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Fuel Use Simulations of High Productivity Container Trains

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ABSTRACT

The AAR's High Productivity Integral Train Project sets line-haul cost goals for advanced-concept intermodal trains. Fuel consumption, largely determined by train resistance, is a major factor in line-haul cost. Integral train design objectives were considered, and Manalytics' engineered cost model was used to estimate round-trip fuel consumption for existing double-stack container trains and hypothetical integral intermodal trains between Los Angeles and Chicago.

INTRODUCTION

In April of 1984, the AAR announced its High Productivity Integral Train Project, dedicated to achieving a major breakthrough in railroad technology for both bulk and intermodal trains (1). Among its goals is a 50 percent reduction in line-haul costs over conventional alternatives. Yet the "conventional" intermodal alternative has become a moving target, since intermodal equipment and operations have changed dramatically in recent years. Double-stack articulated container cars, labeled by the AAR Evaluation Methodology as "the greatest deviation from current practice," (2) are now the state of the art, and are expected to achieve large cost reductions over conventional piggyback. A new generation of motive power and the elimination of cabooses promise additional efficiencies. It would be instructive to compare a state-of-the-art double-stack container train with a hypothetical High Productivity Integral Intermodal Train to determine what further cost reductions can be expected.

Improvements in train design can have multiple objectives, but prominent among them must be reductions in total train resistance and fuel consumption. Reductions in other cost components, such as labor and track maintenance, depend on a variety of institutional and technical factors. Reductions in fuel consumption, however, can be estimated with some confidence by applying an engineered cost model, and fuel accounts for 15-30 percent of line-haul costs.

The use of an engineered cost model allows us to extend our imaginations, assembling desirable design features without the constraints of construction feasibility or cost. It is essential to use an *engineered* cost model, one that uses the technical characteristics of the train and the route to predict performance. Statistical or accounting models would be far less useful.

This paper draws on computer performance simulations to compare the fuel consumption of current double-stack container trains and hypothetical integral trains. Use of the Manalytics Rail Cost Model (RCM) permits a detailed comparison of alternative train consists, and identification of the separate fuel use impacts of weight reduction, aerodynamic changes, and motive power integration (3). In a recent project the Manalytics RCM was highly successful in estimating fuel use when compared with railroad records (4).

The Santa Fe route between Los Angeles and Chicago (actually Hobart Yard to Corwith Yard) was chosen for round-trip fuel consumption simulations, for several reasons. First, it is one of the most heavily used intermodal corridors. Second, it does not currently carry a double-stack train, so we can avoid comparisons with any particular commercial operation. Third, it is a long route (4,530 miles, round trip) with a mix of mountainous, hilly, and flat terrain, providing an ideal demonstration for line-haul fuel consumption improvements. Santa Fe provided a set of timetables for the route, which included information on mileage and compensated ruling grades (5). The cost model track profile was compiled from these data (6).

II. THE BASE CASE

The base case selected for this analysis is a double-stack, cabooseless container train, similar to those used by American President Lines and Sea-Land Service. The base case train consists of 20 cars, each composed of five articulated platforms or wells carrying stacked 45' marine containers. Four General Electric B39-8 locomotives were assigned, representing the state of the art in locomotive design. (The EMD GP60, not yet produced, should yield similar cost model results.)

III. INTEGRAL TRAIN DESIGN

At the heart of all train performance simulators are formulas to calculate rolling resistance and tractive effort. The train must be "designed" in sufficient detail to satisfy those equations. Fortunately, a computer model will accept hypothetical values for train characteristics without confronting the engineering problems involved.

All conventional rolling resistance formulas are derived from the original Davis formula of 1926. For simulations of modern equipment, the "Modified Davis" or "Canadian National" formula (7) is more commonly used, and was adopted for this analysis

$$R = 0.6W + 20N + 0.1V + KV^2$$

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* Manalytics, Inc.

where

R = car rolling resistance in pounds;
W = gross car weight in pounds;
N = number of axles;
V = speed;
K = air resistance factor.

For this analysis, it was assumed that the integral intermodal train, like the base case train, is made up of double-stack container well cars articulated over standard freight car trucks. The line-haul cost reduction goals of the AAR specifications require maximizing the net-to-tare ratio, and double-stack container cars have a substantial net-to-tare advantage over other intermodal types.

What makes a train "integral"? Double-stack cars now being built typically come in articulated "cars" of five wells, sharing six standard trucks. If the articulation was extended through the entire train, it would fit the common conception of an "integral" train.

There would be one less truck for each five-well "car," and fewer axles in total under the train. Since the number of axles is a factor in rolling resistance, articulation of double-stack cars to make an integral train produces a small resistance reduction. One cost model run (Train 1) was made to determine the effect of articulation alone, without any other improvements.

A. Car weight

In designing an integral train, car weight is the obvious target for train resistance reductions. Besides the role of weight in determining resistance on level track, the additional resistance imposed by grades is a function of weight alone. We would expect car weight to be the single most important factor in determining fuel consumption, and the analysis confirms this notion.

Existing double-stack articulated container cars weigh from 28,000 to 35,000 pounds per platform, depending on whether or not the car has bulkheads and whether it is an interior or end platform (7). The base case assumes a 28,000 pound average.

Can an integral train achieve significant platform tare reductions over existing double-stack designs? The trend is toward lighter tare, and it seems reasonable to assume that refinements in existing designs are possible. A design goal of 23,000 pounds per platform has been mentioned, and some interior platform designs have been reduced to 26,000 pounds. If an integral train has fewer end platforms with their extra couplers, draft gear, and trucks, the average could approach the 23,000 pound goal. The likelihood of large reductions below that point is questionable. If only longitudinal structures were involved, their weight could be diminished as a linear function of the weight they must bear: a car that need not pass a 1 million pound squeeze test can have lighter sills. But in practice the weight does not diminish linearly, because the same structure must serve in both tension and compression, must support the lading, and must carry brake, suspension, and securement hardware. A single 100-ton truck assembly weighs 10,500 pounds by itself. To simulate the effect of a dramatic, though perhaps unattainable, weight reduction, a platform weight of 18,000 pounds was used.

Model runs were therefore made with an attainable platform weight of 23,000 pounds, and an optimistic weight of 18,000 pounds, reductions of 18 and 36 percent from the base case.

Existing double-stack cars will hold one 45′ container over one 40′ container. The newest proposed cars will carry two 45′ containers, as is simulated in the base case. AAR specifications for the high productivity train also call for 45′ container positions (8). This makes good sense, particularly for domestic containerization, where one stumbling block has been the reduced cubic capacity of existing containers compared to piggyback trailers. The most attractive, high-value ladings tend to be less dense, accounting for interest in larger containers: a 45′ container has only 5 percent more weight capacity, but 19 percent more cubic capacity than a 40′ container. Both the base case and the hypothetical integral trains are presumed to carry two 45′ long, 8′ wide, 9′6″ high containers of conventional maritime design in each well. The tare for a 45′ container is 8,550 pounds, and the cubic capacity is 3,035 cubic feet. The weight capacity is 64,250 pounds, but in practice, highway load restrictions limit 45′ container loads to about 43,000 pounds, which was used in the analysis for both the base case train and the hypotheticals. The traffic was assumed to be directionally balanced.

The total loaded car weight comes to 131,000 pounds for the base case, and 126,100 or 121,100 pounds for the integral trains. These weights imply a need for 100-ton capacity trucks, as are currently used between the interior platforms of the Gunderson Twin-Stack car. A comparison of platform weights is given below:

Platform Weights

	Base Case (pounds)	*Hypotheticals* (pounds)
Platform Tare	28,000	23,000-18,000
Container Tare	17,100	17,100
Total Tare	45,100	40,100-35,100
Lading Net	86,000	86,000
Platform Gross	131,100	126,100-121,100
Net/Tare	1.91	2.14- 2.45

The net-to-tare ratios shown are substantially better than that of conventional piggyback, which is about 0.67. Cubic capacity shows a slightly different story:

Cubic Capacity and Weight

	Base Case	*Hypotheticals*
Total Tare (pounds)	45,100	40,100-35,100
Container Capacity (cubic feet)	6,070	6,070
Cubic Feet/ Pound	0.13	0.15-0.17

While the hypotheticals yield 12.0 to 28.3 percent more net for the same tare, they improve the cube yield by 15.4 to 33.0 percent. Given that the high value commodities that the railroads hope to attract or retain require higher cubic capacity, this is an important advantage.

Table 1
Los Angeles-Chicago Round-Trip Fuel Use Simulations
Base Case Double-Stack Container Train Versus Hypothetical Integral Trains

Manalytics' Rail Cost Model

	Articulation	Platform Tare (Pounds)	Air Resistance Factor	Motive Power	Round-Trip Time (Hours)	Fuel Used (Gallons)	Fuel Saved (Percent)
Base Case	5-unit cars	28,000	.00040	B39-8	113.5	37,999	--
Integral Trains							
Train 1	complete	28,000	.00040	B39-8	113.4	37,735	0.7
Train 2	complete	23,000	.00040	B39-8	111.8	36,628	3.6
Train 3	complete	18,000	.00040	B39-8	110.4	35,526	6.5
Train 4	complete	28,000	.00034	B39-8	113.3	37,587	1.1
Train 5	complete	28,000	.00021	B39-8	112.8	37,270	1.9
Train 6	complete	28,000	.00040	Integral	108.9	36,482	4.0
Train 7	complete	23,000	.00034	B39-8	111.5	36,485	4.0
Train 8	complete	18,000	.00021	B39-8	109.9	35,015	7.9
Train 9	complete	23,000	.00034	Integral	110.3	34,895	8.2
Train 10	complete	18,000	.00021	Integral	108.4	33,487	11.9

B. Streamlining

Among the design objectives for a high productivity integral train is reduction of air resistance through streamlining. That resistance is determined by the cross-section area and a resistance factor. For a double-stack container train, the basic dimensions are determined by the containers. Two containers, each 9′6″ high and 8′ wide, form a 19′ high, 8′ wide load with a cross-section area of 152 square feet. The Budd/Thrall cars used by APL and ordered by Trailer Train add very little to this cross-section. They raise the containers only about 10 inches off the rail head, and are 10′5″ wide and 3′6″ high. Other options are similar: the Gunderson Twin-Stack car is 10′ 5.5″ wide, with the bulkheads extending about 11′ 9″ above the rails; the ATSF A-Stack containers are 10′3″ wide for most of their height. The smallest double-stack car adds only 12.75 square feet to the cross-section of the containers themselves, so no effort was made to model a reduced cross-section for the integral train. Both base case and hypothetical train simulations used a cross-section of 164.75 square feet.

For air resistance, the original Davis equation uses the form CAV^2, where C is a constant, given as 0.0005 for freight cars, and A is a separate factor based on cross-section area. The Modified Davis equation uses the form KV^2, where K is 0.07 for conventional freight cars, 0.16 for piggyback, and 0.0935 for Flexi-Van containers. However, double-stack cars should have air resistance characteristics closer to those of boxcars than to Flexi-Van containers. The base case therefore uses the Modified Davis boxcar value of 0.07, equivalent in the original Davis Formula to a value of 0.0004 multiplied by the 164.75 square foot cross section.

The choice of an aerodynamic coefficient for a hypothetical integral train is necessarily speculative, but there are two hints available. In 1926, Davis suggested a resistance factor of 0.00034 for trailing cars in a passenger train. The passenger cars then in use presented a smoother exterior and closer coupling than freight cars, and could be a good first approximation for an integral train. Wind tunnel work at Lockheed-Georgia in 1983 (9) found that, for well cars carrying containers, the size of the gap between loads on adjacent cars was the major variable. Streamlining of the containers themselves was found to be of minor significance. At 60 MPH, a sharp break in resistance occurred between gaps of 75 and 45 inches, with the reduced gap lowering air resistance by as much as 50 percent. If we start with the Modified Davis freight car coefficient of .07, a 50 percent reduction would yield a new coefficient of .035. This coefficient would be equvialent to a factor of 0.00021 when applied to a 164.75 square foot cross-section in the original Davis equation. Thus, Rail Cost Model runs were made with air resistance coefficients of .00034 and .00021 applied, to a 164.75 square foot cross-section, reductions over the base case of 15 percent and 48 percent.

In using either value, we are assuming that the gap between containers or adjacent cars is eliminated or reduced to something less than 45″. The wheelbase of a standard 100-ton truck is 70″: containers in articulated well-type cars using standard trucks cannot be closer than about 100″, especially if both upper and lower containers the same length. Reduction or elimination of this gap requires a filler of some kind, the equivalent of the full-width diaphragms introduced on streamlined passenger equipment in the 1930s. For this purpose, a bulkhead car could be advantageous, since the diaphragms could be semi-permanently attached to the bulkheads. This would increase the air resistance of the empty car relative to non-bulkhead designs, but concern for efficiency dictates that no advanced intermodal equipment should ever be run empty.

C. Motive power

The AAR specifications consider train integration and motive power integration as separable. It is possible to imagine an integrated train being pulled by conventional locomotives, and the analysis included cost model runs of that type. Given an integral train, further integration of the motive power into that train is commonly considered to entail mixing power units and container-carrying units, and distributing traction motors throughout the train.

Three benefits are expected from integration of motive power: reduced power unit weight; better adhesion; and reduced car weight. To simulate integral motive power, we can begin with the weight of the prime mover itself. A General Electric 16 cylinder diesel prime mover weighs 57,000 pounds, or 21 percent of total unballasted B39-8 locomotive weight. The power unit must also carry the alternator, radiators, dynamic brakes, and control system. If traction motors are dispersed and buff forces are reduced, the power unit frame need only support the machinery and transmit the same forces as the container-carrying units. The most favorable assumption used for cars was a platform weight of 18,000 pounds to support a load of 103,100 pounds. Doubling the 57,000 pound weight of the prime mover as an approximation yields a power unit weight of 114,000 pounds. All cost model runs made for this analysis allowed for 1,600 gallons of fuel (half a tank) in each power unit, whether integral or conventional locomotive. That much diesel fuel adds 12,000 pounds to the power unit weight. For the integral train, total power unit weight was therefore assumed to be about 126,000 pounds, a little less than half the weight of a conventional locomotive.

Some informal proposals have envisioned power unit modules which could take the place of one or more loads in container cars. The weights estimated above would correspond to such an arrangement, as the power unit would become simply a self-contained, remotely controlled generating unit for electrical power (and compressed air, if air brakes are used). Locomotive prime movers have been used in such applications, so the idea is not too far-fetched.

A double-stack container train is heavy, roughly 6,500 tons. If road locomotives are kept to the minimum necessary to meet schedules over flat and rolling terrain, the train will need helpers over the steepest grades. In the base case simulation, the train was assigned two EMD SD40-2 helpers eastbound over Cajon Pass, where the compensated ruling grade is 2.2 percent. The use of helpers on an integral train is problematical. At the very least, it reduces the esthetic purity of the concept. At worst, it forces a re-examination of the ability of very lightweight cars to withstand longitudinal stresses. Implicit in the assumption of very light car weight is our ability to distribute tractive effort throughout the train rather than concentrating it at the ends.

Tractive effort depends on adhesion and on the weight on the driving wheels. Recent developments in wheel slip control have raised the regularly attainable adhesion to the neighborhood of 25 percent, which is the value used in this analysis for both base case and integral trains. In the base case, all driving wheels are under the locomotive. At a locomotive weight of 286,000 pounds, including fuel, a 25 percent adhesion factor limits tractive effort to 71,500 pounds per locomotive. For the integral train, traction motors can theoretically be distributed under cars as well as under the power unit. Each truck under an articulated car set will carry the gross weight of one platform or well, which for our hypothetical integral train is either 126,100 or 121,100 pounds. The corresponding tractive effort limits would be 31,525 and 30,275 pounds, respectively.

The number of traction motor-equipped trucks is limited by the horsepower available. The 3,910 horsepower units are each capable of producing tractive effort according to the following equation:

$$\text{T.E.} = \frac{3{,}910 \times 375 \times 0.84}{\text{x}};$$

where TE is tractive effort at speed V, 375 is a conversion factor, and 0.84 is an efficiency factor. At 10 MPH, 3,910 horsepower would produce 123,165 pounds of tractive effort, if that much could be transmitted to the rails. In the B39-8 locomotive, only 71,500 pounds can be transmitted, so the locomotive tractive effort will be limited by weight and adhesion until 18 MPH, when the available tractive effort drops below the weight/adhesion limit. In our integral train with powered trucks capable of 30,275—31,525 pounds of tractive effort, 3,910 horsepower could theoretically support four such trucks at 10 MPH.

The actual model runs took a somewhat conservative approach to simulate motive power integration, using three power trucks for each power unit, together capable of 90,825 or 94,575 pounds of tractive effort depending on car weight. As in the base case, the integral motive power simulations used four such 3,910 horsepower power units with a total of twelve power trucks. While tractive effort at higher speeds will still be limited by the horsepower available, the higher tractive effort at low speeds eliminates the need for helpers. The table below compares the tractive efforts available from the base case and integral motive power combinations between 10 and 20 MPH. As the table implies, if motive power integration of this kind is indeed possible, it could provide significant operating improvements at low speeds.

Theoretical Tractive Effort
(Pounds)

MPH	B39-8 *Locomotive*	Integral 3,910 HP PowerUnits *and 3 Power Trucks*
10	71,500	90,825-94,575
11	71,500	90,825-94,575
12	71,500	90,825-94,575
13	71,500	90,825-94,575
14	71,500	87,975
15	71,500	82,110
16	71,500	76,978
17	71,500	72,450
18	68,425	68,425
19	64,824	64,824
20	61,583	61,583

The car weight benefits depend on the reduction in train dynamic forces that motive power integration can achieve. This has already been taken into account in specifying hypothetical platform weights of 23,000 and 18,000 pounds. As the second figure may already be optimistic, no further reductions were made.

C. Rail lubrication and radial trucks

Rail lubrication offers substantial flange resistance reductions on both tangent and curved track. However, rail lubrication, whether applied by on-board or trackside equipment, can be added to either conventional or integral trains, and has not been incorporated into the analysis. Likewise, the analysis makes no provision for the use of radial trucks, which offer flange resistance reductions as well as maintenance savings in either integral or conventional trains.

IV. RESULTS AND CONCLUSIONS

Cost model runs were made for the base case, and for ten hypothetical integral trains with different combinations of the improvements discussed above. Trains 1-6 show the separate effects of articulation, weight reduction, streamlining, and motive power integration. Trains 7 and 8 simulate integral trains pulled by separate locomotives, while Trains 9 and 10 show the effect of complete integration of train and motive power.

The transit time estimates produced by the Manalytics Rail Cost Model serve as a check on the simulation of train operations. All round-trip model runs included 20 hours of idling time for crew changes, inspections, and servicing. Running times ranged from 93.5 hours for the base case down to 88.4 hours for the most optimistic integral train simulation. Round-trip transit times ranged from 113.5 hours to 108.4 hours, or from 56.75 hours to 54.4 hours in each direction. These times compare closely with the 60-hour schedules announced for Santa Fe's new EconoPac service over the same route.

As shown in the table, each of the improvements applied individually to Trains 1-6 reduced fuel consumption by 0.7-6.5 percent from the base case. The effect of integration or articulation *per se*, which reduced the number of axles on Train 1, was very small. The largest savings, as expected, came from the most optimistic weight reduction, Train 3. Perhaps surprisingly, the next largest savings came from the hypothesized features of motive power integration in Train 6. Some of this savings is due to the elimination of helper service, and some is due to weight reduction in the power units themselves.

The reductions possible through streamlining are more modest. The effect of streamlining varies with the square of velocity. The base case train and streamlined Trains 4 and 5 all averaged between 48 and 49 MPH when moving. Speed limits varied between 50 and 70 MPH, depending on terrain, but the train did not always reach the limit when running upgrade. Moreover, some railroads have restricted double-stack trains to 60 MPH due to their high gross weight per operating brake. If the average speed were raised to 60 MPH, air resistance would increase by 53 percent and streamlining would be more important.

If the various features are combined, the results are more dramatic, as shown in the table. It is clear that the results are not simply additive. The savings separately attributable to articulation, 23,000 pound platform weight, and an air resistance factor of .00034 add up to 5.4 percent, or 2,052 gallons (Trains 1, 2, and 4). The combination (Train 7) saved 4.0 percent, or 1,520 gallons. On the other hand, the most ohe table (Train 10) saved 11.9 percent, while its features separately saved a total of only 9.2 percent (Trains 1, 3, 5, and 6). Some of this is easily explained: streamlining had a somewhat greater effect on the most optimistic train because it travelled faster. Beyond some simple observations of this kind, the relationship between separate and combined effects rapidly becomes a complex issue.

These results raise the question of tradeoffs in equipment designs. As stated earlier, the reduction of air resistance by eliminating the gap between containers on adjacent platforms may require some filler device, possibly anchored to bulkheads. This increases weight, and the increased weight may offset the gain from reduced air resistance. We have not considered container weight: lighter containers could reduce total weight beyond what can be achieved through car design. We have not considered cost: what are the construction and maintenance cost impacts of integrated motive power, or fully articulated 100-well trainsets?

One conclusion seems inescapable: double-stack container trains are dominated by their loads. The loads—containers and lading—account for 85 percent of the weight and 92 percent of the air resistance in our most optimistic case. The requirements for motive power are determined by the train's load, not its tare. Indeed, the function of a double-stack car is simply to keep the containers over the railroad wheels and connected together in a train. They offer no protection from the elements, and no support or containment for the lading itself. How much further can the role of a freight car be reduced? A net-to-tare ratio of 0.67 for conventional piggyback improves dramatically with reductions in tare weight; the net-to-tare ratio of 2.45 for our best hypothetical train does not. As railroad cars and motive power move closer to an irreducible minimum, the industry must look elsewhere for dramatic cost reductions.

Certainly, we cannot expect a 50 percent reduction in fuel use by improving what is already a very advanced train. Indeed, the clearest message is not that a High Productivity Integral Intermodal train is not worth pursuing, but that the present state of the art, as exemplified by double-stack container trains, is very good. The better we do, the harder it is to do still better.

There are really *two* challenges implicit in the results of this simulation exercise. Given a free hand at the computer keyboard, we can "design" a High Productivity Integral Intermodal Train that will reduce fuel consumption by roughly 12 percent compared to current double-stack container trains. If it is indeed possible to engineer all the assumed features of such a train, such savings will increase the competitiveness and profitability of rail intermodal transportation. The first challenge is for the industry to achieve as much in practice as we have in theory. But the results given here present a greater opportunity and, perhaps, a greater challenge. The performance gap between existing double-stack container trains and hypothetical integral trains is small compared to the gap between the conventional TOFC equipment still in common use and those same, existing double-stack container trains. The most efficient integral designs the manufacturers can offer will do the railroads little good if they cannot first take advantage of the existing state of the art.

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(2) "High Productivity Integral Train Economic Evaluation Methodology," AAR, March 30, 1984.

(3) The Manalytics Rail Cost Model, also known as the Unit Train Model, was originally described in *Cost Models for Coal Transportation by Common Carrier*, Electric Power Research Institute, March 1979.

(4) *The Manalytics Unit Train Model: Developments and Applications*, in the proceedings of the EPRI/DOE Coal Transportation Costing and Modeling Seminar, Argonne National Laboratory, October, 1984.

(5) My thanks to Mr. T.C. Buckley of Santa Fe Southern Pacific Corp., and to Mr. M.M. Sullivan, of the ATSF Railway, for their assistance. However, neither SFSP nor ATSF bear any responsibility for my findings, and any errors are strictly my own.

(6) The use of ruling grades may somewhat overstate the grades encountered and therefore the fuel saved through weight reduction. However, this tendency diminishes as the length of track links is reduced. Special attention was paid to capturing accurate grade information for mountainous segments.

(7) *Railroad Engineering*, William W. Hay, Second Edition, 1982, page 69.

(8) Information on car weights and technical specifications was drawn from a number of sources, including both industry journals and manufacturers' brochures.

(9) "How important is wind drag in equipment design?", *Railway Age*, March, 1984, page 58.