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EFFECTS OF AXLE LOADS AND TRAIN CAPACITY ON HEAVY HAUL NETWORK PERFORMANCE

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ABSTRACT

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

INTRODUCTION

Heavy Axle Loads and Coal

In the context of freight railroad operations, heavy axle loads (HAL) are generally defined as axle loads greater than the standard of 33 tons. Increasing axle loads can provide additional capacity and increased efficiency in bulk train operations. However, increasing axle loads tends to result in higher track maintenance costs that may offset the capacity and efficiency gains.

Increasing capacity and efficiency in bulk train operations is of particular interest in the case of the major commodity transported using heavy haul service: coal. Coal consumption in the U.S. is at record levels and is growing at a rate of approximately 1.5% per year [16]. The largest market for coal is in sales to electric utilities, which consume approximately 940 million tons of coal per year [16]. Coal is mined in 26 states, but the major coal-producing regions are Appalachia (in West Virginia and Kentucky) and the Powder River Basin (in Wyoming and Montana) [1].

Over 60% of coal is transported by rail [15], accounting for approximately 40% of the tonnage and 20% of the revenues of the rail industry [2]. Of the coal transported by rail, over 85% is carried through unit train service, service characterized by the shipment of bulk commodities in large blocks of cars or trainloads between a small set of origins and destinations [3]. Compared to general merchandise service, unit train service provides improved cycle times, increased equipment utilization, high-speed loading and unloading, and reduced costs.

Although unit coal train service is highly efficient, railroads face a range of challenges in providing the service. These including meeting demand for additional capacity, especially in the Powder River Basin; reducing costs to meet shipper demands and compete with other carriers; and determining how best to integrate unit train operations with other types of operations, including intermodal and general freight [9].

Even neglecting the capacity benefits of HAL, the overall savings from HAL may be quite significant. Saleeby estimated that for a heavy haul coal line with 50 million gross tons (MGT) of traffic annually, shifting to heavy axle loads could save up to $36,000 per track mile per year, a savings of $36 million per year for a 1000-mile line [14].

AAR HAL Research

Since 1988 the Association of American Railroads (AAR) has been operating a test train with 39 ton axle loads at the Facility for Accelerated Service Testing (FAST) at the Transportation Test Center (TTC) in Pueblo, Colorado [8]. To date, over 500 million gross tons (MGT) of traffic has been accumulated on the test track at FAST. Following each of three phases of the HAL testing, the AAR and the AAR Affiliated Lab at the Massachusetts Institute of Technology (MIT) have conducted economic analyses of heavy axle loads operations using the results from the tests at FAST.

In Phase I, the goal was determine whether operations with axle loads above the 33 tons allowed for interchange service were technically feasible and economically desirable [7]. The economic analysis examined the operating and maintenance costs of a typical East coal route, a typical West coal routes, a mountainous route, and a level route. The costs were calculated for operations with 33 ton axle loads, 36 tons axle loads (using the same car design as the 33 ton case, but with the cars overloaded to hold more coal) and 39 ton axle loads. The economic analysis concluded that operation with increased axle loads was technically feasible and was economically desirable under favorable circumstances [7].

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

Table 1. HAL Phase II Line Haul Cost Savings Relative to the Base

Route	Axle Load	Length or Weight-Limited	Percentage Cost Savings Relative to the Base		
			Operating Costs	Track & Bridge Costs	Total
East	36	Length	8.6%	-11.0%	5.8%
		Weight	3.8%	-11.0%	1.7%
	39	Length	3.6%	-24.2%	-0.4%
		Weight	3.0%	-24.2%	-0.9%
West	36	Length	8.7%	-5.9%	6.5%
		Weight	3.7%	-5.9%	2.3%
	39	Length	5.2%	-21.0%	1.3%
		Weight	3.6%	-21.0%	-0.4%

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

Motivation for the Present Study

The study described in this paper, performed for the AAR [5], builds upon and extends the HAL economic analyses. Based on review of the previous work, the MIT Affiliated Lab hypothesized that the previous results could be significantly enhanced through development of a network scope, extending the range of axle loads studied, and taking a new approach to modeling equipment design. These areas are discussed in the following paragraphs.

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

Further, heavy axle loads may have a significant effect on network operations. If net traffic is held constant, then increasing the net capacity per train (through increasing axle loads or other means) leads to a reduction in the number of trains required to move the required amount of coal. As trains are removed from the network, congestion is reduced and cycle times tend to improve, leading to a further reduction in the number of trains required. However, modeling the cycle time effect requires analysis at a network level.

On the other hand, heavy axle loads may lead to deterioration in network operations performance, as heavy axle loads tend to increase track maintenance. Previously Romps studied the effects of track maintenance on operations [13]. Robert and Martland used Romp's approach to study the effects of track maintenance on reliability for the HAL Phase II East and West length-limited coal routes [12]. They showed that although heavy axle loads increase track maintenance and, thus, delay from track closures; this increased delay is offset by a reduction in the number of trains. A computer model developed for analyzing performance of large-scale unit train networks, UTRAIN, offers the opportunity to examine the effects of heavy axle loads on operations at a network level [11], [9].

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

30 to 45 tons for aluminum cars with 2-axle or 3-axle advanced trucks.

The axle load of a car is largely a function of equipment design. For this study a new approach to modeling was required for examining a range of axle loads. In previous studies, two car types were examined: a "100-ton car," designed to hold 100 tons of coal with an axle load of 33 tons; and a "125-ton car," designed to hold 125 tons of coal with an axle load of 39 tons. The 36 ton axle load case was modeled as an overloaded 100-ton car. The 100-ton car (operating as designed or overloaded) and 125-car are commercially available coal cars. Both are the same length, but the 125-ton car is taller.

Examining a range of axle loads requires assuming either that commercially available cars are sub-optimally loaded (either loaded for more or less than designed), or that some other car could be designed to meet a particular axle load. The approach taken for this study was to use the box design for the 125-ton car for all cases except the base case, but lengthen or shorten the box to meet a particular axle load. This allows for distinguishing between the effects of axle load and car capacity for a range of different cases.

ANALYSIS METHODOLGY

Determining the effect of HAL operations on typical coal distribution networks required developing a set of equipment parameters that varied by axle load, analyzing network operations, analyzing track maintenance parameters, and developing a cost model. These steps are described in the following sections.

Development of Equipment Parameters

The basic equipment parameters used for the study were taken from information compiled by the AAR dated March 1997 [5]. The base case consists of operations with 106-car trains with aluminum 100-ton cars and advanced trucks (since the cars are aluminum they hold approximately 112 tons of coal, but have axle loads of 33 tons). For all other cases, the train length is the same, the cars are aluminum, and advanced trucks are used, but the cross section of the car is equivalent to that of the 125-ton car (which is taller than the 100-ton car), and the car length is adjusted to meet a specified axle load. Thus, cars are assumed to be fully loaded at every axle load. Three truck types are considered: a 2-axle truck with 36-inch diameter wheels, a 2-axle truck with 38-inch wheels, and a 3-axle truck with 36-inch. wheels. The maximum acceptable axle load for 36-inch wheels is assumed to be no more than 39 tons. However, no detailed analyses of the practical axle load for 36-inch wheels was identified in the study.

Figures 1 and 2 show how the equipment parameters vary as a function of axle load for the car types considered in the study. Figure 1 is a graph of car length versus axle load. Note that based on the cross section for the 125-ton car, a car with 3-axle trucks would be over 70 feet long for axle loads greater than 36 tons. A car with 2-axle trucks and 33 ton axle loads would be approximately 45 feet long, 8 feet shorter than the standard length of approximately 53 feet. Cars with 2-axle trucks and 36-inch wheels are slightly longer cars with 38-inch wheels, because the cars with 36-inch wheels hold slightly more coal, requiring additional length.

Figure 2 plots net weight per train as a function of axle load. The net weight per train is significantly greater than that of the base case for all cases with the cross section of the 125-ton car. Assuming length-limited trains, net weight per train increases with axle load because heavier axle loads translate into longer cars and a greater percentage of the total train length being used to haul coal. However, the axle load effect on train capacity is small compared to the effect of increasing the car cross section.

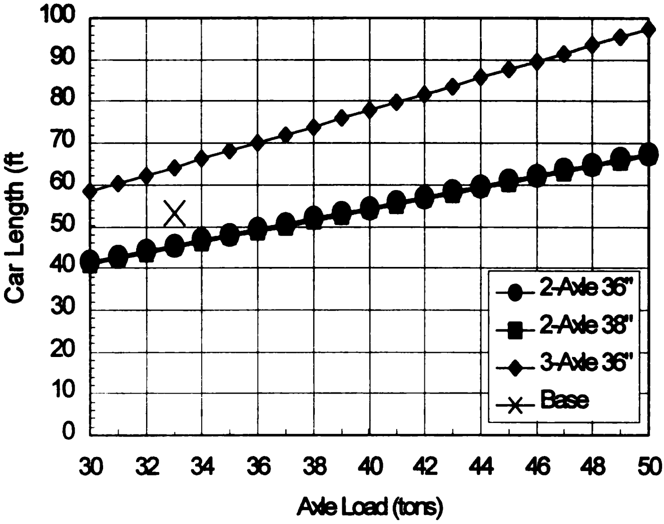

Figure 1. Car Length versus Axle Load

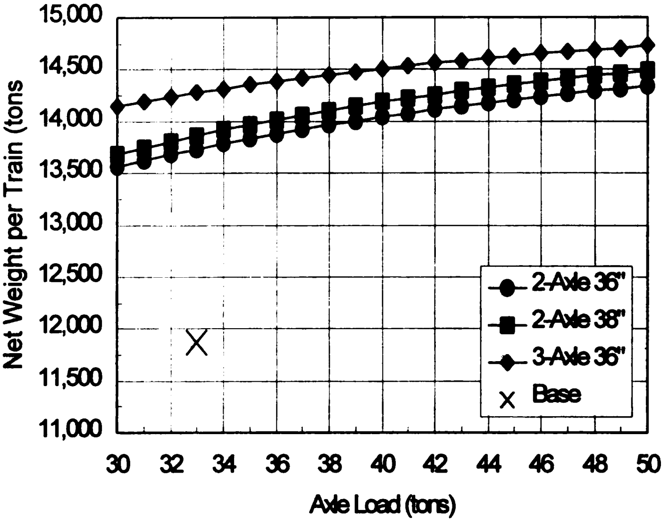

Figure 2. Net Weight per Train versus Axle Load

For the network and track maintenance analysis it was not feasible to analyze each truck type at every axle load, so a set of 22 test cases was defined. For each of two networks, the following cases were analyzed:

- **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

Network Analysis

Two rail networks were analyzed in the study: a typical Eastern and a typical Western coal distribution network. For each network operations were analyzed for the 11 cases listed above, for a total of 22 test cases.

The parameters for the networks we have developed are based on discussions with representatives of U.S. railroads, and on previous work performed for the AAR [10]. 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.

The analysis of network operations was performed using the simulation model UTRAIN. UTRAIN models the actual operations of a full unit train network, including loading and unloading, inspection and servicing, and line operations of trains traveling between a number of different origins and destinations [11], [9].

For this study, UTRAIN was used to determine the cycle time and equipment requirements for meeting demand for each case studied. In moving from the base case to heavier axle loads, fewer train sets are required to meet the same demand (assuming length-limited trains), for two major reasons:

- Each car holds more coal, so even if each train set has the same cycle time, fewer train sets are required.
- Removing train sets from the network reduces congestion, which acts to decrease cycle times. With a faster cycle, the number of train sets may be further reduced, as each

remaining train set is more productive.

On the other hand, for heavier axle loads maintenance requirements increase, causing additional track closure, and potentially more train delay, which increases cycle time. Also, heavier trains require more time for loading and unloading.

For each of the cases analyzed, the track maintenance requirements were first determined as described in the following section. Next, an initial estimate was made of the number of train sets required to meet demand. The simulation was run and the results were examined. If UTRAIN showed that demand could not be met with specified number of train sets, more train sets were added and the simulation was run again. If the simulation showed that there were extra train sets, and that more coal was been shipped than necessary, then the simulation was re-run with fewer trains. This process was repeated until the minimum cycle time and number of train sets required to meet demand was determined. The results used for a particular iteration were obtained by averaging the results over 20 simulation runs. The process was performed for each of the 22 cases.

Table 2 summarizes the results for cycle times and train set requirements calculated using UTRAIN. The first three columns of the table identify each case by the network, car type and axle load. The fourth column lists the net capacity per train, and the fifth column lists the car length. The next two columns list the cycle time and number of train sets required, assuming not network effects (cycle time is held constant). The eighth and ninth columns list the cycle time and number of train sets required, determined using UTRAIN. The last column gives the extra percent reduction in the number of train sets, assuming network effects.

For the East network the table indicates that increasing train capacity results in a reduction in cycle time of up to 6 hours, from an initial value of approximately 3 days and 18 hours. Even without considering the change in cycle time, the increase in train capacity results in a reduction in the number of train sets required. The cycle time reduction increases equipment savings by 4% to 6%. For the West network the results are similar. Increasing train capacity results in a reduction in cycle time of up to 11 hours from an initial value of 5 days and 19 hours. The cycle time reduction increases equipment savings by 5% to 6%. Thus, for the networks modeled in this study, reducing the number of train sets by increasing axle loads eases network congestion and has a beneficial effect on cycle times.

Table 2. Cycle Times and Equipment Requirements

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

Track Maintenance Analysis

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

The TRACS model [4] provides a state-of-the-art computer modeling approach that combines engineering deterioration models with life-cycle costing techniques to estimate track maintenance costs as a function of track components, track condition, traffic mix and volume, maintenance policies, and unit cost inputs. The basic TRACS approach is to estimate track component deterioration rates as a function of the stresses induced by each specified car type, and to determine the cumulative deterioration that triggers maintenance activities, resulting in a time series of maintenance costs.

Similar to the approach followed in previous HAL analyses, for this study TRACS was used to project component lives for rail, ballast and ties. Component lives for turnouts were projected using TRACS's damage factor exponent approach, but calibrated to the results from the HAL Phase II economic analysis [7]. 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 [7], [10].

Given track maintenance requirements, annual hours of track closure were determined in the same manner as that described by Robert and Martland [12]. Maintenance hours were derived from maintenance costs using a set of track maintenance productivity rates. An additional set of assumptions was used to determine the daily probabilities of 4-hour and 8-hour maintenance windows by track segment.

Cost Analysis

A simple cost model was developed to compare the costs per net ton-mile calculated for each case. Track maintenance costs were determined using HALTRACK, as described above. Operating costs were determined using unit costs from the HAL Phase III economic analysis [6]. The total variable cost, excluding bridges, is the sum of the track maintenance and operating costs. Fixed costs were not considered in the study.

In previous HAL analyses, operating costs were calculated for the following categories: train crews, locomotive ownership, locomotive maintenance, car ownership, car maintenance, and fuel. The basic approach of this study was to use unit costs for the East and West length-limited base cases for the East and West base cases. The unit costs from the HAL Phase III length-limited 125-ton car cases were used for all other cases, as detailed elsewhere [5].

RESULTS

This section summarizes the analysis results. As discussed in the previous section, a total of 22 cases were analyzed. For each the East and West network, the following cases were considered:

Base Case: 33 ton axle loads

2-Axle Trucks, 36-Inch Wheels: 33, 36 and 39 ton axle loads

2-Axle Trucks, 38-Inch Wheels: 39, 42 and 45 ton axle loads

3-Axle Trucks, 36-Inch Wheels: 30, 33, 36 and 39 ton axle loads

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

For the East and West base cases, operations costs (measured in dollars per 1,000 net ton-miles) are approximately 27% lower than the costs projected for the HAL Phase III economic analysis [6], primarily as a result of the assumption that aluminum cars would be used. Track costs (excluding bridges) for the East and West base cases are approximately 27% higher. Overall, costs for the East and West base cases are approximately 20% lower than the costs projected in the HAL Phase III analysis.

The results indicate that, compared to the base case, all other cases result in increased net train capacity and decreased cycle time. Together these effects result in reduced operating costs. However, heavy axle loads result in increased maintenance that tends to offset the savings in operating costs. Figure 3 summarizes the percentage savings for each case relative to the base case.

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

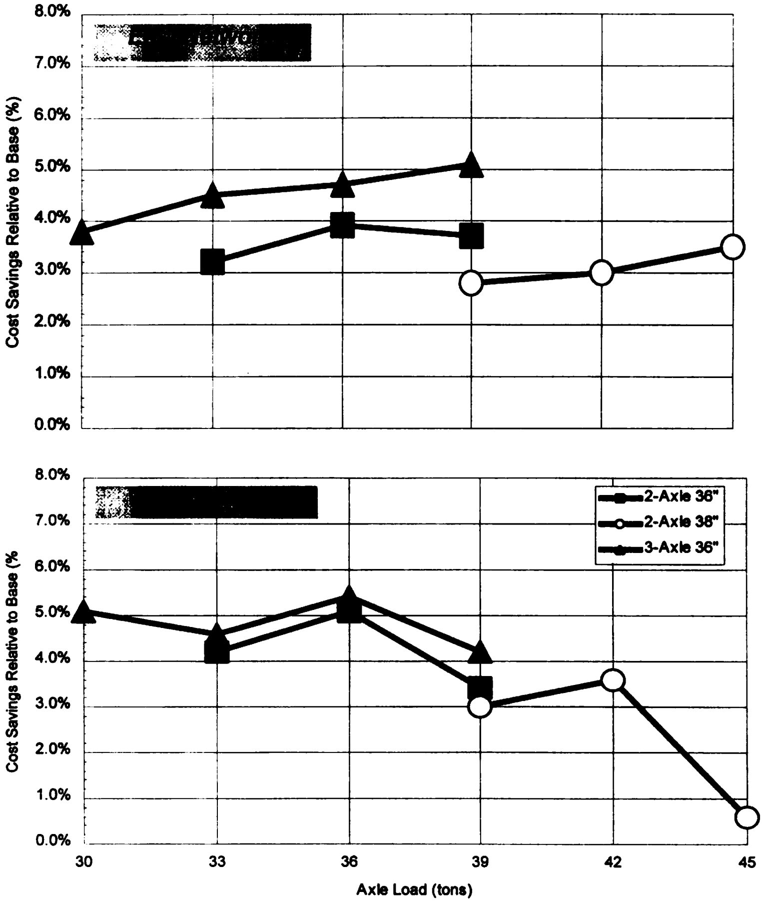

Figure 3. Summary of Cost Savings Relative to the Base Case

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

CONCLUSIONS

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

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

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

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

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

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