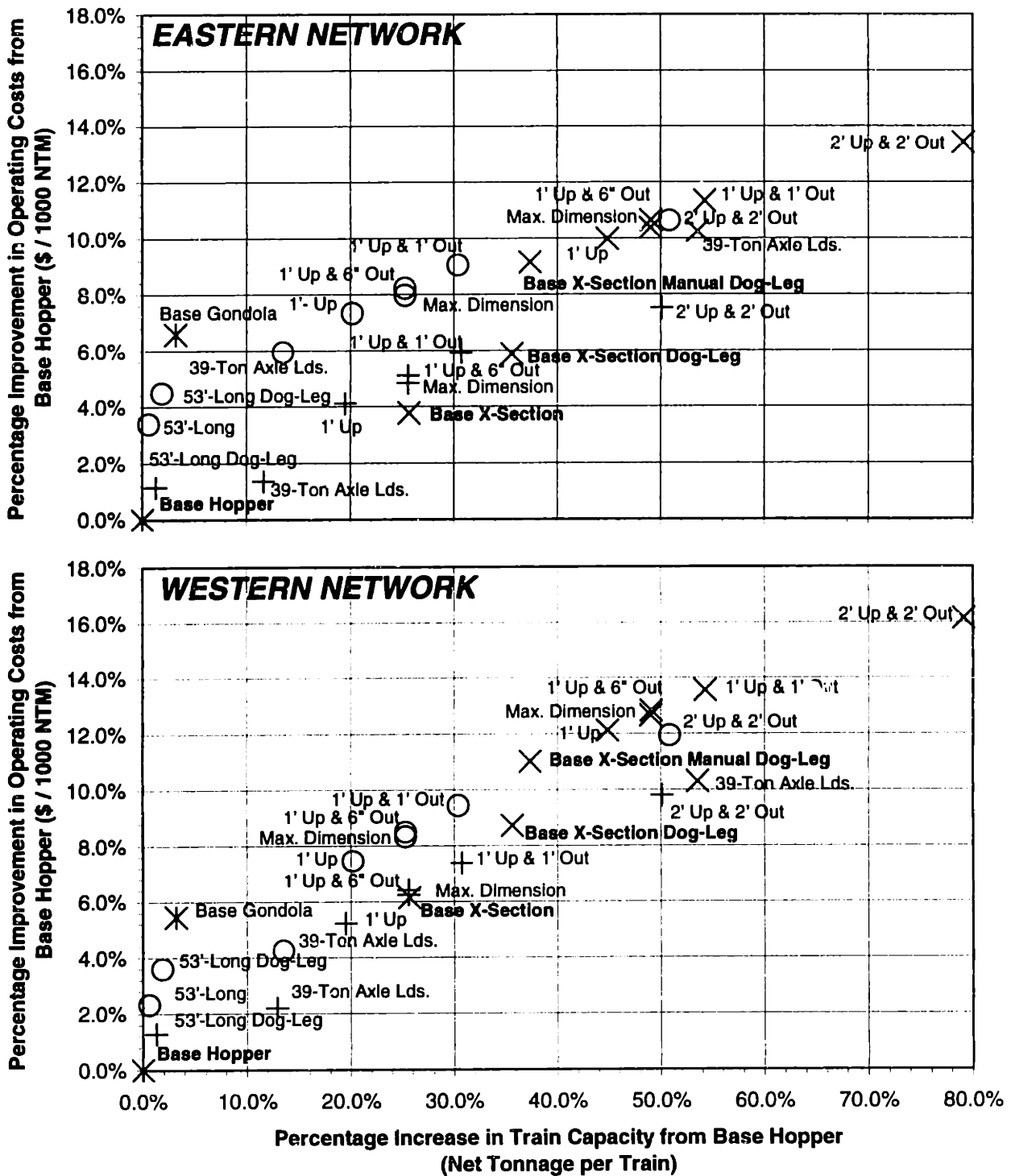
Figure 7-15: Articulated versus Other Hopper Scenario Operating Cost Savings versus Capacity

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7.4 Operating Cost Sensitivity Analyses

The operating cost results attained in this study, outlined in the previous sections of this chapter, are very sensitive to many of the equipment and operating assumptions and to the parametric design methodology. Six specific operating cost sensitivity analyses were conducted as a part of this study, entailing the following parameters:

- Train make-up assumption – length-limited versus weight-limited
- Cycle time / network congestion
- Car ownership costs
- Car spacing and coupling system
- Equipment net-to-tare ratio
- Cross-section utilization

The first factor is paramount in determining net train capacity for alternative vehicle designs. The second factor, cycle time, is extremely important in determining equipment costs. The car and locomotive ownership costs vary directly with the average velocity of the equipment cycle. Equipment ownership costs account for approximately 45% of total operating costs in the East and 30% of total costs in the West. The third parameter, car ownership cost, was typically the second largest cost component contributing to operating cost savings. The car ownership costs were also not very well established in relation to many of the other cost factors. Therefore, the cost results are very sensitive to the specific assumptions that were employed in determining the alternative car designs. The final three parameters are instrumental in determining capacity by means of train density, as measured by net linear load. Cost efficiency is directly related to train capacity as governed by train density.

With the exception of the train make-up and cycle time investigations, the sensitivity analyses were only conducted on the East gondola car scenarios. The base gondola car is the main base case of this study due to its superior line-haul operating cost and capacity performance over the base hopper car and due to its similarity to the base cases of the prior HAL research versus the hopper car design. The sensitivity analyses were conducted only on the East and not on both the Eastern and Western networks because the purpose of these analyses was only to identify the parameters and assumptions most critical in estimating operating costs. Determining the relative order of magnitude of the effects from changes in each of the

key parameters was adequate for a parametric analysis. An investigation of one network was deemed satisfactory in order to suit the needs of the purposes of the sensitivity analyses.

The operating cost sensitivities are quoted in three fashions. Within the figures, the magnitudes of the sensitivities are measured in absolute terms – dollars per 1000 net ton miles. The magnitudes of the sensitivities are also gauged with respect to the base case cost. These percentages are depicted in the figures and discussed in the text. Finally, in the discussion of the sensitivity results, the relevance of the sensitivity range is also quoted in relation to the cost saving improvements of each case. The percentage change in the level of the savings is given with respect to the level of the original cost savings of the primary analysis.

7.4.1 Length-Limited versus Weight-Limited Train Sensitivity Analysis

7.4.1.1 Operating Cost Benefit Comparison

An important caveat of this study is the length-limited train assumption. The operating cost and capacity benefits are greatly reduced for weight-limited trains. Figure 7-16 depicts the operating cost savings for the key alternatives considered in the gondola car analysis for both length-limited and weight-limited train assumptions. For the high/wide scenarios, the weight-limited operating cost benefits range from about 30% to 45% as great as the length-limited benefits in the East and from 15% to 30% as great in the West.

In the East, 50 – 70% of the operating cost benefit differential is due to differences in crew cost savings, 20 – 40% is due to differences in fuel cost savings and about 9% is due to track cost savings differences. The equipment costs are almost perfectly independent of the train make-up assumption because both cases require the same number of total car-miles and car-days and locomotive-miles and locomotive-days due to the locomotive multiplier assumption. The number of train-miles is all that differentiates the length and weight-limited cases, in terms of these cost-driving statistics. Since transportation costs are the cost components most sensitive to train-miles, they compose over 90% of the total differential in all cases.

In the West, 70 – 80% of the operating cost benefit differential is on account of differences in crew cost savings. 10 – 20% of the differential is due to differences in fuel cost savings and 4 – 8% is due to track cost savings differences. Again, equipment costs exhibit no appreciable change between length and weight-limited train cases. The crew cost differential accounts for a greater portion of the total operating

cost differential in the West than in the East because crew costs account for 17% of total operating costs in the West and only 10% in the East. The importance of the track cost differential is less in the West than the East because track accounts for about 20% of total operating costs in both regions, while fuel costs, which are much more sensitive to the train make-up assumption than track costs, comprise 16% of the total in the West and only 13% in the East. The effects of the train make-up assumption on operating cost benefits are more pronounced in the West than in the East because transportation costs account for more of total operating costs in the West.

The heavier axle load and 3-axle truck alternatives are more adverse to the train make-up assumption than the high/wide alternatives in Figure 7-16. In the heavier axle load and 3-axle truck cases, the crew cost differential composes less of the total differential and the fuel cost differential composes more. Without the train-mile and crew cost benefit, as in the weight-limited case, the operating costs increase in relation to the base case for all of these alternatives, except the East 39-ton case. This is because none of these alternatives enjoys a significant car ownership advantage over the base case; in fact, the 42-ton and 3-axle cases suffer from a car ownership cost increase. Therefore, the operating cost benefits are more dependent upon the crew cost reduction. The heavier axle load scenarios also suffer from a track cost increase over the base case. Eliminating most of the crew cost benefit by assuming weight-limited, instead of length-limited trains, therefore has a more adverse effect on the overall level of operating cost benefits versus the base case.
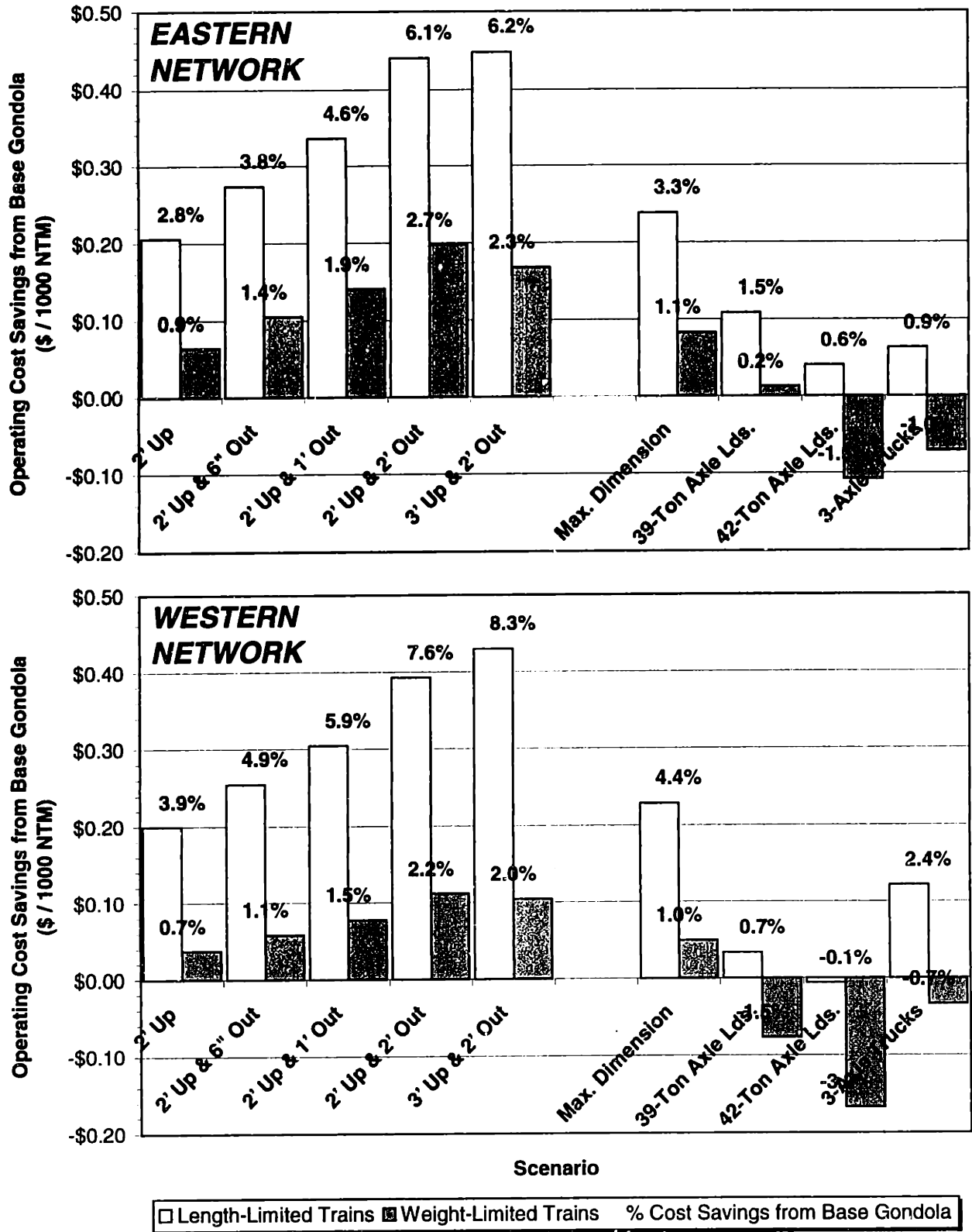
Figure 7-16: Gondola Scenario Length-Limited versus Weight-Limited Train Operating Cost Savings

7.4.1.2 Operating Cost and Capacity Benefit Comparison

Figure 7-17 illustrates the impedance imposed by weight-limited trains on the alternative car design methodologies investigated in this study much more dramatically than in Figure 7-16. The alternative cases are much more tightly packed about the base case (origin) assuming weight-limited trains than assuming weight-limited trains. The incremental capacity boosts of all of the alternative cases are effectively eliminated under the weight-limited train make-up assumption. This explains the close proximity of all of the weight-limited alternatives to the vertical axis. The largest capacity increase is less than 2% for weight-limited trains, but was 47% for length-limited trains.

The slight capacity enhancement that exists in the weight-limited case is attributable to the net-to-tare improvements of the alternative car designs over the base case. Each car holds more coal and there are the same number of cars per train as the base case (because the gross weight of each car is the same) for all scenarios but the heavier axle load and 3-axle truck alternatives. These alternatives will have fewer cars per train than the base case since the cars are heavier, but will also have approximately the same total gross train trailing weight.

The 3-axle truck case actually exhibits a capacity reduction versus the base for the weight-limited case. The 3-axle car does have a slightly better net-to-tare ratio than the base, but the cars are very long and hold a large volume of coal each in relation to the other alternatives. Due to the fact that there must be an integer number of cars in a train and the inflexible nature of the weight limit, the net train capacity declined for this specific case. The train, with one additional car, exceeds the maximum allowable weight limit. In other words, this result is a peculiarity due to the assumptions inherent in the analysis.
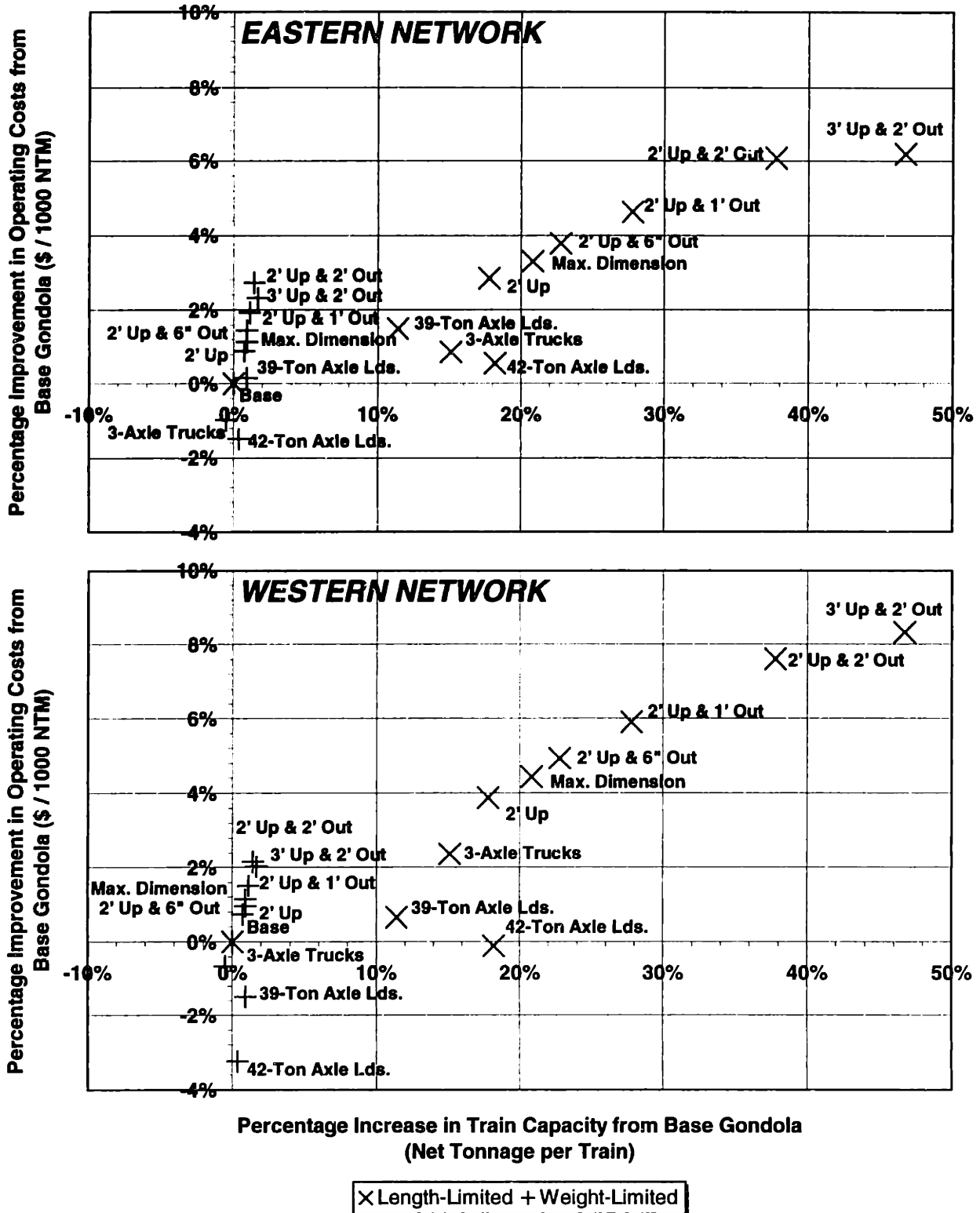
Figure 7-17: Gondola Scenario Length-Limited versus Weight-Limited Train Operating Cost Savings versus Capacity

7.4.2 Cycle Time Sensitivity Analysis

In moving from the gondola base case train to trains with cars of alternative designs with increased capacity, fewer train sets are required to meet the same demand (assuming length-limited trains), for two major reasons:

1) Each train holds more coal, so even if each train set has the same cycle time, fewer train sets are required.

2) Removing train sets from the network reduces congestion at bottlenecks, 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.

If a network is near capacity, then operating fewer, but heavier trains can have a compound effect on the number of train sets required in length-limited operations due to the presence of the second factor effecting cycle time. However, if the additional train capacity is created by increasing axle loads, such as in the 39-ton axle load alternative, maintenance requirements increase, causing additional track closure, and potentially more train delay, which increases cycle time.

The gondola base case cycle time of the Eastern network is much different from the Western network because of the different distances, track conditions, presence of other traffic, and network structures. The Western network is closer to operating at capacity. Both the East and the West were modeled in this sensitivity analysis because of the vast differences between the two networks and because of the importance of the network effects on cycle time discovered in the Optimal Axle Load study. In the Optimal Axle Load study, the network congestion effect on cycle time boosted operating cost savings on the order of an additional 4 – 6% in relation to the base case [1].

The results of this study assumed that cycle time was constant across alternative cases. Three gondola and two hopper scenarios were analyzed by re-running the UTRAIN model for each specific scenario in order to determine the exact cycle time given changes in train capacity and the number of trains required to transport the total net tonnage. Cycle times were reduced up to 5.5% in the East and 7.2% in the West for the scenarios explored. The West is more sensitive to changes in train capacity because the Western network operates closer to capacity, so a reduction in the number of train sets has more effect on bottleneck congestion alleviation. A reduction in cycle time reduces equipment (car and locomotive) ownership costs.

Figure 7-18 illustrates the additional operating cost savings in relation to the East and West base gondola cases from reductions in cycle time. Even though the cycle time reduction is larger in the West than for the respective East case, equipment ownership costs are a much more significant portion of total operating costs in the East than the West, so the Eastern operating costs are more sensitive to changes in the cycle time. The additional operating cost benefits from reductions in cycle time vary from 0.3% to 2.5% in the East and from 1% to 1.9% in the West. The Maximum Dimension and 39-Ton Axle Load cases have more of an effect in the West than the East because the cycle time reduction of these cases is much more significant in the West than the respective East case. The congestion relief at network bottlenecks in the West is very sensitive to moderate reductions in cycle time.

The base hopper case operating costs are negatively affected 0.6% in the East and 0.3% in the West. The base hopper car holds less net tonnage than the base gondola due to its heavier tare weight. Thus, the number of train sets required for the base hopper case increases from the base gondola case, which invokes an increase in network congestion and cycle time.

Overall, the level of operating cost savings is very sensitive to the cycle time assumption and the effects of network congestion. The Eastern gondola high/wide case operating cost benefits are improved an additional 35 – 50% over the base gondola and 30 – 35% in the West. The benefits of the 39-ton axle load case are improved an additional 20% in the East and are doubled in the West. The articulated hopper benefits over the base hopper are increased on the order of 25% in the East and 15% in the West.
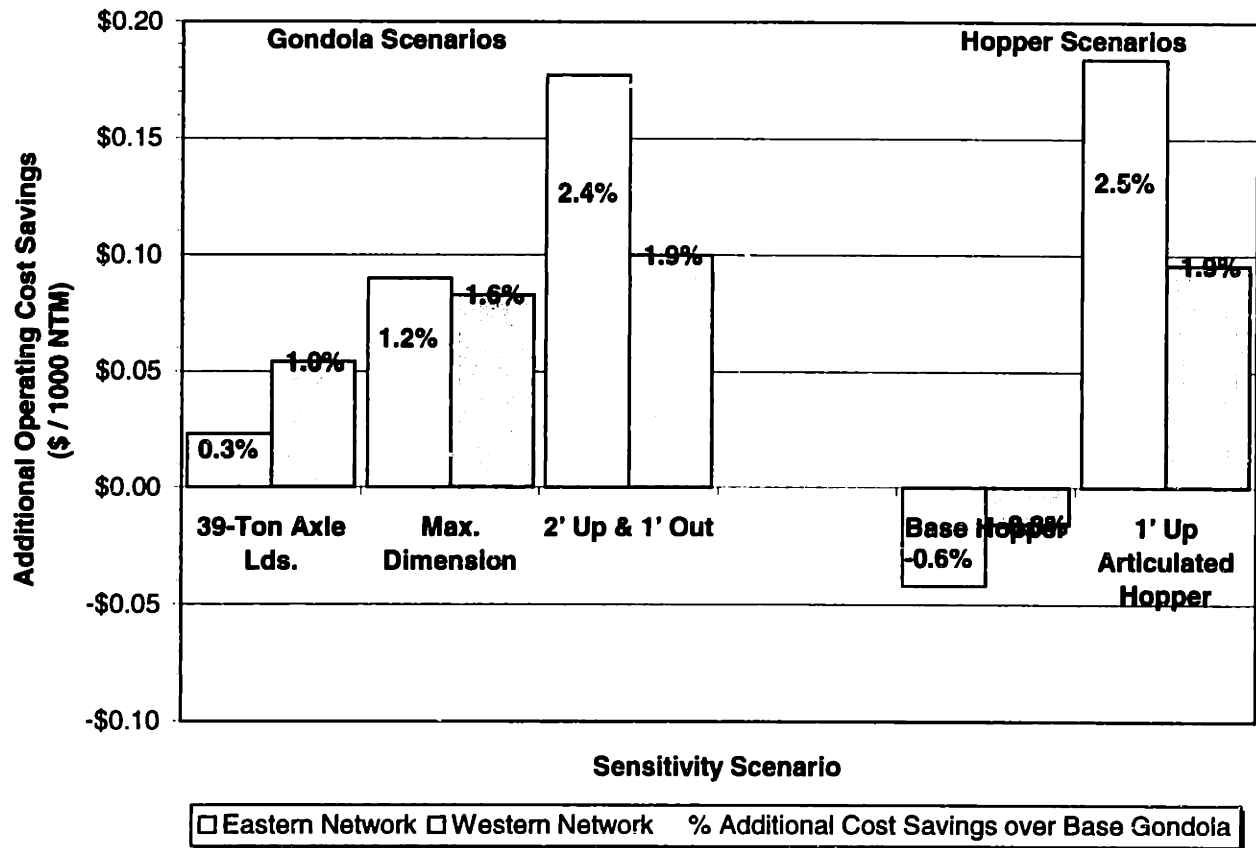
Figure 7-18: Eastern and Western Cycle Time Operating Cost Sensitivity

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7.4.3 Car Ownership Cost Sensitivity Analysis

Car ownership costs are the second largest cost component in the East gondola base case, constituting 19% of total operating costs. In the West, car ownership accounts for 11% of the total costs. The proportions are even greater for the rapid-discharge base hopper cases. The car ownership costs were, unfortunately, not as well established in relation to many of the other cost factors. Car ownership data is very inconsistent in that car costs vary widely depending upon many extraneous factors for each purchase order – market supply and demand, order size, et cetera. Therefore, the cost results are very sensitive to the specific assumptions that are employed in determining the alternative car designs.

Figure 7-19 depicts the operating cost sensitivity to a range of car ownership cost assumptions for the high/wide, Maximum Dimension and 3-Axle Truck cases. The conservative car ownership value results from the assumption that car ownership does not vary with the dimensions of the car for a majority of cases with shorter lengths than the base case. The optimistic car ownership value results from assuming that the car ownership varies directly with the extreme length of the car, as in the Optimal Axle Load study [1], regardless of the car cross-section.

The car length adjustment factor was set to the same value as was used in the Optimal Axle Load study [1]. 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 in the prior study, as it resulted in approximately equal initial costs for the 100-ton car and a car with 2-axle trucks, 36-inch wheels and the 125-ton car cross section, shortened to accommodate 33-ton axle loads. In this study, eliminating a foot from the base gondola reduced the car box surface area in such a fashion as to lower car ownership $510. Eliminating a foot from the 39-ton axle load gondola reduced the car ownership cost $680. This is very close to the $700 Optimal Axle Load study assumption, further supporting the adoption of the linear cost estimate as an optimistic car ownership adjustment value.

From Figure 7-19, it is apparent that the operating cost savings of the alternative car designs over the base case are very sensitive to the car ownership cost assumptions. The conservative car cost assumption reduces the operating cost benefits 0.4 – 1.5% in relation to the base case cost level for the high/wide alternatives. This is 15 – 25% of the benefits of the high/wide design approach. The optimistic car cost assumption increases the operating cost savings 1.5 – 2.5% in relation to the base case cost level. This is an additional 40 – 55% of operating cost savings. There appears to be more of an up-side than a down-

side to the range of reasonable car ownership costs in relation to the costs actually utilized in the udy. The costs of car designs that have the largest cross-sections and shortest lengths are more effected by the optimistic and conservative car ownership assumptions since these designs vary the most from the base case.

The conservative car ownership cost scenario is an extra-optimistic cost estimate for the 3-Axle Truck car, since this design is 15 feet longer than the base case, but assumed to cost the same as the base. In cases of longer cars, the "conservative" estimate becomes an optimistic estimate. The 3-axle design is relatively more effected by the definitions of an assumed reasonable range of car ownership costs because this design is drastically more different from the base case design than any of the other alternatives.

Figure 7-20 depicts the sensitivity results of the heavier axle load car operating costs to car ownership cost deviations. Since these car designs are much different from the base gondola, the range of operating cost sensitivity to the car ownership cost assumption is very large, especially in relation to the magnitude of each scenario's operating cost benefits over the base case.

Assuming the car ownership cost per car-day derived from the HAL Phase III results [4], the operating cost is increased 2.4% for the 39-ton design and 1% for the 42-ton axle load design in relation to the base case. The variation between the HAL III 36-ton and 39-ton car ownership unit costs was used as the same increment of variation between the 39-ton and 42-ton axle load car ownership unit cost assumptions. The length-adjusted car ownership case, which was devised by expanding the base gondola car's length in order to hold the extra lading and by assuming the base car costs and the $700/foot linear adjustment factor, improves the 39-ton scenario 0.7% but worsens the 42-ton scenario costs 0.2%.

Assuming the 39-ton axle load scenario unit car ownership cost improves the 42-ton scenario operating cost savings 0.7% with respect to the base gondola. Assuming the base gondola car ownership costs improves the 39-ton scenario operating costs 2% and the 42-ton scenario 3.4% in relation to the base case. This extreme level of additional benefits is enough to put these car designs on an operating cost performance level of the Maximum Dimension and "2 Feet Up and 6 Inches Out" alternatives.
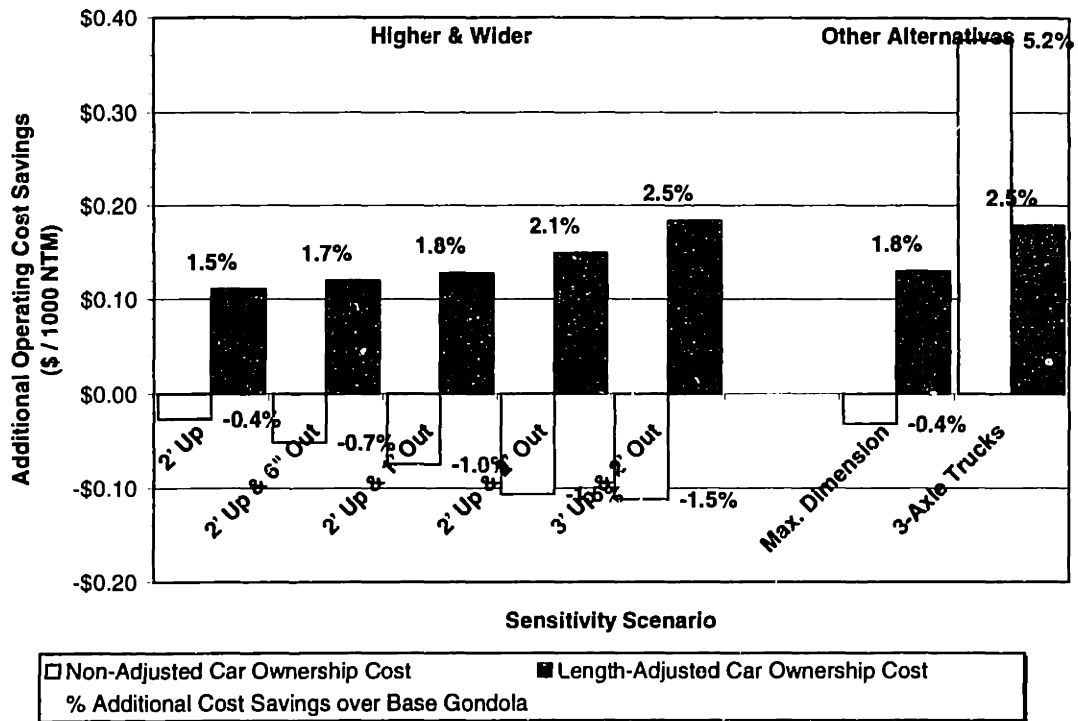
Figure 7-19: Eastern 36-Ton Axle Load Gondola Scenario Car Ownership Operating Cost Sensitivity
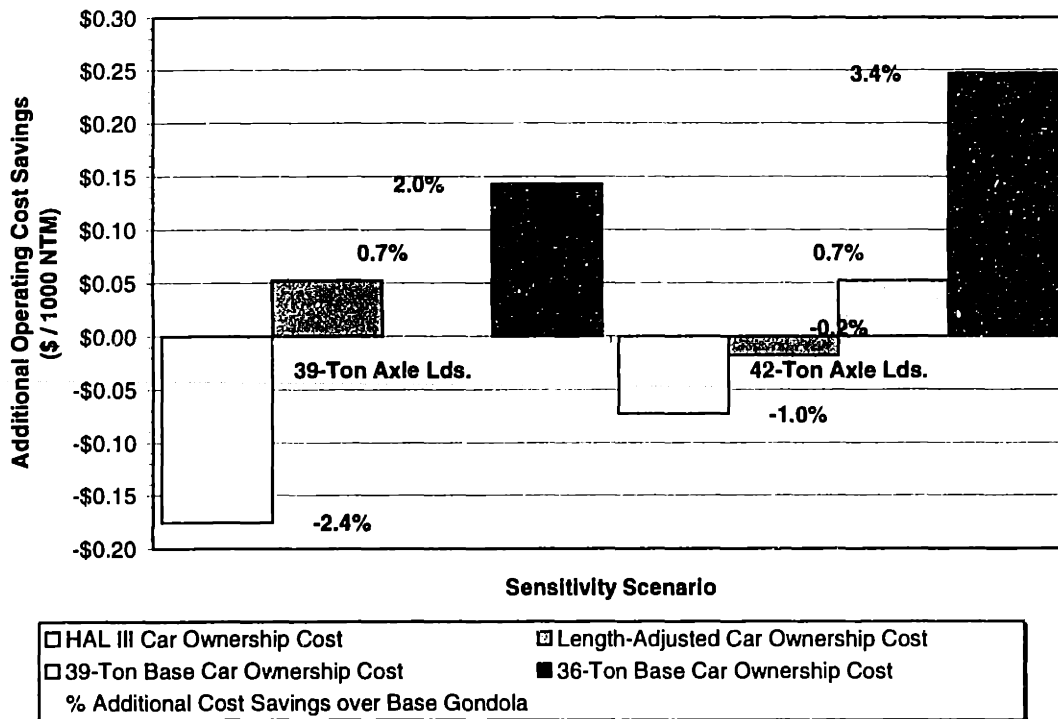
Figure 7-20: Eastern Heavier Axle Load Gondola Scenario Car Ownership Operating Cost Sensitivity

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7.4.4 Car Spacing and Fixed Drawbar Sensitivity Analysis

A greater volume of net tonnage may fit into a fixed length of train by decreasing the spacing between cars, thereby increasing the number of cars in a train length. This increase in train capacity will reduce the number of trains required to ship a set amount of lading, and the subsequent drop in train-miles will reduce crew costs. The use of fixed drawbars improves operating costs by:

- Reducing car tare, thus increasing the net weight per car
- Improving car maintenance costs

Even though fixed drawbar connectors are less expensive to purchase than a conventional coupling system, car ownership costs increase overall due to the assumed car maintenance availability costs of blocked cars. The car fleet must be enlarged in order to compensate for a reduction in car availability due to car maintenance activities. Even though each individual car is assumed to perform more reliably than a car with a conventional coupling system due to the elimination of maintenance-intensive coupling system components and the reduced force environment procured by blocked cars, a failure resulting in removing a car from service for repair necessitates removing a whole block of cars from service. Actual car maintenance costs are reduced for the same reasons as individual car reliability is improved – due to the elimination of maintenance-intensive coupling system components and the reduced buff and draft forces between blocked cars.

Figures 7-21 and 7-22 depict the additional operating cost savings attainable through reducing car spacing by varying degrees and through the use of fixed drawbars. Retrofitting the gondola car designs with fixed drawbars reduces operating costs on the order of 0.1 – 0.3%. This is a trivial amount in comparison to other alternative design methodologies; however, it may be worth pursuing for two reasons. First, it might be possible to increase the maximum weight of weight-limited trains over a given route if fixed drawbars are utilized since the inherent reduction in buff and draft forces will reduce the likelihood of a train pull-apart situation. Secondly, it might be easier to reduce car spacing by using fixed drawbars in place of a conventional coupling system. The combined operating cost benefits engendered by reduced car spacing and blocking cars are more significant than either method alone.

Drawing the cars of the gondola scenarios closer together is worth 0.2 – 0.3% in operating cost savings per foot of reduced car length. This level of savings is relatively minor compared to other alternative design methodologies, but should be pursued, if possible, since there are no associated implementation

costs to reducing car spacing. The only limitation to the amount of space that can be eliminated between cars is governed by the tolerances desired for curving allowance. The corners of the car boxes of adjoining cars must not run in to each other when negotiating extremely sharp curves, such as a loop-track at a coal mine loading facility.

The 3-axle truck car design is not as much affected by car spacing assumptions since a reduction of 1 or 2 feet between cars for a 68-foot long car is not as relevant as the same spacing reduction for a 53-foot long or shorter car. There are fewer gaps between the longer 3-axle truck cars that can be effectively filled with lading in a length-limited train. From one angle, the 3-axle truck car could be viewed as a method for reducing car spacing since it is another mechanism by which the empty gaps between cars are reduced.

The most extreme scenario investigated was the case of using fixed drawbars and reducing car spacing by 2 feet. The operating cost savings of this scenario were observed to be on the order of 0.6 – 0.7%. This compares to a 1.1 – 1.6% maximum operating cost benefit from car spacing alone, if the cars are brought together, as in the articulated design instance.

Overall, fixed drawbars and reduced car space car designs have second-order benefits in relation to the high/wide and other car design concepts. Retrofitting the gondola car designs with fixed drawbars improved operating cost benefits less than 3% in all cases. This is a very small amount in comparison to other alternative design methodologies. Fixed drawbars might be worth pursuing in order to increase the maximum weight of weight-limited trains since the inherent reduction in buff and draft forces will increase the maximum allowable drawbar force.

In order to have a relatively modest impact on operating costs, car spacing must be reduced substantially, such as through fully articulating the cars. Drawing the cars of the gondola scenarios closer together improves operating cost savings less than 5% per foot of reduced car length. This level of savings is relatively minor compared to other alternative design methodologies, but should be pursued, if possible, since there are no associated implementation costs to reducing car spacing.

Figure 7-21: Eastern High/Wide Gondola Scenario Car Spacing and Fixed Drawbar Operating Cost Sensitivity
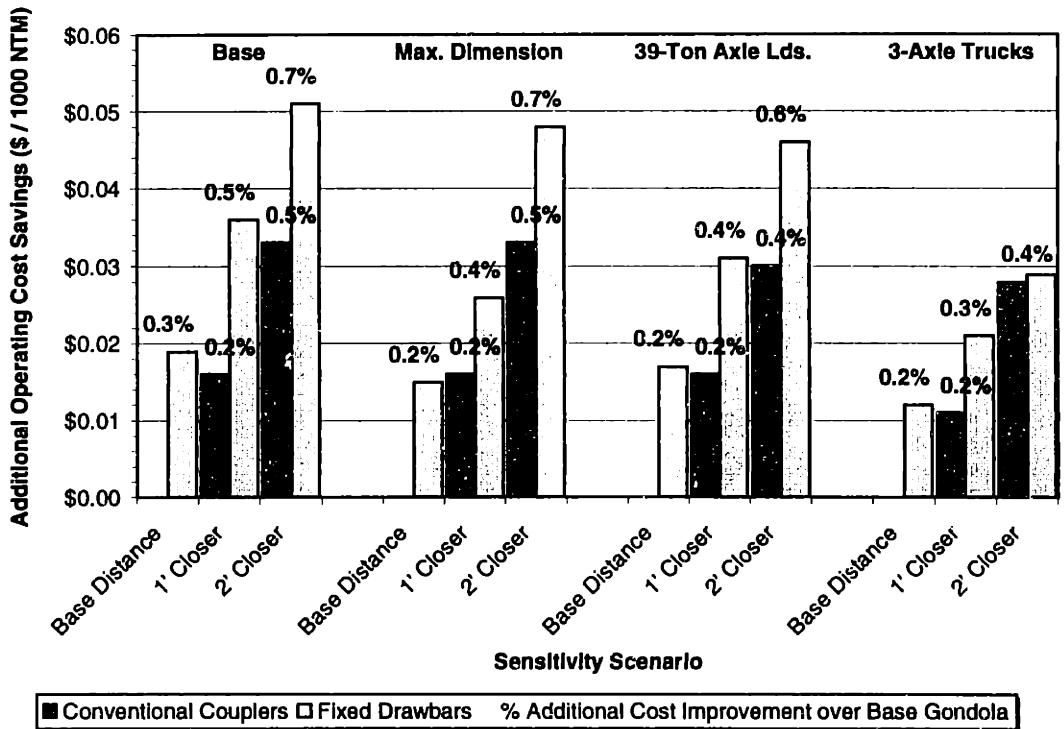
Figure 7-22: Eastern Other Alternative Gondola Scenario Car Spacing and Fixed Drawbar Operating Cost Sensitivity

7.4.5 Freight Car Net-to-Tare Sensitivity Analysis

The alternative car designs of this study are imaginary. They were devised using a parametric design methodology wherein one of the major assumptions dealt with how the tare weight of an alternative car design should be adjusted from the base car given changes in car length and cross-section from the base case. For the high/wide design procedure, a mid-point tare weight was chosen using the mean net-to-tare ratio between assuming no change to the car tare given the dimensional changes and a linear change in car body tare with extreme car length.

Every operating cost component is affected by the car net-to-tare assumption by the way in which the cost modeling was devised in this study. The operating cost savings results are thus very sensitive to the assumed net-to-tare weight of each alternative car design. A reduction in the tare weight of a car means that more net lading weight may be added to the car while keeping the gross weight and axle loadings the same. The capacity of a length-limited train is increased. For a fixed cross-section, the length of the car must increase in order to accommodate the extra lading, thus decreasing the number of cars in a length-limited train. The cars also weigh less when empty, reducing the level of gross ton-miles in a complete train cycle between origin and destination. The resulting reduction in train-miles, car-miles, car-days, locomotive-miles, locomotive-days, and gross ton-miles reduces the magnitudes of all of the operating cost components.

Figure 7-23 depicts the additional operating savings or costs incurred by changing the car design net-to-tare assumption. The base for each scenario is the actual mean net-to-tare ratio assumed in the study. The optimistic net-to-tare cases assume that the car tare is fully length-adjusted regardless of the cross-section dimensions. The conservative net-to-tare cases assume that the alternative car tare weight is the same as the base car regardless of its dimensions. The results of the sensitivity analysis indicate that the operating costs of each scenario are effected by plus or minus 0.5 – 1.5% in relation to the base gondola. The more extreme cross-section car designs have the shortest assumed car length and thus the wider range of net-to-tare ratio assumptions. Therefore, the more extreme cross-section car designs have a greater range of reasonable net-to-tare assumptions and appear more cost sensitive to the tare weight estimation methodology utilized.

Figure 7-24 depicts the additional operating savings or costs incurred by improving or worsening the alternative car design net-to-tare ratio by 10%. The end result is a range of operating costs or savings of +/- 1.0 – 1.5% in relation to the base gondola cost level. The 3-axle truck car is somewhat less sensitive

to the net-to-tare assumption than the other alternative car designs due to its extreme length. It takes a much larger amount of coal to increase the car length enough to reduce the number of cars in a train as significantly as in the shorter car designs.

Overall, reasonable deviations in the net-to-tare assumptions in the alternative car designs do not "make or break" the alternative design methodologies, including the high/wide design approach. However, the net-to-tare assumption does have a significant effect on the level of operating cost savings for the alternative designs in relation to the base case. The bottom line savings of the alternative designs are effected on the order of 10 – 20% for the reasonable net-to-tare range of this sensitivity analysis.

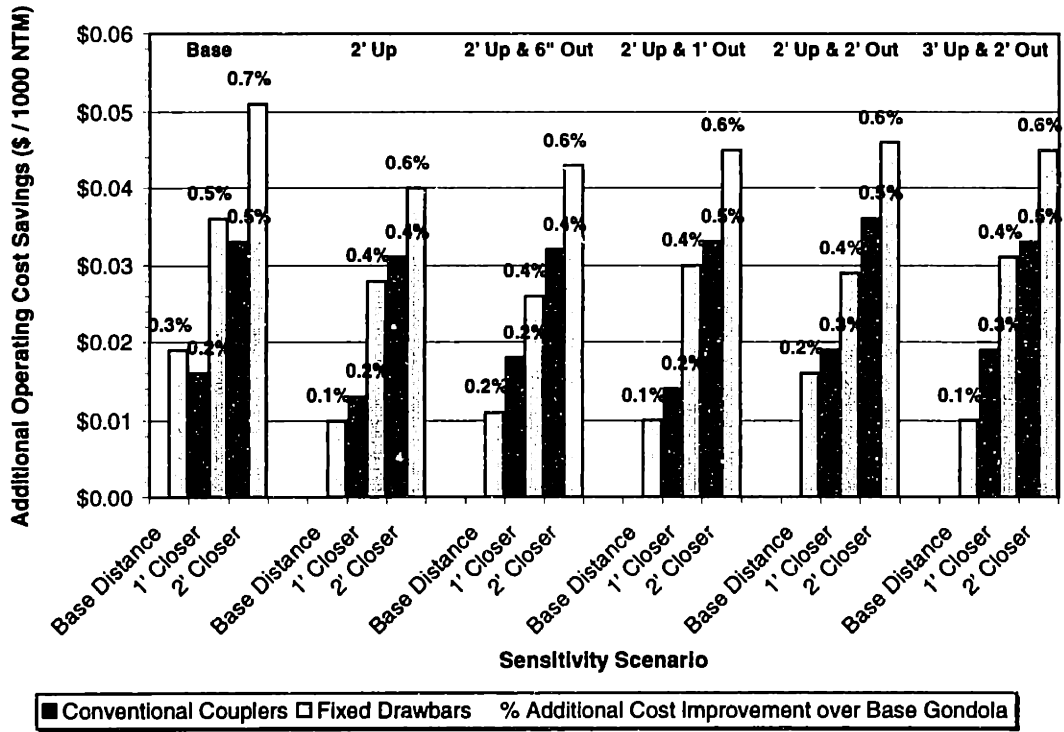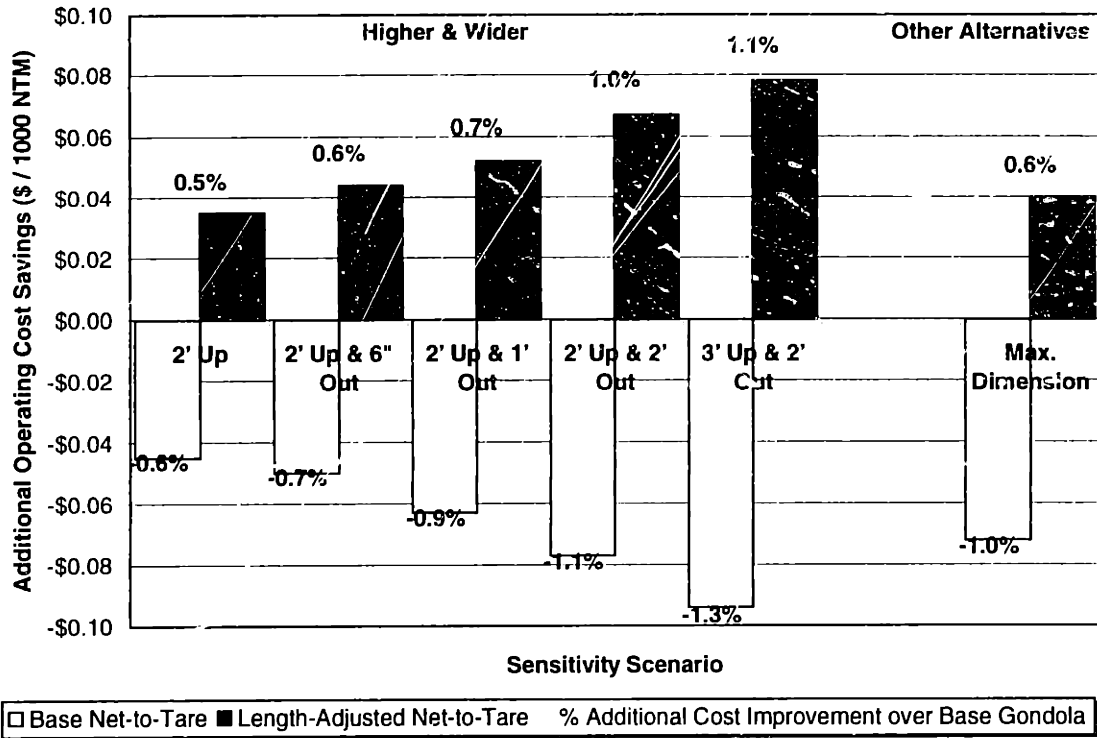**Figure 7-23: Eastern High/Wide Gondola Scenario Net-to-Tare Operating Cost Sensitivity**
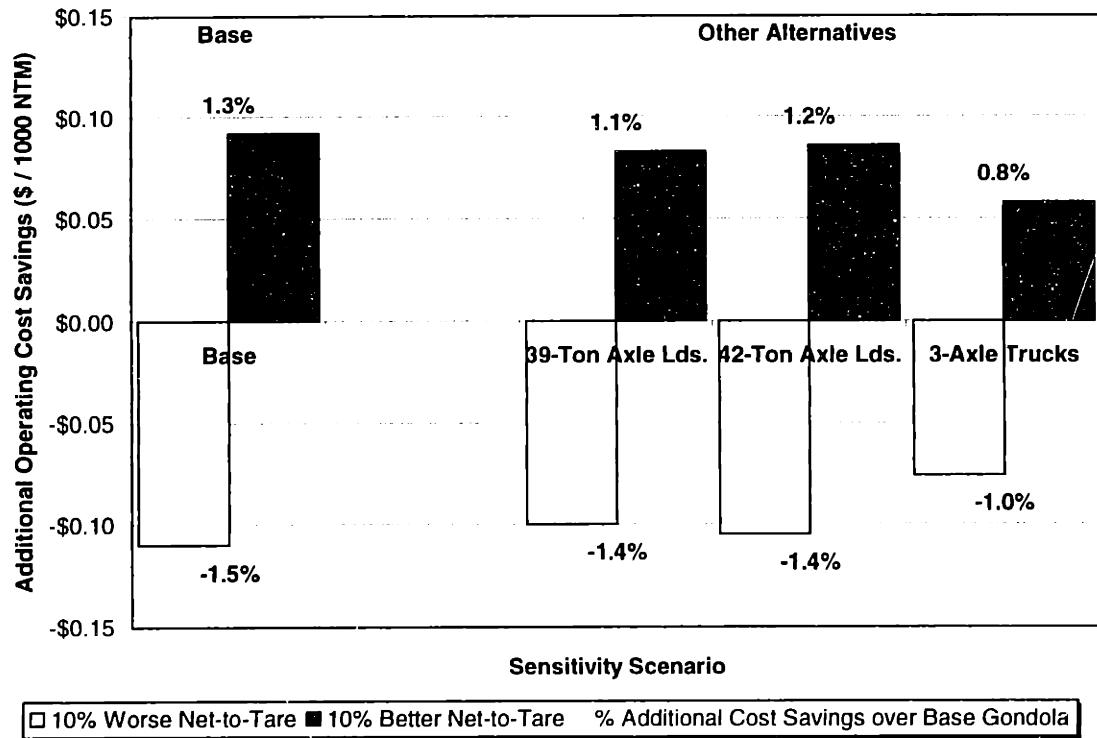
Figure 7-24: Eastern Other Alternative Gondola Scenario Net-to-Tare Operating Cost Sensitivity

7.4.6 Freight Car Cross-Section Utilization Sensitivity Analysis

Decreasing the proportion of a car design's extreme cross-section, which is not empty or utilized for the car structure, shortens the car length required to hold the same net capacity. Shortening a car is assumed to have a positive effect on the tare weight of the car, thus increasing the car capacity. The overall result is a reduction in all of the cost driving units (e.g. train-miles, car-miles, et cetera) and a reduction in every operating cost component.

The results of an investigation of the sensitivity of operating costs to car utilization are summarized in Figure 7-25. The additional operating cost savings over the base gondola case were calculated for each alternative gondola car design assuming a 5% and a 10% cross-section utilization improvement upon each alternative car design. Judging by the range of cross-section utilization values for a variety of actual existing car designs investigated that are similar to the base gondola and for the range of utilization levels attained for the alternative gondolas, a 5% utilization seems reasonably possible in some instances. A 10% utilization improvement over a bathtub based gondola design is probably an optimistic goal.

Figure 7-25 indicates that a cross-section utilization improvement of 5% could increase the operating cost savings of the alternative high/wide gondola designs 0.6 – 0.7% in relation to the base gondola. A 10% utilization improvement could increase operating cost savings 1.0 – 0.3% further beyond the base gondola. Operating cost savings are somewhat less sensitive to the utilization level at more extreme cross-sections because the mid-point net-to-tare ratio improvement exhibits decreasing returns. This is due to the fact that the fixed truck weight-related tare weight component becomes a more significant portion of the total car tare weight as the car length shortens.

The two scenarios in Figure 7-25 where the car length is fixed at 53.1 feet (the base and 39-ton axle load cases) indicate that there is no operating cost benefit by improving the cross-section utilization for a car design with a fixed length. An improved utilization of the available space results in a reduction in the extreme car height in order for the total car capacity to remain unchanged. The reduction in car box height is countered by increases in other box dimensions. Therefore, the net-to-tare and car length does not change and the car ownership assumption of the box surface area adjustment factor stays the same, so operating costs remain unchanged. This explains why there has been little incentive for car designers to improve upon the base 53-foot gondola and hopper car designs by maximizing the volume available within the 53-foot set length. The only improvements, such as the bathtub design concept, result from a need to increase capacity with an increase in axle loads.

The 3-axle truck car operating costs are extremely sensitive to the cross-section utilization level. This car is very long – on the order of 68 feet – so that any modification to the design that leads to a shorter car length, and thus a shorter truck spacing, will lead to a car width increase as dictated by the Plate C-1 extreme car width / truck spacing relationship. A shorter car has a less excessive overhang at the center when cornering and can therefore be wider. This cross-section increase compounds the benefits of the cross-section utilization improvements.

The car cross-section utilization level is a critical assumption in parametric car design. For car designs that are not constrained to a fixed length, improving cross-section utilization has a modest implication on operating costs. Utilization improvements can be made in conjunction with another car design approach in order to significantly enhance the cost efficiency of an alternative car design. Improving the utilization level by 5% for the high/wide gondola designs can improve operating costs a further 10 – 25% beyond the base gondola car cost level.
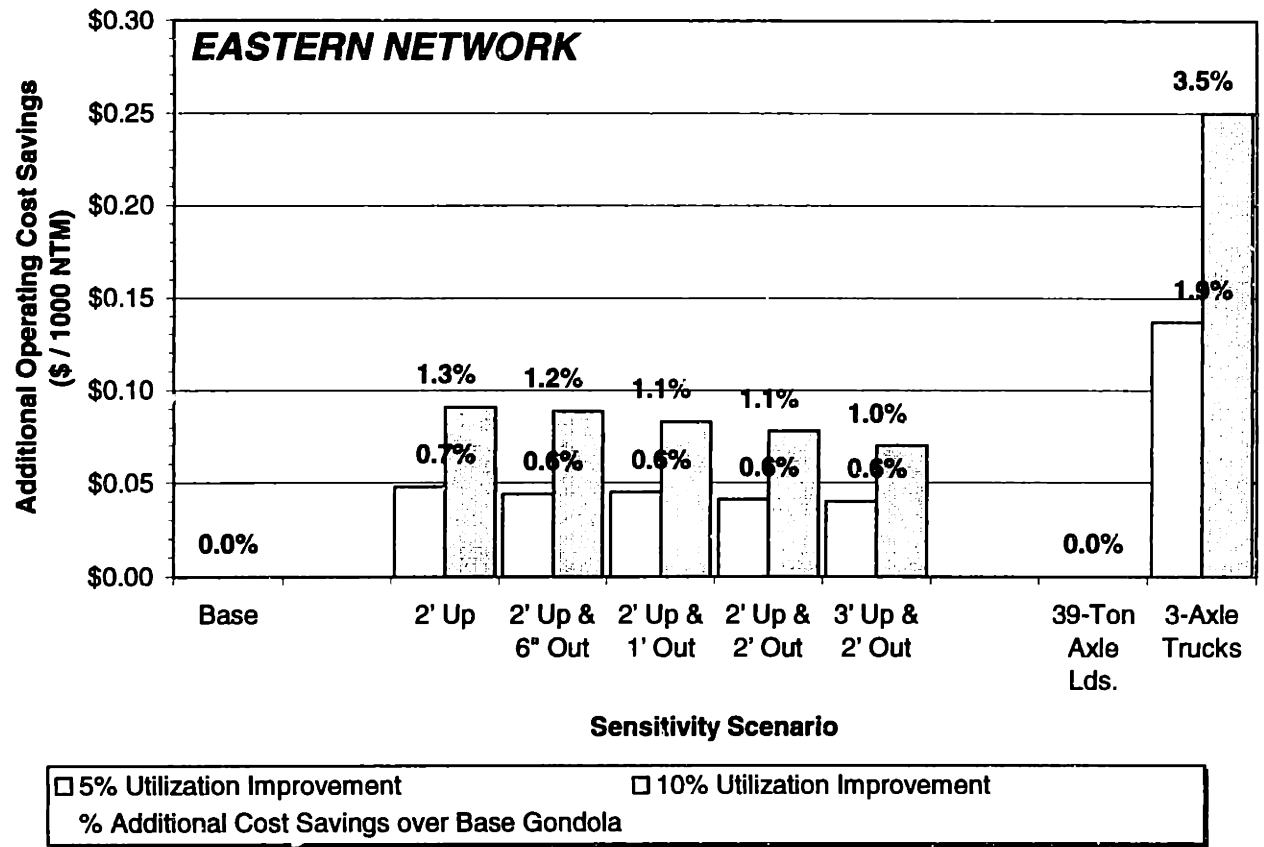
Figure 7-25: Eastern Gondola Scenario Cross-Section Utilization Operating Cost Sensitivity

7.5 Implementation Issues

The operating cost and capacity benefit results outlined in Sections 7.2 and 7.3 of this chapter do not include consideration of the implementation costs for the alternative car designs. Incremental costs could be incurred from adverse impacts of any new equipment-type on clearances, bridges, unloading facilities or by implementing any new operating practices, such as the use of displaced locomotive power. The implementation costs and related issues were discussed in detail in Chapter 6. This Section takes the estimated cost impacts from that chapter and relates them to the operating benefit results in Sections 7.2 and 7.3, in order to gain an understanding of the approximate order of magnitude of each incremental implementation cost with respect to the incremental benefits for the alternative car designs considered.

A comparison of clearance increase costs is not provided in this section because an implementation cost for clearances was not estimated in Chapter 6. These costs are extremely site and route specific and are also very sensitive to the degree to which clearances are improved. A discussion of clearances and the related issues is provided in Section 6.1.

7.5.1 Incremental Bridge Costs

The incremental bridge costs were estimated at $0.160 / 1000 NTM in the East and $0.114 / 1000 NTM in the West in Section 6.2. These cost estimates represent the HAL bridge economic analysis [3] cost results for increasing axle loads from 36 tons to 39 tons when applied to the representative coal distribution networks, assuming a constant bridge impact cost per mile across the networks. In both the East and West, these cost magnitudes represent 2.2% of the base gondola cost and 2.1% of the base hopper operating cost.

In the East, the ramification of including bridge costs in the 39-ton axle load gondola scenario is that the cost savings of 1.5% are eliminated. Overall, the 39-ton axle load scenario operating costs are 0.7% higher than the base gondola. This is so despite the use of 36-inch diameter wheels and the corresponding net-to-tare benefit of the heavier car. In the West, including bridge costs in the 39-ton axle load gondola operating cost calculations reverts a 0.7% operating cost benefit into a 1.5% operating cost in relation to the base case.

Assuming a simple linear bridge cost relationship with axle load, the 42-ton axle load gondola scenario operating costs increase 3.8% in the East and 4.5% in the West over the base gondola, when bridge costs

are included. This linear relationship is likely a conservative estimate, judging from the HAL II economic bridge results when axle loads are increased from 33 to 39 tons [3]. The relationship is more likely exponential in nature.

If increasing linear loading on bridges by reducing axle spacing has exactly has the same result on bridges and bridge costs as increasing axle loads, then the increased loading of the "1 Foot Up" and the "1 Foot Out" gondola cases are directly comparable to the estimated bridge costs from Section 6.2. The operating cost benefits of these two scenarios are depicted in Figure 7-2. The incremental bridge costs are comparable to the operating cost benefits of these two scenarios. Thus, if the axle spacing and axle load increase effects have relatively the same effect on bridge costs, the operating cost savings of the high/wide alternative car design methodology are effectively eliminated. The capacity increases from such alternative car designs will not coincide with an operating cost benefit. In fact, if any other implementation costs are incurred, such as clearance increases or unloading facility modifications, the capacity increase from alternative car design will arise only at an additional overall cost.

As noted in Section 6.2, these bridge cost estimates are likely very conservative for two reasons:

1) Bridge impact costs are likely to be lower on low density lines than on higher density lines, on a per mile basis.

2) The effects of increased axle loads are probably greater on bridge costs than the effects of decreased axle spacing.

Regardless of the conservative estimate, the conclusion of bridge impact costs is that they are potentially threatening to the economic attractiveness of alternative car design as envisioned in this study. Further, more in-depth research is therefore mandated in order to draw conclusive results of the bridge cost / axle spacing and operating benefit / bridge cost relationships.

7.5.2 Incremental Unloading Facility Costs

The costs for modifying unloading facilities were devised in Section 6.3 and summarized in Table 6-4. Bottom-dump facilities were imagined to have no appreciable implementation costs associated with alternative car designs, unless modifications are necessary for thaw shed dimensions (i.e. length). Rotary-dump facilities do have costs associated with modifying the dumpers in order to accommodate alternative

car designs. These costs vary over quite a wide range since they are extremely sensitive to the average volume of coal shipped and the average length of haul for each unloading method and facility.

The dumper cost estimates can be compared to the gondola operating cost benefit estimates of Figure 7-2. In the East, for the high/wide alternative car designs, random car rotary dumper implementation costs are equivalent in magnitude to 1.2% of total base gondola operating costs. Unit train rotary dumper costs for accommodating shorter are as large as 4.6% of operating costs. This means that approximately six inches of additional height or width must be applied to the high/wide design cars in order to overcome the random car dumper implementation costs, on average. In the East, the unit train dumper costs are only surmountable with fairly extreme height and width increases. Modifying unit train rotary dumpers represents a formidable obstacle to high/wide car design implementation. Only the facilities with the highest volumes and longest lengths of haul could find economic benefit to changing over to high/wide car designs. Timing is a critical consideration for dumper costs. If a dumper is at a stage wherein it needs a major maintenance overhaul or replacement, then the incremental costs of modifying the dumper to accommodate high/wide cars may not be very large at all.

In the West, for the high/wide alternative car designs, random car rotary dumper implementation costs are on the order of 0.6% of the base gondola operating cost magnitude. Unit train rotary dumper costs are approximately as large as 1.4% of total operating costs. Unit train rotary dumper implementation costs are not nearly as significant a barrier to high/wide car design as in the East. A high/wide car must be at least 6 inches higher or wider than the base car in order to compensate for the average unit train dumper modifications in the West. The impact of dumper costs is much reduced in the West in comparison to the East because of the higher average volume of coal that destined to Western unit train rotary-dump facilities and the much longer average length of haul in the West.

The rotary dumper implementation costs for a longer 3-axle truck car design are generally much greater than the operating benefits perceived to be available from such a car design. In the East, combining the estimates of the 3-axle truck car incremental operating benefits and dumper costs results in overall cost increases of 11% for the random car dumper and 5.7% for the unit train dumper, in relation to the base gondola costs. In the West, the inclusion of the dumper costs with the operating benefits results in an overall 3.4% cost increase over the base case. The only scenario in which the 3-axle truck car dumper modifications do not overcompensate for the estimated operating benefits is in the Western unit train dumper case. Here, the dumper implementation costs are 1.7% the size of the base case operating costs, reducing operating cost savings to 0.7% over the base gondola.

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Overall, rotary dumper modification costs are quite significant. For alternative high/wide car design, the costs pose a formidable barrier to the Eastern utilities. These facilities might be more likely to switch to an articulated hopper design, except for the highest volume and longest distance cases. In the West, the implementation costs are substantial, but do not eliminate high/wide alternative car designs from future consideration.

7.5.3 Incremental Displaced Locomotive Power Costs

Section 6.4 discusses implementation considerations for displaced power practices and derives cost estimates of introducing such operating techniques in order to handle the heavier trains proposed in conjunction with alternative car designs. The cost of implementing displaced power operations in the East was estimated at $0.035 / 1000 NTM, while in the West, the cost was estimated to be $0.017 / 1000 NTM. These cost magnitudes represent 0.5% and 0.3% of the base gondola operating cost levels in the East and West, respectively.

By comparing the cost magnitudes for initiating displaced power trains to the operating cost savings of Figure 7-2, it is immediately apparent that, in both the East and West, the implementation costs of displaced power are quite low. The increased weight of trains due to alternative car designs does not pose a serious threat to the benefits achievable by introducing the alternative car designs.

CHAPTER 8: SUMMARY AND CONCLUSIONS

This chapter summarizes the ideologies, explorations, findings, and major conclusions of the preceding chapters. Section 8.1 describes the purpose, motivation, and origins of this investigation, providing also a brief story-line of the research that led to this Optimal Car Design study. Section 8.2 outlines the approach and procedures utilized in order to conduct the analyses. Section 8.3 summarizes the analysis results. Section 8.4 summarizes the conclusions drawn from the analysis results. Finally, Section 8.5 recommends approaches to and directions for future research and a future Optimal Car Design program.

8.1 Introduction and Background

This study identifies effective methods for enhancing the productivity of coal heavy-haul unit train operations through improved railcar design. Car design can be modified in order to maximize train capacity in such a way as to minimize total costs and maximize network capacity. Total cost was defined as the sum of direct track, transportation, equipment and incremental implementation costs. Network capacity is a function of line and terminal capacity and was measured in terms of net train capacity.

The economic analyses of HAL Phases I to III demonstrated that it is possible to reduce overall costs by increasing axle loads from 33 to 36 tons, but not by increasing axle loads from 36 to 39 tons [3][2][4]. The Optimal Axle Load study reinforced these conclusions, even for congested networks where the capacity benefits of 39-ton axle load cars would be quite important [1]. The HAL III results indicated that the use of improved-suspension trucks further reduced overall costs [4]. The HPIT project and Optimal Axle Load study both demonstrated the value of lighter, aluminum car body design to bulk operations [14][1]. The Optimal Axle Load study also showed that overall costs can further be reduced and capacity further enhanced by increasing net train capacity through increased the net load per linear foot of train, or train density[1].

This study embraced the concept of net train capacity, and explored the potential benefits and implementation implications of increasing train capacity in a generic parametric context. This study extended beyond prior AAR research by considering a broader range of alternative car designs, the factors influencing optimal car design and implementation issues. More account of geometric constraints and other practical considerations and implementation issues was taken in this study than in previous work. Issues regarding increasing clearances, intensifying bridge loading, constraints at customers' unloading facilities and different operating practices that are required for heavier trains were investigated.

The primary objective of this study was to use a parametric approach for analyzing vehicle design in order to bound the benefits of different design methodologies, while taking into consideration the implementation ramifications of each alternative design methodology, in order to provide direction for any further in-depth study, if warranted. This objective was accomplished by isolating and investigating the relevance of each car design parameter that affects net train capacity and by identifying car design methodologies that simultaneously improve total costs and enhance capacity.

Car design affects net train capacity through six distinct mechanisms: axle load, axles per car, cross-section dimensions, cross-section utilization, car spacing and car net-to-tare. The major drawback to the traditional HAL approach is that increasing axle loads inherently increase track costs, thus compromising the operating and capacity benefits. By considering a broader range of car design parameters that affect train capacity, car design methodologies were developed that increase train capacity without raising axle loads.

8.2 Analysis Methodology

The six car design parameters that affect operational productivity through net train capacity were manipulated in order to construct alternative car designs under three basic methodologies: higher, wider and shorter cars; heavier cars; and 3-axle truck car design. Within the framework of these three basic alternative car design methodologies, other parameters and design characteristics were altered in order to identify the best approach to undertake for optimal car design. For example, one specific car type considered was a "Maximum Dimension" car. This car design was constrained by current clearance and center-of-gravity limits, but had somewhat better cross-section utilization than conventional 53-foot coal cars. Unique alternative hopper car designs included examination of longitudinally oriented doors, removing the automatic-discharge equipment from the cars and articulation.

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Alternative car designs were derived based upon both a conventional 53-foot bath-tub gondola and on a rapid-discharge open-top hopper. The alternative designs were contrived using a parametric design approach. A parametric analysis enabled many alternatives to be modeled and analyzed reasonably accurately without addressing intricate car design details.

Operations with alternative car designs were modeled over representative Eastern and Western U.S. coal distribution networks. The network approach provided a good indication of the total system cost impacts on the complete movement of coal from origin to destination.

Cost estimates were based on the results of the HAL Phase III analysis [4] for the most part. The track costs were calculated using the TRACS [29] model and using costing and methodology techniques based upon the HAL economic analyses. Transportation costs and equipment costs were estimated using simple cost factors applied to unit costs derived from the HAL III analysis. Fuel cost for a scenario was assumed to be a function of gross ton miles based on the HAL III fuel cost per gross ton-mile. Crew costs were based on train-miles.

Locomotive ownership costs were assumed to be a function of locomotive consist days. A cost multiplier was applied to the locomotive ownership unit cost of the HAL III analysis in order to ensure a constant level of horsepower per trailing ton across all scenarios. The use of a multiplier approach allowed realistic locomotive costs to be estimated without needing to consider the intricacies of the specific size and type of locomotives across every scenario or the number of locomotives in each consist. The locomotive maintenance costs calculated as a function of locomotive consist miles. The cost multiplier was also applied to the locomotive maintenance costs.

Car ownership costs were derived from costs of base cars provided by the AAR and by applying the HAL III costing methodology. Car ownership was assumed to vary as a function of car-type, car box surface area, truck-type, wheel size and coupling system. The ownership costs were quoted in terms of amortized cost per car-day. The locomotive and car ownership costs for the base cases were based on cycle times over the networks as predicted by UTRAIN [9]. Car maintenance costs were assumed to be a function of car-miles, axle load, truck-type and coupling system, as interpreted from the HAL III results.

Operating cost savings and capacity benefits were compared across all of the alternative scenarios in relation to the respective base cases. Investigation of the basic car design methodologies was expanded by considering sensitivity analyses of critical parameters. These parameters included: car spacing and

coupling system, cross-section utilization, car ownership costs, net-to-tare, length versus weight-limited trains and cycle time. The results of the operating cost and capacity benefit analyses and sensitivity analyses were compared to the perceived magnitudes of the implementation issues. Ultimately, optimal car designs were recommended for further study.

8.3 Result Summary

Figure 8-1 summarizes the operating cost and system capacity benefits of the more promising alternative car designs investigated. The high/wide gondola alternatives, 39-ton axle load gondola, and high/wide articulated hopper alternatives are depicted. The cost and capacity benefits are quoted in relation to the base gondola design for the gondola and hopper alternatives depicted in Figure 8-1. The base hopper car is also depicted in relation to the base gondola. Note that the alternative hopper car designs are discussed in relation to the base hopper car in the text of this section, but depicted in Figure 8-1 in relation to the base gondola. Overall, the results outlined in Figure 8-1 and some of the interim findings not illustrated in this figure, but discussed in the result findings in Chapter 7 are summarized in this section.

EASTERN NETWORK

(y-axis) Percentage Improvement in Operating Costs from Base Gondola ($ / 1000 NTM)

2' Up & 2' Out
3' Up & 2' Out
2' Up & 1' Out
1' Up & 1' Out
2' Up & 6" Out
1' Up & 6" Out
Max. Dimension
1' Up   Max. Dim.
2'- Up
Base X-Section Manual Dog-Leg
39-Ton Axle Lds.
Base Gondola
Base X-Section Dog-Leg
Base X-Section
Base Hopper

WESTERN NETWORK

(y-axis) Percentage Improvement in Operating Costs from Base Gondola ($ / 1000 NTM)

1' Up & 1' Out
3' Up & 2' Out
1' Up & 6" Out
2' Up & 2' Out
Max. Dim.
2' Up & 1' Out
1' Up
2' Up & 6" Out
Max. Dimension
Base X-Section Manual Dog-Leg
2'- Up
Base X-Section Dog-Leg
39-Ton Axle Lds.
Base Gondola
Base X-Section
Base Hopper

Percentage Increase in Train Capacity from Base Gondola
(Net Tonnage per Train)

✕ Base Cases   ✕ Articulated Hoppers   + Gondolas

Figure 8-1: Summary of Operating Cost and Capacity Improvements Relative to the Base Gondola

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8.3.1 Base Gondola and Hopper Cost Performance versus HAL Analyses

An important aspect of this study to consider when evaluating the findings is that the results are quoted in relation to an extremely efficient base case by modern standards. Operations with the aluminum, 36-ton axle load, bathtub gondola car are significantly enhanced beyond any of the prior HAL analysis scenarios. The alternative car designs investigated throughout this study are much more cost efficient and capacity effective than any of the HAL equipment types or typical operating practices of today. In effect, the operating cost savings and capacity benefits are quoted in relation to the current best practice.

Both the length-limited and weight-limited base gondola cases have drastically lower operating costs than the HAL Phase II base case – 53-foot, 33-ton axle load, steel gondola. Operations with the base gondola are 17 – 18% cheaper in the length-limited case and 14 – 15% less expensive in the weight-limited case. These dramatic operating cost improvements in both the length and weight-limited cases are due to a 20% increase in car capacity and car design technological progression on three fronts:

- Increased railcar gross rail load / axle load
- Improved railcar suspension system
- Reduced railcar empty weight

Improved-suspension trucks reduce operating costs on the order of 3% in the East and 4% in the West for both length and weight-limited cases. Increasing axle loads reduces operating costs 6½% in the East and 5½% in the West length-limited cases and 3% in the East and 2% in the West weight-limited cases. Most strikingly, lighter aluminum cars reduce operating costs on the order of 8% in all cases.

8.3.2 Alternative Gondola Car Design Performance

The high/wide alternative gondola car design operating cost benefits range from 1-6% in the East and 1-8% in the West, for the alternatives considered. The savings increase with the size of the cross-section. The capacity benefits reach 47% with the extreme "3-Foot Higher and 2-Foot Wider" case. Overall, even more "modest" high/wide car design scenarios provide for quite significant increases in capacity, on the order of 15 –30%.

A very striking observation from the results is that, excluding implementation cost issues, increased capacity comes with a cost benefit. Even when including these additional costs, many of the alternative

car designs will provide additional cost savings from the base case. This is contrary to most capacity enhancement alternatives.

The potential of the high/wide car design concept versus the traditional HAL approach is very clear. The high/wide concept improves transportation and equipment costs and enhances capacity without the negative effects on the track structure and thus without suffering the inherent track cost ramifications. Going even further, the high/wide concept actually reduces track costs. This observation, of course, results when bridges are excluded from consideration.

Crew cost savings are the primary source of operating cost benefits. The crew costs decrease directly with the reduction in train-miles characteristic of the alternative cases. The level of train-miles declines since the number of trains required to move a fixed tonnage of coal drops as the net capacity of a train increases.

Car ownership costs are another major contributor to operating cost savings. These costs improve for the high/wide cases since the shorter cars have lower car box surface areas and improved net-to-tare ratios.

The drop in tare is due to a reduction in the size of the relatively heavy longitudinal components on the underside of the car. Improving the net-to-tare ratio, while holding the total gross weight constant, means that the total number of cars required to move a fixed tonnage of coal can be reduced. The net-to-tare improvement subsequently reduces the fuel, track, locomotive ownership, and locomotive and car maintenance costs.

The larger the cross-section of a scenario, the shorter the assumed car length, the greater the train capacity, and thus the greater the relative changes in the cost benefits for the high/wide scenarios. The "3 Feet Up and 2 Feet Out" case, with its 15.1-foot height and 12.7-foot width, boasts 6.2% savings in the East and 8.3% savings in the West, which is the best of all the scenarios considered. This scenario also provides a very attractive capacity boost, however, the extremely large dimensions also intensify the gross linear loading to a level of 7,780 pounds per foot, 44% over the base. This loading magnitude could easily increase bridge implementation costs beyond the operating benefits and may not even be feasible due to bridge loading complications.

A more reasonable range of attractive higher/wider alternatives include the "Maximum Dimension" car, the "2-Foot Up" case, the "2-Foot Up and 6-Inch Out" case, and the "2-Foot Up and 1-Foot Out" case. The operating cost benefits of these cases range 2.8-4.6% in the East and 3.9-5.9% in the West.

The 39-ton axle load scenarios suggest modest operating cost benefits of 1.5% in the East and 0.7% in the West. Interestingly, the operating cost benefits are more substantial for the 39-ton case in relation to the 36-ton case than was found in the HAL analyses for three reasons:

1) Bridge costs were excluded from operating costs in this study.
2) The 39-ton cars in this study were assumed to have lighter 36-inch diameter wheels, as opposed to the heavier 38-inch wheels of the HAL analyses.
3) The HAL effect on track costs was found to be less significant over a network than on mainlines since the relatively fixed maintenance costs for ties and routine maintenance dominate on lower density lines and since rail fatigue is less of an issue on low density track with decent rail quality.

The attractiveness, if any, of the 39-ton axle load (or similar higher axle load) option stems from the fact that a significant 11% capacity boost may be garnered without suffering large implementation cost penalties from clearance modifications or from unit train rotary dumper modifications. Bridge impact costs are clearly an issue, though, as dictated by the HAL analyses [3]. A moderately higher axle load car design option, therefore, might be a relatively attractive way to increase capacity in some instances.

The 42-ton axle load alternative is not an attractive option. The operating benefits are extremely low in the East case, at 0.6%, and are non-existent in the West, even excluding bridge implementation costs. The track cost increases were estimated on the order of 6% in the East and 14% in the West, excluding bridges.

The 3-axle truck car is also not an attractive option. This option did improve operating costs 0.9% in the East and 2.4% in the West, but there is a much larger rotary dumper cost penalty required for lengthening cars as would be required in the 3-axle case, as opposed to shortening the cars as in the higher/wider cases.

Alternative high/wide car designs with 39-ton axle loads, as opposed to 36-ton axle loads, have a train capacity improvement on the order of 2% over the respective 36-ton designs. This is because, for a fixed

car cross-section, the 39-ton axle load car designs are longer than the 36-ton car designs. Thus, there are fewer cars in a length-limited train with the higher axle loads and fewer gaps empty of lading located between cars. The operating cost benefits of the 39-ton cars are typically about the same but a little less than the equivalent 36-ton case. The cost improvements in transportation and other cost components from going to the higher axle loading are met with an equivalent or greater combined increase in track and car ownership costs. This does not include bridge costs, which would serve to hinder the 39-ton axle load cases even further. Therefore, advancing to 39-ton axle loads is not recommended for high/wide car design.

8.3.3 Alternative Hopper Car Design Performance

8.3.3.1 Transverse and Longitudinal-Door Designs

The base gondola case is 6.6% more operating cost efficient in the East and 5.5% more efficient in the West than the base hopper case. The base hopper is not as operating cost efficient as the base gondola for two reasons:

1) The gondola car has a lower tare weight than the hopper car.
2) The hopper car has higher car ownership costs than the gondola car.

The fact that the gondola car has a lower tare means that it is able to carry more coal for the same total gross weight. The 23% greater hopper car ownership costs stem from a more complicated design that involves unloading doors and automatic rapid-discharge equipment.

The operating cost savings of the high/wide hopper car designs reach 7.5% for the "2-Foot Up and 2-Foot Out" case over the base hopper in the East and 9.8% in the West. This extreme car design also boasts a 50% capacity boost over the base hopper car.

The higher axle load scenarios are not attractive alternatives with respect to operating cost benefits in comparison to the other car design methodologies. This is especially true considering that there is not any unloading implementation cost for hopper cars since these cars do not need to be rotary dumped in order to be unloaded.

The longitudinal-door design improves cross-section utilization by reaching lower in the Plate diagram towards the rails. Increasing the volume of lading close to the rails increases the COG-limit allowing the car to reach a more extreme height before reaching the upper limit. Thus, a longitudinal-door car design may ultimately be higher than a transverse-door car design. The longitudinal-door car design was also assumed to decrease car tare by 3,000 pounds.

Both the improved net-to-tare and cross-section utilization factors act to enable a shorter car design than would otherwise be possible with transverse doors for a given extreme car cross-section and gross weight. Therefore, more cars are able to fit in the length-limited train, increasing train capacity and decreasing train-miles. The longitudinal-door car design doubles both the operating cost and capacity benefits over the transverse-door benefits for high/wide alternative car design up to the COG-limit.

8.3.3.2 Manual-Discharge Design

The cost efficiency and capacity effectiveness of a hopper car design can be improved by removing the automatic rapid-discharge equipment. Removing this equipment improves line-haul operating costs in two ways:

- Reduced car ownership cost
- Reduced car tare

The automatic door operating equipment was assumed to cost an $8,000 premium above a manual-discharge bottom-dump door system. The equipment was also assumed to weigh 1,500 pounds. Removing this equipment from the cars was used as a method for increasing the car net capacity.

The major drawback of removing the unloading automation equipment from the cars is that the cars must be unloaded in a different fashion. There are two alternative unloading mechanisms. Either wayside equipment must be installed that springs the doors open for unloading and shuts them again as the cars pass by or the doors must be opened and closed manually by personnel at the unloading site. The costs of instituting either of these unloading methods must be weighed against the improved line-haul operating costs from removing the automatic-dump equipment. The results of this sort of economic analysis will be very case specific. The manual-discharge design will appear more attractive for cases with higher levels of tonnage or longer average lengths of haul in which the line-haul operating costs are a more significant portion of the total cost.

For all of the high/wide and the heavier axle load alternatives, the operating cost benefits of the manual-discharge design are uniformly 3% in the East and 2% in the West over the subsequent rapid-discharge design. The benefits are larger in the East than in the West because they primarily stem from reduced car ownership costs. Combining the manual-discharge and dog-leg design innovations enables the high/wide alternatives to exceed the operating cost benefits of the base gondola in relation to the base hopper.

The manual-discharge car design does not have a very significant impact on capacity. The manual-discharge car design increases train capacity between 0% and 2% above the subsequent rapid-discharge car design for all of the alternative scenarios considered.

8.3.3.3 Articulated Hopper Design

The articulated car design offers vastly superior operating cost benefits and capacity enhancements beyond the base hopper car than any other alternative hopper design concept. Articulating the base hopper car decreases operating costs 3.8% in the East and 5.5% in the West.

The benefits of articulation are compounded by combining this design concept with the longitudinal dog-leg door design. The articulated dog-leg base hopper car exhibits operating cost savings of 5.9% in the East and 8.7% in the West. These are 4.8% and 7.4% greater benefits from the base hopper than the stand-alone longitudinal-door design.

Adding the manual-discharge design idea to the dog-leg approach does not enhance the increment of benefit from the articulated design concept, but it does further escalate operating savings to 9.2% in the East and 11% in the West, still assuming the base hopper extreme exterior cross-section.

The hopper car operating costs can be improved beyond the base gondola cost level while keeping the base hopper extreme cross-section dimensions.

The operating cost benefits of the articulated hopper car design concept stem from four factors:

- Decreased car spacing
- Decreased tare
- Improved cross-section utilization

- Reduced car maintenance expenses

By articulating hopper cars, the 5.7-foot distance between the coupler faces and the inside edge of the car box is essentially eliminated from each car. The cars are joined together by an articulated joint, thus eliminating the empty space over the couplers and conventional coupling system.

The weight of an articulated joint is 1,500 pounds lighter than a conventional coupling system. This means that, for each pair of couplers that are eliminated, approximately 1,500 pounds of extra lading can be placed in each "car."

Extra lading may also fit into a car section due to the fact that the long articulated car may be loaded as a single, long trough. The volume conventionally lost to the heaping of coal at the ends of each individual car is captured in an articulated design. The gained volume of coal acts effectively as an improvement in cross-section utilization.

Buff and draft forces are reduced throughout a train by utilizing articulated cars. Also, conventional coupling systems and related components are high maintenance cost items. Reducing the forces by eliminating the coupler parts reduces the maintenance costs of articulated cars in relation to conventional cars. This maintenance cost benefit, however, is approximately equaled by a subsequent rise in car ownership costs as a result of reduced car availability. If one of the sections of an articulated car is bad-ordered, then the whole string of articulated cars must be removed from service for repair.

For the high/wide alternatives, articulation advances operating cost benefits from 10% in the East and 12.1% in the West for the "1 Foot Up" case to 13.4% in the East and 16.1% in the West for the "2-Foot Up and 2-Foot Out" case.

The cost benefits of the articulated hopper car design are striking; however, the capacity benefits are even more extraordinary. Articulating the base hopper car boosts train capacity 26%. Incorporating the dog-leg door design improves capacity a further 10%, to a level 36% higher than the base hopper.

The "1-Foot Up" articulated car design offers a capacity increase of 45% over the base hopper at a GLL of 7,480 pounds per foot. The articulated Maximum Dimension scenario offers a 49% capacity boost over the base hopper, which is comparable to the most extreme high/wide design alternatives of the automatic and manual-discharge hopper cars. The amazing fact is that this level of capacity is possible

without exceeding the bounds of Plate C. The GLL of this option is around 7,660 pounds per foot. There will be a capacity and operating cost benefits tradeoff with bridge costs that merits a much more detailed investigation of the promising articulated hopper design concept.

The articulated car design concept is capable of increasing train capacity on the order of 80% above the base hopper for the most extreme cross-section considered. A capacity increase on the order of only 50% is possible with non-articulated concepts. This capacity enhancement does come with a major drawback – increased gross linear loading. The extreme high/wide articulated car design, "2 Feet Up and 2 Feet Out", offers a train capacity 79% greater than the base hopper, but at a gross linear load of 9,120 pounds per foot. This exceeds the AREMA 8,000-pound per foot design load recommendation for bridges built since 1967 and is therefore not practically feasible.

8.3.4 Operating Cost Sensitivity Analysis

The sensitivity of the operating cost benefits derived from the alternative designs to six key parameters was tested. The parameters are listed here, in order of decreasing importance:

1) Length versus weight-limited train assumption
2) Car ownership cost
3) Cycle time / congestion
4) Cross-section utilization
5) Net-to-tare
6) Car spacing and fixed drawbars

The operating cost results were found to be extremely sensitive to the train make-up assumption. The car ownership and cycle time / congestion assumptions were also found to be very important to the level of operating cost savings for a reasonable range of variation in each parameter. Cross-section utilization and net-to-tare were also found to significantly impact the benefit estimates, but not to the same degree as car ownership or cycle time. Car spacing and fixed drawbars had a relatively minor impact on the operating cost benefit results.

8.3.4.1 Length-Limited versus Weight-Limited Train Sensitivity Analysis

An important caveat of this study is the length-limited train assumption. The operating cost and capacity benefits are greatly reduced for weight-limited trains. For the high/wide scenarios, the weight-limited operating cost benefits range from about 30% to 45% as great as the length-limited benefits in the East and from 15% to 30% as great in the West.

The number of train-miles is all that differentiates the cost driving statistics of the length and weight-limited cases. Crew costs typically compose on the order of ¾ of the total operating cost differential between length and weight-limited trains.

The largest capacity increase is less than 2% for weight-limited trains, but is 47% for length-limited trains. The slight capacity enhancement that exists in the weight-limited case is attributable to the net-to-tare improvements of the alternative car designs over the base case.

8.3.4.2 Car Ownership Cost Sensitivity Analysis

Car ownership costs are the second largest cost component in the East gondola base case, constituting 19% of total operating costs. In the West, car ownership accounts for 11% of the total costs. The proportions are even greater for the hopper cases. The car ownership costs were, unfortunately, not as well established in relation to many of the other cost factors. Related data is very mixed in that car costs vary widely depending upon many extraneous factors for each purchase order – market supply and demand, order size, the customer, et cetera. Therefore, the cost results are very sensitive to the specific assumptions that are employed in determining the alternative car designs.

The conservative car cost assumption reduced the operating cost benefits by 15-25% for the high/wide design approach. The optimistic car cost assumption increased the operating cost savings by 40-55%. There appears to be more of an up-side than a down-side to the range of reasonable car ownership costs in relation to the costs actually utilized in the study. The costs of car designs that have the largest cross-sections and shortest lengths are more effected by car ownership assumptions since these designs vary the most from the base case. Since the heavier axle load car designs are much different from the base gondola, the range of their operating cost sensitivity to the car ownership cost assumption is very large.

8.3.4.3 Cycle Time Sensitivity Analysis

Estimated cycle times were reduced up to 5.5% in the East and 7.2% in the West for the scenarios explored, due to reducing congestion at network bottlenecks. The West was more sensitive to changes in train capacity, and thus the number of trains operating on the network, because the Western network was assumed to operate closer to capacity. A reduction in cycle time reduces equipment (car and locomotive) ownership costs.

Overall, the level of operating cost savings are very sensitive to the cycle time assumption and the effects of network congestion. The Eastern gondola high/wide case operating cost benefits were improved an additional 35-50% over the base gondola and 30-35% in the West. The benefits of the 39-ton axle load case were improved an additional 20% in the East and were doubled in the West. The articulated hopper benefits over the base hopper were increased on the order of 25% in the East and 15% in the West. Even though the cycle time reduction was larger in the West than for the respective East case, equipment ownership costs are a much more significant portion of total operating costs in the East.

8.3.4.4 Freight Car Cross-Section Utilization Sensitivity Analysis

Decreasing the proportion of a car design's extreme cross-section that is not empty or utilized for the car structure shortens the car length required to hold the same net capacity. Shortening a car was assumed to have a positive effect on the tare weight of the car, thus increasing the car capacity.

The car cross-section utilization level is a critical assumption in parametric car design. For car designs that were not constrained to a fixed length, improving cross-section utilization had a modest implication on operating costs. There was absolutely no operating cost benefit to improving the cross-section utilization for a car with a fixed length.

Utilization improvements can be made in conjunction with another car design approach in order to significantly enhance the cost efficiency of an alternative car design. A cross-section utilization improvement of 5% could improve the operating cost savings of the alternative high/wide gondola designs a further 10 – 25%.

8.3.4.5 Freight Car Net-to-Tare Sensitivity Analysis

Every operating cost component is effected by the car net-to-tare assumption. The operating cost saving results are, thus, quite sensitive to the assumed net-to-tare weight of each alternative car design. A reduction in the tare weight of a car means that more lading may be added to the car while keeping the gross weight and axle loadings at a constant level.

Overall, reasonable deviations in the net-to-tare assumptions in the alternative car designs do not "make or break" the alternative design methodologies, including the high/wide design approach. However, the net-to-tare assumption does have a significant effect on the level of operating cost savings for the alternative designs. The bottom line savings of the alternative designs are affected on the order of 10-20% for the reasonable net-to-tare range of this sensitivity analysis.

8.3.4.6 Car Spacing and Fixed Drawbar Sensitivity Analysis

A greater volume of net tonnage may fit into a fixed length of train by decreasing the spacing between cars, thereby increasing the number of cars in a train length. The use of fixed drawbars improves operating costs by:

- Reducing car tare, thus increasing the net weight per car
- Improving car maintenance costs

Even though fixed drawbar connectors are less expensive to purchase than a conventional coupling system, car ownership costs increase overall due to the assumed car maintenance availability costs of blocked cars. The car fleet must be enlarged in order to compensate for a reduction in car availability due to car maintenance activities. A failure resulting in removing a car from service for repair necessitates removing a whole block of cars from service. Actual car maintenance costs are reduced due to the elimination of maintenance-intensive coupling system components and the reduced force environment procured by blocked cars.

Retrofitting the gondola car designs with fixed drawbars improved operating cost benefits less than 3% in all cases. This is a trivial amount in comparison to other alternative design methodologies. Fixed drawbars might be worth pursuing in order to increase the maximum weight of weight-limited trains since the inherent reduction in buff and draft forces will increase the maximum allowable drawbar force.

Drawing the cars of the gondola scenarios closer together improves operating cost savings less than 5% per foot of reduced car length. This level of savings is relatively minor compared to other alternative design methodologies, but should be pursued, if possible, since there are no associated implementation costs to reducing car spacing. The only limitation to the amount of space that can be eliminated between cars is governed by the tolerances desired for curving allowance. The corners of the car boxes of adjoining cars must not run in to each other when negotiating extremely sharp curves, such as a loop-track at a coal mine loading facility.

8.3.5 Implementation Issues

Incremental costs could be incurred from adverse impacts of any new equipment-type on clearances, bridges, unloading facilities or by implementing any new operating practices, such as the use of displaced locomotive power. The costs associated with bridges were found to be very significant. The costs associated with unloading facilities were found to be moderate for alternative high/wide car designs, except in the case of unit train rotary dump facilities in the East, where the costs are extremely substantial. Displaced power costs were found to be relatively minor. A comparison of clearance increase costs was not provided since these costs are extremely site and route specific and are also very sensitive to the degree to which clearances are improved.

8.3.5.1 Incremental Bridge Costs

The incremental bridge costs were estimated at 2.2% of the base gondola cost and 2.1% of the base hopper operating cost. These cost estimates represented the HAL bridge economic analysis [3] cost results for increasing axle loads from 36 tons to 39 tons when applied to the representative coal distribution networks, assuming a constant bridge impact cost per mile across the networks. The ramifications of including bridge costs in the heavier axle load gondola scenarios are that the cost savings are eliminated.

If increasing linear loading on bridges by reducing axle spacing has exactly has the same result on bridges and bridge costs as increasing axle loads, then the incremental bridge costs effectively eliminate the operating cost savings of the high/wide alternative car design methodology. The capacity increases from such alternative car designs would not coincide with an operating cost benefit. The effects of increased axle loads, however, are probably greater on bridge costs than the effects of decreased axle spacing.

8.3.5.2 Incremental Unloading Facility Costs

Bottom-dump facilities were imagined to have no appreciable implementation costs associated with alternative car designs, unless modifications are necessary for thaw shed dimensions (i.e. length). Rotary-dump facilities do have costs associated with modifying the dumpers in order to accommodate alternative car designs. These costs vary over quite a wide range since they are extremely sensitive to the average volume of coal shipped and the average length of haul for each unloading method and facility.

In the East, the unit train dumper costs are only surmountable with fairly extreme height and width increases under the high/wide design methodology. Modifying unit train rotary dumpers represents a formidable obstacle to high/wide car design implementation. Only the facilities with the highest volumes and longest lengths of haul could find economic benefit to changing over to high/wide car designs. If, however, a dumper is at a stage wherein it needs a major maintenance overhaul or replacement, then the incremental costs of modifying the dumper to accommodate high/wide cars may not be very large at all.

In the West, Unit train rotary dumper implementation costs are not nearly as significant a barrier to high/wide car design. A high/wide car must be at least 6 inches higher or wider than the base car in order to compensate for the average unit train dumper modifications in the West. The impact of dumper costs is much reduced in the West in comparison to the East because of the higher average volume of coal that destined to Western unit train rotary-dump facilities and the much longer average length of haul in the West.

The rotary dumper implementation costs for a longer 3-axle truck car design are generally much greater than the operating benefits perceived to be available from such a car design. The only scenario in which the 3-axle truck car dumper modifications do not overcompensate for the estimated operating benefits is in the Western unit train dumper case where the overall operating cost benefit is modest.

8.3.5.3 Incremental Displaced Locomotive Power Costs

The implementation costs of displaced power are quite low. These cost magnitudes represent 0.5% and 0.3% of the base gondola operating cost levels in the East and West, respectively. The increased weight of trains due to alternative car designs does not pose a serious threat to the benefits achievable by introducing the alternative car designs.

8.4 Conclusions

8.4.1 Overview and Source of Benefits

Alternative car design is capable of simultaneously improving total cost and increasing network capacity for heavy-haul coal unit train service. The cost and capacity improvements of the alternative designs arise primarily from increasing net train capacity. The benefits from increasing train capacity originate from two broadly defined sources:

- Increased train gross linear loading
- Improved train carrying efficiency (i.e. net-to-gross, or net-to-tare)

Increasing train capacity by increasing linear loading decreases operating costs because fewer trains are able to transport the same amount of lading. This phenomenon only occurs for length-limited trains. Increasing train capacity by improving the carrying efficiency decreases operating costs because fewer cars are able to transport the same amount of lading. This phenomenon is independent of the limiting train size parameter (i.e. length or weight).

Total cost can also be improved by implementing new car technologies or designing cars in such a way as to reduce car ownership and car maintenance expenses.

8.4.2 Capacity Framework for Car Design versus HAL Approach

A broader and more systematic approach to cost improvement and capacity enhancement than the traditional HAL methodology is a better way to improve upon current best operating practices. From a car design perspective, train capacity, defined at the most diminutive level, is a function of six components:

- Axle load
- Number of axles per car
- Car cross-section
- Cross-section utilization

- Car spacing
- Car Net-to-Tare

The traditional HAL approach focused solely on increasing axle loads as a method for improving productivity. Increasing axle loads has a detrimental effect on track costs. The operating cost benefits from increasing axle loads are thus off-set by this increase in track costs. Expanding the car design emphasis to encompass all of the parameters that affect train capacity provides a mechanism with which to circumvent the detrimental HAL effect on track costs and provides more avenues of opportunity for productivity enhancement.

Examples of the benefits from improved car design without increasing axle loads exist from Canadian, Indian and Australian experiences. The Canadians and Indians have both benefited from decreased car lengths due to improved cross-section utilization in the Canadian case and increased cross-section dimension in the Indian case. The Australians have benefited from reduced car tare and increased linear loading from a number of sources.

8.4.3 Alternative Car Design Benefit and Cost Tradeoff

Train capacity can be maximized in such a way as to minimize total costs and maximize network capacity. Changes in total cost are the sum of incremental track, transportation, equipment, and implementation benefits and costs. Network capacity is a function of both line and terminal capacities across all the components of a network.

Two basic car types were investigated in this study:

- Bathtub gondola
- Rapid-discharge open-top hopper

Three basic alternative design concepts were applied to these two basic car types:

- High/wide (increased cross-section)
- Heavier (increased axle load)
- 3-axle truck (increased axles)

Within the framework of these three basic alternative design concepts, an effort was made to improve cross-section utilization, net-to-tare and car spacing.

The 3-axle truck and heavier design concepts do improve productivity over the base cases, but not as efficiently as the high/wide design methodology. Total operating cost benefits are greater for an incremental train capacity increase with the high/wide approach.

The 3-axle truck car is very long and therefore has a narrow width due to the truck center spacing. The 3-axle truck car also suffers a tare weight and car maintenance penalty from the heavy 3-axle trucks. The long cars also have a high ownership cost due to the necessary longitudinal strengthening. The rotary dumper costs for the longer 3-axle truck cars are also higher than for shorter high/wide cars.

The heavier car designs suffer a track cost penalty from increased axle loads and a car ownership cost penalty due to the necessary strengthening from higher loading. Increasing the axle loads to the extent that requires 38-inch diameter wheels also incurs a substantial tare weight penalty. These cars, being 53 feet long, do not suffer from unloading implementation costs, but do incur a bridge cost increase larger than any of the incremental operating cost benefits.

The high/wide design approach offers operating cost benefits on the order of 2% per foot of additional height or width in both the East and the West for the gondola car. The height benefits drop to about 1% per foot in the East and 1½% per foot in the West for advances beyond the conventional 98-inch center-of-gravity limit. For the hopper car designs, the cost benefits are 2% per foot in the East and 2½% per foot in the West for height increases and 2% per foot of additional width. Incorporating a longitudinal dog-leg door design approximately doubles the height benefits when car length is not fixed.

The high/wide design approach offers a network capacity increase on the order of 9% per foot of additional height or width for the gondola car and 10% per foot of additional height or width for the hopper car. For the hopper car, incorporating a longitudinal dog-leg door design approximately doubles the height benefit when car length is not fixed.

In implementing the high/wide design approach, it is best to increase car height to the center-of-gravity limited maximum first and then increase width to whatever dimension is most appropriate, considering clearance issues and costs. Increasing the cross-section utilization in order to design a Maximum

Dimension car has an equivalent operating cost benefit of increasing width (or height) an additional 3 inches over the basic Plate C and center-of-gravity bound car design.

The high/wide hopper car design productivity can be improved over the base hopper car by not only incorporating dog-leg doors, but also by removing the automatic rapid-discharge equipment and by articulating the cars. Removing the discharge equipment reduces car ownership costs and car tare weight so as to improve operating costs a further 4½% in the East and 3½% in the West. Articulation improves operating costs a further 5% in the East and 7½% in the West and boosts capacity about 25% compared to the base hopper.

The operating cost benefit calculations are very sensitive to the train make-up assumption. The capacity benefits are all but eliminated if train size is limited by weight instead of length. The operating cost benefits are also reduced by one-half or more.

If the network is assumed to be congested, the cycle time reductions offered by the alternative high/wide car designs might improve operating costs a further 1 – 2½% in the East and 1 – 2% in the West over the base gondola.

Car ownership costs could improve costs up to 2% over the base gondola or increase costs up to 1%. The net-to-tare of these alternative high/wide cars could affect costs by up to 1% in relation to the base gondola.

An additional 5% of cross-section utilization could improve operating costs a further ½%. The benefits from fixed drawbars and decreased car spacing are minor, but could be as high as about ½% over the base gondola.

Bridge costs are an important factor in both the East and West. If bridge costs increase directly with linear loading to the same degree as the costs increase with axle load above the base case, the incremental bridge costs will approximately off-set most or all of the operating cost benefits. The bridge cost estimates of this study, however, are felt to be quite conservative and probably overstate the incremental cost of bridges for modest increases in linear loading. For extreme increases in linear loading, the bridge cost impact may be greater than from equivalent axle load effects, especially if bridge design loads are exceeded, mandating immediate bridge replacement before the alternative car design is introduced into service.

The dumper costs are much more extreme in the East than in the West. The shorter average length of haul and lower average coal traffic volume of the East necessitate a car cross-section increase of "2 Feet Up and 1 Foot Out" in order to compensate for the average incremental rotary dumper costs. In the West, a cross-section increase of 6 inches in either height or width is all that is required to off-set the average dumper costs.

The incremental cost of implementing displaced power operations is very small compared to the operating benefits available from high/wide cars. Clearance costs might be non-existent for modest width increases, such as 6 inches and might even be quite low for increases in width out to 1 foot or more.

8.4.4 Optimal Car Design

An important conclusion of this study is that there is not any one single optimal car design. Optimal car design depends upon many site, service, route and network-dependent variables, that alter the objective and conclusion of which car design is optimal. The evaluation of an optimal car design is based upon total cost efficiency and network capacity effectiveness. The demand for increased capacity, the relative economics of other capacity enhancement alternatives, incremental operating cost benefits and incremental implementation costs (such as bridge costs, loading and unloading costs, clearance enhancement costs and costs for changing operating practices) must all weigh in to the decision. The improved productivity offered by a car design can also be limited by restrictions imposed by the intended operating environment of the design (i.e. unrestricted interchange service versus single-line captive service). Ultimately, the best car design for a specific service depends upon the tradeoff between operating cost and capacity benefits and implementation costs so that equilibrium between minimal total costs and adequate capacity is reached.

Four specific alternative car designs indicate the most promise for more productive coal heavy-haul railroading:

- High/wide, dog-leg, rapid-discharge hopper
- Articulated, dog-leg, manual-discharge hopper
- Higher axle load, 53-foot gondola
- High/wide, bathtub gondola

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The primary reason behind the presence of four alternative car design methodologies is a difference in optimal unloading method depending upon the service scenario. The capital costs of a rotary dumper are high, necessitating high utilization levels in order to be cost efficient. Gondola cars, which are very cost efficient cars for line-haul operations due to their low tare and low ownership costs are rotary dumped. This makes rotary dumping attractive for longer hauls where the line-haul operating costs are a larger portion of the total logistics cost to the customer. Overall, rotary dumping is the most cost efficient unloading method for high volume facilities and long hauls.

Bottom dumping from hopper cars is more attractive for facilities with a lower volume of coal and/or a shorter average length of haul. Hopper cars are not as efficient as gondola cars on the line-haul portion of the trip, but they also do not need expensive rotary dump equipment for unloading. Hoppers are unloaded on a simple trestle system or over a pit. If the coal is not frozen and the hopper cars are equipped with automated rapid-discharge doors, the unloading rate can exceed that of rotary dumping.

The high/wide, dog-leg rapid discharge hopper car offers increased capacity and reduced operating costs over the traditional hopper car design. This design is shorter than 53 feet and has 36-ton axle loads. This is the least operating cost efficient and capacity effective design of the four alternatives proposed. This design, however, will have the lowest total costs for customers with the lowest traffic volumes and shortest average lengths of haul, where the unloading costs are a relatively large portion of total costs and more advanced fixed unloading equipment would prove be cost prohibitive.

The articulated, dog-leg, manual-discharge hopper car design offers dramatic operating cost and capacity improvements over the base hopper and gondola cars. This design incorporates 36-ton axle loads. This alternative will be best for the widest range of facility volumes and haul-lengths. In many instances where the gondola car is currently the best option, the articulated hopper will perform more optimally. The articulated design offers a similar operating cost level relative to the high/wide gondola design approach for a similar cross-section; however, the gross linear load of the articulated hopper is much higher than the respective gondola design. There is a bridge cost / capacity tradeoff that must be carefully considered, since it limits the cost benefits of the articulated design. The articulated hopper design offers more capacity than the high/wide gondola design and does not require expensive rotary-dump unloading equipment. Articulated hoppers could also be designed in such a way as to enable dumping over a rotary dumper pit, further easing the implementation of such a car design concept.

The higher axle load, 53-foot gondola option arises from the fact that in some cases the unloading alteration costs will be cost prohibitive for gondola operations. The results indicate that moderate axle load increases that do not necessitate a change from the 36-inch diameter wheel set can improve operating costs and increase capacity. For example, the 39-ton increased axle load gondola option offers a modest operating cost improvement with an 11% capacity enhancement. Adding bridge costs into consideration results in a total cost increase of ½% in the East and 1½% in the West from the base gondola. Despite the cost increase, this option may be desirable for the capacity increase it offers, especially in the East, in instances where avoiding high rotary dumper alteration costs would be desirable. This case is more likely to be attractive for facilities with low to moderate volumes of coal and with dumpers that have long remaining life expectancies.

The high/wide, bathtub gondola design offers impressive cost savings and capacity increases. This design is shorter than 53 feet and has 36-ton axle loads. This alternative will be best for the highest volume facilities and the longest average haul lengths. Unloading costs will be minimized using unit train rotary dumpers equipped to exclusively handle the shorter cars. Operating costs are also lower at a given gross linear load than the articulated hopper design, thus the sum of operating and bridge costs can be minimized at a higher level of network capacity than the hopper option. Rotary dumping is also a very attractive option for services that unload in colder climates where coal might freeze.

8.5 Recommendations for Future Research

The primary recommendation of this study is to continue research on heavy-haul rail car design to a greater level of detail so that more specific optimal vehicle designs might be more confidently proposed for service introduction. The recommended optimal car designs of this study constitute a radical departure from the conventional current perception of future heavy-haul railcar design, which is an aluminum 53-foot 39-ton axle load gondola car. Therefore, before solidly pronouncing a new direction for the industry to proceed in search of productivity benefits, a thorough investigation of the market attractiveness of the optimal car design concepts must be undertaken.

The next logical step for research on heavy-haul rail vehicles is therefore to conduct a more intensive investigation of vehicle design in the context of an explicit operating environment. The results and conclusions of this study must be combined with the findings of the AAR's concurrent vehicle design investigation, conducted by Kent Johnson of Premiere Engineering Corp., in order to identify and outline the major benefits and drawbacks of various car designs and car design methodologies in a practical

sense. These two studies have provided insight and knowledge that should be used in unison in order to devise the most promising explicit car designs for the next stage of investigation.

Definitive car designs must be proposed and devised for any further in-depth investigation, based on the recommended design methodologies of this study and the concurrent vehicle design study. The sensitivity analyses of this study indicate that the level of operating cost savings is extremely sensitive to the assumed vehicle parameters. Each specific design scenario could be optimized given the explicit design considerations and inherent constraints of the car-type and the equipment's operating environment.

In order to optimize the alternative equipment designs, the operating environment within which the equipment is expected to operate must be considered and defined. This may be unrestricted interchange service, limited interchange service, online (non-interchange) service, or a captive service. The relative merits of each design are highly route and service specific, depending largely upon the volume of demand, average length of haul and the characteristics of the distribution network.

Dynamic models such as the AAR's NUCARS model [56] could be used to estimate the handling characteristics of shorter, higher, and/or wider cars with different centers of gravity. The track/train dynamics of alternative car designs must meet the minimum safety specifications.

Once the specific vehicle designs have been established, an economic analysis of the alternatives must be performed in relation to a single or selection of current practice, conventional base cases. The East and West coal mainlines used in the HAL analyses were expanded to more extensive and realistic, representative Eastern and Western coal networks in the Optimal Axle Load study and in this study. These generic networks could be expanded again to explicit Eastern and Western heavy-haul network case studies, modeled after real coal distribution networks, and featuring a varied selection of origins and destinations typical of U.S. operations.

The case study approach implies a massive data acquisition and compilation effort in order to conduct a thorough analysis. Forming partnered relationships between the AAR and the affected parties could minimize this effort by tailoring the analysis methodology to match the information available and by requesting the information in a format tailored to the AAR's input needs.

A detailed case study approach could involve calibrating UTRAIN [9] to the networks, network operations, and traffic flows in order to determine alternative scenario equipment requirements and cycle

times. The TRACS computer model [29] and HALTRACK spreadsheet model [30] could be utilized to calculate the track maintenance requirements and track costs by calibrating them to the network base cases using actual observed unit costs, component lives, and maintenance intervals, and the HAL analysis inputs and methodologies. TEM/RECAP [28] could be used to explicitly model the network operating costs by calibrating the model to the network base case using actual observed unit costs, car and locomotive parameters, and the network topography.

The effects of the alternative car designs, and ultimately the optimal designs, on system capacity need to be more thoroughly addressed. One of the great benefits of the articulated and high/wide vehicle design methodologies is that capacity is increased in conjunction with lowering operating costs, including track costs. This is contrary to the standard HAL approach, in which increasing the axle load raises track costs but may or may not lower total operating costs overall. Almost every other capacity enhancement alternative – double or triple-tracking, lengthening sidings, increasing speeds, improving communications and signaling systems, et cetera – increases total costs.

The HAL analyses stressed the operating cost benefits from increasing railcar capacity, but skimmed over the capacity implications of the heavier axle load car designs. This study took an initial step towards an evaluation of capacity increases by depicting the results simultaneously in terms of operating cost and capacity. The cost dimension should be expanded to include total incremental benefits *and* costs, including implementation costs. The effects of the alternative car designs on both line and terminal capacity should be assessed in relation to traffic demands, infrastructure supply capabilities, and alternative capacity enhancement options. UTRAIN [9] and the Intermediate Terminal Model [59] could be used in conjunction to gauge the effects of alternative car designs on network capacity.

Two areas of equipment costs need to be studied in greater detail than was undertaken in this study:

- Car ownership
- Car maintenance

The sensitivity and importance of the operating cost results to the car ownership cost assumptions was highlighted in this study. The car maintenance costs for the less conventional alternative designs (blocked cars, manual-discharge doors, et cetera) were not based on a substantial amount of data or an intensive investigation. Substantial changes in these cost components from the assumptions of this study could have a significant bearing on the overall conclusions.

This study has indicated the relative importance of four incremental costs associated with optimal car design in relation to the extent of the operating benefits available:

- Clearances
- Bridges
- Unloading facilities
- Displaced locomotive power

These costs are highly scenario specific, and need to be studied in greater detail in the context of the network case studies.

Clearances, of course, depend upon the specific route considered and the standard to which that route was constructed. Horizontal clearance improvement costs can be quite significant, especially with respect to track center spacing of mainlines, sidings and yards. The clearance limits must be inventoried for the case studies under consideration, with further consideration of the intended operating environment of the optimal car design (i.e. unrestricted interchange service, limited interchange service, online (non-interchange) service, or captive service) in order to determine the costs, if any, associated with the horizontal dimensions of the optimal car design.

The HAL Phase II bridge analysis [3] estimated the effects of increased axle loads on the fatigue life of a variety of typical bridges. Applying these results to alternative car design scenarios indicated that the cost / benefit tradeoff of an optimal car design must include this significant cost component. Decreasing axle spacing, however, affects the nature of bridge loading and bridge fatigue in a different manner than increasing axle loads. This, therefore, necessitates a more in-depth investigation similar to the HAL approach.

The AAR has funded an additional study addressing the costs associated with restructuring unloading facilities due to changes in car geometry [54]. The findings of that report were used in this study, and were found to be very sensitive to the specific facility characteristics, unloading method, volume of coal and average length of haul. This is especially true for rotary dumpers. The unloading facility modifications, therefore, need to be explicitly modeled within the case study framework.

The increased train capacity and thus the heavier train trailing weights inherent in optimal car design will necessitate modifying operating practices to accommodate displaced locomotive power within trains in order to maintain drawbar forces at a safe level so as to avoid train pull-aparts and derailments. The incremental costs associated with instituting such operating practices and the practical implementation issues appear are unavoidable and should thus be accurately surveyed.

As indicated by the preliminary implementation investigations of this study, a broader economic analysis is an absolute necessity in addressing optimal car design. The HAL analyses and Optimal Axle Load study were based upon steady-state conditions. Steady-state analysis provides a clear understanding of the different costs associated with each vehicle design. However, a steady-state analysis does not consider implementation issues, nor does it necessarily indicate how quickly or in which way new technologies should be implemented. Hence, it would be useful to consider the implementation costs and to examine the timing of costs and benefits to the railroads and their customers. The implementation costs associated with renewing car fleets, modifying unit-train rotary dump facilities, upgrading bridges and improving horizontal clearances are sizeable in relation to optimal car design benefits and are complicated by the issue of fragmented economics regarding who pays versus who benefits from alternative vehicle designs.

A broader economic analysis could also imply extending the investigation in order to study the implications of optimal car design on other commodities. Grain is an obvious first choice. Increasing the dimensions of grain hopper cars could increase the grain distribution network capacity and lower total costs. By not raising axle loads, track costs are not increased, which could be very important on the poorer track structure inherent on low density grain network branch lines. Shortening the grain cars could also increase grain terminal siding capacity. Other bulk commodities, such as iron ore, plastics, and petrochemical and other liquid products could benefit from optimal vehicle design, similarly to coal traffic operations. Using shorter cars for traffic susceptible to switching operations could increase the standing capacity of classification yards. Also, the costs of auto-haul traffic could be reduced dramatically through a doubling of capacity by placing automobiles two-abreast during transport, if permitted by wider horizontal clearances.

The manner in which a subsequent study is carried forth is critical to its success. Lessons can be learned from feedback received from the HPIT project [15]. This project, described in Section 2.4, was an alternative vehicle design project similar to the optimal vehicle design concept.

It was suggested that the AAR could have had better results and a more profound impact on the future of vehicle design if it would have marketed the project – especially the promise indicated by the interim economic analysis results [15]. HPIT was felt to have had very good information, but the key railroad innovators were never really attracted to the project and thus the railroad industry never provided solid support for the project. The suppliers had inadequate research and development funds for such radically different technological concept development and thus needed sponsors to take a financial interest in the design effort. The benefits of any new proposals must be identified and understood by the beneficiaries in order to stimulate the development and introduction of a concept. The AAR has begun to market the Optimal Car Design philosophy for improving heavy-haul railroading productivity, but must be aggressive and extensive in its actions in order to "sell" a potentially revolutionary ideology to the industry, such as Optimal Car Design.

Another suggestion is that all stakeholders involved in a project should be partnered together in order to garner the support and commitment necessary to carry out the investigation efficiently and effectively [15]. For example, the case study approach requires an intimate relationship between all of the affected parties – the AAR, AAR member railroads, coal mines, electric utilities, ports, and equipment suppliers – in order to calculate the total logistics cost of coal movements and to determine optimal system equilibrium in the face of fragmented economic benefits and ulterior motivations. Without the dedicated involvement and support of every stakeholder, it will be much more difficult to implement the recommended actions of any study.

Timeliness is of the essence. Both the railroads and the suppliers felt that the HPIT project moved too slowly [15]. One of the HPIT concepts – the stack train – was put into service by the free market while the HPIT committees were still studying them. The marketplace is very fast moving. The AAR has to produce the bottom-line results quickly in order to hit the market. Haste should be made in performing the next phase of optimal vehicle design investigations in order to maintain interest and to make recommendations for the future of heavy-haul car design before large investments in another type of car are committed (i.e. 53-foot 125-ton aluminum car).

In summary, the primary recommendation of this study is to continue research on heavy-haul rail car design to a greater level of detail so that more specific optimal vehicle designs might be more confidently recommended. Car design is a critical component to heavy-haul productivity and future competitiveness, therefore it is important to fully understand the economics and practical implications of any results and

conclusions. The recommended research program for Optimal Car Design would extend beyond this and other prior studies in five major ways:

1) Contrive explicit prototype car designs using the four recommended concepts outlined in this Optimal Axle Load study and the conclusions of the concurrent vehicle design study performed by Kent Johnson of Premiere Engineering Corp.

2) Quantify costs more thoroughly where either cost estimates were based on relatively little data or where results were demonstrated to be extremely sensitive to cost assumptions. Two areas of costing, in particular, are noted for needing improvement:

- Equipment ownership and maintenance costs
- Incremental implementation costs: bridges, unloading facilities, clearances and displaced power operations

3) Consider the optimal car design implications on other commodity groups: grain, other heavy-haul solid bulk, liquid bulk, and automotive.

4) Perform a system study with three major attributes:

- Assessment of definitive alternative car designs
- Detailed case study modeling approach
- Network capacity enhancement evaluation with respect to total incremental costs and benefits, the demand for increased capacity and other capacity options

5) Investigate the implementation issues and subsequent ramifications: fragmented economics, car fleet renewal and timing.

In order to better ensure the success of any subsequent research, three factors in the design and approach methodology are deemed crucial:

1) Marketing of the optimal vehicle design concept and the interim results should be undertaken in order to stir the interest and garner the sponsorship and financial support of the beneficiaries

2) Partnering should occur between the affected parties of the study in order to get the support and commitment necessary to carry out the investigation and implement the recommended actions

3) Timeliness is critical in dealing with the free market in order to have a full impact on the future of heavy-haul car design before major investments are undertaken and technology becomes entrenched.

The five recommended actions and three recommended aspects for carrying out these actions could lead to a very solid and rewarding Optimal Car Design research project for the railroad industry and its customers.

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APPENDIX A: TABLES OF ALTERNATIVE CAR DESIGN PARAMETERS

Table A-1: Higher Gondola Car Characteristics

Freight Car Characteristics	Base Gondola	1' Up	2' Up	3' Up
Exterior Dimensions (ft):				
Extreme Length	53.1	48.4	45.6	42.9
Extreme Height	12.4	13.5	14.3	15.1
Extreme Width	10.7	10.7	10.7	10.7
Length Between Truck Centers	40.5	35.8	33.0	3C.3
Interior Dimensions (ft):				
Maximum Length	47.7	43.0	40.?	37.6
Maximum Width	9.9	9.9	5.?	9.9
Average Height	9.3	10.4	11.1	12.0
Weights (lbs):				
Gross	286,000	286,000	286,000	286,000
Net	243,000	244,065	244,730	245,433
Tare	43,000	41,935	41,270	40,567
Statistics:				
Gross Linear Load (lbs/ft)	5,388	5,912	6,273	6,667
Change from Base (%)	0%	10%	16%	24%
Net Linear Load (lbs/ft)	4,578	5,045	5,368	5,721
Change from Base (%)	0%	10%	17%	25%
Extreme Length Change from Base (ft)	0.0	-4.7	-7.5	-10.2
Extreme Length Change from Base (%)	0%	-9%	-14%	-19%
Net Cross-Section (sq ft)	92	103	110	118
Change from Base (%)	0%	11%	19%	28%
Cross-Section Utilization (%)	69.5%	71.4%	72.5%	73.6%
Net-to-Tare Ratio	5.65	5.82	5.93	6.05
Net-to-Gross Ratio	0.850	0.853	0.856	0.858
Change from Base (%)	0%	0.4%	0.7%	1.0%
Box Surface Area (sq ft)	1,546	1,524	1,513	1,506
Change from Base (%)	0%	-1%	-2%	-3%

Table A-2: Wider Gondola Car Characteristics

Freight Car Characteristics	Base	6" Out	1' Out	2' Out
Exterior Dimensions (ft):				
Extreme Length	53.1	50.8	48.8	45.3
Extreme Height	12.4	12.4	12.4	12.4
Extreme Width	10.7	11.2	11.7	12.7
Length Between Truck Centers	40.5	38.3	36.3	32.8
Interior Dimensions (ft):				
Maximum Length	47.7	45.5	43.5	40.0
Maximum Width	9.9	10.4	10.9	11.9
Average Height	9.3	9.3	9.3	9.3
Weights (lbs):				
Gross	286,000	286,000	286,000	286,000
Net	243,000	243,504	244,003	244,849
Tare	43,000	42,496	41,997	41,151
Statistics:				
Gross Linear Load (lbs/ft)	5,388	5,627	5,856	6,309
Change from Base (%)	0%	4%	9%	17%
Net Linear Load (lbs/ft)	4,578	4,791	4,996	5,401
Change from Base (%)	0%	5%	9%	18%
Extreme Length Change from Base (ft)	0.0	-2.3	-4.2	-7.8
Extreme Length Change from Base (%)	0%	-4%	-8%	-15%
Net Cross-Section (sq ft)	92	97	102	111
Change from Base (%)	0%	5%	10%	20%
Car Cross-Section Utilization (%)	69.5%	69.8%	70.0%	70.4%
Net-to-Tare Ratio	5.65	5.73	5.81	5.95
Net-to-Gross Ratio	0.850	0.851	0.853	0.856
Change from Base (%)	0%	0.2%	0.4%	0.8%
Box Surface Area (sq ft)	1,546	1,514	1,487	1,442
Change from Base (%)	0%	-2%	-4%	-7%

Table A-3: Higher and Wider Gondola Car Characteristics

Freight Car Characteristics	Base Gondola	2' Up & 6" Out	2' Up & 1' Out	3' Up & 1' Out	2' Up & 2' Out	3' Up & 2' Out
Exterior Dimensions (ft):						
Extreme Length	53.1	43.7	42.0	39.6	39.0	36.8
Extreme Height	12.4	14.3	14.3	15.1	14.3	15.1
Extreme Width	10.7	11.2	11.7	11.7	12.7	12.7
Length Between Truck Centers	40.5	31.1	29.4	27.0	26.5	24.2
Interior Dimensions (ft):						
Maximum Length	47.7	38.3	36.7	34.2	33.7	31.4
Maximum Width	9.9	10.4	10.9	10.9	11.9	11.9
Average Height	9.3	11.1	11.1	12.0	11.1	12.0
Weights (lbs):						
Gross	286,000	286,000	286,000	286,000	286,000	286,000
Net	243,000	245,201	245,661	246,278	246,443	247,035
Tare	43,000	40,799	40,339	39,722	39,557	38,965
Statistics:						
Gross Linear Load (lbs/ft)	5,388	6,545	6,808	7,231	7,326	7,778
Change from Base (%)	0%	21%	26%	34%	36%	44%
Net Linear Load (lbs/ft)	4,578	5,611	5,848	6,227	6,313	6,718
Change from Base (%)	0%	23%	28%	36%	38%	47%
Extreme Length Change from Base (ft)	0.0	-9.4	-11.1	-13.5	-14.0	-16.3
Extreme Length Change from Base (%)	0%	-18%	-21%	-25%	-26%	-31%
Net Cross-Section (sq ft)	92	116	121	130	132	142
Change from Base (%)	0%	26%	32%	41%	44%	54%
Car Cross-Section Utilization (%)	69.5%	72.7%	73.0%	74.1%	73.4%	74.5%
Net-to-Tare Ratio	5.65	6.01	6.09	6.20	6.23	6.34
Net-to-Gross Ratio	0.850	0.857	0.859	0.861	0.862	0.864
Change from Base (%)	0%	0.9%	1.1%	1.3%	1.4%	1.7%
Box Surface Area (sq ft)	1,546	1,483	1,458	1,451	1,415	1,410
Change from Base (%)	0%	-4%	-6%	-6%	-8%	-9%

Table A-4: Other Alternative Gondola Car Characteristics

Freight Car Characteristics	Base Gondola	Maximum Dimension	39-Ton Axle Lds	42-Ton Axle Lds	3-Axle Trucks
Exterior Dimensions (ft):					
Extreme Length	53.1	44.3	53.1	53.1	69.3
Extreme Height	12.4	14.3	13.5	14.1	14.3
Extreme Width	10.7	10.7	10.7	10.7	10.1
Length Between Truck Centers	40.5	31.7	40.5	40.5	56.7
Interior Dimensions (ft):					
Maximum Length	47.7	38.9	47.7	47.7	63.9
Maximum Width	9.9	9.9	9.9	9.9	9.3
Average Height	9.3	11.5	10.4	11.0	11.1
Weights (lbs):					
Gross	286,000	286,000	315,000	336,000	429,000
Net	243,000	245,084	270,758	287,234	366,097
Tare	43,000	40,916	44,242	48,766	62,903
Statistics:					
Gross Linear Load (lbs/ft)	5,388	6,459	5,933	6,329	6,193
Change from Base (%)	0%	20%	10%	17%	15%
Net Linear Load (lbs/ft)	4,578	5,535	5,100	5,410	5,285
Change from Base (%)	0%	21%	11%	18%	15%
Extreme Length Change from Base (ft)	0.0	-8.8	0.0	0.0	16.2
Extreme Length Change from Base (%)	0%	-17%	0%	0%	30%
Net Cross-Section (sq ft)	92	114	103	109	104
Change from Base (%)	0%	24%	11%	18%	12%
Car Cross-Section Utilization (%)	69.5%	75.0%	71.4%	72.3%	72.2%
Net-to-Tare Ratio	5.65	5.99	6.12	5.89	5.82
Net-to-Gross Ratio	0.850	0.857	0.860	0.855	0.853
Change from Base (%)	0%	0.9%	1.2%	0.6%	0.4%
Box Surface Area (sq ft)	1,546	1,509	1,668	1,740	2,225
Change from Base (%)	0%	-2%	8%	13%	44%

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Table A-5: Alternative 39-Ton Axle Load Gondola Car Characteristics

Freight Car Characteristics	39-Ton Base Gondola	53' Long 39" Wheels	Maximum Dimension	2' Up & 6" Out	2' Up & 1' Out	2' Up & 2' Out	3' Up & 2' Out
Exterior Dimensions (ft):							
Extreme Length	53.1	53.1	48.5	47.9	46.0	42.7	40.2
Extreme Height	13.5	13.4	14.3	14.3	14.3	14.3	15.1
Extreme Width	10.7	10.7	10.7	11.2	11.7	12.7	12.7
Length Between Truck Centers	40.5	40.5	35.9	35.3	33.4	30.1	27.6
Interior Dimensions (ft):							
Maximum Length	47.7	47.7	43.2	42.5	40.7	37.4	34.9
Maximum Width	9.9	9.9	9.9	10.4	10.9	11.9	11.9
Average Height	10.4	10.2	11.5	11.1	11.1	11.1	12.0
Weights (lbs):							
Gross	315,000	315,000	315,000	315,000	315,000	315,000	315,000
Net	270,758	267,128	271,849	271,967	272,490	273,333	274,038
Tare	44,242	47,872	43,151	43,033	42,510	41,667	40,962
Statistics:							
Gross Linear Load (lbs/ft)	5,933	5,934	6,492	6,576	6,845	7,374	7,834
Change from Base (%)	0%	0%	9%	11%	15%	24%	32%
Net Linear Load (lbs/ft)	5,100	5,033	5,603	5,678	5,921	6,398	6,815
Change from Base (%)	0%	-1%	10%	11%	16%	25%	34%
Extreme Length Change from Base (ft)	0.0	0.0	-4.6	-5.2	-7.1	-10.4	-12.9
Extreme Length Change from Base (%)	0%	0%	-9%	-10%	-13%	-20%	-24%
Net Cross-Section (sq ft)	103	101	114	116	121	132	142
Change from Base (%)	0%	-1%	11%	13%	18%	29%	39%
Car Cross-Section Utilization (%)	71.4%	71.1%	75.0%	72.7%	73.0%	73.4%	74.5%
Net-to-Tare Ratio	6.12	5.58	6.30	6.32	6.41	6.56	6.69
Net-to-Gross Ratio	0.860	0.848	0.863	0.863	0.865	0.868	0.870
Change from Base (%)	0.0%	-1.3%	0.4%	0.4%	0.6%	1.0%	1.2%
Box Surface Area (sq ft)	1,668	1,651	1,649	1,620	1,591	1,541	1,533
Change from Base (%)	0%	-1%	-1%	-3%	-5%	-8%	-8%

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Table A-6: Transverse-Door Hopper Car Characteristics

Characteristics	Base Hopper	6" Up	39-Ton Axle Lds.	42-Ton Axle Lds.
Exterior Dimensions (ft):				
Extreme Length	53.0	50.7	53.0	53.0
Extreme Height	13.3	13.8	14.3	14.9
Extreme Width	10.7	10.7	10.7	10.7
Length Between Truck Centers	40.5	38.2	40.5	40.5
Interior Dimensions (ft):				
Maximum Length	47.3	44.9	47.3	47.3
Maximum Width	10.1	10.1	10.1	10.1
Average Height	8.8	9.3	9.8	10.4
Weights (lbs):				
Gross	286,000	286,000	315,000	336,000
Net	235,500	236,174	262,848	279,051
Tare	50,500	49,826	52,152	56,949
Statistics:				
Gross Linear Load (lbs/ft)	5,392	5,638	5,939	6,335
Change from Base (%)	0%	5%	10%	17%
Net Linear Load (lbs/ft)	4,440	4,656	4,956	5,261
Change from Base (%)	0%	5%	12%	18%
Extreme Length Change from Base (ft)	0.0	-2.3	0.0	0.0
Extreme Length Change from Base (%)	0%	-4%	0%	0%
Net Cross-Section (sq ft)	89	94	99	105
Change from Base (%)	0%	5%	12%	18%
Car Cross-Section Utilization (%)	62.8%	63.9%	65.1%	66.3%
Net-to-Tare Ratio	4.66	4.74	5.04	4.90
Net-to-Gross Ratio	0.823	0.826	0.834	0.831
Change from Base (%)	0%	0.3%	1.3%	0.9%
Box Surface Area (sq ft)	1,486	1,475	1,603	1,672
Change from Base (%)	0%	-1%	8%	13%

Table A-7: Higher & Wider Longitudinal-Door Hopper Car Characteristics

Freight Car Characteristics	Base Hopper	53'-Long Dog-Leg	1' Up	1' Up & 6" Out	1' Up & 1' Out	2' Up & 2' Out
Exterior Dimensions (ft):						
Extreme Length	53.0	53.0	45.3	43.5	41.9	36.5
Extreme Height	13.3	12.6	14.3	14.3	14.3	15.1
Extreme Width	10.7	10.7	10.7	11.2	11.7	12.7
Length Between Truck Centers	40.5	40.5	32.7	30.9	29.3	24.0
Interior Dimensions (ft):						
Maximum Length	47.3	47.3	39.5	37.7	36.1	30.7
Maximum Width	10.1	10.1	10.1	10.6	11.1	12.1
Average Height	8.8	8.9	10.7	10.7	10.7	11.7
Weights (lbs):						
Gross	286,000	286,000	286,000	286,000	286,000	286,000
Net	235,500	238,492	240,603	241,172	241,659	243,313
Tare	50,500	47,508	45,397	44,828	44,341	42,687
Statistics:						
Gross Linear Load (lbs/ft)	5,392	5,392	6,316	6,578	6,834	7,836
Change from Base (%)	0%	0%	17%	22%	27%	45%
Net Linear Load (lbs/ft)	4,440	4,496	5,314	5,547	5,774	6,666
Change from Base (%)	0%	1%	20%	25%	30%	50%
Extreme Length Change from Base (ft)	0.0	0.0	-7.8	-9.6	-11.2	-16.5
Extreme Length Change from Base (%)	0%	0%	-15%	-18%	-21%	-31%
Net Cross-Section (sq ft)	89	90	109	114	120	141
Change from Base (%)	0%	1%	22%	28%	34%	59%
Car Cross-Section Utilization (%)	62.8%	67.2%	71.5%	71.7%	71.9%	74.0%
Net-to-Tare Ratio	4.66	5.02	5.30	5.38	5.45	5.70
Net-to-Gross Ratio	0.823	0.834	0.841	0.843	0.845	0.851
Change from Base (%)	0%	1.3%	2.2%	2.4%	2.6%	3.3%
Box Surface Area (sq ft)	1,486	1,499	1,465	1,438	1,415	1,371
Change from Base (%)	0%	1%	-1%	-3%	-5%	-8%

Table A-8: Other Alternative Longitudinal-Door Hopper Car Characteristics

Freight Car Characteristics	Base Hopper	53'-Long Dog-Leg	Maximum Dimension	39-Ton Axle Lds	42-Ton Axle Lds	3-Axle Trucks
Exterior Dimensions (ft):						
Extreme Length	53.0	53.0	43.5	53.0	53.0	68.4
Extreme Height	13.3	12.6	14.3	13.5	14.0	14.3
Extreme Width	10.7	10.7	10.7	10.7	10.7	10.1
Length Between Truck Centers	40.5	40.5	31.0	40.5	40.5	55.9
Interior Dimensions (ft):						
Maximum Length	47.3	47.3	37.7	47.3	47.3	62.6
Maximum Width	10.1	10.1	10.1	10.1	10.1	9.6
Average Height	8.8	8.9	11.3	9.8	10.5	10.7
Weights (lbs):						
Gross	286,000	286,000	286,000	315,000	336,000	429,000
Net	235,500	238,492	241,102	265,858	282,067	361,227
Tare	50,500	47,508	44,898	49,142	53,933	67,773
Statistics:						
Gross Linear Load (lbs/ft)	5,392	5,392	6,575	5,939	6,335	6,273
Change from Base (%)	0%	0%	22%	10%	17%	16%
Net Linear Load (lbs/ft)	4,440	4,496	5,543	5,012	5,318	5,282
Change from Base (%)	0%	1%	25%	13%	20%	19%
Extreme Length Change from Base (ft)	0.0	0.0	-9.5	0.0	0.0	15.3
Extreme Length Change from Base (%)	0%	0%	-18%	0%	0%	29%
Net Cross-Section (sq ft)	89	90	114	99	106	103
Change from Base (%)	0%	1%	28%	12%	20%	16%
Car Cross-Section Utilization (%)	62.8%	67.2%	75.0%	69.7%	71.0%	71.3%
Net-to-Tare Ratio	4.66	5.02	5.37	5.41	5.23	5.33
Net-to-Gross Ratio	0.823	0.834	0.843	0.844	0.839	0.842
Change from Base (%)	0%	1.3%	2.4%	2.5%	2.0%	2.3%
Box Surface Area (sq ft)	1,486	1,499	1,459	1,603	1,685	2,151
Change from Base (%)	0%	1%	-2%	8%	13%	45%

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Table A-9: Higher & Wider Manual-Dump Longitudinal-Door Hopper Car Characteristics

Freight Car Characteristics	Base Hopper	53'-Long Non-Auto Transverse	53'-Long Non-Auto Dog-Leg	1' Up	1' Up & 6" Out	1' Up & 1' Out	2' Up & 2' Out
Exterior Dimensions (ft):							
Extreme Length	53.0	53.0	53.0	45.5	43.7	42.0	36.7
Extreme Height	13.3	13.3	12.6	14.3	14.3	14.3	15.1
Extreme Width	10.7	10.7	10.7	10.7	11.2	11.7	12.7
Length Between Truck Centers	40.5	40.5	40.5	33.0	31.1	29.5	24.1
Interior Dimensions (ft):							
Maximum Length	47.3	47.3	47.3	39.7	37.9	36.3	30.9
Maximum Width	10.1	10.1	10.1	10.1	10.6	11.1	12.1
Average Height	8.8	8.8	9.0	10.7	10.7	10.7	11.7
Weights (lbs):							
Gross	286,000	286,000	286,000	286,000	286,000	286,000	286,000
Net	235,500	237,027	240,019	242,000	242,469	242,928	244,551
Tare	50,500	48,973	45,981	44,000	43,531	43,072	41,449
Statistics:							
Gross Linear Load (lbs/ft)	5,392	5,392	5,394	6,284	6,548	6,803	7,804
Change from Base (%)	0%	0%	0%	17%	21%	26%	45%
Net Linear Load (lbs/ft)	4,440	4,469	4,527	5,318	5,551	5,778	6,673
Change from Base (%)	0%	1%	2%	20%	25%	30%	50%
Extreme Length Change from Base (ft)	0.0	0.0	0.0	-7.5	-9.4	-11.0	-16.4
Extreme Length Change from Base (%)	0%	0%	0%	-14%	-18%	-21%	-31%
Net Cross-Section (sq ft)	89	89	91	109	114	120	141
Change from Base (%)	0%	1%	2%	22%	28%	34%	59%
Car Cross-Section Utilization (%)	62.8%	63.0%	67.3%	71.5%	71.7%	71.9%	74.0%
Net-to-Tare Ratio	4.66	4.84	5.22	5.50	5.57	5.64	5.90
Net-to-Gross Ratio	0.823	0.829	0.839	0.846	0.848	0.849	0.855
Change from Base (%)	0%	0.6%	1.9%	2.8%	3.0%	3.2%	3.8%
Box Surface Area (sq ft)	1,486	1,493	1,505	1,473	1,445	1,421	1,376
Change from Base (%)	0%	0%	1%	-1%	-3%	-4%	-7%

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Table A-10: Other Alternative Manual-Dump Longitudinal-Door Hopper Car Characteristics

Freight Car Characteristics	Base Hopper	53'-Long Non-Auto Transverse	53'-Long Non-Auto Dog-Leg	Maximum Dimension	39-Ton Axle Load	3-Axle Trucks
Exterior Dimensions (ft):						
Extreme Length	53.0	53.0	53.0	43.7	53.0	68.8
Extreme Height	13.3	13.3	12.6	14.3	13.6	14.3
Extreme Width	10.7	10.7	10.7	10.7	10.7	10.1
Length Between Truck Centers	40.5	40.5	40.5	31.2	40.5	
Interior Dimensions (ft):						
Maximum Length	47.3	47.3	47.3	37.9	47.3	63.0
Maximum Width	10.1	10.1	10.1	10.1	10.1	9.6
Average Height	8.8	8.8	9.0	11.3	10.0	10.7
Weights (lbs):						
Gross	286,000	286,000	286,000	286,000	315,000	429,000
Net	235,500	237,027	240,019	242,469	267,345	362,796
Tare	50,500	48,973	45,981	43,531	47,655	66,204
Statistics:						
Gross Linear Load (lbs/ft)	5,392	5,392	5,394	6,543	5,942	6,235
Change from Base (%)	0%	0%	0%	21%	10%	16%
Net Linear Load (lbs/ft)	4,440	4,469	4,527	5,547	5,043	5,273
Change from Base (%)	0%	1%	2%	25%	14%	19%
Extreme Length Change from Base (ft)	0.0	0.0	0.0	-9.3	0.0	15.8
Extreme Length Change from Base (%)	0%	0%	0%	-18%	0%	30%
Net Cross-Section (sq ft)	89	89	91	114	101	103
Change from Base (%)	0%	1%	2%	28%	13%	15%
Car Cross-Section Utilization (%)	62.8%	63.0%	67.3%	75.0%	69.8%	71.3%
Net-to-Tare Ratio	4.66	4.84	5.22	5.57	5.61	5.48
Net-to-Gross Ratio	0.823	0.829	0.839	0.848	0.849	0.846
Change from Base (%)	0%	0.6%	1.9%	3.0%	3.1%	2.7%
Box Surface Area (sq ft)	1,486	1,493	1,505	1,466	1,622	2,162
Change from Base (%)	0%	0%	1%	-1%	9%	45%

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APPENDIX B: FIGURES OF ALTERNATIVE CAR DESIGN PARAMETERS
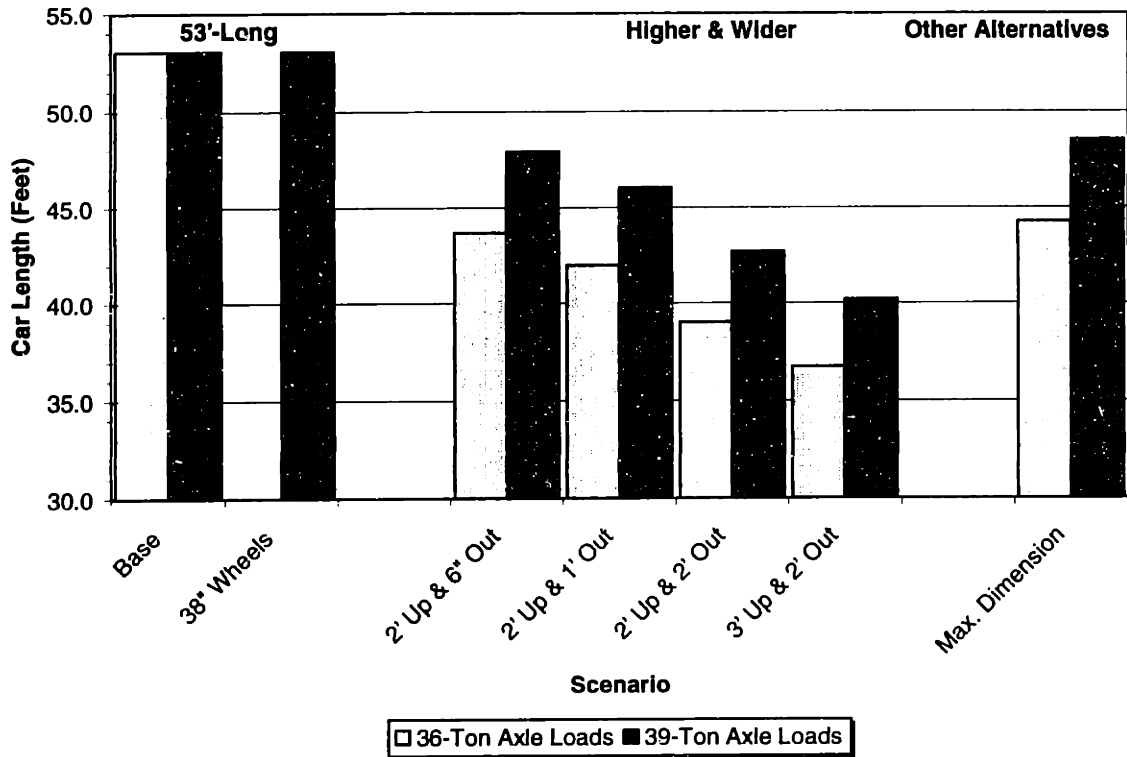
Figure B-1: 315-Kip vs. 286-Kip Gondola Car Length by Scenario
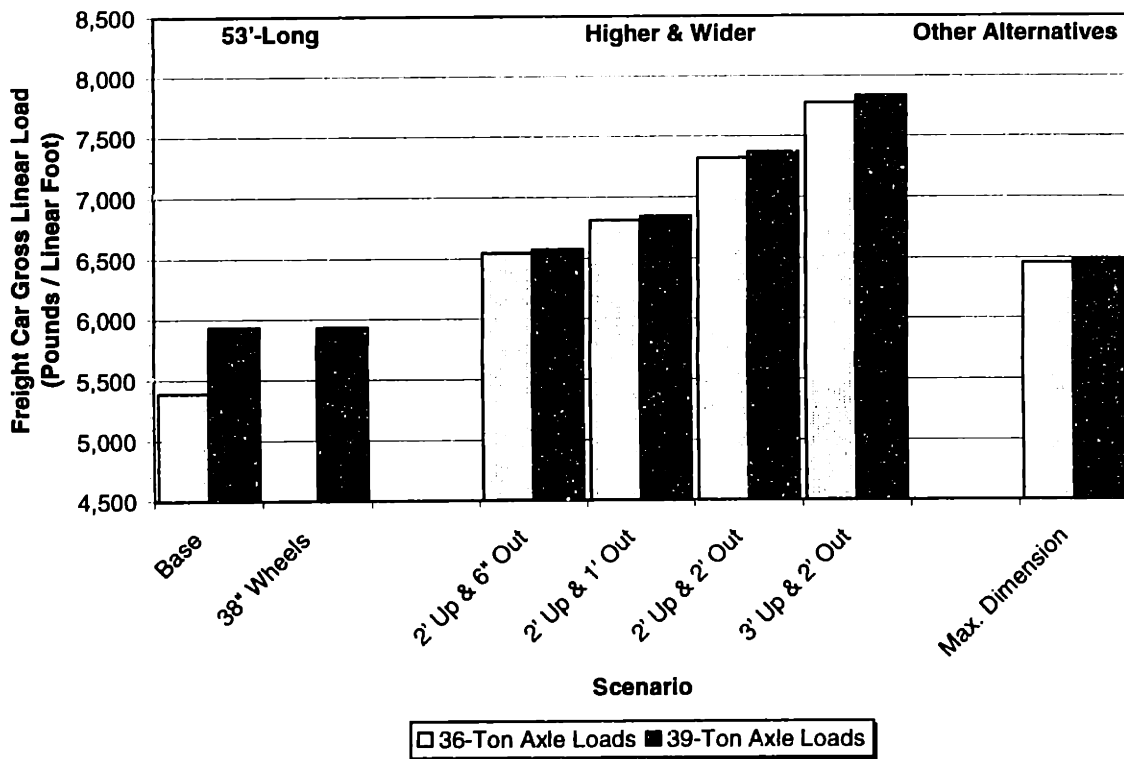
Figure B-2: 315-Kip vs. 286-Kip Gondola Car Gross Linear Load by Scenario
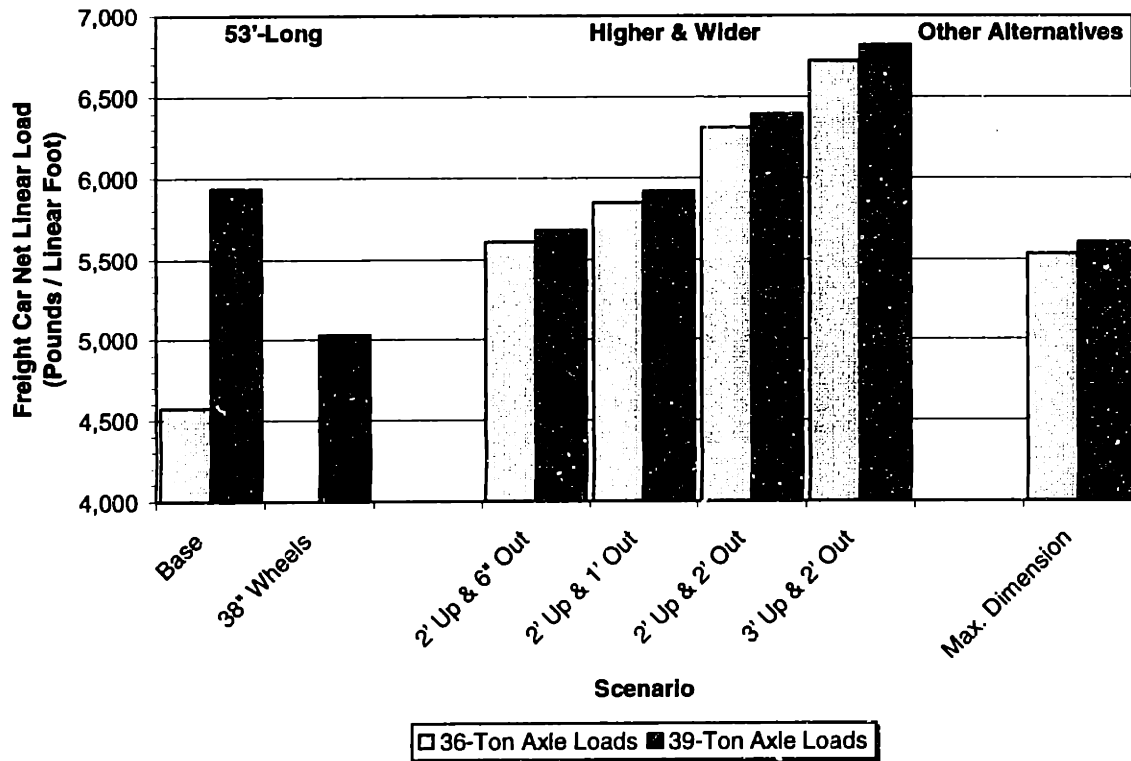
Figure B-3: 315-Kip vs. 286-Kip Gondola Car Net Linear Load by Scenario
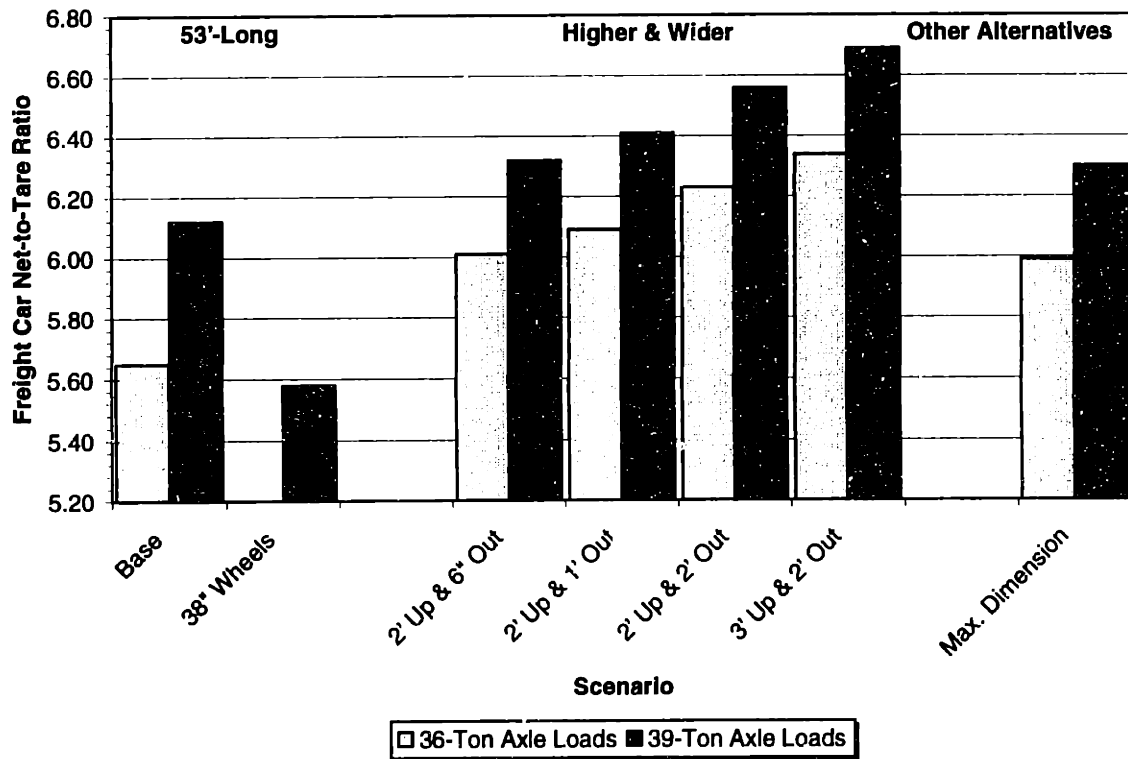
Figure B-4: 315-Kip vs. 286-Kip Gondola Car Net-to-Tare Ratio by Scenario

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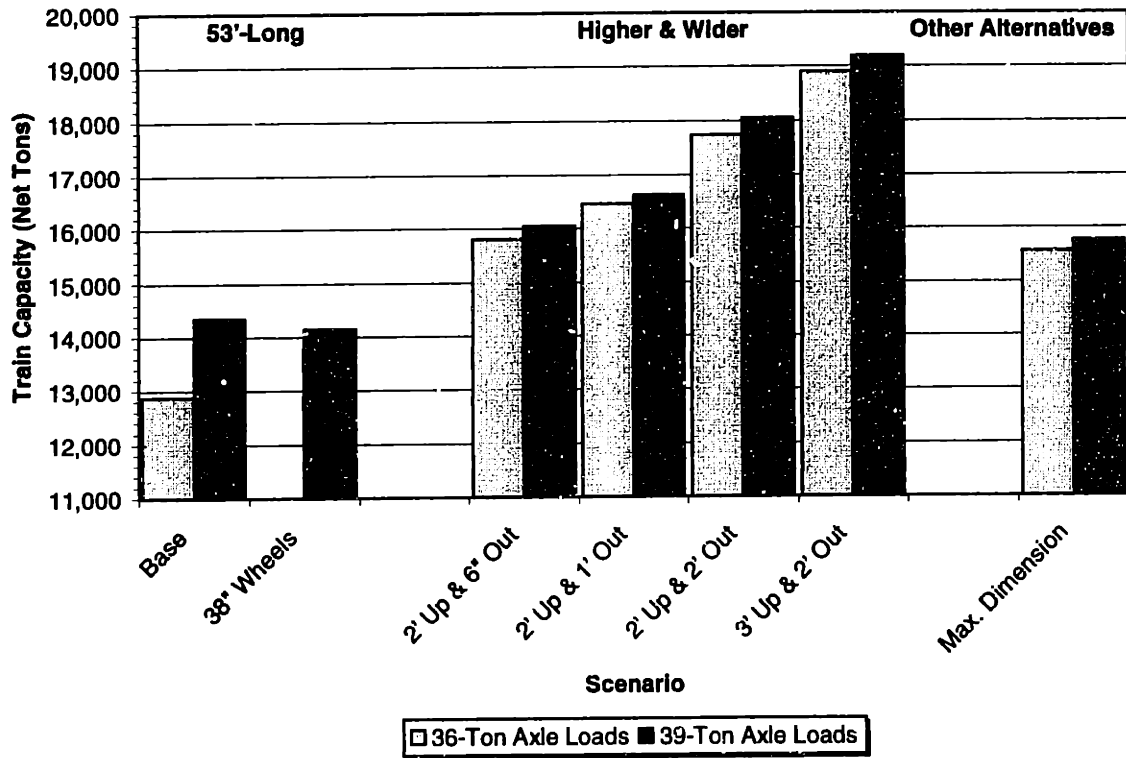
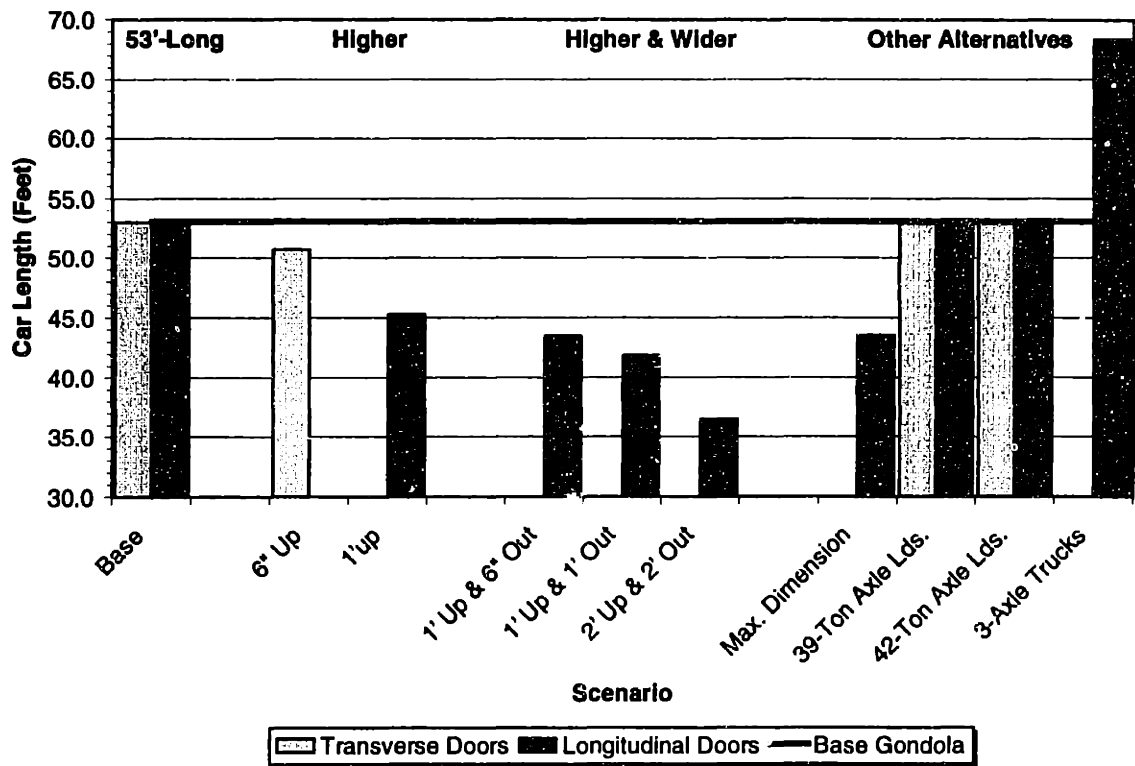**Figure B-5: 315-Kip vs. 286-Kip Gondola Car Train Capacity by Scenario**

Figure B-6: Transverse and Longitudinal-Door Hopper Car Length by Scenario
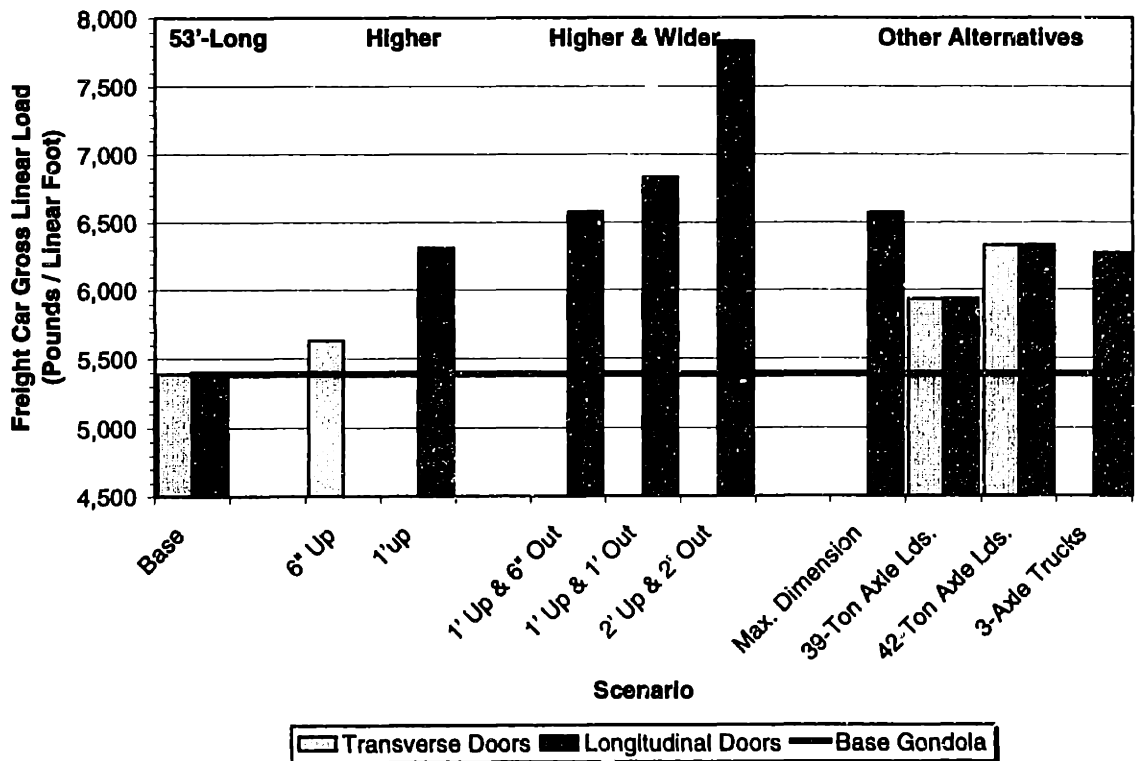
Figure B-7: Transverse and Longitudinal-Door Hopper Car Gross Linear Load by Scenario

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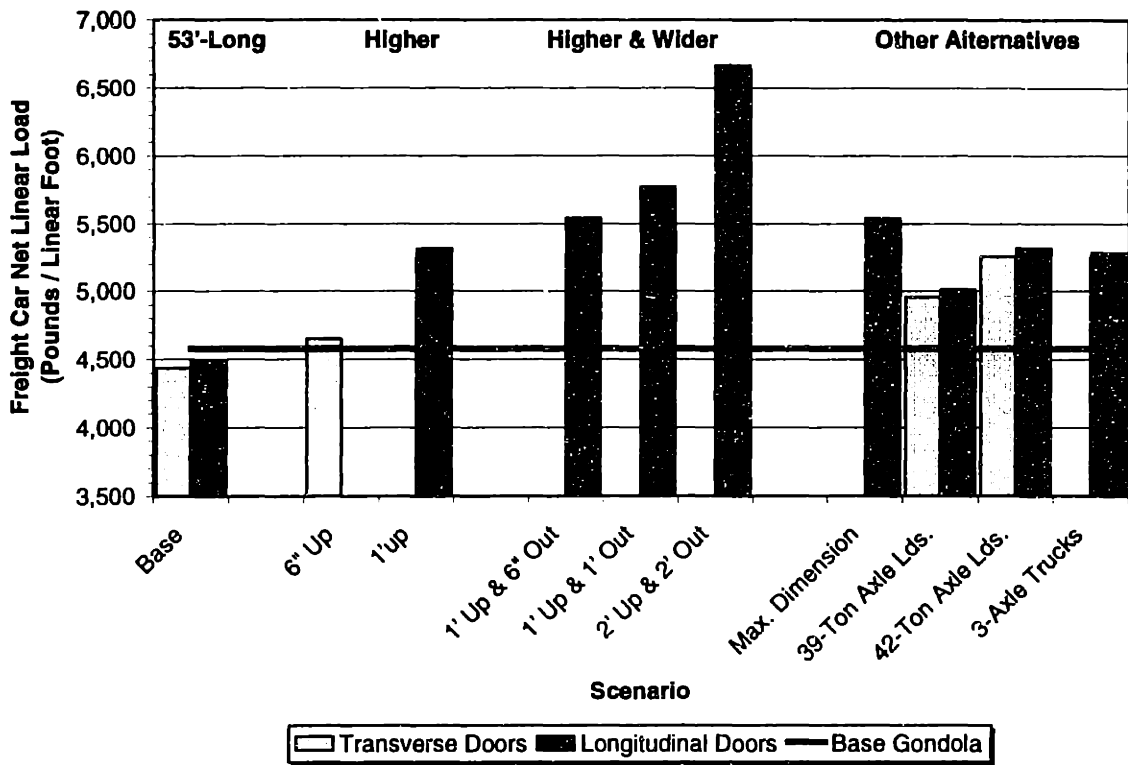
Figure B-8: Transverse and Longitudinal-Door Hopper Car Net Linear Load by Scenario
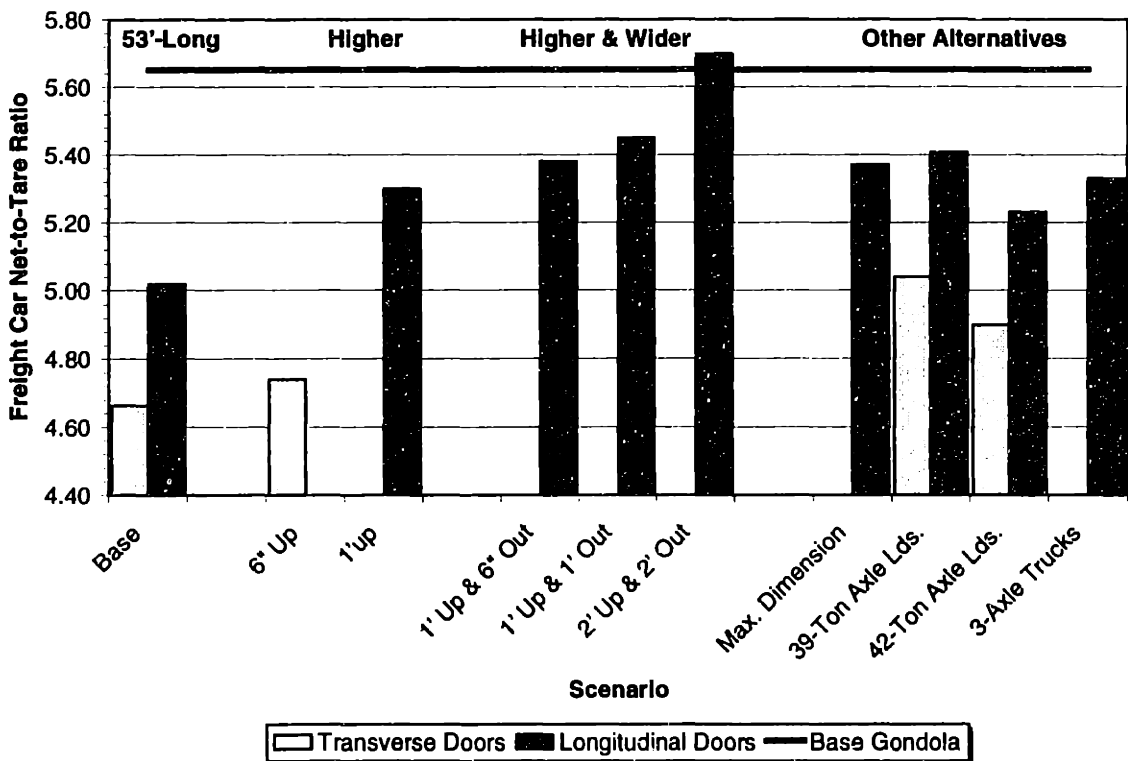
Figure B-9: Transverse and Longitudinal-Door Hopper Car Net-to-Tare Ratio by Scenario
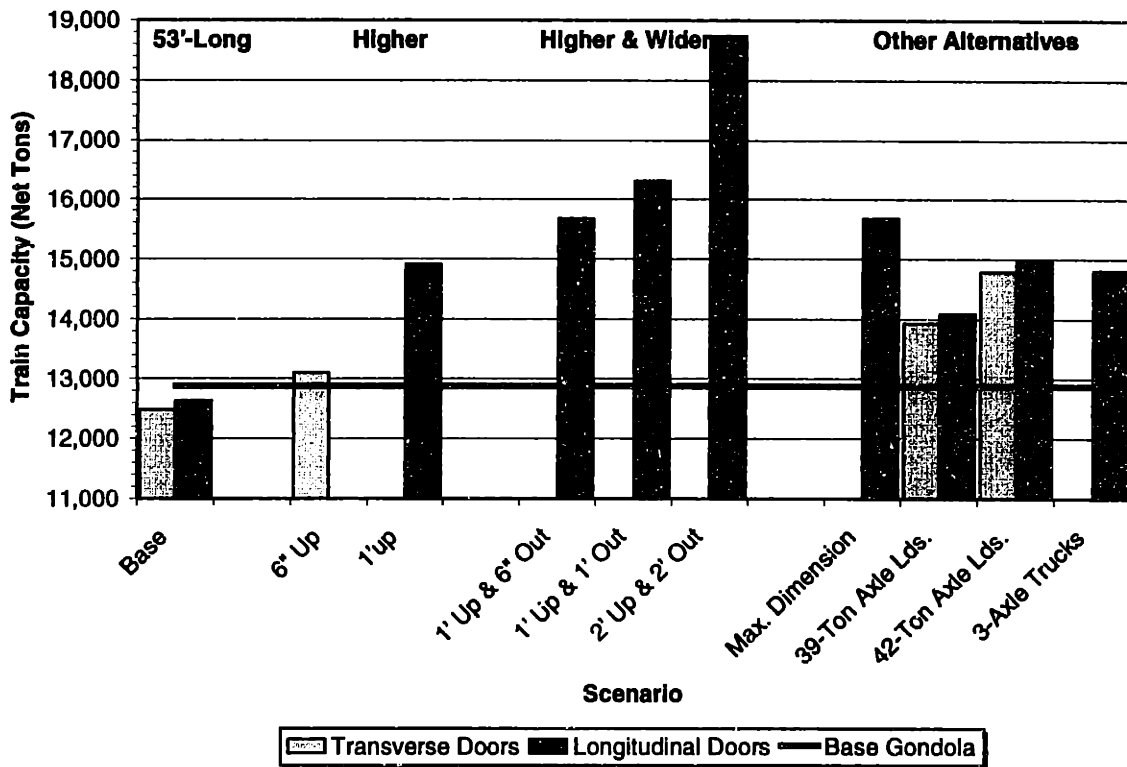
Figure B-10: Transverse and Longitudinal-Door Hopper Car Train Capacity by Scenario
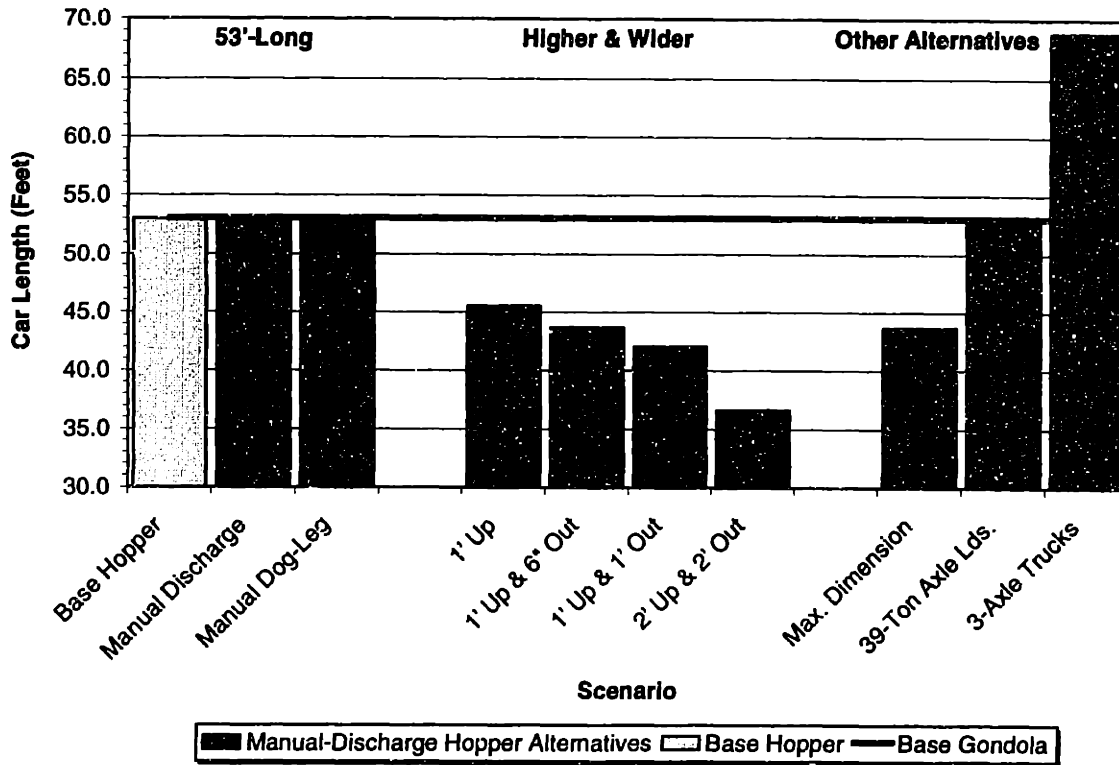
Figure B-11: Manual-Discharge Hopper Car Length by Scenario
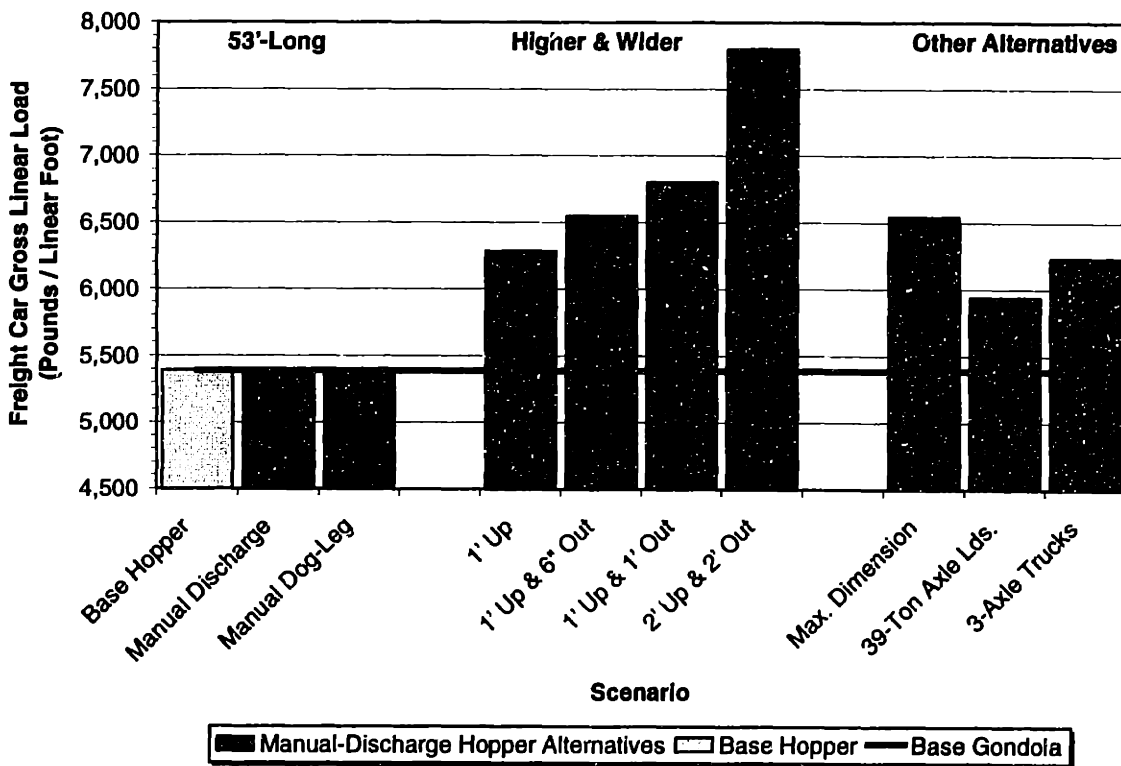
Figure B-12: Manual-Discharge Hopper Car Gross Linear Load by Scenario
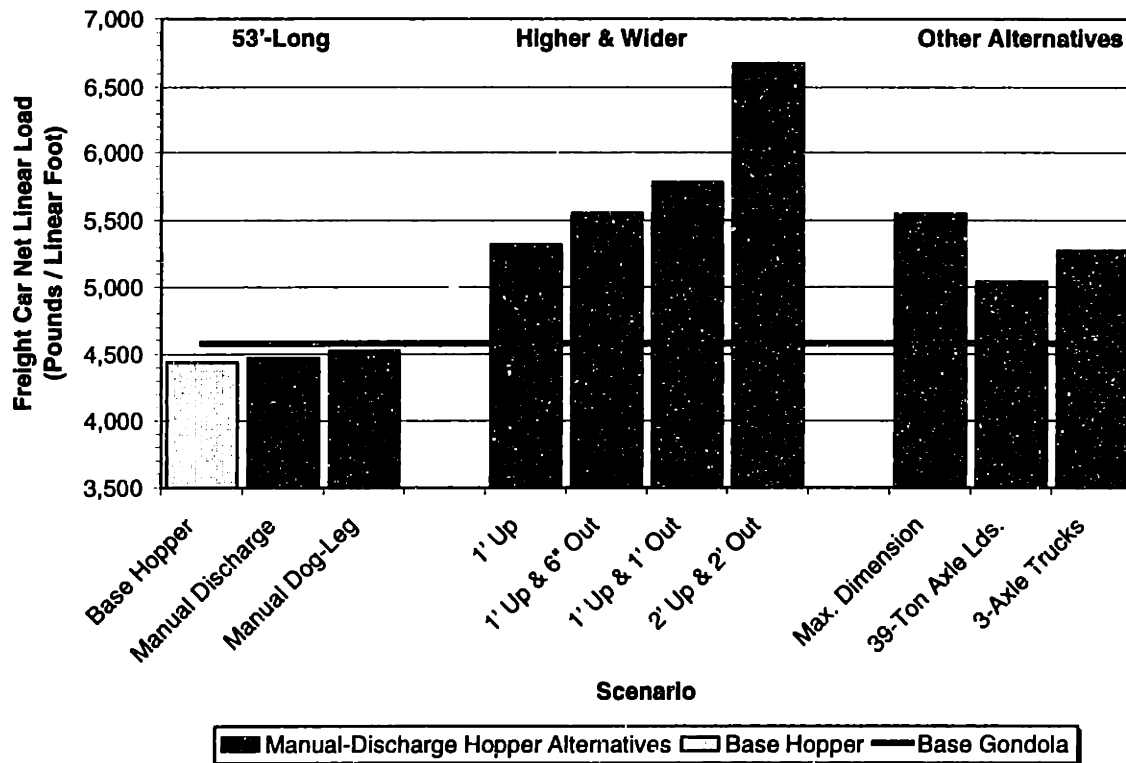
Figure B-13: Manual-Discharge Hopper Car Net Linear Load by Scenario
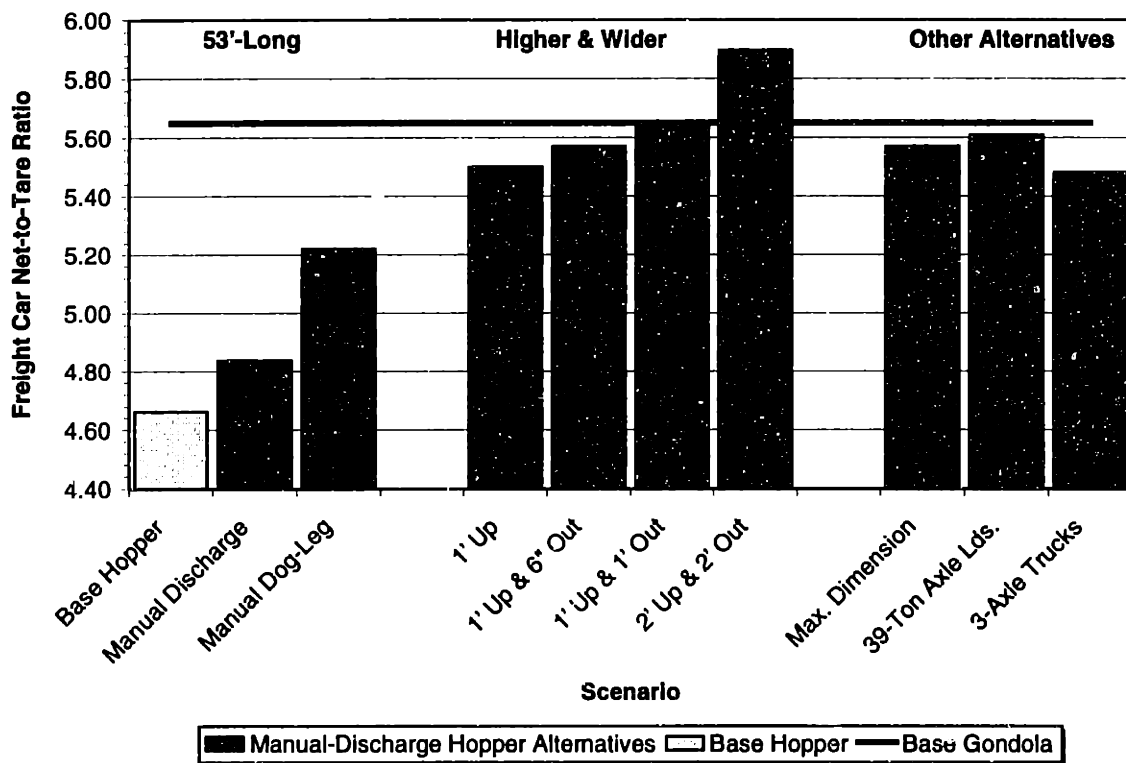
Figure B-14: Manual-Discharge Hopper Car Net-to-Tare Ratio by Scenario
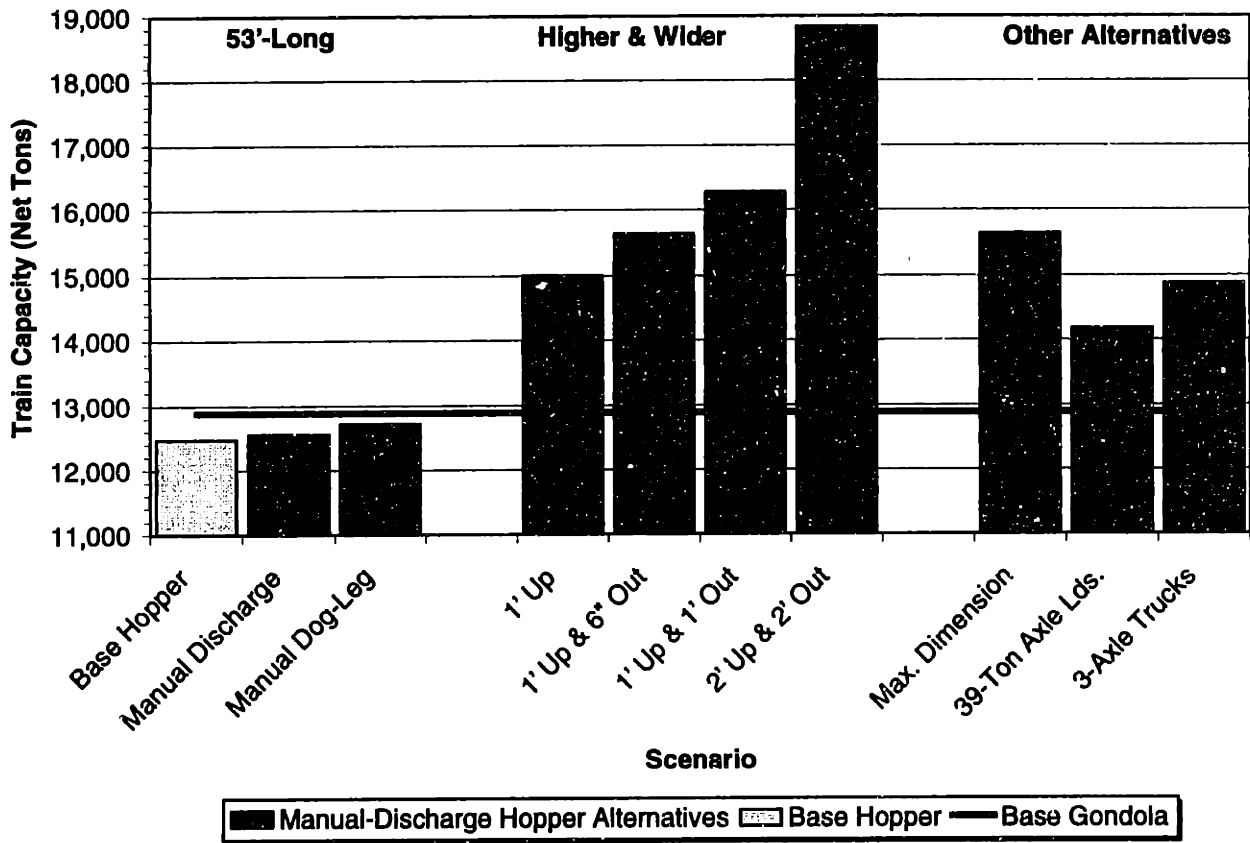
Figure B-15: Manual-Discharge Hopper Car Train Capacity by Scenario
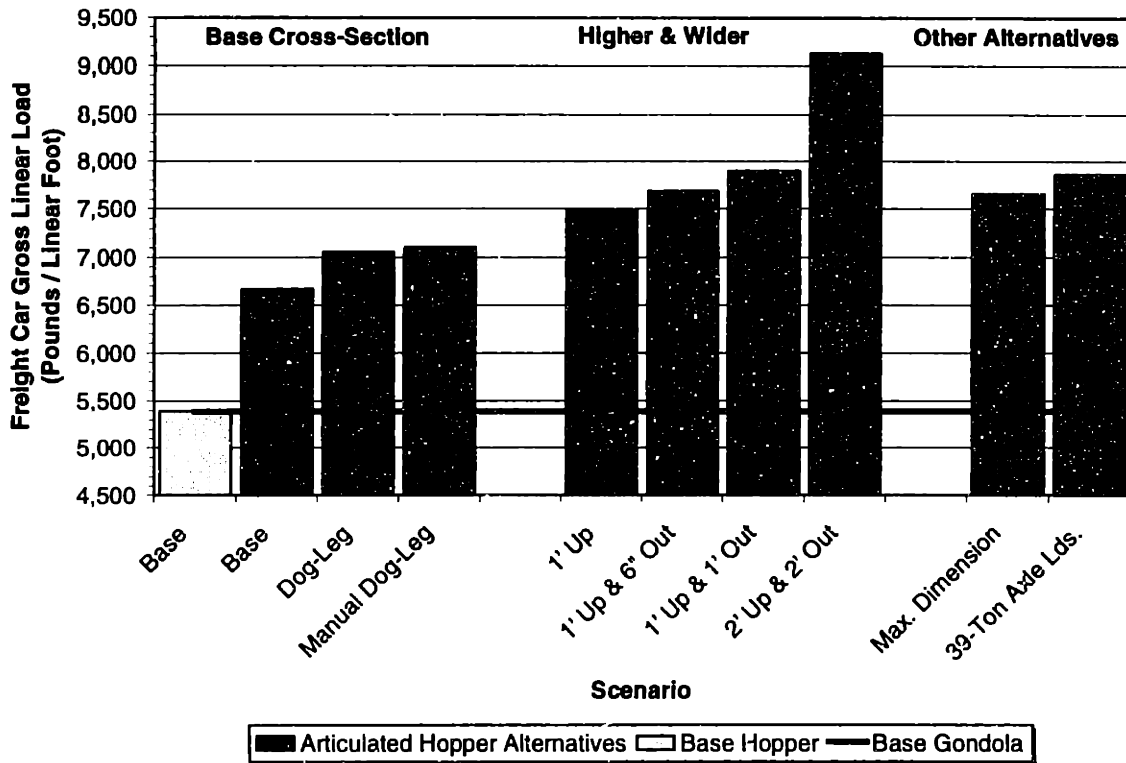
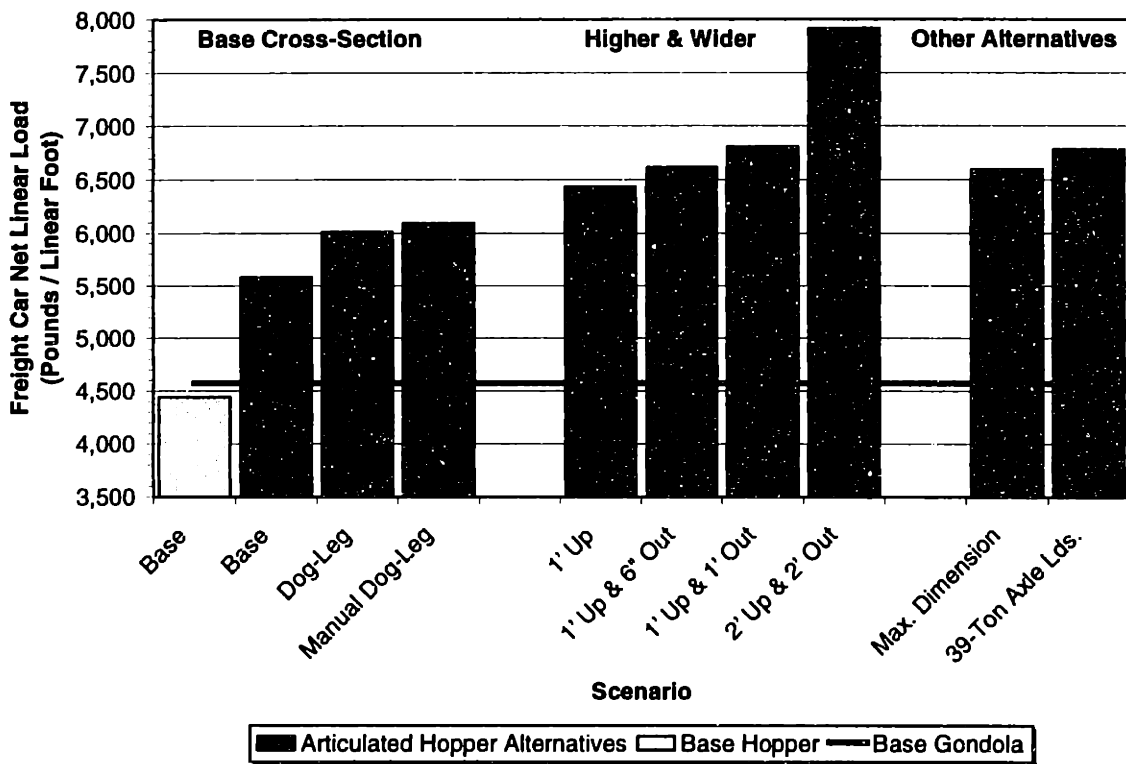**Figure B-16: Articulated Hopper Car Gross Linear Load by Scenario**

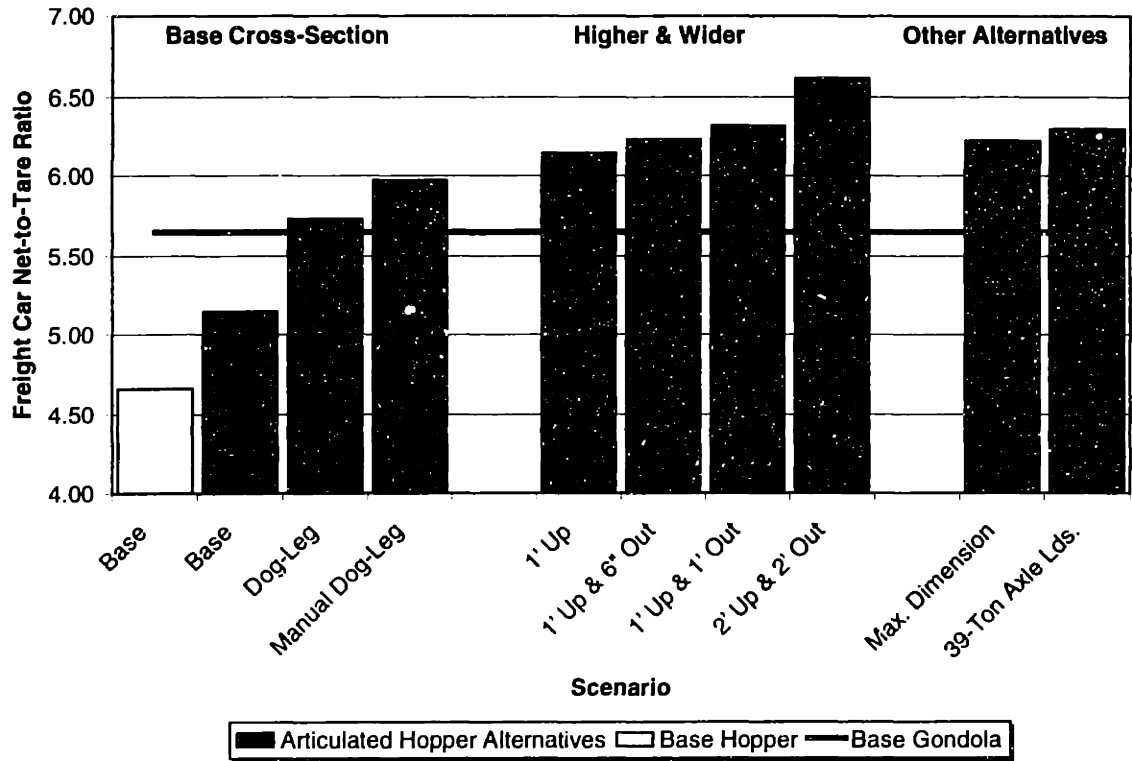**Figure B-17: Articulated Hopper Car Net Linear Load by Scenario**
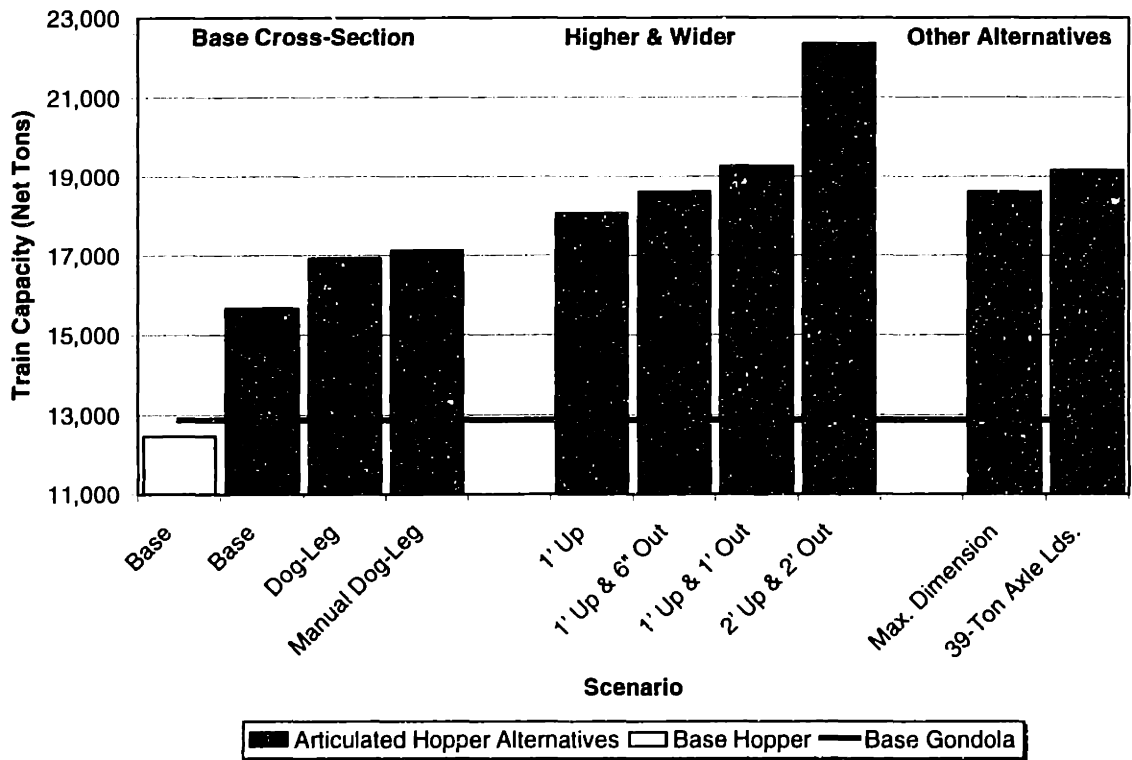
Figure B-18: Articulated Hopper Car Net-to-Tare Ratio by Scenario

Figure B-19: Articulated Hopper Car Train Capacity by Scenario