Introduction of Heavy Axle Loads by the North American Rail Industry

by Carl D. Martland

The Association of American Railroads (AAR) initiated the Heavy Axle Load (HAL) Research Program in 1988 in order to "provide guidance to the North American railroad industry about whether to increase axle loads and to determine the most economic payload consistent with safety" (Kalay and Martland 2001). The research demonstrated the technical feasibility and economic desirability of increasing axle loads and the ability of technology to mitigate the adverse effects of heavier loads. In 1991, the industry decided to accept cars with 286,000 lb. gross vehicle weight (286k GVW) in interchange service. Since then, more than 90% of all bulk equipment acquired has been rated for 286k GVW. By 2010, nearly 100% of coal traffic and 30% of general freight moved in 286k loads.

Technological improvements resulting from the HAL research program have been critical in enabling the industry to reduce costs of 286k operations. Stronger materials, better designs, and improved maintenance techniques reduced life cycle costs for rail and other track components. Bridge costs did not increase as much as expected, because of technological developments and better understanding of their ability to withstand HAL loads.

Net benefits of HAL operations to railroads, suppliers, and their customers were approximately $6 billion between 1994 and 2010. Annual net benefits exceeded $600 million in 2010. Benefits included reductions in equipment expense, more efficient operations, and increases in line capacity. Given the technological advances in railroad engineering over the past 20 years, further increases in GVW or loading density should now be considered.

OVERVIEW OF THE HAL RESEARCH PROGRAM

This paper has two major objectives. First, it estimates the net benefits achieved by increasing the maximum GVW to 286k, taking into account impacts on operations and infrastructure. Second, it reviews the literature related to HAL implementation and the technological developments that helped mitigate infrastructure costs resulting from HAL loads.

Strengthening track to allow larger, heavier cars has long been a major factor helping railroads improve their productivity (Hay 1982; Chapman and Martland 1997 and 1998). If cars can carry more freight, then fewer cars, trains, crews, and gallons of fuel are needed to carry any given amount of freight. Decisions to increase load limits must balance these benefits against potentially higher infrastructure costs.

During the 1970s, the widespread introduction of the 100-ton car (GVW of 263,000 pounds) caused havoc with the track structure for many railroads. Rail that was adequate for 70-ton cars (GVW of 200,000 pounds) was unable to withstand the higher forces associated with 100-ton operations. Instead of replacing rail because of wear or battered joints, railroad replaced rail because of fatigue and risks of broken rails. Zarembski (1981) concluded that fatigue would limit rail life on tangent (i.e., straight) track, reducing rail life from 580 million gross tons (MGT) under mixed freight to 416 MGT under 70-ton unit trains and to 267 MGT under 100-ton unit trains. Until the rail life problem could be resolved, it was impossible to consider any further increase in GVW.

During the 1980s, railroads and the supply industry addressed fatigue by developing harder rails and better maintenance techniques, including grinding the rail in order to maintain the proper

shape of the rail head so as to control the forces at the wheel/rail interface. In June 1987, the Transportation Research Board's Committee on Railway Maintenance sponsored a conference on "Rail: Replacement Strategies and Maintenance Management" at the University of Illinois that featured presentations by AAR and DOT researchers, steel manufacturers from Japan and Europe, other suppliers of maintenance services, rail engineering officials, and consultants. Roger Steel, the chief metallurgist for AAR's Research and Test Department, chaired a remarkable session in which he allowed steel manufacturers from Japan and the UK to describe what they were doing, then challenged them to develop better steel more attuned to the needs of the heavy haul railroads. It was clear that the rail industry was pushing suppliers to improve their metallurgies in order for rail to withstand the forces of HAL operations.

In the mid-1980s, Burlington Northern Railroad (BN) was the leader in the introduction of better rail and better maintenance, because its coal routes were the highest density lines in North America. BN knew that its rail in high density mainline track would last up 1,400 MGT and that premium rail in high-degree curves would last 300-500 MGT:

> Advancements in rail technology (head hardened and fully heat treated rail, clean steel practices), lubrication, road bed improvement (undercutting and shoulder cleaning) and rail grinding have all contributed to this increase in rail life. However, it has been the practice of rail grinding that has allowed the full potential of these improvements and advancements to produce the rail longevity characteristics we now enjoy. (Glavin 1989, p. 239)

BN knew that heavier axle loads would increase the efficiency of moving rapidly growing volumes of coal out of the Powder River Basin in Wyoming. They therefore initiated an internal study (Newman, Zarembski, and Resor 1990) of the feasibility of increasing GVW limits from 263,000 to 315,000 pounds (initially known as the 125-ton car). BN and other railroads were aware that heavier axle loads had already been introduced in Australia (Marich 1986), but it was unclear whether such loads would be technically and economically feasible under North American operating conditions. With fresh memories of the troubles from introducing 100-ton cars, senior railroad executives deferred further increases in GVW without thorough assessment of the technical and economic feasibility of heavier loads. The HAL Research Program focused on coal, by far the highest-volume commodity handled by railroads.

The HAL research began in 1988 and continued through 2000 in five phases. Much of the research was conducted at the 2.4-mile High Tonnage Loop of the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center in Pueblo Colorado. Operation commenced in the mid-1980s with a train of cars loaded to 263,000 pounds GVW (axle loads of 33 tons). In HAL Phase I, the same cars were loaded to 315,000-pounds (axle loads of 39 tons), allowing a direct comparison of stresses and deterioration for 33- and 39-ton axle loads. These tests confirmed that it was technically feasible to increase axle loads. Economic feasibility was examined under the supervision of industry officials with backgrounds in engineering, operations, planning, and economics. The economic analysis built upon the FAST/HAL research, research conducted by individual railroads and government agencies, and the experience of other heavy haul railroads. At the end of Phase I, the HAL Economic Advisory Committee concluded that an increase to either 286,000 lb. or 315,000 lb. GVW for 4-axle equipment would reduce overall costs for operations over good infrastructure. Increasing to 286,000 GVW (36-ton axle loads) was most cost effective, primarily because costs related to rail fatigue, turnout deterioration, bridge life, routine maintenance, and freight car wheels would rise more than linearly with axle loads (Hargrove 1991).

In 1991, the major railroads began to introduce 286k GVW loads in interchange service via bilateral agreements. The pace of implementation was limited by concerns about bridges and the ability of premium components and better maintenance to limit cost increases, two issues that became the focus of HAL Phase II. New tests at FAST and sophisticated engineering analyses addressed life cycle costs of rail, turnouts, field welds, bridges, and other areas most sensitive to

increases in axle loads. Phase II concluded that a) bridge costs would be manageable, b) net benefits would be somewhat greater than predicted in Phase I, because of technological advances, and c) the best option would still be to increase GVW limits to 286,000 pounds (Hargrove et al. 1995). In 1995, the industry adopted a design specification (known as S-259) for 286k cars that would be accepted in interchange service.

HAL Phases III and IV examined the extent to which better equipment could ameliorate the stresses associated with 39-ton axle load operations. The trucks of a rail car hold the wheel sets in place and determine how lateral and vertical forces are transmitted through the car body and the wheels into the track structure. By adding cross-bracing and other technical improvements, so-called "improved suspension" trucks can reduce curving resistance, thereby extending both wheel and rail life. Phase III repeated many Phase II tests using upgraded equipment running over the same infrastructure as in Phase II. Since improved suspension trucks were also expected to reduce the need for lubrication,   Phase IV tested operations with the upgraded equipment over dry track. Although the industry did not choose to implement the types of improved suspension trucks tested in Phases III and IV, the railroads did adopt better trucks, which were installed in the FAST equipment for Phase V.

Following the completion of Phase V, the HAL research program continued as one of the AAR's Strategic Research Initiatives (Kalay, LoPresti, and Davis 2012). As a result of this continuing research, the industry adopted new recommendations and specifications for track components, structures, equipment, inspection, and maintenance. In 2003, the industry adopted a new design standard (M-976) for trucks for 286k cars, and in 2004 the industry adopted a new design standard (S-286) for 286k cars used in interchange service.

The economic analyses conducted for Phases I to V of the HAL research encompassed the following steps:

- Determine the characteristics of freight cars, locomotives, and trains used to transport coal, assuming GVW of 263k, 286k, and 315k.
- Define the characteristics of hypothetical routes representing typical conditions for high density coal lines in the east and in the west.
- Estimate engineering costs per 1,000 net ton-miles for operating coal trains over each route.[1]
- Estimate operating benefits for each route using AAR models.[2]
- Estimate net benefits/1,000 NTM for each route.

The major sources of information concerning the economics of heavy axle loads are the HAL economic analyses completed at the end of Phase I (Hargrove 1991), Phase II (Hargrove et al. 1995; Hargrove et al. 1996), Phase III (Guins, Robert, and Martland 1998), Phase IV (Martland, Guins, and Hargrove 1999), Phase V (Kalay and Martland 2001), TTCI's thorough review of research results and benefits from Phases I, II, and III (Kalay and LoPresti 2000), and a subsequent TTCI summary of HAL research (Stone and Conlon 2004).

The HAL economic analyses identified potential operating benefits that would commence as soon as GVW were increased. With more tons per load, fewer cars and less fuel would be needed to transport a given amount of freight, and more net tons could be handled without increasing the number of train-miles or crews. What was unknown were the rate and extent of HAL implementation, the actual impacts on track costs, and the ability of equipment to withstand heavier loading. Now that HAL loads have been operating for more than 20 years, it is possible to document the nature and extent of implementation, to estimate the benefits of HAL operations, and to determine whether or not the life cycle costs of infrastructure increased following the implementation of 286k operations.

IMPLEMENTING 286K GVW OPERATIONS

Initial Steps Toward Implementation (1991 to 1999)

Some railroads began to allow 286k GVW cars in interchange service only after extensive studies, others were ready to make changes based upon the AAR's research and the high quality of their infrastructure, and some proceeded cautiously until they were sure that their infrastructure (especially bridges) could handle the loads. Concurrently with Phase I of the HAL program, Burlington Northern conducted a thorough, independent study of the potential costs and benefits of HAL operations (Newman, Zarembski, and Resor 1990). The study, which was conducted by Zeta-Tech, used an approach similar to what was used in the AAR's HAL Economic Analysis for Phases I and II. As an internal railroad study, it used route-specific data and costs and addressed implementation issues. Based upon their review of the Australian experience, they anticipated that increases in bridge maintenance and the need to strengthen or replace bridges would be the major factors causing maintenance costs to rise with axle load. Although their models and assumptions were not always the same as the AAR's, they also concluded that an increase in GVW to 286k was justifiable.

CN also worked with Zeta-Tech to evaluate potential costs and benefits of HAL operations, using the same methodology that had been used with BN. As of the end of 1992, CN retained a maximum GVW of 263,000 pounds for essentially all four-axle cars, based primarily upon their reluctance to invest heavily in strengthening a large number of bridges to handle a relatively small incremental volume of traffic (Worth 1993).

CSX Transportation formed an inter-disciplinary team to assess HAL economics (Shughart 1991). While strategic planners were interested in the potential cost savings, many transportation officers were wary of heavier loads, based upon their experience in the 1970s. The CSX study addressed potential economies that the AAR study did not consider, e.g., fewer waybills to process, more capacity for staging yards for coal traffic, lower costs for loading and unloading, ability to ease strict restrictions on load limits, and fewer derailments as a result of fewer trains. Instead of modeling steady state costs, as was done in the AAR study, CSX projected cash flows, including tax consequences, for a long-term investment horizon. They concluded that the investments required to enable heavier axle loads could be competitive with other CSX projects. By 1991, CSX had begun loading of existing equipment to 270,000 lbs., but had not yet decided whether to purchase new equipment that would allow heavier loads.

Before 1990, NS had already made the necessary investments to bring essentially the entire railroad up to a quality adequate for handling 286k loads (McClellan 1991). Since they had operated 286k cars for many years in unit coal trains that originated and terminated on line, they did not need a detailed study to move ahead. By 1991, NS had already started to order 286k steel/aluminum cars with 120-ton payloads for their coal traffic.

Prior to the HAL research program, UP had made major investments in track and structures to provide the capacity necessary to move large volumes of coal from the Powder River Basin in Wyoming (Wimmer 2003; Van Trump 2009). UP originally moved coal in 263k equipment weighing 30 tons, but switched to 286k aluminum cars (tare weight of 22 tons) once they were introduced in 1990. To handle the heavy tonnage at lower expense, UP increased routine inspections and maintenance and improved their track components for their high density coal routes.

By 1999, each Class I railroad allowed at least limited operation of 286k cars. Some accepted any 286 cars, but others accepted HAL loads only for specific routes. Embargoes, where imposed, were based upon bridges and light rail. The benefits of HAL operations were insufficient to justify replacing or upgrading existing equipment. Instead, the railroads purchased new 286k cars as needed to replace 100-ton cars that were retired or to provide additional capacity to handle growing traffic volumes.

Extent of HAL Implementation in 2012

The original impetus for HAL came from the railroads that were hauling large volumes of coal, and coal has indeed been the commodity benefiting most from HAL operations. Table 1 shows carloading data for the Class I railroads for bulk commodities with the highest average tons per load. Variations among railroads reflect differences in local conditions, e.g., the age and capacity of equipment, the ability of access lines and customers to handle heavier cars, and differences in density of commodities. Note that the average shown at the bottom of the table is a weighted average of the tons/load for the individual railroads; this is not equal to the average tons/load for the industry, as cars that move over more than one Class I railroad are counted more than once. The final row in this table estimates the extent of implementation. If all traffic were fully loaded to a gross vehicle weight of 286k, the average tons per load would be approximately 112.5 tons in steel cars and 121.5 tons in aluminum cars (see Table 3). If half of the cars were steel, then the average tons per load would be about 117 tons. Essentially all coal traffic, which averaged just under 117 tons/car in late 2012, appears to be moving as 286k loads. HAL is not as fully implemented for the other commodities shown in this table, as the average tons/load is less than 112.5 tons for each commodity for each of the Class Is. For iron ore and crushed stone, there are wide differences in the average tons per load, which is likely caused by the use of old cars for some services. For the other commodities, the average tons/load are less variable across the Class Is. The extent of implementation can be estimated by comparing the average tons per load to what would be achieved if all traffic moved as 286k loads. For an older fleet of steel cars, the average load would be about 103 tons per car at 25% implementation (100 tons/car x 0.75 + 112.5 tons/car x 0.25 = 103.125 tons/car) and about 106 tons per car at 50% implementation (100 tons/car x 0.5 + 112.5 tons/car x 0.5 = 106.25 tons/car). For a new fleet of aluminum cars, the average load would be 116 tons at 50% implementation (110 tons/car x 0.5 + 121.5 tons/car x 0.5 = 115.75 tons/car). For a fleet with an equal mix of steel and aluminum cars, the average load would be about 111 tons at 50% implementation (i.e., an average of 106 for steel cars and 116 for aluminum cars). Coal is known to move in both steel and aluminum cars, and the high average tons/car for coal indicates a very high rate of implementation of 286k loads. Table 1 shows a range of estimates for the other commodities, because the mix of steel and aluminum cars is unknown; the low number assumes a mix of steel and aluminum cars and the high number assumes all steel.

The full benefits of the 286k GVW limit cannot be achieved unless there is a match between the cubic capacity of the car and the density of the commodity; it is quite possible that a car rated for 286k GVW can be fully loaded without reaching the 286k limit. The extent of implementation therefore may be underestimated for some of the commodities listed in Table 1.

Another approach to estimating the extent of implementation is to use data from wheel impact load detectors (WILD data). For example, Figure 1 shows the distribution of axle loads for loaded traffic on representative UP routes in 2003. Traffic was separated into three categories based upon axle loads: non-HAL (6-34 tons), HAL (34-37 tons), and Ultra HAL (>37 tons). The chart shows that all but 6% of coal was HAL traffic – and none was Ultra HAL. The figure also shows that HAL loads and overloads were a quarter to nearly half of all axle loads on two primary merchandise corridors.

Table 1: **Extent of HAL Implementation in 2012 (Commodities with an average of more than 104 tons/load on at least two Class I railroads)**

	Corn	Wheat	Iron Ore	Coal	Crushed Stone	Sand & Gravel	Hydraulic Cement
BNSF	106.1	107.3	105.6	119.2	106.7	101.5	106.5
CSX	105.0	104.6	106.2	113.9	101.3	99.0	108.5
GTW	100.8	103.8	78.3	117.5	84.9	103.0	111.5
KCS	103.0	102.4		120.2	110.1	110.2	104.0
NS	104.4	102.4	94.7	111.9	103.8	101.7	107.0
SOO	100.1	100.8		118.7		106.2	107.7
UP	106.9	104.4	97.4	118.3	104.6	104.3	107.2
Average	104.8	105.1	86.1	116.7	102.4	102.9	107.3
% Implemented	0-40%	0-40%	0-50%	90-100%	0-20%	0-25%	20-60%

Source of Data: *STB Quarterly Report of Freight Commodity Statistics*, Third Quarter 2012.

Figure 1: Extent of HAL Implementation on UP, September 2003
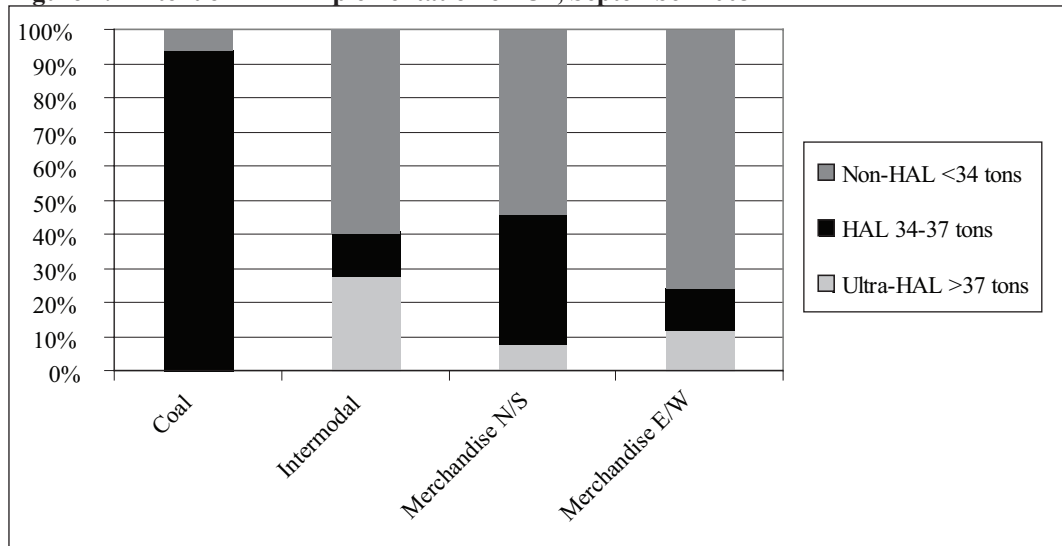
Source of Data: Wimmer, 2003.

Figure 1 also shows that 29% of axle loads on this route were over 37 tons for intermodal traffic. It is well-known that loaded containers that are double-stacked on articulated intermodal cars may cause some of the axle loads to exceed 36-tons. This potential problem is exacerbated by the fact that many international containers may be overloaded (Ogard 2012). However, excessive axle loads on articulated intermodal equipment were evident well before Phase I of HAL, and the average loads for intermodal traffic have been little if at all affected by the adoption of the 286k GVW limit. Therefore, the rest of this paper addresses the costs and benefits of HAL operations for coal and general freight, without consideration of intermodal traffic.

Factors Influencing the Rate of Implementation

Railroads initially implemented HAL by increasing the maximum load for existing bulk equipment (open top hoppers, covered hoppers, and gondolas).   The ability to do so depended upon the cubic capacity of the cars and the average density of the commodities, and it was not always possible to

load cars to 286k. Over time, cars designed for 286k GVW were added to the fleet, either to replace older cars or to expand the capacity of the fleet. By 2000, essentially all new bulk equipment was designed for 286k loads.

Since the predicted benefits of HAL operations were insufficient to justify early retirement of 263k cars, the rate of implementation was quickest where the traffic growth was greatest. The role of traffic growth was most evident for coal. In the west, HAL loadings and average tons/load increased rapidly as coal production ramped up in the Powder River Basin; coal tonnage nearly doubled from 1982 to 1986 and increased another 50% by 2008 (Table 2). The fleet had to be expanded to handle all of this new traffic, and once the GVW limit was increased, all the new acquisitions were designed for 286k. Despite the drop in 2009, coal traffic was still more than 250% of the 1982 levels. By 2009, in the west, nearly all coal traffic moved in 286k loads. In the east, there was a completely different story. Between 1982 and 2008, there was essentially no increase in the tons of coal handled by eastern railroads. In 2009, coal tonnage dropped well below 1982 levels, because of the recession. The average tons/load therefore increased more slowly in the east than in the west.

Table 2: Coal Tonnage and Average Tons/Load, Selected Years

	Year	U.S.	East	West
Tons (Millions)	1982	523	337	187
	1986	705	344	361
	2008	879	340	539
	2009	787	292	495
Tons/load	1982	91.6	88.9	97.1
	1996	104.5	101.1	108.0
	2008	113.9	108.8	117.4
	2009	115.0	110.4	117.9

Source of Data: AAR, *Analysis of Class I Railroads*, various editions.

The rate of HAL implementation is also limited by infrastructure characteristics. HAL loads can only be handled over routes where the track structure and bridges are capable of handling the stresses imposed by 286k operations. For coal traffic, this is a relatively minor problem, because coal generally moves in very large quantities from mines to power plants or ports; there will be sufficient operating benefits to justify considerable investments in infrastructure. For other commodities, notably grain, the ability to handle 286k loads may be constrained by track quality on light density lines or load limits on bridges; shippers located on lines limited to 263k operations may be at a disadvantage compared with other shippers, because their transport costs will be slightly higher (Bitzan and Tolliver 2003). Although most grain shipments are expected to eventually move in 286k loads (Prater and Sparger 2012), major investments may be needed for this to happen. Resor et al. (2000) estimated that investments costing nearly $7 billion would be required to enable 286k loads to move over all of the nearly 50,000 route-miles operated by short line and regional railroads. As of 2011, according to a survey conducted by the American Short Line and Regional Railroad Association (ASLRRA), the proportion of route-miles open to 286k loads was 55% for short lines and 63% for regional railroads (ASLRRA 2012). Bridges are the most critical problem for small railroads, because of the potential for catastrophic failure and the high costs of strengthening or replacement. ASLRRA estimated that approximately two-thirds of bridges on small railroads were able to handle 286k loads in 2011. If traffic volumes are high enough – more than 200 carloads per mile per year according to Bitzan and Tolliver (2003) - then small railroads will be able to finance investments necessary to upgrade their infrastructure.

BENEFITS FROM HAL OPERATIONS

Predicted Benefits, HAL Phases I and II

Benefits of 286k operations depend upon the extent of implementation, car characteristics, and unit costs. The most important benefits fall into the following areas:

Fewer freight cars and car-miles.   HAL allows more freight to be moved in each car, thereby reducing the carloads and car-miles needed to move a given amount of freight. The HAL effects must be separated from the effects of the concurrent introduction of higher capacity aluminum cars. The benefits from these lighter cars were similar to the HAL benefits, because both changes allowed more freight to be carried per car. The differences between steel 263k and aluminum 263k need to be attributed to the change in materials, while the HAL benefits need to be based upon a comparison between 263k aluminum cars and 286 aluminum cars. Table 3 shows the characteristics of typical steel and aluminum cars. The net weight is the weight of the shipment; the tare weight is the weight of the empty freight car; the gross vehicle weight (GVW) is the combined weight of the car plus the shipment.

Table 3: Characteristics of Bulk Equipment

Equipment	Net Tons	Net-Tare	Gross-to-Net	Ratio to Base	Reduction in MGT
Steel 263	101.0	3.31	1.604	100.00%	
Steel 286	112.5	3.69	1.542	96.15%	-3.851%
Aluminum 263	110.0	5.12	1.391	100.00%	
Aluminum 286	121.5	5.65	1.354	97.37%	-2.635%

Source of data: Martland 2000.

Higher net-to-tare and lower gross-to-net weight.   The ratio of net tons to the tare weight of the equipment generally increases with GVW. The ratio of gross-to-net weight is a related measure that gives the gross tons to be moved to move a single net ton of freight. For unit trains with 100% empty return, this ratio is calculated as:

$$\text{Gross-to-net} = (\text{Net Weight} + 2* \text{Tare Weight})/(\text{Net Weight})$$

If gross tonnage is reduced, there will be a corresponding reduction in train-miles, crew miles, locomotives, locomotive miles, and fuel consumption. Table 3 shows differences in the ratios of net-to-tare and gross-to-net for steel and aluminum cars along with the reduction in MGT achieved by moving from 263k to 286k loads.

Fewer train crews.   There will be a small reduction in train crews as a result of better gross-to-net ratios; there will be a larger benefit if trains are length-limited as opposed to weight-limited.

Table 4 summarizes the results from Phase II for the 80 MGT western coal route and the 30 MGT eastern coal route.   Both 286k and 315k operations were predicted to reduce total costs, with the greatest reductions for 286k operations. The largest expected increases in costs were for track maintenance and bridges. Although the percentage reduction in costs related to cars, locomotives, and train operations were predicted to be less than the percentage increases in infrastructure costs, the absolute savings were more than sufficient to cover the cost increases.

Table 4: Summary of Phase II Results

	West 263	West 286	West 315	East 263	East 286	East 315
Track						
- Maintenance	100%	111.3%	132.7%	100%	122.6%	147.5%
- Capital	100%	102.6%	108.6%	100%	106.5%	110.0%
Total Track	100%	105.0%	115.1%	100%	110.3%	118.8%
Bridges	100%	112.7%	156.9%	100%	114.0%	137.7%
Operations	100%	90.4%	93.8%	100%	91.1%	95.3%
Total	100%	92.6%	97.5%	100%	94%	99.6%

Source: Hargrove et al. 1996.

Capacity. Since fewer trains would be needed, HAL was expected to increase line capacity. Benefits associated with operating fewer trains were predicted to be more than enough to offset the added time needed for track maintenance on high density lines (Romps 1993; Robert and Martland 1997; Guins, Robert and Martland 1998; Robert, Martland and Guins 2003). Although line capacity was a minor issue for most railroads when Phase I was completed in 1990, it has since become a significant issue for the industry (Cambridge Systematics 2007).

Actual HAL Benefits: Reductions in Equipment Acquisitions

The widespread implementation of HAL traffic began in the mid-1990s, and the savings from buying cars with larger capacity began immediately. The first column in Table 5 shows the fleet size as of 1993 for three types of equipment used to haul bulk traffic; the second column shows the maximum fleet size for each of these types of equipment for the period 1994 to 2010. If the fleet size increased, as it did for covered hoppers and gondolas, then new cars must have been acquired, as shown in the third column. In addition, cars had to be acquired to replace cars that were retired because of age or condition. Assuming an average life of 40 years for freight cars, the average annual retirement rate would be 2.5%. Over the 17-year period from 1994 to 2010, 42.5% of the fleet would have been replaced. If the original fleet consisted entirely of 263k cars, then an equal number of 263k cars would have been needed to replace the retired cars. If that had been the case, then it would have been necessary to acquire 441,000 new bulk cars. However, if the older cars could be replaced with 286k cars with a 10% boost in average loading capacity, then only 414,000 cars would have been needed. Since the vast majority of all covered hoppers, gondolas, and hoppers acquired since 1993 were designed to handle 286k GVW, the rail industry (consisting of railroads, car supply companies, and customers) avoided purchasing 27,000 bulk freight cars, an average of about 1,600 per year. At an average cost of about $67,000 in 2010, the annual savings in capital expenditures exceeded $100 million per year (Table 6).

Table 5: Estimating the Number of Bulk Freight Cars Acquired From 1994 to 2010

Car Type	Fleet Size in 1993	Max after 1993	Min new after 1993	Annual Retirements	Total New Cars 263k GVW	Total New Cars 286k GVW
Covered Hopper	302,903	414,418	111,515	7,573	240,249	227,375
Gondola	148,541	220,238	71,697	3,714	134,827	128,514
Hopper	190,094	175,350	-14,744	4,752	66,046	57,967
Total	641,538	810,006	168,468	16,038	441,122	413,856

Source of Data: AAR, *Railroad Facts*, various editions.

Table 6: **Savings in Equipment Acquisition for Bulk Transportation (Reduction in Purchases of Covered Hoppers, Hoppers, and Gondolas at $67,000/car)**

	Total, 1994 to 2010	Average Annual 1994 to 2010	Total Savings 1994 to 2010	Average Annual Savings
Estimated New 286 Cars Acquired (1000s)	414	24.3		
Estimated New Cars Required, if GVW were still 263k (1000s)	441	25.9		
Reduction in cars purchased because of increase in HAL limit (1000s)	27	1.6	$1.8 Billion	$107 million

Actual HAL Operating Benefits for Coal Traffic

Estimating the operating benefits required additional assumptions concerning train length, locomotive consists, fuel consumption, and shipment characteristics (Table 7). The average number of cars on a train could be limited by either train length or train weight. Train length is limited by the length of sidings on single track lines, by the layout of yards and terminals, or by the nature of loading and unloading operations. Train weight is limited by locomotive characteristics and equipment technology; train weight limits can be overcome by using distributed power, i.e., by placing additional locomotive units within or at the end of a train. Railroads have, for many years, been increasing siding length, improving locomotive technology, and using distributed power to enable the use of longer, heavier trains (e.g., Van Trump 2009). The analysis in this paper therefore assumes that most trains are length-limited rather than weight-limited. The assumptions in Table 7 make it possible to estimate changes in service units resulting from the shift to HAL operations. By using larger cars, railroads had to move fewer loads, which resulted in fewer car-miles. Since there were fewer car-miles, there were fewer train-miles and locomotive-miles. Since the gross-to-net tonnage ratio was lower, there were fewer gross ton-miles, providing additional savings related to locomotives and fuel consumption.

Table 7: **Equipment and Operating Assumptions Used to Estimate Operating Savings**

Characteristics of Operations	Parameter	Comments
Average cars/train, 263k operations and length-limited 286k operations	120	Typical unit train
Average cars/train, 286k weight-limited operations	110	The gross weight of 110 286k cars equals the gross weight of 120 263k cars
Fraction of 286k trains that are length-limited	2/3	Conservative estimate
Average locomotives/train	2.7	Average locomotive miles per train-mile in 2008
Average locomotive miles per day	174	Locomotive miles divided by total locomotives in 2008
Average car-miles per carload	1216	Average loaded car-miles per carload in 2008 plus 100% empty return
GTM/gallon	484	Average for Class Is, 2010

Source of Data: AAR, *Railroad Facts*, various editions.

Unit costs were estimated using aggregate data provided by railroads to the STB. These costs are intended to support a reasonable estimate of the costs associated with operating unit trains. In any particular situation, costs could be significantly higher or lower than these industry averages. Moreover, there are other costs that are not considered at all; for example, yard costs are not considered because yards are a minor factor in bulk unit train operations.

Table 8: Unit Costs Used to Estimate Operating Savings from 286k Operations

Cost Category	Unit Cost	Comments
Crew cost	$9.93 per mile	Total wages for train crews divided by total train-miles for 2010
Locomotive purchase	$1.17 million	Average cost of new or rebuilt locomotives in 2008
Locomotive ownership	$135 thousand per year	Assuming cost of capital 11% and 30-year life
Locomotive maintenance	$1.00 per locomotive-mile	Locomotive labor, fringe benefits, and materials & supplies divided by total locomotive miles in 2008
Car maintenance	$0.036 per car-mile	Freight car labor, fringe benefits, and materials & supplies divided by total car-miles in 2008
Fixed cost per load	$160 per load	Estimated costs for local switching to place cars for loading and unloading plus general administrative expense
Fuel	$2.24 per gallon	Average for 2010

Source of Data: STB, *Analysis of Class I Railroads 2009*; AAR, *Railroad Facts 2011*.

Because the cars each carry more freight, there are fewer cars to load and unload and fewer car-miles. Table 9 estimates savings related to the increase in average tons per load for coal. As noted above, the average tons per load would be about 117 tons if coal moved entirely in 286k cars and if the fleet of coal cars were equally made up of steel and aluminum equipment. Since the average tons per load was 110 for all loads hauled from 1994 to 2010, the average extent of HAL implementation for coal was 59% because (110 actual tons/car – 100 base tons/car)/(117 max tons/car – 100 base tons/car) x 100%. = 59%).

At an estimated cost of $160 per load, the cumulative benefit of reducing the number of loads was $0.8 billion and the annual benefit in 2010 was $110 million for local switching, loading, unloading, and general administration (Table 9, row f). For each load that is eliminated, an entire trip is eliminated, saving car-miles, both loaded and empty, for an estimated cumulative benefit of $220 million, and an annual benefit of $30 million by 2010 (Table 9, row g). Since more freight is carried per train, fewer crews were needed, saving $340 million over the entire period, and $50 million per year by 2010 (Table 9, row h). The total savings related to reducing the number of carloads of coal is estimated to be $1.36 billion for 1994 to 2010 and $190 million per year by 2010. Since there were 7.06 million carloads of coal in 2010, the estimated operating benefits were approximately $27 per car.

Table 9: Operating Savings Resulting From Fewer Carloads
      ($160/load, $0.0360 per car-mile and $9.93/train-mile)

	Total or Average 1994 to 2010	Amount in 2010	Total Savings 1994 to 2010 (millions)	Savings in 2010 (millions)
a. Total Tons of Coal Shipped	13 billion	814 million		
b. Average Load with 263k GVW (50% steel and 50% aluminum cars)	105 tons/car	105 tons/car		
c. Loads Required with 263k GVW (= a/b)	123 million	7.75 million		
d. Actual Loads	118 million	7.06 million		
e. Actual Average Tons/load (a/d)	110	115		
f. Reduced loads and related savings @ $160 per load	5 million	0.69 million	$800	$110
g. Car-mile savings @ $0.036 per car-mile	6,100 million	840 million	$220	$30
h. Train-mile savings (crew costs for length-limited 120-car trains @ $9.93 per mile; 2/3 of trains are length-limited)	34 million	5 million	$340	$50
i. Total savings			$1,360	$190
j. Savings per carload of coal			$12	$27

Source of Data: Tables 7 and 8; tons and loads (rows a and d) are from AAR, *Railroad Facts, various editions.*

The next category of savings results from the fact that the ratio of GTM to NTM is lower with HAL equipment. If half of the 286k cars are steel and half are aluminum, then there would be a 3.2% reduction in MGT if all traffic moved in HAL equipment (see Table 3 above). The number of locomotives, locomotive-miles, gallons of fuel, train-miles and other service units needed to move a given quantity of coal can be estimated with the parameters given in Table 7 above. Table 10 shows the actual loads of coal handled by Class I railroads from 1994 to 2010 (Column 2) as well as the loads handled in 2010 (Column 5). If HAL had not been implemented, then more service units would have been required. The amount of the hypothetical increase (and therefore the estimated savings) depends upon the extent of HAL implementation. In 2010, when HAL was essentially fully implemented for coal traffic, 3.3% more service units would have been needed if GVW had not been increased (since 1/(1-.032) = 1.033). The avoided increase in service units and the estimated cost savings for 2010 are shown in Columns 6 and 7 of Table 10. The percentage savings for the entire period were lower (0.59 x 3.3% = 1.95%), because the average implementation is estimated to be 59% for the entire period (Table 10, Columns 3 and 4). The cost savings related to locomotives, locomotive-miles, train-miles, and fuel are calculated using the assumptions and unit costs from Tables 7 and 8 above. The crew savings in this table relate only to weight-limited trains (so there is no double counting of crew savings in Tables 9 and 10). Together, the cumulative savings resulting from the reductions in MGT and car-miles are estimated to be $1.365 billion, while the savings in 2010 are estimated to be $145 million or approximately $20.50 per car.

Table 10: Operating Benefits for Coal Traffic Resulting from the Reductions in MGT and Car-Miles

1. Service Units (SU)	2. Total SU 1994-2010 (millions)	3. Increase in SU 1994-2010 if GVW were still 263k	4. Total Savings 1994-2010 ($ million)	5. Actual SU in 2010	6. Increase in SU in 2010 if GVW were still 263k	7. Savings in 2010 ($ million)
a. Coal loads	123 million			7.06 million		
b. Car-miles (@ 1216 per load)	150 billion			9.42 billion		
c. Train-miles @ 120 cars per train (cost savings for weight-limited trains)	417 million	8 million	$80	26 million	0.9 million	$9
d. Locomotive Miles @ 2.7 locomotives per train	3,365 million	65.5 million	$65	212 million	7.0 million	$7
e. Locomotive-years @ 174 miles/day	53,000	1,030	$140	3,340	110	$15
f. Net Ton-miles @ 608 miles per ton	8 trillion			0.5 trillion	16.5 billion	
g. Gross ton-miles @ 1.5 gross tons per net ton	12 trillion			0.75 trillion	24.75 billion	
h. Fuel saved (@ 484 GTM/gallon)	25 billion	50 million	$1,080	1.55 billion	50 million	$114
i. Total			$1,365			$145
j. Savings per car			$11			$20.50

Source of Data: coal loads are from AAR, *Railroad Facts,* various editions; all other entries are calculated using efficiency factors and unit costs from Tables 7 and 8.

Actual Operating Benefits for Traffic Other than Coal

Substantial amounts of other bulk commodities move as 286k loads. The evidence from WILD data such as that obtained by UP (Figure 1 above) indicates that more than a quarter of general freight moved in HAL loads more than 10 years ago, and the percentage of HAL freight is certainly higher today. To estimate benefits for non-coal traffic, a conservative assumption was made that 30% of non-coal general freight moved in HAL loads in 2010. This assumption is consistent with the traffic data presented above in Table 1 and Figure 1.

The benefits associated with car acquisitions for these commodities were included in the savings estimated in Table 5 above. The operating benefits would likely be similar, on a per-car basis, to the $27 and $20.50 per car estimated for coal in 2010 in Tables 9 and 10 above. For these 4.5 million non-coal HAL loads, total operating benefits in 2010 are therefore estimated to be $209 million. If

cumulative benefits were similar to those for coal, they would be estimated to be at least 7 times as great, i.e., on the order of $1.5 billion.

Table 11: Estimated HAL Implementation as of 2010

Category	2010 Loads	Estimated HAL Loads	Estimated HAL %	Estimated Operating Benefit per Car in 2010	Total Operating Benefit in 2010
Coal	7.06 million	7.06 million	100%	$47.50	$335 million
General Freight	14.6 million	4.4 million	30%	$47.50	$209 million
Total, without intermodal	21.7 million	11.46 million	53%	$47.50	$544 million
Total, with intermodal	29.2 million	11.6 million	40%	$47.50	$544 million

Source of Traffic Data: AAR, *Railroad Facts,* 2012.

The total benefits from HAL therefore were on the order of $6 billion from 1994 to 2010 and $600 to $700 billion per year by 2010:
- Equipment acquisition (Table 6): $1.8 billion ($107 million per year for all bulk equipment)
- Fewer loads of coal (Table 9): $1.4 billion ($190 million per year)
- Better net-to-gross for coal (Table 10): $1.4 billion ($145 million per year)
- Operating benefits, other traffic (Table 11): $1.5 billion ($209 million per year)
- Total: $6.1 billion ($651 million per year)

These benefits were spread among car owners, customers, suppliers, and railroads. Car owners benefited from being able to purchase capacity at a lower cost per ton. Railroads saved fuel because they moved less gross tonnage, and they operated fewer trains with fewer locomotives and fewer car-miles than they would have if the GVW had not been increased. Who has profited from HAL is a question that is beyond the scoped of this paper, because such a question must delve into hitherto unexplored pricing issues.

INCREASES IN INFRASTRUCTURE COSTS RESULTING FROM HAL OPERATIONS

Predicted Increases, HAL Phase II

The effects of HAL operations on infrastructure costs were estimated for hypothetical eastern and western coal routes using detailed engineering models for track components and bridges. The base cases had operating, route, and component characteristics typical for high density coal lines in each region. The western route had 80 million gross tons per year, including 45.12 million tons of coal and 34.88 tons of equipment. The eastern route had 30 million gross tons, including 17.28 million net tons of coal. In the 286k case, the net tonnage remained the same (45.12 million tons per year in the west and 17.28 million tons in the east), but the gross tonnage declined because of improved gross-to-net. Life cycle costs were predicted to rise for rail, ties, ballast & subgrade, turnouts, bridges, and routine maintenance. Estimated cost increases included both capital and operating expenditures, assuming full implementation of HAL. Track costs for both the base case and the 286k case assumed that the maintenance and replacement of rail, turnouts, ties, and ballast had reached a steady state. Increases in bridge costs were estimated by considering the effect of HAL on reducing the life of bridges and major bridge components.

Table 12 shows the base case costs and the predicted increases in costs once HAL operations were fully implemented. The base case costs in Phase II were approximately $46,000/mile for the 80-MGT route and $21,000 for the 30-MGT route. TTCI estimated that 10,500 miles of mainline track were more similar to the 80-MGT route, while 46,200 miles were more similar to the eastern route. Hence, base case track costs for the total of 56,700 miles of high density mainlines were estimated to be $1.5 billion/year, and the HAL effect under 286k loads was estimated to be $124 million per year. The added costs for bridges increased the HAL effect for both routes.

The predicted increases in track costs were estimated on a yearly basis by considering the projected cost increase of approximately $0.08 per 1,000 NTM together with the estimated extent of HAL implementation. Although HAL was essentially fully implemented for coal by 2010, only abut 40% of the total traffic moved in cars with 286k axle loads (see Table 11 above). Adjusting for the extent of implementation, the predicted annual increase in costs would have been approximately $50 to 60 million in recent years rather than the $135 million shown in the table. The adjusted prediction of cumulative cost increases for the entire period (from 1991 to 2011) would have been $0.7 billion, based upon the extent of HAL implementation.

The Phase II Economic Analysis included detailed estimates of costs for each major component of the track structure. Overall, the HAL effect was predicted to be much greater for maintenance expenditures than for capital expenditures. Spot surfacing, rail defects, and rail grinding were expected to be the maintenance expenses most affected by HAL, while shorter lives for rail and turnouts were expected to cause the greatest increases in capital costs. Costs related to ties and fasteners were not expected to increase significantly under 286k loads.

Table 12: HAL Phase II Base Case Costs and Cost Increases Resulting from 286k Operations

	Annual MGT Base Case	Track-Miles	Annual Cost per Mile	Annual Cost (Millions)	Annual MGT 286k Case	% Increase	Increase (Millions)
Track							
Western Route	80	10,500	$46,000	$480	76.4	5.0%	$24
Eastern Route	30	46,200	$21,000	$970	28.7	10.3%	$100
Total Track				$1,450		8.6%	$124
Bridges							
Western Route	80	N.A.	N.A.	$30	76.4	12.7%	$4
Eastern Route	30	N.A.	N.A.	$50	28.7	14.0%	$7
Total Bridges				$80		13.8%	$11
Total				$1,530		8.8%	$135

Source of Data: Hargrove et al. 1996. pp. 23-24.

Because of the risks associated with bridge fatigue, railroads were careful to determine whether bridges would need to be strengthened or replaced before introduction of HAL traffic (Newman et al. 1990; Sweeney et al. 1996). In Phase II, the HAL Economic Analysis estimated increases in bridge costs based upon analysis of the effects of heavier loads on typical bridges. For timber structures, it was assumed that railroads would either replace the caps or replace the entire structure at some point during the next 20 years (i.e., by 2012). For steel structures, a thorough engineering

analysis was conducted to determine the effect of higher axle loads on stresses on and fatigue life of critical bridge components (Sharma 1995). The shorter fatigue life was converted into an equivalent increase in annual costs for bridge maintenance. Analyses were completed for a representative sample of bridges provided by the Class I railroads; the results were used to estimate bridge costs by choosing sets of bridges to represent what might be found on typical eastern or western coal routes.

Actual Effects of HAL on Infrastructure Costs

The actual effects of HAL on infrastructure costs were less than expected, primarily because costs related to rail, turnouts, and bridges either declined or rose much less than predicted. For rail, the single most costly track component, costs actually declined; better rail metallurgies and more effective grinding techniques allowed railroads to increase rail life and reduce lifecycle costs (e.g., Clark et al. 1999; Martland and Massot 1999). Following the widespread introduction of HAL traffic, rail life and life cycle costs were better, not worse. Turnouts were another area where initial FAST/HAL results indicated that increasing axle loads could cause major increases in cost. As was the case with rail, new technologies and better maintenance practices extended component lives and reduced life cycle costs despite the introduction of HAL traffic (Byers 2007). As expected, there were concerns with ballast and subgrade (Worth 1993).

Research conducted as part of subsequent phases of the HAL and tests conducted by individual railroads led to a better understanding of bridge strength, efficient means of strengthening bridges, and railroad-specific programs for upgrading and replacing weak structures (Unsworth 2003). The actual expenses related to bridges were not as severe as anticipated, in part because the pace of implementation was slow enough to allow railroads time to prepare for the increase in axle loads within the context of their normal engineering budgets.

Analysis of aggregate operating plus capital expenditures on track and structures (CAPEX) provides more evidence that HAL traffic did not lead to an increase in infrastructure costs.[3] When capital and operating expenditures are combined, the average cost per 1,000 revenue ton-miles (RTM) increased from $6.70 in 1990 to $9.41 in 2010. However, when expressed in constant 2010 dollars, the average expenditures per 1,000 RTM declined from $10.25 in 1990 to $9.41 in 2010. The decline is more pronounced if the railroad cost recovery index is used to convert expenditures to constant dollars, as unit costs for labor, fuel, and materials and supplies increased more rapidly than general inflation over this 20-year period.

Aggregate analysis, which cannot document cost changes related to specific shifts in traffic mix or axle loads, does support two important conclusions. First, infrastructure expenses per revenue ton-mile declined from 1990 to 2010, despite the rise in 286k traffic. Second, rising traffic volume had a much larger impact on infrastructure expense than the predicted 8.8% increase resulting from full HAL implementation (Table 12 above). As shown in Table 13, total CAPEX, in 2010 constant dollars, rose 50% from $10.59 billion to $15.92 billion from 1990 to 2010, a period in which revenue ton-miles rose 63% from 1,033 billion to 1,691 billion.[4]

Table 13: Index of Constant Dollar Expenditures per Revenue Ton-Mile, 1990 to 2010

Expenditures on Way and Structures by Class I Railroads	1990	1995	2000	2005	2010
Operating Expense	$4.28 billion	$5.45 billion	$5.03 billion	$6.50 billion	$8.07 billion
Capital Expense	$2.64 billion	$3.65 billion	$4.55 billion	$5.36 billion	$7.85 billion
Total CAPEX	$6.92 billion	$9.10 billion	$9.58 billion	$11.86 billion	$15.92 billion
Revenue Ton-Miles	1,033 billion	1,306 billion	1,466 billion	1,696 billion	1,691 billion
$/1000 RTM	$6.70	$6.97	$6.53	$6.99	$9.41
Federal Reserve Implicit Price Deflator for GDP (2005 = 100)	72.593	81.710	88.903	100.461	111.045
Total CAPEX (2010 $)	$10.59 billion	$12.37 billion	$11.97 billion	$13.11 billion	$15.92 billion
$/1000 RTM (2010 $)	$10.25	$9.47	$8.16	$7.73	$9.41
Railroad Cost Recovery Index (RCR, 1981 = 100)	139.9	160.4	187.1	238.9	294.9
$/1000 RTM (using RCR)	$14.12	$12.81	$10.29	$8.62	$9.41

Source of Data: AAR, *Railroad Facts*, 2011 edition.

SUMMARY AND CONCLUSIONS

Nearly 100% of coal traffic and approximately 40% of all freight now moves in 286k loads. If all bulk traffic had continued to move in 263k cars, many more cars would have been purchased, more trains would have been operated, and more fuel would have been consumed. Cumulative benefits were approximately $6 billion from 1994 to 2010, and annual benefits were $600 to $700 million in 2010.

The greater stresses caused by HAL traffic were predicted to increase expenditures for track and structures by $135 million per year at full implementation (Table 12 above). Adjusting for the actual level of implementation, the predicted increases would have been $50 to $60 million in 2010 and a total of $0.7 billion from 1994 to 2010. Had the predictions been accurate, the net benefits of HAL implementation would still have been more than $500 million in 2010 and more than $5 billion for the entire period. In fact, because of the technological research and development, investments by railroads in better components, improved inspection technologies, and better maintenance management, constant dollar infrastructure expenditures per 1000 RTM actually declined. The net benefits from the introduction of HAL and from the improvement of the track structure are now well in excess of $600 million per year.

Railroads, and their customers and suppliers, are already starting to introduce shorter cars that retain the 286k GVW limit, a strategy that was investigated as part of the HAL research (Robert 1997; Guins et al. 1998; Chapman 1998; Wille 1998; Chapman, Martland, and Guins, 2003). Shorter 286k cars provide most of the cost and capacity benefits of heavier cars without increasing stresses

on the track structure; their impacts on bridges are similar to the impacts that would be imposed by 315k cars. In North America, there has been little interest in operating with axle loads in excess of 36-tons, although such loads have been operated by mining railroads in Australia since the 1980s (Marich 1986). More recently, FMG, a new iron ore railway in Australia, began to move iron ore 256 km from mine to port in the world's first cars designed for 44-ton (40 metric ton) axle loads (Shughart 2012). Higher axle loads can clearly be justified in certain circumstances, especially when track and equipment can be designed or upgraded for an operation that is controlled by the shipper, as was the case with FMG.

The industry should consider taking further steps to improve capacity, either by increasing axle loads or by continuing to invest in shorter 286k cars. Technological improvements have extended the life of track components, improved equipment, and enhanced inspection capabilities, while investments in bridges and track have strengthened the mainline infrastructure. Higher fuel costs and greater concerns with line capacity make it more important to pursue the most efficient means for transporting bulk commodities. Modest increases in GVW (e.g. an increase from 286k to 290k) would provide immediate operating benefits with minor impacts on track and structures. An increase in GVW to 315k, long considered the next logical step, may be justified now or in the not too distant future. Even heavier loads might be justifiable for special circumstances or restricted routes.

Whether or not higher loads or loading densities can be justified is a question that can be addressed using the results of FAST/HAL research and the models and evaluation techniques developed as part of that research. As documented in this paper, the benefits from implementing more efficient equipment can be very substantial. Even a small increase in axle loads or loading density, if the infrastructure is able to withstand that added stress, can result in very substantial savings for the railroads, their suppliers, and their customers.

It makes sense to conclude this review of the decades-long process of implementing HAL traffic with the first sentence of the first paper describing the economic interpretation of the Phase I HAL research:

> *The history of freight railroad technology shows a pattern of increasing vehicle size with increasing axle loads as developments in materials and engineering knowledge have made their use technically feasible and economically desirable* (Hargrove, 1991 p. 227).

Is there any reason to believe that 286k is the ultimate limit?

Endnotes

1. The TRACS model (Martland and Auzmendi 1989; Auzmendi 1994; Hargrove and Martland 1990 and 1991) was used to estimate deterioration rates and lifecycle costs related to rail, ties, ballast and routine maintenance. TRACS was calibrated based upon studies conducted in cooperation with individual railroads, including, most recently, studies of wear and fatigue on a high density coal route operated by Norfolk Southern (Clark, Bowman, and Martland 1999; Martland and Massot 1999). A model developed by MIT and TTCI was used to estimate turnout maintenance requirements and lifecycle costs (Smith, E.W. et al. 1993). Results from TRACS and the turnout model were incorporated into HALTRACK, a spreadsheet model that was used repeatedly in the economic analyses conducted as part of Phases II to V of the HAL research. A sophisticated structural analysis supported the estimates of the effects of HAL on bridges (Sharma 1993).

2. TTCI estimated the costs of operating a specific train consist over a particular route by using the Train Energy Model and the Rail Energy Cost Analysis Package, known collectively as TEM/RECAP (Stephens 1989). This model had previously been used to assess various options for increasing fuel efficiency by reducing train resistance (Smith, M.E. 1987).

3. It would be possible, but well beyond the scope of this paper, to investigate how much lower infrastructure costs would have been had GVW limits not been increased. The engineering models used in the HAL research could be used to compare 263k and 286k operations over routes with current engineering and traffic characteristics.

4. Costs rose less rapidly than revenue ton-miles because of economies of density. In Table 12, the cost per mile per annual MGT was predicted to be $575 in the west ($46,000 per mile/80MGT) vs. $700 in the east ($21,000 per mile/30MGT). A 267% increase in density therefore resulted in a predicted 18% decrease in costs per mile per MGT for these two routes. If the same relative proportions applied to CAPEX for rail infrastructure, a 63% increase in traffic would produce a 4.2% decrease in costs per mile per MGT (18% x 0.63/2.67 = 4.2%). In fact, between 1990 and 2010, constant dollar CAPEX for rail infrastructure declined 8.9% from $10.25 per 1000 RTM to $9.41 per 1000 RTM. A portion of the actual decline can be attributed to the 2.6% to 3.9% decrease in the ratio of gross-to-net vehicle weight for HAL traffic (see Table 3), which led to a similar reduction in MGT per RTM.

Acknowledgments

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