Improving Energy Efficiency of Intermodal Trains Using Machine Vision and Operations Research Analysis

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Abstract

Intermodal trains are typically the fastest freight trains operated in North America. The aerodynamic characteristics of many of these trains are often relatively poor resulting in high fuel consumption. However, considerable variation in fuel efficiency is possible depending on how the loads are placed on railcars in the train. Consequently, potential fuel savings are substantial depending on the loading configuration of a particular train. An automated, wayside, machine-vision system was developed and installed at BNSF's Logistic Park intermodal yard, near Chicago to monitor loading patterns of passing intermodal trains. This information is necessary but not sufficient to evaluate the efficiency of loading patterns. In order to make use of the data, an evaluation method is needed that compares the possible configurations and provides information on which is the most efficient. Identification of the best pattern is non-trivial because of the variability in intermodal loads and railcars available to transport them. We developed a scoring system based on two attributes — the aerodynamic coefficient and slot efficiency. The aerodynamic coefficient is calculated using the Aerodynamic Subroutine of the Train Energy Model. Slot efficiency represents the difference between the actual and ideal loading configuration given the particular set of railcars in the train. Intermodal load information is obtained from the machine-vision output and railcar type from the Automatic Equipment Identification (AEI) tag. Using this system we can compute the characteristics of each train and determine how much improvement is possible given the particular combination of railcars and loads. To assist railroads in implementing these results we have developed an optimization model that can be integrated into intermodal terminal software systems to help managers make the best decisions regarding how to load trains so as to maximize their energy efficiency.

What's new?

A new and advanced image acquisition system and machine vision algorithms have been developed to monitor the loading efficiency of intermodal trains. The system evaluates the loading pattern of each intermodal train and provides a quantitative measurement of its aerodynamic efficiency. An optimization model has also been developed that can be integrated into the decision support systems used by terminal managers to enable them to load intermodal trains as efficiently as possible.

Introduction

Railroads are the largest transporter of intercity freight in North America, and intermodal (IM) freight recently surpassed coal as the leading source of freight revenue among US railroads. This traffic and its steady growth indicate its importance to railroad operating costs [12], and fuel is the second largest of these costs, comprising approximately 12 % of US railroads' total in 2004 [3].

IM trains are typically the fastest freight trains operated in North America. However, the aerodynamic characteristics of many of these trains are often relatively poor resulting in high fuel consumption. Lai & Barkan [17] conducted a series of analyses to compare both the relative and absolute effects of different loading patterns and operating practices on train make-up and energy efficiency. They found that aerodynamic characteristics significantly affect intermodal train fuel efficiency. Trains can be more efficiently operated if loads are assigned not only based on slot utilization but also by better matching loads with cars, which is referred to as "slot efficiency". The results showed that train resistance can be lowered by as much as 27% and fuel savings by 1 gal/mile per train.

The substantial energy savings that may be accrued due to improved loading patterns suggest the potential benefit of a system to monitor intermodal train loading. Consequently, the BNSF railway recently installed an automated, wayside, machine-vision system at one of its principal intermodal terminals. The system monitors the aerodynamic efficiency and determines the loading patterns of containers and trailers on intermodal trains [16]. A digital video recording system is used to record passing trains, and machine vision algorithms analyze the images for detection of loads and measurement of gaps.

After recording a train, the video is processed and histograms of upper and lower gaps are generated to represent the loading pattern of the train. This information is necessary but not sufficient to evaluate the efficiency of loading patterns. In order to make use of the data, a scoring system is needed to compare the actual configuration to the ideal configuration. The output provides feedback to terminal managers after trains are loaded. To further assist railroads in implementing these results, we developed a load assignment model to help terminal managers make the best decisions regarding how to load trains so as to maximize their energy efficiency.

In this paper, we introduce the wayside machine vision system and the scoring systems. Then we describe the intermodal operations at terminals and present a loading optimization model.

Wayside Machine Vision System

An automated, wayside, machine-vision (MV) system to record and analyze the loading patterns of intermodal trains was developed. The system monitors intermodal trains and determines their loading efficiency from the analysis of each load type, its placement on the railcar, and its location in the train. The data are provided by a digital video recorded as the train passes by a wayside camera and computer. MV algorithms detect the loads present on the train and identify their type, size and position. From these data, loading efficiency is determined based on the gaps present compared to the ideal loading configurations for the particular railcars in the train.

Image Acquisition System

The image acquisition system acquires digital videos of passing trains and includes a video camera and lens, wayside computer, and imaging software [16]. A permanent system has been installed at the BNSF Railway's Logistics Park – Chicago intermodal facility, (known as LPC). This installation features hardened components housed in an equipment bungalow and on two towers. The camera is installed on one of the towers inside a weather-proof housing. The other tower provides an antenna for communication with the main LPC yard office (Figure 1). This connection allows data to be transmitted directly to BNSF's computer systems for analysis. The LPC installation will be fully automated. Presence loops on either side of the wayside system will detect the arrival of a train and trigger the onset of video capture, followed by analysis and reporting to BNSF.

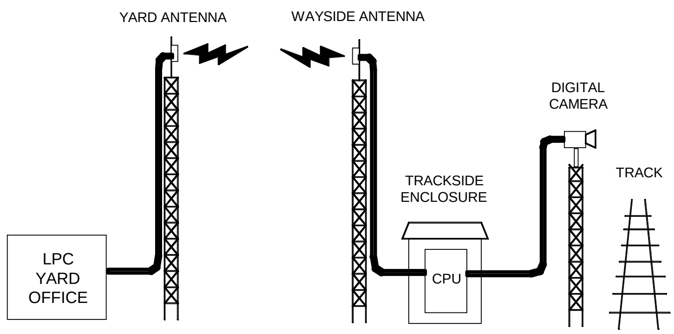


Figure 1: Automated, wayside image acquisition system as installed at BNSF Railway's Logistics Park Intermodal Facility

Machine Vision Algorithms

There are several steps involved in detecting and extracting relevant information from the digital video generated from the image capture system. First, the software separates the image of the train from the background in each frame. The frames, with the unwanted background information removed, are then analyzed using a velocity estimation module that enables the patching of consecutive frames to produce a panoramic image of the entire train (Figure 2).

Figure 2: An example panoramic image of part of a train cut into multiple pieces for image display purposes

Detection of Edges and Load Identification

The loads on the train and their loading pattern are processed from the constructed panorama. The algorithm follows a decision tree path in which it first determines if a particular location has a gap or a train object. If the lack of a gap (train pixels in the panoramic image constructed) is determined due to train pixels being present in the area of the panoramic image, it then proceeds to find the top horizontal edge of the load and creates a simple vertical projection of color intensities and uses this projection to distinguish the difference between a trailer and a container. The height is then checked on the loads identified as containers to determine if they are double stacked. If so, the system finds the dividing line between the upper and lower containers and then their individual vertical boundaries in order to establish their individual sizes.

Gap Estimation and Measurement

The gap is measured by the homography that is initially calculated from the camera parameters and a training image. This allows the program to determine the distance in real world measurement units as long as the pixels that are being visualized are on the plain formed by the loads and/or side of the train that the camera images. Once the blue gap lines are determined in the images (Figure 3), the distance between two consecutive blue lines that do not have a load object between them gives the gap length in pixels. These units are then homographically converted into a measurement of gap length measured in feet as described above.

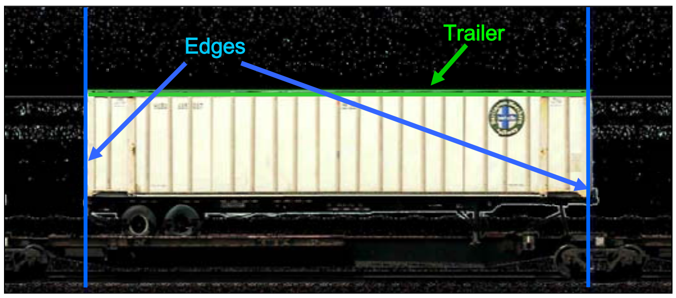


Figure 3: Detection of gap boundaries (marked in blue) and identification of the object between the gap edges (marked with a green boundary to indicate a trailer)

Loading Pattern Monitoring

After recording a train, the video is processed and histograms of upper and lower gaps are generated to represent the loading pattern of the train. This information is necessary but not sufficient to evaluate the efficiency of loading patterns. In order to make use of the data, a scoring system is used to compare the actual configuration to the ideal configuration.

Gap Histogram

For typical flat and spine cars, there is only one level of gaps because they cannot be double stacked; however, for well cars, there is a histogram for each level due to the two levels in each unit. An upper level gap is the gap between two upper level containers, which exists whenever there are at least two double stacked containers in the train. Similarly, a lower level gap is the gap between two lower level loads (Figure 4).

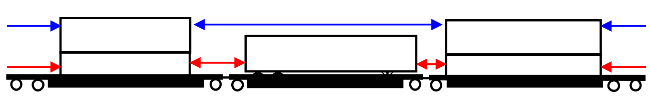
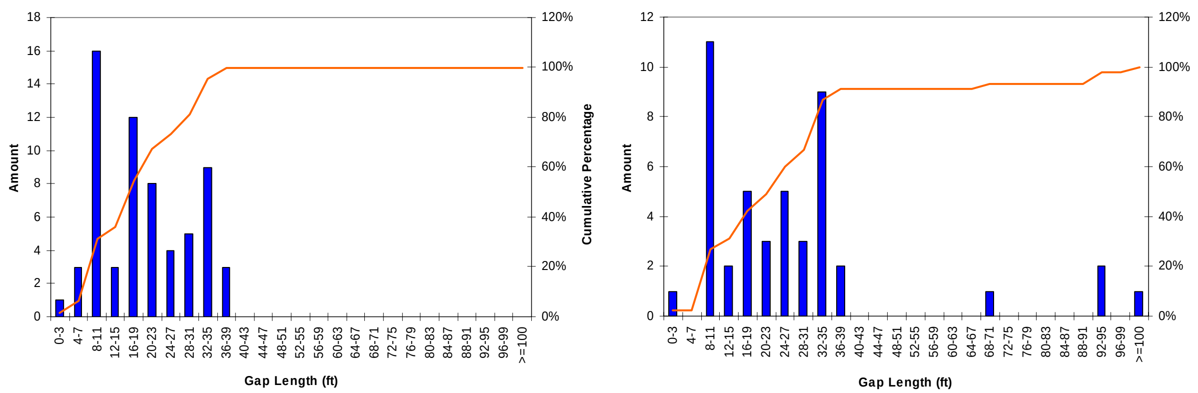


Figure 4: Illustration of upper level gaps (blue lines) and lower level gaps (red lines)

Figure 5a shows the distribution of upper level gaps, and Figure 5b shows lower level gaps. As can be seen, the loading pattern of this train is not very efficient since there are quite a few gaps over 12 ft and several very large gaps in the upper level. The slope of the cumulative percentage gives the user a rough idea of the gap lengths. The steeper the slope the better the efficiency, because it indicates a higher percentage of short gaps.

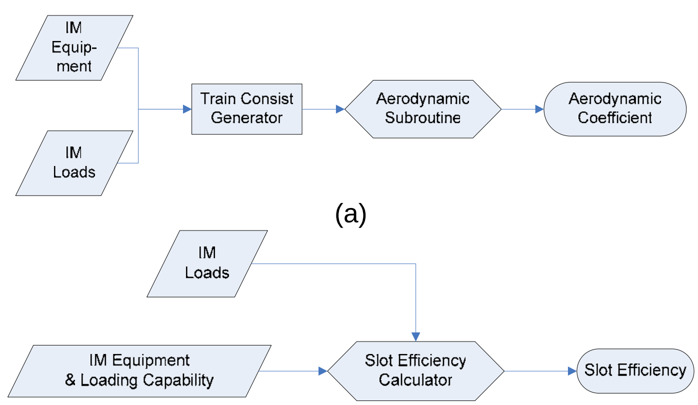


(a) (b)

Figure 5: The frequency diagram of the (a) lower level gaps and (b) upper level gaps in an example train

Scoring System

The gap histogram shows the distribution of gap lengths in a train regardless of railcar types. Since railcars differ in which IM loads are most efficiently loaded on them, the histogram alone is not sufficient to evaluate the maximum possible efficiency of loading patterns. Hence, a scoring system based on two attributes, the aerodynamic coefficient and slot efficiency, was developed. The aerodynamic coefficient is calculated using the Aerodynamic Subroutine of the Train Energy Model (Figure 6a). The intermodal load information is obtained from the machine-vision output, and railcar type from the Automatic Equipment Identification (AEI) tag [17]. The train consist generator can match the loads with cars and create a data input of train consists for the Aerodynamic Subroutine [11]. The aerodynamic coefficient is then computed for efficiency evaluation.



(b)

Figure 6: The process of generating (a) aerodynamic coefficient (b) slot efficiency in scoring system

The coefficient can be used to estimate fuel consumption; the lower the value, the greater the fuel efficiency. However, it cannot determine the loading efficiency of different types of trains. For example, trains with well cars generally have poorer aerodynamics than trains with spine cars because of the large gaps between the well-car units. Hence, when comparing different types of trains, a higher aerodynamic coefficient does not necessarily indicate a poor loading pattern.

The second attribute, slot efficiency, represents the difference between the actual and ideal loading configuration given the particular set of railcars in the train. The intermodal load information is again obtained from the machine-vision output, and railcar type from the Automatic Equipment Identification (AEI) tag. Every slot in each type of railcar has an ideal load that can be determined by using the loading capability of each railcar acquired from the Universal Machine Language Equipment Register (UMLER) manual [4]. With the data above as input, slot efficiency is computed using Equation 1, which is then averaged resulting in the final value for the train (Figure 6b).

The slot efficiency of each slot is calculated as follows:

$$\text{Slot Efficiency} = \frac{\text{Length of Actual Load}}{\text{Length of Ideal Load}} \times 100\% \qquad (1)$$

For example, a 53' trailer on a 53'-slot spine car unit generates the lowest aerodynamic resistance and has the highest score (100%) for this size slot. A 45-foot trailer on a 53'-slot spine car unit would receive a 75% score. Slot efficiency is similar to slot utilization except that it also factors in the energy efficiency of the load/slot combination.

The scoring system can provide terminal mangers feedback on loading performance for trains after they have been loaded. To further assist railroads in fuel savings, a load assignment model is needed to help terminal managers make the best decisions regarding how to load trains so as to maximize their energy efficiency [18].

Loading Assignment at Intermodal Terminals

At intermodal terminals, containers and trailers of a variety of lengths are assigned to available well, spine or flat cars by terminal managers [7,21]. In this study, we focus on intermodal services of the BNSF Railway between Chicago and Los Angeles (LA). Trains are mostly loaded or unloaded only at Chicago or LA, so there is little container shifting occurring enroute [6,14]. The intermodal cars used for these trains typically shuttle back and forth between terminals as a complete train with little reconfiguration of the individual cars in the trains.

Intermodal loads, i.e. trailers or containers, range in length from 20 to 57 ft. There is considerable variety in the design and capacity of intermodal railcars with different numbers of units and slots, and thus loading capabilities. An intermodal railcar can have one or more units permanently attached to one another (via articulation or drawbar). A unit is a frame supported by at least two trucks, providing support for one or more platforms (a.k.a. slots). For example, Figure 7a shows an articulated 3-unit well car, and Figure 7b is a 5-unit spine car. A platform (or slot) is a specific container/trailer loading location. As a result, each well-car unit has two slots because of their accommodation of two containers, one stacked on the other (a.k.a. “double stack”), and each spine-car unit has one slot (Figure 7).

(a)

(b)

Figure 7: (a) a 3-unit well car with 6 slots (b) a 5-unit spine car with 5 slots

There are also a number of loading rules developed for safety purposes and various feasible and infeasible combinations of IM load and car configuration. Because intermodal cars in a train are not generally switched in and out at terminals, managers primarily control the assignment of loads but not the configuration of the equipment in a train. Consequently, we treat the train make-up as given in this study. Terminal managers often use computer software [19] as decision making tools in complying with loading rules; nevertheless loading assignment is still a largely manual process and does not consider aerodynamic efficiency.

Optimization of Aerodynamic Efficiency

Aerodynamic drag is a major component of train resistance, particularly at high speeds [5,15]. The Association of American Railroads (AAR) supported research on wind tunnel testing of rail equipment, including large-scale intermodal car models [13]. The results were used to develop the Aerodynamic Subroutine of the Train Energy Model (TEM) [9]. These experiments showed that gap length between IM loads and position-in-train were the two important factors affecting train aerodynamics [10]. In our analysis, larger gaps result in a higher aerodynamic coefficient and greater resistance (Figure 8).

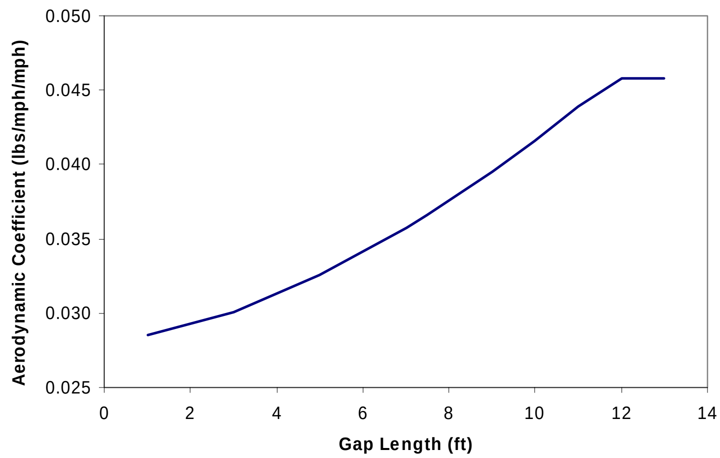


Figure 8: Critical gap length of well cars

The wind tunnel tests also showed that the front of the train experiences the greatest aerodynamic resistance due to headwind impact. The relationship between aerodynamic resistance and position-in-train effect is represented by equation 2 derived from the wind tunnel testing [10]:

$$C_D A(ft^2) = 14.85824e^{-0.29308k} + 9.86549e^{-0.00007k} + 10.66914 \quad (2)$$

where k is the unit position in the train and $C_D A$ is the drag area which represents the aerodynamic resistance in ft^2. The adjusted factor associated with each gap is computed by dividing the drag area of a given unit by the drag area of the 100^{th} unit (Table 1).

k	Drag area (ft^2)	Adjusted factor
1 (locomotive)	31.618	1.5449
2	28.801	1.4073
3	26.700	1.3046
4	25.133	1.2280
5	23.963	1.1709
6	23.091	1.1283
7	22.440	1.0964
8	21.954	1.0727
9	21.591	1.0550
10	21.320	1.0418
100	20.466	1.0000

Table 1: Adjusted factor of each gap in the train

The loading problem is formulated as a linear integer programming model in which the objective function is minimization of the adjusted gap length in the train [18]. Adjusted gap length accounts for both length and position-in-train effect, which is equal to the adjusted factor times gap length.

Minimize Total Adjusted Gap Length (3)

Subject to:

Loading Capability

Double Stack Constraints
Weight Constraints
Length Constraints

Minimizing total adjusted gap length creates the most efficient train configuration. However, not all loads can be assigned to all slots. The loading assignment must conform to the loading capability of each unit as well as length & weight constraints.

An Empirical Application

We used the model to analyze the optimal loading pattern for a typical intermodal train and loads. The example train is comprised of ten 5-unit 53'-slot spine cars and ten 5-unit 48'-slot spine cars with a total of 100 slots (Figure 7b). There are 180 loads available for this train: sixty 53' trailers, seventy 48' trailers, and fifty 40' trailers. The task is to assign 100 of the 180 loads to the 100 available slots so that the loading pattern of the train will have maximum fuel efficiency.

Certain restrictions apply to the loading pattern when assigning loads to slots [1,2,20]. For example, a 48'-slot spine car cannot handle containers or trailers greater than 48', while a 53'-slot spine car can handle containers or trailers of any length up to 53', although use of loads shorter than 53' reduces the aerodynamic efficiency. To ensure that the loading assignment follows the loading rules, possible loading combinations are specified for each car. In this example, we assume that none of the units are constrained by a weight limit and the optimization process is based solely on minimization of the total adjusted gap length.

CPLEX 9.0 incorporated with GAMS [8] was used to solve the model. The optimal solution suggested loading the first ten 53'-slot spine cars with fifty 53' trailers and assigning fifty 48' trailers to the following ten 48'-slot spine cars. The objective value, i.e., the total adjusted gap length, associated with this solution was 514 feet.

As discussed above, current terminal operations do not consider aerodynamic efficiency when loading IM trains. For the same train and loads, the least efficient loading pattern of a fully-loaded train would be to load the first ten 53'-slot spine cars with the fifty 48' trailers, and the following ten 48'-slot spine cars with fifty of the 40-foot trailers. The total adjusted gap length in this case would be 1,170 feet, which is 2.3 times higher than the optimally loaded train.

To quantify the fuel savings, we computed the aerodynamic coefficients and fuel consumption of the best and worst loaded trains using the Train Energy Model (TEM) and the Aerodynamic Subroutine [11]. The aerodynamic coefficient of the train with the best loading pattern found is 5.72 lbs/mph^2 whereas the coefficient for the worst loading pattern is 7.64 lbs/ mph^2, a 34% difference.

TEM was then used to compute the fuel consumption for each case using a representative rail line [9]. We chose a 103-mile segment that was typical of an intermodal route with gentle grades, curves, and rolling topography in the Midwest for this analysis. The train with the most efficient loading pattern would consume 763 gallons of fuel; whereas the fuel consumption of the train with the least efficient loading pattern would be 861 gallons. Thus, the estimated fuel savings in this example would be 0.95 gallons per mile (13 %). Extrapolating this over the entire length of the LA to Chicago route results in a potential fuel savings of over 1,500 gallons per train. Considering there are more than 50 trains per day on this route, the potential annual fuel savings are substantial.

Conclusion

The MV system detects the loading patterns and computes the loading efficiency of the train. Integration of this metric termed “slot efficiency” can provide intermodal terminal mangers feedback on loading performance for trains and can be integrated into the software support systems used for train loading.

An intermodal loading assignment model has been developed to help terminal managers load more fuel efficient IM trains. Depending on the particular train configuration, the potential fuel savings over the BNSF Chicago – LA line can be as high as 1,500 gal/train by applying the automatic loading assignment models. The complete model is intended to be incorporated into terminal operation software to help mangers improve their decisions regarding how to load trains so as to maximize their energy efficiency as well as minimize emissions.

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