Machine Vision Analysis of the Energy Efficiency of Intermodal Trains

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Summary: 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 are developing an automated, wayside, machine-vision system that will enable railroads to monitor the loading efficiency of intermodal trains. The system uses an advanced camera that images each container or trailer as trains pass by. 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 assignments.

Index Terms: energy efficiency, aerodynamics, fuel use, intermodal, machine vision, image analysis algorithms.

1. INTRODUCTION

Intermodal freight is the second largest source of U.S. railroad revenue and the fastest growing segment of freight traffic [1]. This traffic has grown more than three-fold from 3 million trailers and containers in 1980, to 10 million in 2004 [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 over $3 billion on fuel in 2003 making it their second largest operating expense [3]. Furthermore, fuel cost has increased by more than 60% since 1998 making fuel efficiency more important than ever [4]. Intermodal train fuel efficiency is affected by the equipment and loading patterns so investigation of these effects and options to improve them is worthwhile.

At intermodal terminals, containers or trailers are assigned to available well, spine or flat cars [5,6]. Although computer software [7] is often used by terminal managers to assist in this task, it 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 spaces (a.k.a. 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 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.

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, so the Association of American Railroads (AAR) supported research on wind tunnel testing of rail equipment, including large-scale intermodal car models [11,12]. The results were used to develop the Aerodynamic Subroutine of the AAR's Train Energy Model (TEM) [13].

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 equal to or greater than 12' behave as distinct objects on whose surfaces boundary layers are reinitialized [14,15].

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. We 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 [16].

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 [13]. 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 [13,19]:

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

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/mph)
V = Train speed (mph)

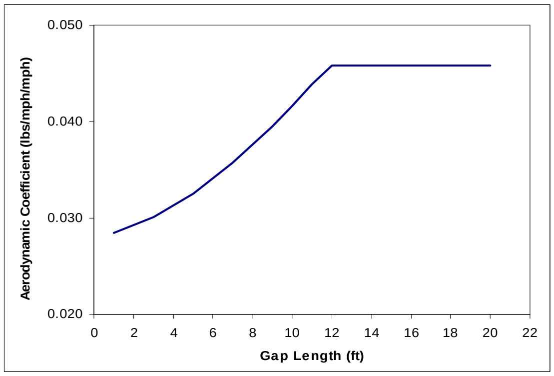
The C term can be computed from the Aerodynamic Subroutine by specifying a train consist. Bearing and rolling resistance are related to train weight and are computed using the equations in TEM [13].

3. MATCHING INTERMODAL LOADS WITH CARS

The capacity of well cars is usually constrained by the length of the well. 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 1 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 [14]. Consequently, we term 12 ft the critical gap length for intermodal load spacing on the well cars.

Figure 1: Critical gap length of well cars

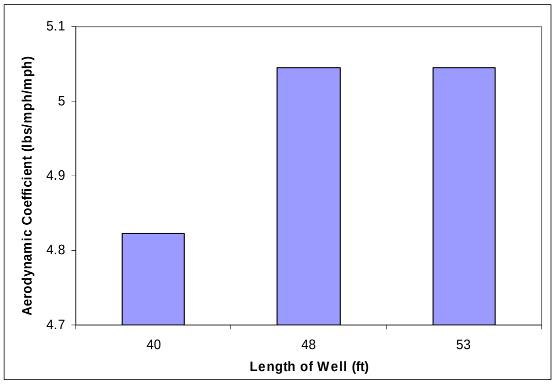


3.1 Aerodynamic Coefficient and Train Resistance

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.

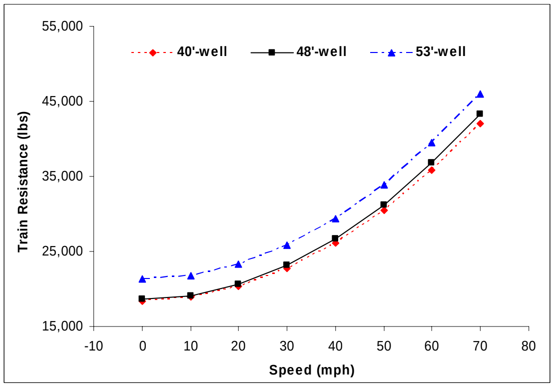
For a train of 20 cars with 40-foot double stack containers, the aerodynamic coefficient increases from 4.82 to 5.05 lbs/mph/mph when 48-foot or 53-foot-well cars are used instead of 40-foot (Figure 2). Using either 48-foot or 53-foot-well cars results in the same aerodynamic resistance because the gap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

Figure 2: 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 3). 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 [20].

Figure 3: The train resistances of double-stack 40-foot containers on 40-foot-well, 48-foot-well, or 53-foot-well cars



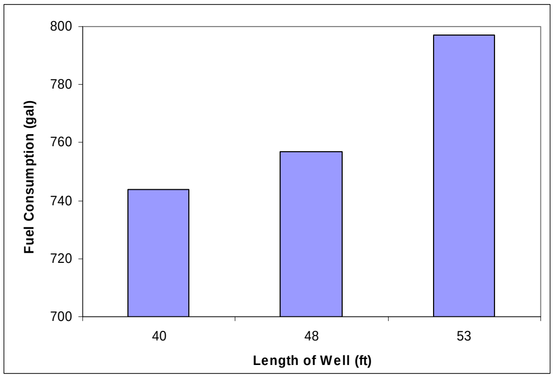
3.2 Fuel Consumption

In the analyses above, each data point represents the effect on train resistance at a specific speed; however, a train's speed will actually 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 Midwest 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.

Figure 4 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 examples ranged from 0.13 gal/mile to 0.52 gal/mile.

Figure 4: The fuel consumption of double-stack 40-foot containers on 40-foot-well, 48-foot-well, or 53-foot-well cars

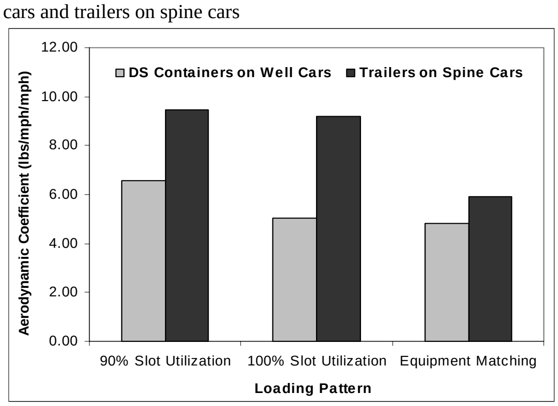


3.3 Slot Utilization vs. Equipment Matching

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 5). 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 5: 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 5). 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” [16]. 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 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 will allow 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.

The data from the train is 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 ideal loading configurations for the particular railcars in the train.

4.1 Image Acquisition System

The image acquisition system acquires videos of passing trains. It 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 into an AVI file 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.

Using the camera’s FireWire interface, the images are sent to a laptop computer that controls image acquisition and video storage. A Dell Inspiron is being used that features a 3 GHz processor, FireWire port, 60 GB, 7200 rpm hard drive, and 1 GB of RAM.

This setup has been used as a test bed for development of the machine vision system. Videos have been collected for testing and debugging on the Chillicothe Subdivision of BNSF’s Chicago Division, near Coal City (MP 54.7), and just outside of Streator (MP 77), Illinois. Principal testing of the system has been at the Coal City location because the double track main line is spaced far enough apart to allow videotaping of trains on either track from in between the two. This eliminates the possibility of another train behind the subject train, which would confound the current MV algorithms for identifying intermodal loads. A library of videos including a wide range of intermodal car and load combinations has been collected and is being 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.

4.2 Machine Vision Algorithms

The software component deals with the processing of the video generated from the Image Capture System. There are multiple steps to intelligently detect and extract relevant information from the visual data. The first section of the software segments the image of the train from the background in each frame. The frames, with the unwanted background information removed, are then subjected to a velocity estimation module that enables the patching of consecutive frames to produce a panoramic-like image of the entire train. Line detection algorithms, along with the prior information regarding the loading patterns, is then 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. The significant information provided by the system can then be analyzed and visualized by constructing a gap histogram using separate software modules.

4.2.1 Separating the Train from the Background

Figure 6 depicts the background subtraction procedure of segmenting only the train pixels from a given frame. The core of the process is based on a reference background frame that estimates what the background looked like when the frame (with the train) was captured. A difference image between the estimated background frame and the current frame gives rise to an image where higher intensities mean a higher probability of being a train. A simple thresholding filter is then used to determine the pixels that form the foreground train object. The changes that appear in the background pixels (from moving objects in the background, such as clouds) with respect to the current background estimate are fed back to the system to update the background estimate frame.

The velocity is calculated between consecutive images in the video (Figure 7). It is computed by finding the best correlation shifts for all the three-color signals in the adjacent foreground extracted (train pixels only) frames. These color signals are simply the integral of all the color energy found in that column of the frame at that time. 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 are then pieced together (Figure 8). 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 is unlike 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 this panorama of the entire train with a single camera position (Figure 9).

Figure 6: The background subtraction module extracts the train and separates it from the background

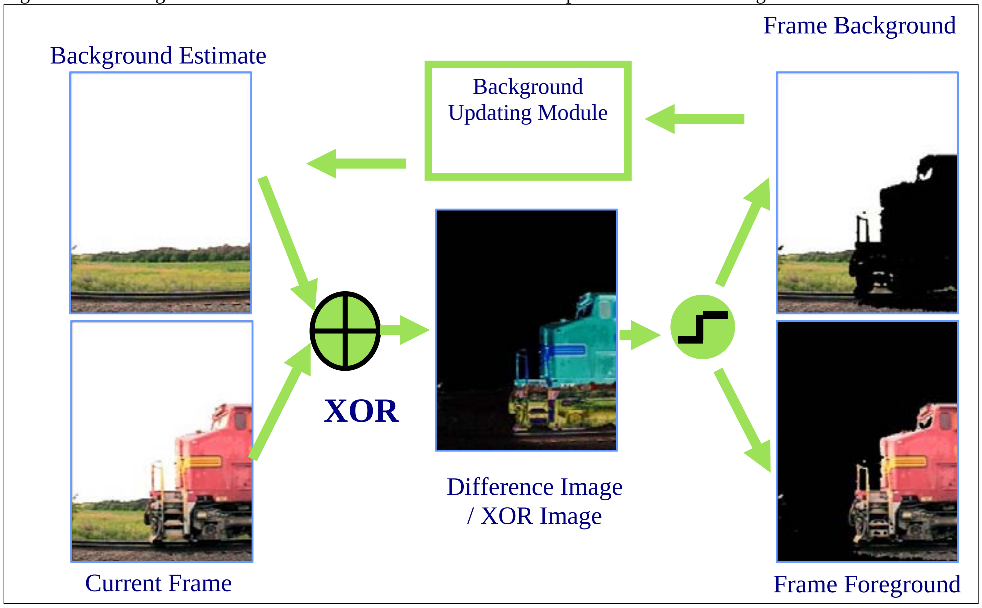


Figure 7: Velocity Estimation

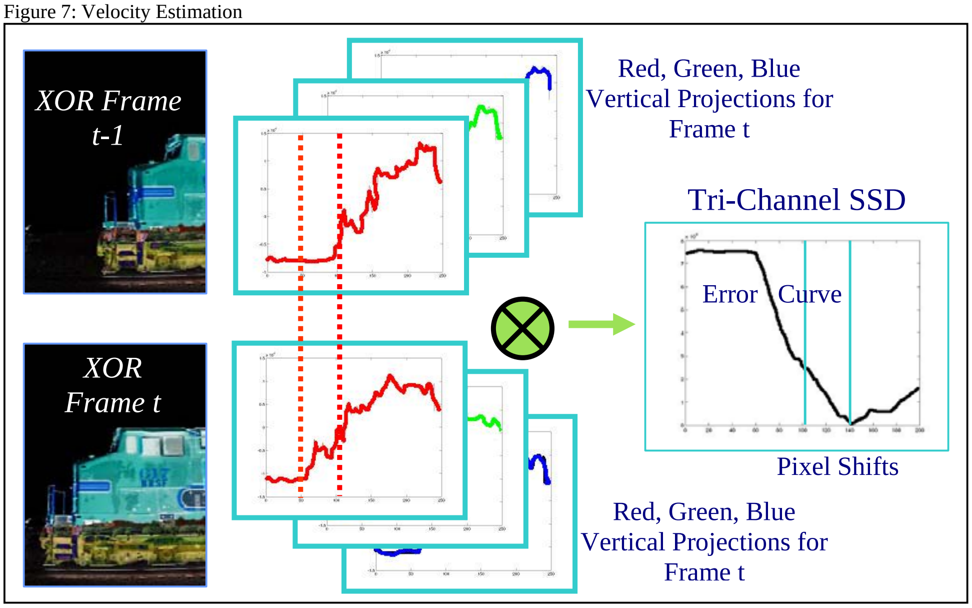


Figure 8: Assembling consecutive frame center sections to form the panorama-like image

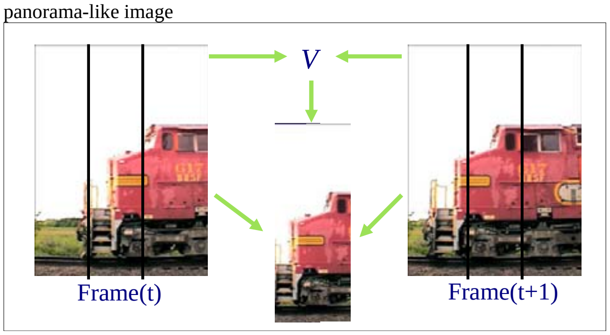


Figure 9: Example panoramic image of part of a train cut into multiple pieces for displaying image

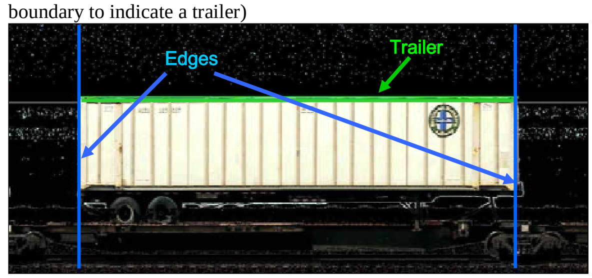
4.2.2 Detection of Edges and Load Identification

The loads on the train and their loading pattern are then processed from the constructed panorama. The algorithm follows a decision tree path where it first determines if a particular location has a gap or an object. If the lack of a gap (train pixels in the panoramic image constructed) is determined, 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 between a trailer and a container.

4.2.3 Gap Estimation and Measurement

The gap is measured by the homography that is initially calculated from the camera and one training image. This will in effect allow the program to determine the distance in real world measuring units as long as the pixels that are being visualized are on the plain formed by the containers/train face that the camera images. Once the blue gap lines are determined in the images (Figure 10), the distance between two consecutive blue lines which do not have an object between them gives the pixel gap length. It is then transformed into real world gap length by using the homography described above.

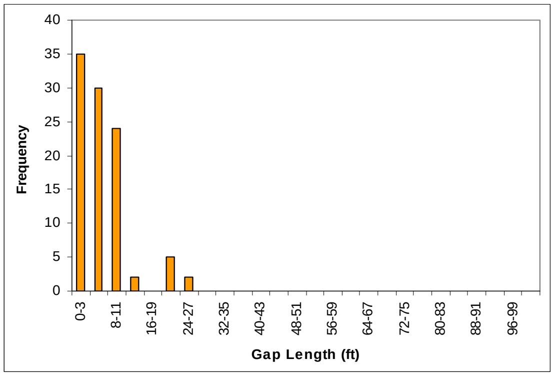
Figure 10: A successful detection of gap boundaries (marked in blue) and identification of the object between the gap edges (marked with green boundary to indicate a trailer)



4.3 Load Monitoring

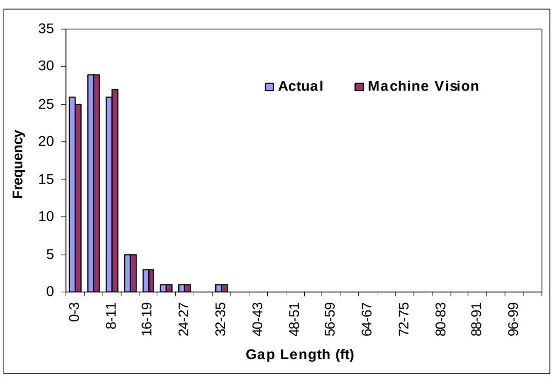
After capturing a train, the video is processed and a histogram is generated to represent the loading pattern of the train (Figure 11). In this example, all the gaps are less than 30 ft and most of them are less than 11 ft indicating an efficiently loaded train.

Figure 11: The frequency diagram of gap lengths in an example train



Currently, the identification program tends to have better performance on trailers than double stack containers. 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 12).

Figure 12: The frequency diagram of gap lengths from actual train data vs. MV data



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

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

Where:

L_{MV} = Total gap length from MV Output

L = Total gap length of actual train data

For example, if the total gap length from the MV output is 750 (ft) and that from the actual data is 720 (ft), the gap accuracy is 96 %. In the example of the train loaded with trailers (Figure 12), the gap accuracy is 99 %.

5. DISCUSSION

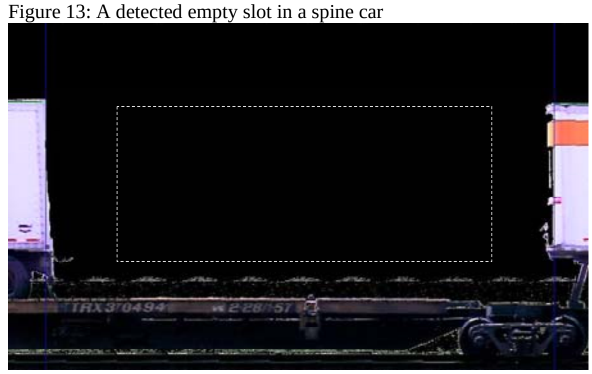
The current practice of measuring loading efficiency using the metric, slot utilization, has a beneficial effect on train energy efficiency. For example, improving slot utilization on some typical intermodal trains from 90% to 100% reduced the aerodynamic coefficient by 3% to 23% depending on train type [16].

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 are significant. 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, a score index is developed based upon the aerodynamic effects of intermodal load-and-car combination to evaluate the 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 13).

Figure 13: 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 be integrated into the software support systems used for train loading.

7. ACKNOWLEDGEMENTS

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