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A COMPUTER VISION SYSTEM FOR MONITORING THE ENERGY EFFICIENCY OF INTERMODAL TRAINS

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ABSTRACT
Intermodal trains are typically the fastest trains operated by North American freight railroads. It is thus ironic that these trains tend to have the poorest aerodynamic characteristics. Because of constraints imposed by equipment design and diversity, there are often large gaps between intermodal loads and these trains incur greater aerodynamic penalties and increased fuel consumption compared to other trains.

We conducted train energy analyses of the most common intermodal train configurations operated in North America. It was found that matching intermodal loads with cars of appropriate length reduces the gap length thereby improving airflow. Properly matching cars with loads also avoids use of cars that are longer and thus heavier than necessary. For double stack containers on well cars, train resistance may be reduced by as much as 9% and fuel savings by 0.52 gallon per mile per train. Proper loading of intermodal trains is therefore important to improving energy efficiency.

We have developed a wayside machine vision system that automatically scans passing trains and assesses the aerodynamic efficiency of the loading pattern. Machine vision algorithms are used to analyze these images and detect and measure gaps between loads and develop a quantitative index of the loading efficiency of the train. Integration of this metric that we call "slot efficiency" can provide intermodal terminal mangers feedback on loading performance for trains and be integrated into the software support systems used for loading assignment.

1. INTRODUCTION
Intermodal (IM) freight recently surpassed coal as the leading source of freight revenue among US railroads [1]. This traffic – as measured by the number of trailers and containers on railcars – has grown by 77 percent from 6.2 million in 1990, to 11 million in 2004 [1,2]. Because of constraints imposed by equipment design and diversity, intermodal trains incur greater aerodynamic penalties and increased fuel consumption compared to their general freight counterparts. This is particularly ironic given that these trains are typically the fastest freight trains operated. Class I railroads spent more than $4.3 billion on fuel in 2004 making it their second largest operating expense [1]. As of 2004, fuel costs had increased by more than 88% since 1998, and this trend continues, making fuel efficiency more important than ever [3]. Intermodal train fuel efficiency is affected by the equipment and loading patterns so investigation of these effects and options to improve them is worthwhile [4].

1.1 Loading assignment at intermodal terminals
At intermodal terminals, containers or trailers are assigned to available well, spine or flat cars [5,6]. 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 may be a single unit, or have up to five units permanently attached to one another (via articulation or drawbar). A unit is a frame supported by two trucks, providing support for one or more platforms (a.k.a. slots). For example, Figure 1a is a 2-unit flat car, Figure 1b is a 5-unit spine car, and Figure 1c shows an articulated 3-unit well car specially designed to "double

stack" containers, thereby doubling their capacity without lengthening a train. The term "well" means a depressed center section providing a platform only inches above the rails enabling "double stack." A platform (or slot) is a specific container/trailer loading location. Most units have a single slot; however, well-car units have two slots because of their ability to hold two containers, one stacked on the other (Figure 1).

There are also a number of loading rules developed for safety purposes and various feasible and infeasible combinations of IM load and car configuration. Terminal managers often use computer software [7] tools to aid their decision-making in complying with loading rules; nevertheless loading assignment is still a largely manual process. The principal metric used to measure the efficiency of loading is "slot utilization" [8]. Although the details vary depending upon the particular combination of intermodal load and car being considered, slot utilization is basically a metric used to measure the percentage of the slots on intermodal cars that are used for loads. Slot utilization does not take into account the size of the space compared to the size of the load. Although perfect slot utilization indicates maximal use of the spaces available, it is not intended to, nor does it ensure, that intermodal cars are loaded to maximize the energy efficient operation of intermodal trains. Two trains may have identical slot utilization, but different loading patterns and consequent train resistances.

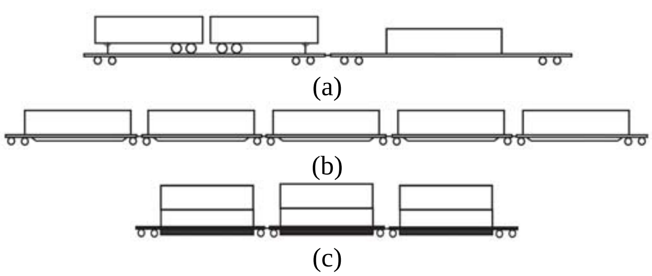


Figure 1. (a) a 2-unit flat car (b) a 5-unit spine car with 5 slots (c) a 3-unit well car with 6 slots

1.2 Wind tunnel testing and Train Energy Model (TEM)

During the 1980's, a number of studies focused on technologies to reduce train resistance and therefore reduce fuel costs [9,10]. Aerodynamic drag was known to be a major component of the total tractive resistance particularly at higher speeds [11], so the Association of American Railroads (AAR) supported research on wind tunnel testing of rail equipment, including large-scale intermodal car models [12,13]. The results were used to develop the Aerodynamic Subroutine of the AAR's Train Energy Model (TEM) [14].

From these wind tunnel tests, it was found that the lead locomotive experienced the highest drag and this decreased until about the 10th unit or car in the train, after which, drag remained roughly constant per unit for the remainder of the train. They also found that closely-spaced containers or trailers behave as one long load. Conversely, loads spaced greater than about 12 ft behave as distinct objects on whose surfaces boundary layers are reinitialized [15,16].

Improving the loading patterns of intermodal trains has the potential to improve railroad fuel efficiency and reduce emissions. Maximizing slot utilization will enhance energy efficiency, but matching intermodal loads with appropriate length intermodal car slots can further reduce gap length between loads, and thus improve airflow. Lai & Barkan [4] 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.

2. METHODOLOGY

We considered two approaches to maximizing intermodal train energy efficiency; slot utilization and equipment matching. The aerodynamic coefficient, train resistance and fuel consumption are computed for a series of different train scenarios using the Aerodynamic Subroutine [17] and TEM [14]. Train resistance is the sum of the forces opposing the movement of a train [18]. The greater the resistance, the more energy is required to move the train. Therefore, it is a major factor affecting fuel economy.

The resistance equation in this study can be represented as [14,19]:

$$R = R_{Bk} + R_{Rk} + CV^2 \quad (1)$$

Where:

R = Train resistance (lbs)
R_{Bk} = Bearing resistance acting on vehicle k (lbs)
R_{Rk} = Rolling resistance acting on vehicle k (lbs)
C = Aerodynamic coefficient (lbs/mph^2)
V = Train speed (mph)

The C term can be computed from the Aerodynamic Subroutine by specifying a train consist. Bearing and rolling resistance are related to train weight and are computed using the equations in TEM [14].

3. MATCHING INTERMODAL LOADS WITH CARS

The capacity of IM cars is usually constrained by the length of the slot. For example, a 5-unit articulated double stack well car with a 40-foot well cannot handle containers greater than 40 ft long in the bottom position, whereas a 5-unit car with a 48-foot well can handle containers up to 48 ft in length [5,6,20,21]. Consequently, cars with longer wells are more flexible; however, if loaded with containers less than the maximum they allow, then the gaps between loads are correspondingly larger, and less aerodynamically efficient. We conducted efficiency analyses to determine the potential differences in resistance for different train loading configurations.

Figure 2 shows the effect of gap length for double stack well cars. The larger the gap length, the higher the aerodynamic coefficient for gaps less than 12 ft. The aerodynamic coefficient does not increase for gap lengths greater than 12 ft because closely-spaced loads are seen as one continuous body and widely-spaced loads are seen as discrete bodies [15,16]. Consequently, we term 12 ft the critical gap length for intermodal load spacing on well cars.

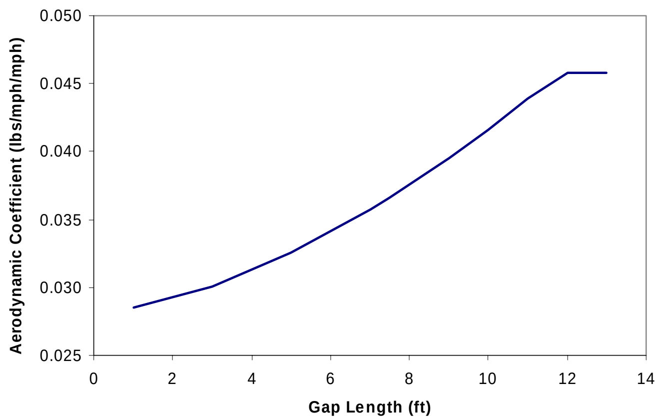


Figure 2. Critical gap length of well cars

3.1 Aerodynamic coefficient and train resistance

A train of 3 locomotives and 100 units (20 five-unit cars) was chosen as suitably representative for our analyses. A 40-foot container can be assigned to a car with 40-foot, 48-foot or 53-foot wells; however, only use of a car with 40-foot wells would result in the shortest gap and the best aerodynamics. In this example, the gap between two double stack 40-foot containers would increase by 8 ft if 48-foot-well cars were used or by 13 ft if 53-foot-well cars were used.

For a train of 20 cars with 40-foot double stack containers, the aerodynamic coefficient increases from 4.82 to 5.05 lbs/mph^2 when 48-foot or 53-foot-well cars are used instead of 40-foot (Figure 3). Using either 48-foot or 53-foot-well cars results in the same aerodynamic resistance because the gap lengths in both cases are greater than the critical gap length.

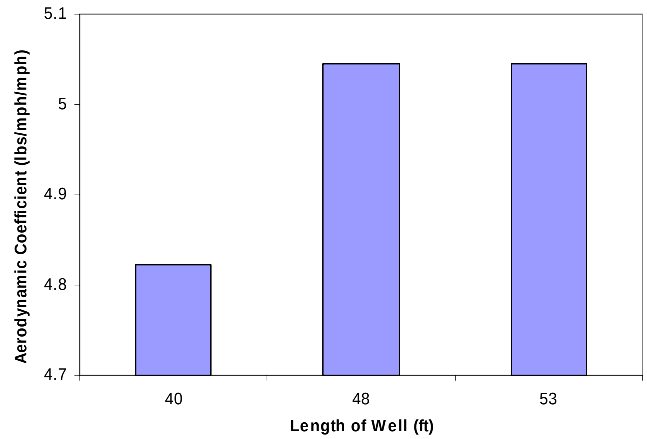


Figure 3. The aerodynamic coefficients of double-stack 40-foot containers on 40-foot-well, 48-foot-well, or 53-foot-well cars

The total train resistance is calculated for these three train configurations for speeds up to 70 mph. As expected the train with 40-foot-well cars had the lowest resistance at all speeds (Figure 4). The train with 48-foot-well cars had higher resistance mainly because of the aerodynamic penalty, but also due to the heavier weight of the longer car. The train with 53-foot-well cars suffered the same aerodynamic penalty as the 48-foot-well cars, but because of their greater length had a 34% higher weight penalty, resulting in correspondingly greater bearing resistance (TTX, 1999).

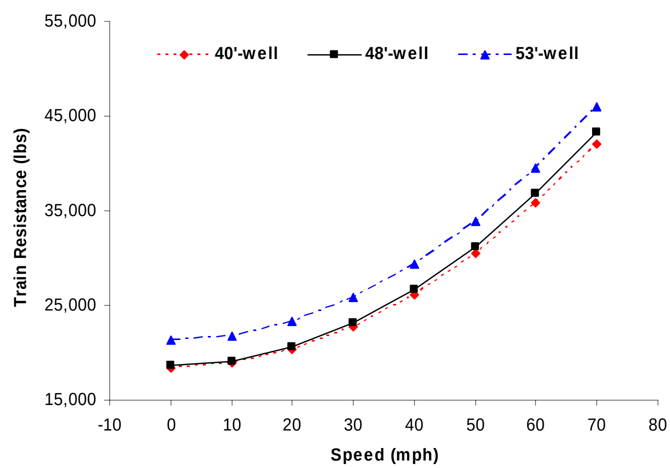


Figure 4. The train resistances of double-stack 40-foot containers on 40-foot-well, 48-foot-well, or 53-foot-well cars

3.2 Fuel consumption

In the analyses above, each data point represents the effect on train resistance at a specific speed; however, a train's speed will vary as it traverses a route. In addition to resistance, the power to ton ratio, route characteristics, and train schedule will all affect fuel consumption. Therefore, the distribution of speed profiles and throttle setting is needed to estimate how much energy can be saved. TEM was used to compute and compare the fuel consumption for each case using a representative rail line.

A typical intermodal route in the midwestern United States was chosen for this analysis. It is 103-miles in length with gently rolling topography, grades generally under 0.6% and curves less than 3 degrees. It has a high density of intermodal trains with as many as 50 per day.

Figure 5 shows the fuel consumption of the three different train configurations. Compared to 40-foot double stack containers on cars with 40-foot wells, placing the containers on 48-foot-well cars would consume an additional 13 gallons of fuel per train on this route mainly due to the aerodynamic effect. Furthermore, the weight penalties of a train with the same loads on 53-foot-well cars would require an extra 40 gallons of fuel per train. The estimated fuel savings in these two examples ranged from 0.13 gal/mile to 0.52 gal/mile, respectively. Extrapolating this over the entire length of the LA to Chicago route results in a potential fuel savings of over one thousand gallons per train.

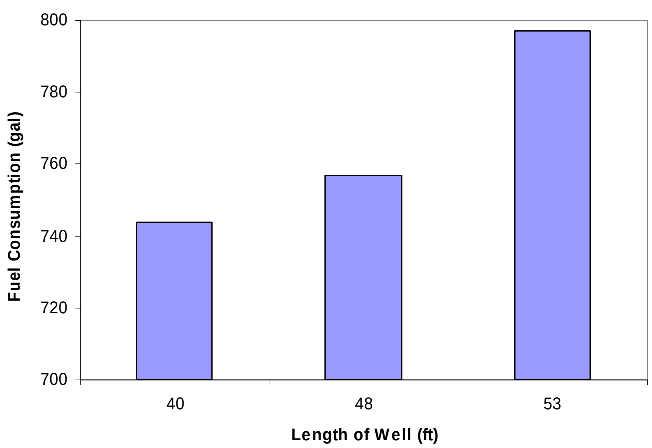


Figure 5. The fuel consumption of double-stack 40-foot containers on 40-foot-well, 48-foot-well, or 53-foot-well cars

3.3 Slot utilization vs. equipment matching

Maximizing slot utilization has a positive effect on train energy efficiency because it eliminates empty slots and the consequent large gaps that would otherwise occur. However, as should be evident from the prior example in which all the trains considered had 100% slot utilization there is still the potential for substantial improvement in efficiency depending on the specific load-and-car combinations that are used. Simply maximizing slot utilization does not ensure that the lowest aerodynamic resistance is achieved, whereas proper matching of intermodal loads with cars can. Consequently, matching is a better metric for energy efficiency than slot utilization.

For example, for a train of 20 48-foot-well cars loaded with 40-foot containers, the aerodynamic coefficient decreases by 23% if slot utilization is improved from 90% to 100% (Figure 6). However, if the 48-foot-well cars are replaced with 40-foot-well cars, the aerodynamic coefficient is reduced by another 5%. Note that in both cases, slot utilization is 100%.

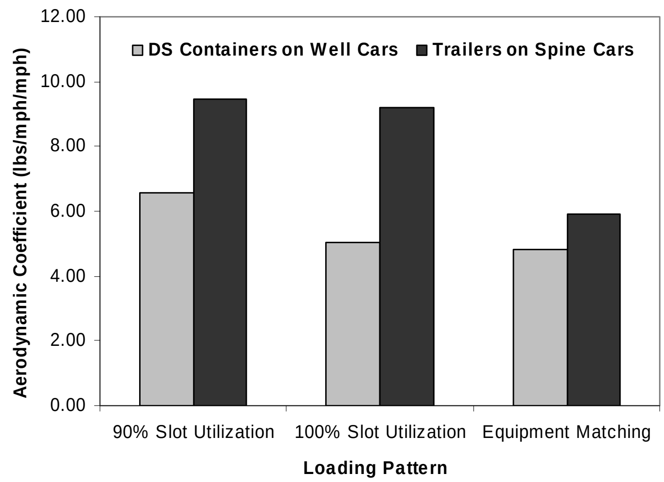


Figure 6. The aerodynamic coefficient of 90% slot utilization, 100% slot utilization or equipment matching for double stack containers on well cars and trailers on spine cars

Similarly, the aerodynamic coefficient decreases by 3% if slot utilization is increased from 90% to 100% for a train of 20 53-foot-slot spine cars with 48-foot trailers (Figure 6). Replacing 53-foot-slot spine cars with 48-foot-slot spine cars reduces the aerodynamic coefficient by another 36%.

Accordingly, a train can be more efficiently operated if loads are assigned not only based on slot utilization but also better matching of intermodal loads with cars which has been termed "slot efficiency" [4]. This effect will be especially pronounced for the units in the front of the train where the aerodynamic effect is greater.

4. WAYSIDE MACHINE VISION (MV) SYSTEM

The substantial energy savings that may be accrued due to improved loading patterns suggested a potential benefit of a system to monitor intermodal train loading. Consequently the BNSF Railway supported development of an automated, wayside, machine-vision (MV) system to record and analyze the loading patterns of intermodal trains. The system allows unattended monitoring of intermodal loads to determine their loading efficiency from the analysis of each load type, its placement on the railcar, and its location in the train. This system provides feedback on specific trains originating from particular terminals to help managers create more efficiently loaded trains. Also, it enables BNSF personnel to assess trains not loaded by their own company, i.e. interchange trains.

A digital video is recorded of trains passing by a wayside camera and computer installation. MV algorithms detect the IM loads on each individual are in the train and identify their type, size and position. From these data, loading efficiency is determined based on the gaps present compared to ideal loading configurations for the particular type of railcars in the train.

4.1 Image acquisition system

The image acquisition system acquires videos of passing trains. The portable version is made up of the video camera and lens, laptop computer, and imaging software.

A Sony DFW-V500 digital video camera with a 1/2" color CCD sensor captures video in non-compressed YUV format and transfers it to a computer via a FireWire 1394 serial bus at 30 frames per second, saving it in AVI format. A Tamron lens with low aspheric distortion, a variable focal length of 6-12mm, and an f-stop of 1.0 for low lighting conditions is used. The camera is rotated 90 degrees to provide a larger vertical field of view for capturing the height of loaded double stack car.

A portable machine vision system was developed and used at two locations on the Chillicothe Subdivision of BNSF Railway's Chicago Division; near Coal City, Illinois (MP 54.7), and just outside of Streator, Illinois (MP 77). This is the BNSF's principal route for transcontinental intermodal traffic and sees upward of 50 IM trains per day. It was thus a good location to obtain a large amount of data on a wide variety of trains. Principal testing of the system was at the Coal City location because the double track main line is spaced far enough apart to allow video recording of trains on either track from a location between the two. This eliminates the possibility of having another train move behind the subject train, which would confound the current MV algorithms for identifying intermodal loads. A substantial library of videos including a wide range of intermodal car and load combinations was collected and used to develop and test the MV algorithms.

A preliminary field demonstration of the system was conducted at the Coal City location in September 2004. Videos of a passing intermodal trains were captured and immediately following the passage of the train, the MV algorithms were run on the laptop computer creating a panoramic image of the train with intermodal loads identified, edges marked, and a histogram of the gap lengths between the loads created from this data.

A permanent, automated wayside version of this system has since 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 7 & 8). 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.

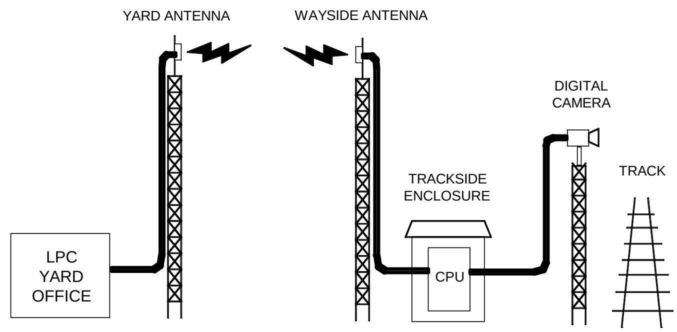


Figure 7. Automated, wayside image acquisition system as installed at BNSF Railway's Logistics Park (LPC)

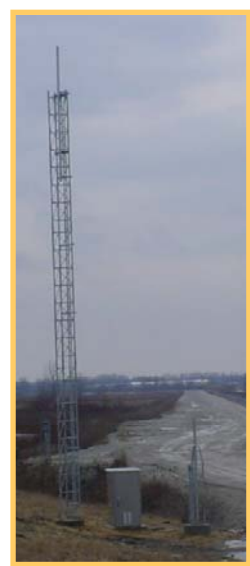


Figure 8. Side view of Logistics Park – Chicago image acquisition system installation

4.2 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. Line detection algorithms, along with the prior information regarding the loading patterns, are used in the next stage to make intelligent inferences concerning the location of the containers and the gaps between them. Certain distinguishing characteristic patterns of trailers and containers are used to determine the location and type of loads. Information regarding the identification, location and spacing of IM loads, is then analyzed and histogram of gap lengths and several diagnostic statistics are generated using separate software modules.

4.2.1 Separating the train from the background

In order to more easily process the train video using machine vision algorithms, the background area is removed from the video frames leaving primarily the train in the image. The initial algorithm functioned if the background was fairly stable during the time it took for a train to pass by. However, changes in the background, such as movement of clouds or wind-induced motion of trees, sometimes caused problems in the images that confounded later stages of the algorithm. Consequently, a more complex method using a probabilistic learning algorithm was developed (Figure 9). This method uses the initial part of the video, before the train appears, to model the variation in the background pixels. The recursive equations are also used to constantly update these parameters as the video is analyzed. Mean values are computed for each background pixel and the standard deviation of the median values is used to represent the changing background model. Pixels from each successive frame are then compared to the standard deviations to determine if they are a train pixel or a background pixel. The pixels designated as belonging to the train are then added to the new image as seen in the lower right of Figure 9. The current method aids in eliminating objects that move due to changes in the background or due to vibration created by the passing train, thus increasing the accuracy of the load edge detection in Section 4.2.4.

4.2.2 Continual estimation of train velocity

The velocity is calculated between consecutive images in the video (Figure 10). It is computed by finding the best correlation shifts for all three-color signals in the adjacent foreground extracted (train pixels only) frames. These color signals are the integral of all the color energy found in a prescribed vertical column of each frame. The correlations can be used to calculate the sum of squared error at various pixel shifts and the lowest error value gives the pixel shift that best estimates the velocity of the train. The central pieces of the frames with the background removed, are then pieced together (Figure 11). The middle section of every frame in the video contributes to the construction of the panorama. The panorama is constructed, a section at a time, using each frame’s central section. It is concatenated to the existing panorama based on its pixel velocity relative to the previous frame. This method differs from normal panoramic image generation, which are constructed by piecing together images taken while moving the camera location. Our approach utilizes the movement of the train and the consecutive video frames to create panorama of the entire train with a single camera position (Figure 12).

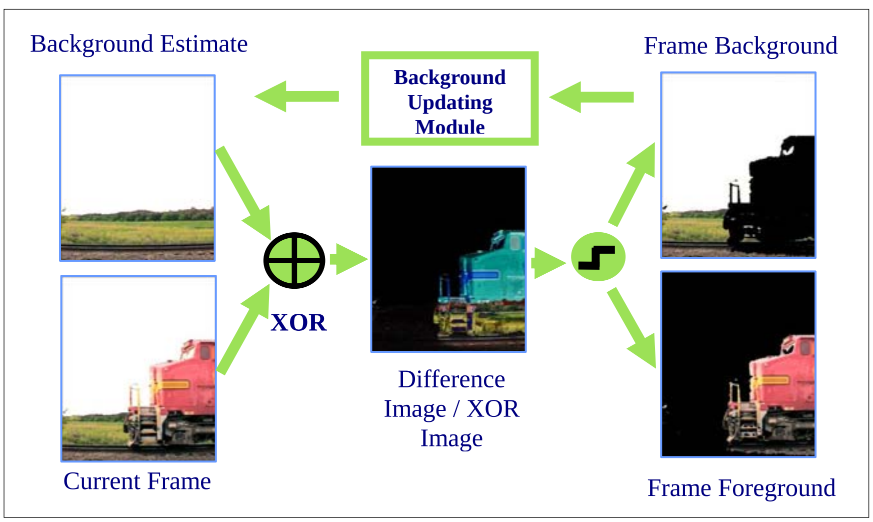


Figure 9. The background subtraction module extracts the train and separates it from the background

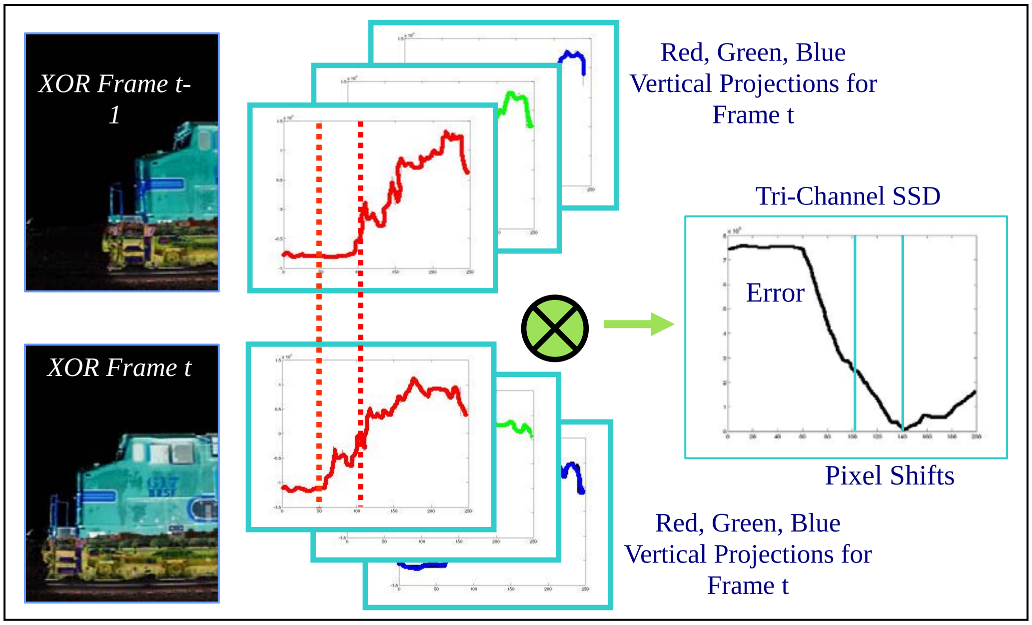


Figure 10. Velocity estimation

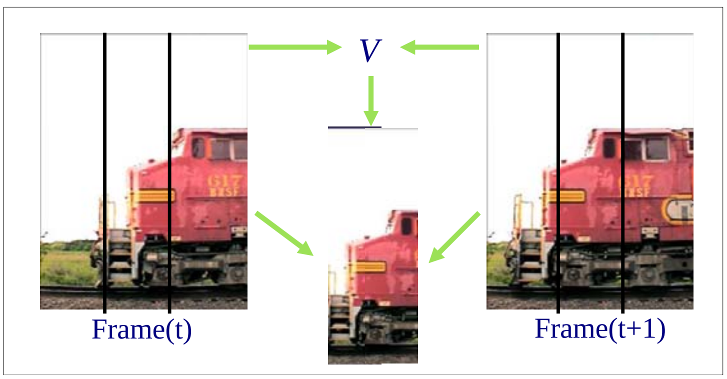


Figure 11. Assembling consecutive frame center sections to form the panorama-like image

Figure 12. Example panoramic image of part of a train cut into multiple pieces for image display purposes

4.2.3 Detection of edges and load identification

The loads on the train and their loading pattern are then 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 to be a container to determine if it is 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.

4.2.4 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 13), 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 13. 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)

4.3 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.

4.3.1 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 14).

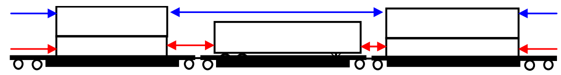
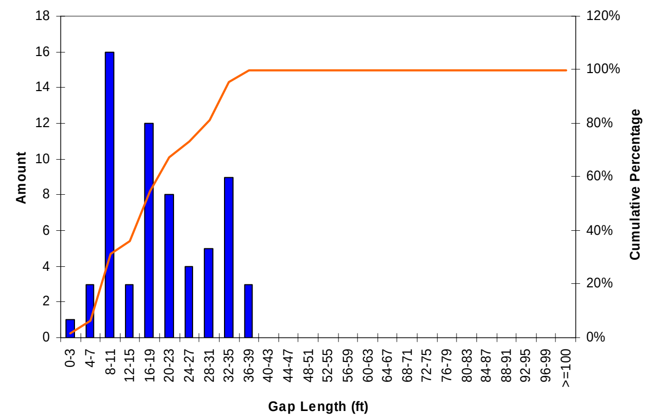
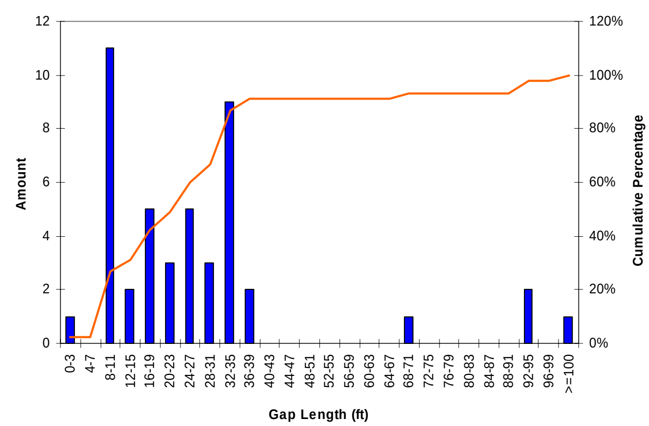


Figure 14. Illustration of upper level gaps (blue lines) and lower level gaps (red lines)

Figure 15a is for the upper level gaps, and the Figure 15b is for the lower level gaps. As can be seen, the loading pattern of this train is not very efficient since there are quiet 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 means more gaps are short.



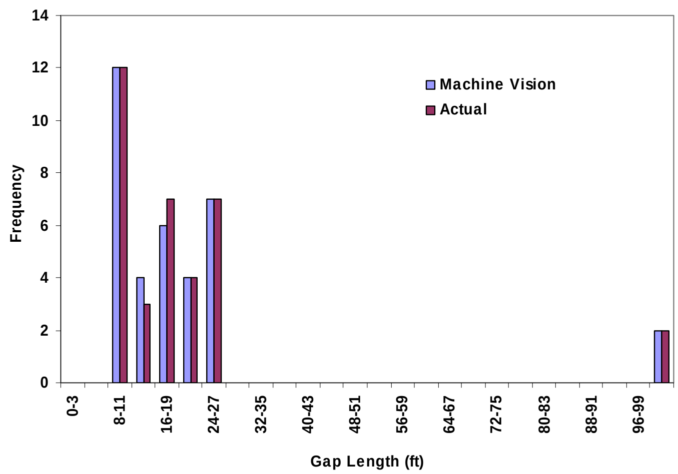
(a)



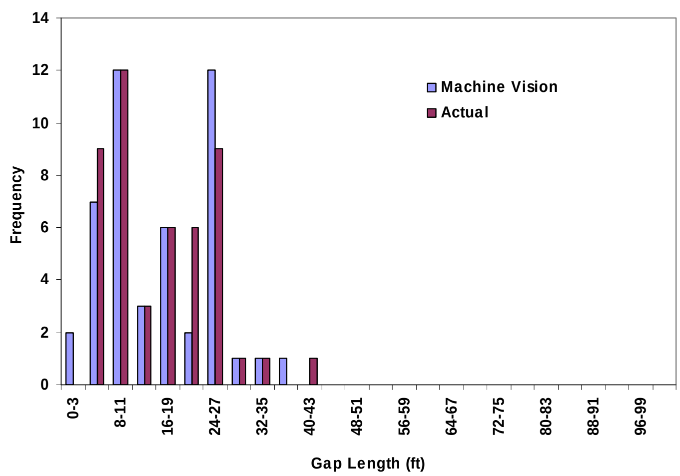
(b)

Figure 15. The frequency diagram of the (a) lower level gaps and (b) upper level gaps in an example train

To evaluate the accuracy of the MV system, we manually determined the actual length and distribution of gaps and then compared this to what the MV algorithms calculated (Figure 16).



(a)



(b)

Figure 16. The frequency diagram of actual train data vs. MV data of the (a) upper level gaps and (b) lower level gaps in an example train

An index, gap accuracy, is used to evaluate the accuracy of the MV output compared to the actual data. It is defined as follows:

$$Gap\ Accuracy = (1 - \frac{L_{MV} - L}{L}) \times 100\% \qquad (2)$$

Where:

L_{MV} = Total gap length from MV output

L = Total gap length of actual train data

In the example above, the total length of the lower level gaps from the MV output was 756 (ft), whereas the actual data was 752 (ft), for a gap accuracy of 99 %. The gap accuracy for the upper level gaps in this train was also 99 %.

5. DISCUSSION

The current practice of measuring intermodal loading efficiency using the metric, slot utilization, has a beneficial effect on train energy efficiency. For example, improving slot utilization on some typical intermodal trains from 90% to 100% reduced the aerodynamic coefficient by 3% to 23% depending on train type [20].

Matching intermodal loads with cars of an appropriate length to maximize slot efficiency results in improvement in bearing, rolling and aerodynamic resistances. This can provide greater energy efficiency than slot utilization alone. If the loads and cars are matched, the aerodynamic benefit ranged from 5% to 36%. Over the 103-mile long route considered, the benefit in the example of well cars decreased estimated fuel consumption by 0.13 to 0.52 gal/mile depending on the load-and-car combinations analyzed. When these amounts are extrapolated to the 800 to 2,000 mile distances typical of many intermodal trains, the potential for fuel savings can be substantial. Consequently, intermodal trains can be more efficiently operated if loads are assigned not only based on slot utilization, but also better matching of intermodal loads with cars.

The MV system uses an advanced camera that images each container or trailer as trains pass by. MV algorithms are used to analyze these images so as to detect gaps between loads and develop a quantitative index of the loading efficiency of the train.

Combined with the car information from AEI, an index is developed based on the aerodynamic effects of intermodal load-and-car combination to evaluate slot efficiency. At the macro level, the data collection and analysis system could be deployed to monitor system-wide intermodal train loading efficiency. At the micro level, it can provide feedback on specific trains originating from particular terminals to help managers create more efficiently loaded trains. For example, detection of an empty slot where there was space to place a 28' trailer on a spine car (Figure 17).

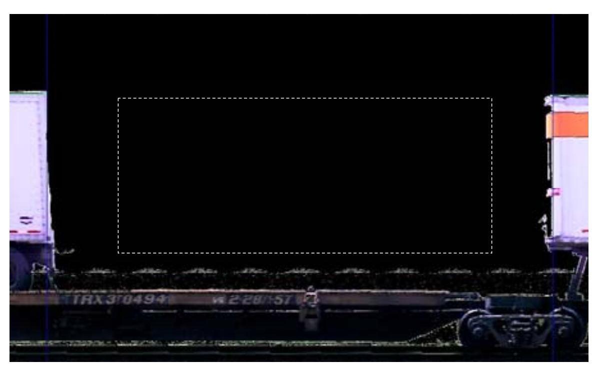


Figure 17. A detected empty slot in a spine car

6. CONCLUSION

Two approaches for improving intermodal train energy efficiency, slot utilization and slot efficiency, were evaluated. Slot efficiency in which intermodal loads are matched with cars of an appropriate length reduces the gap length between loads, thereby improving airflow and also avoids the weight penalty of using cars that are larger than necessary for the load. Compared to slot utilization, maximizing slot efficiency offers additional potential to reduce fuel consumption and intermodal train operating costs because of improved aerodynamics and in some cases lower weight.

The MV system detects the loading patterns and computes the loading efficiency of the train. Integration of this metric that we call "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.

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