Monitoring the Aerodynamic Efficiency of Intermodal Train Loading Using Machine Vision

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ABSTRACT

Intermodal freight generates one of the highest sources of revenue among all traffic types transported by North American railroads. Intermodal trains, however, use equipment that is not aerodynamically efficient compared to other types of rolling stock, and typically operate at higher speeds, creating significant aerodynamic drag. This high resistance associated with the movement of intermodal trains results in significant annual operating expenses in the form of fuel expenditures. However, opportunities exist to reduce the aerodynamic drag through improved equipment design and loading practices. The University of Illinois at Urbana-Champaign is developing a machine vision system to evaluate intermodal train energy efficiency based on container and trailer loading arrangement, the gap lengths between them, and the type of rolling stock used. A prototype machine vision system has been installed at BNSF Railway's Logistics Park Chicago facility to demonstrate the feasibility of the system. This machine vision system consists of a camera, computer, and machine vision algorithms. The algorithms separate the train from the background and detect the edges of the containers and trailers to identify and measure the specific intermodal loads. After the edges and loads are identified, the gaps between loads are located and measured. The system's outputs are the loading configurations and measurements, gap length histograms, and aerodynamic scores based on loading configurations and gap lengths. BNSF and UIUC are currently installing an intermodal efficiency measurement system at a location on BNSF's principal intermodal corridor from Chicago to Los Angeles, the Transcon.

INTRODUCTION

Intermodal freight transportation generates one of the highest sources of revenue for North American railroads. In 2003, intermodal freight traffic surpassed coal as the number one source of revenue for North American freight railroads. The subsequent recession caused a decrease in intermodal traffic volumes and coal once again became the leading revenue generator. As the economy recovers, intermodal traffic volumes are slowly increasing to their earlier levels, and this trend is expected to continue for the foreseeable future. In May of 2010, North America intermodal traffic volumes were at 1,057,262 trailers and containers originated, which is up 19.2% from May of 2009 (*1*).

Despite the fact that intermodal trains account for a large percentage of revenue for freight railroads, they are generally the least efficient train type in terms of energy consumption. Improving the energy efficiency of intermodal trains can provide reductions in annual operating costs due to fuel consumption. Fuel expenditures represent one of the largest components of Class I annual operating expenses. In 2007, Class I railroads spent $12.2 billion on fuel, representing 25.8% of their total operating cost (*2*). In comparison to highway freight transportation, intermodal trains capitalize on several efficiencies inherent to railway transportation. These efficiencies include the use of a low-friction steel-on-steel interface, closely coupled vehicles (i.e. railcars), and rolling stock capable of transporting multiple trailers or containers.

Currently, most railway intermodal loading methodologies encourage terminal managers to load trains in a manner that maximizes intermodal equipment utilization. Alternatively, adopting a loading protocol that matches containers and trailers to their appropriate rolling stock capacity (e.g. slot length) to minimize gaps between loads will reduce the aerodynamic resistance for intermodal trains. To evaluate the feasibility of improving intermodal train loading operations, the BNSF Railway is funding research at the University of Illinois at Urbana-Champaign (UIUC) with the objective of developing a machine vision system to analyze gaps between intermodal loads and monitor and evaluate the energy efficiency of intermodal freight trains.

INTERMODAL TRAIN AERODYNAMICS AND ENERGY EFFICIENCY

North American intermodal rolling stock consists of flat cars, spine cars, and well cars (Figure 1). These cars have a variety of designs and loading capabilities, which result in varying gap lengths between loads on adjacent railcars or platforms/wells. If gaps between loads exceed 6 feet (1.8 meters) in length, the loads are aerodynamically separate and the aerodynamic drag increases significantly due to the change in the boundary layer (*3*). In addition to equipment variety, intermodal freight trains are among the fastest trains operated by North American freight railroads. Intermodal trains are often operated at speeds of up to 70 miles-per-hour (mph), [112 kilometers-per-hour (kph)] to remain competitive with highway trucks that have traditionally offered more reliable and flexible service.

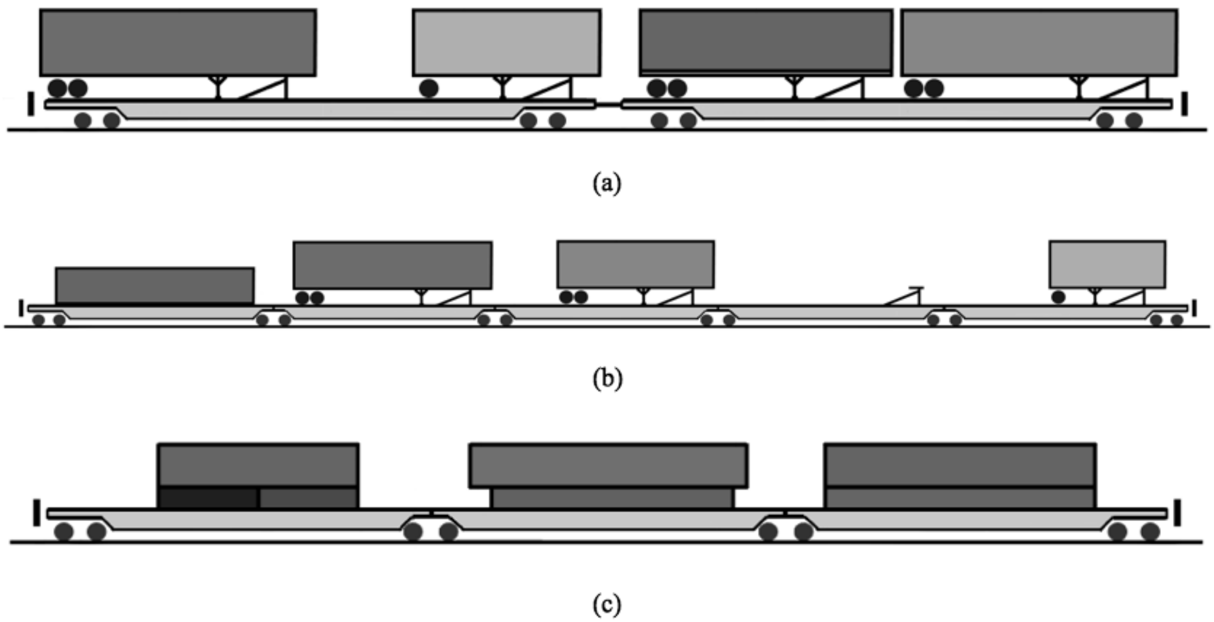

FIGURE 1 Typical North American intermodal rolling stock: (a) two-unit flat car with trailers (b) five-unit articulated spine car with a container trailers, and (c) three-unit articulated well car with containers.

Train Resistance

Train resistance is the summation of frictional and other forces that a train must overcome in order to move (*4*). The general equation for train resistance is $R = AW + BV + CV^2$, where A is the bearing resistance, B is the flange resistance, and C is the aerodynamic resistance (*4*). The A term varies with the weight (W) of the railcar or train, the B term varies linearly with train speed (V), and the C term increases exponentially as train speed increases. Due to the exponential nature of train aerodynamic resistance, any methods of reducing the aerodynamic coefficient significantly reduce train resistance and warrant further study. Aerodynamic drag reduction can take on several forms including redesign of intermodal rolling stock and/or installing aerodynamic reduction attachments, container/trailer design improvements, and improved loading practices. This latter option provides an economical alternative to redesigning railcars or containers/trailers, which requires significant capital investment and design considerations regarding compatibility with existing container and trailer types.

Optimizing Intermodal Train Loading

UIUC is investigating methods for optimizing intermodal loading to reduce gap lengths between containers/trailers. The most common intermodal terminal loading practice is *slot utilization*. In slot utilization, the number of loads on an intermodal train is maximized, with the objective of filling all available slots. This method does not require minimization of the gaps between adjacent loads, since the load is only required to fit in a slot that is equal to or longer than its length - as opposed to an optimal slot. An alternative measure to evaluate intermodal loading and minimize gaps between adjacent loads is *slot efficiency*. Not only does this method minimize the gaps between loads, but it also maximizes the utilization of all slots on the train. In other words, the number of containers per unit length of train is maximized. In 2005, Lai and Barkan compared the benefits of slot efficiency and slot utilization (*5*). The potential savings from switching from slot utilization to slot efficiency can be as much as 1 gallon of fuel per mile, depending on the specific rolling stock and loads available (*6*). Additionally, Lai, Barkan, and Önal developed an optimization model that minimized a train's gap lengths given specified loads (*7*). Lai, Barkan, and Ouyang expanded the earlier optimization model to account for loading multiple trains simultaneously and the uncertainty of incoming loads (*8*). In addition to modeling, the BNSF Railway is funding UIUC to develop a machine vision system that will be used as a diagnostic tool to evaluate current train loading practices and future loading improvements (*6*).

MACHINE VISION SYSTEM DEVELOPMENT

A typical machine vision system acquires images from a digital camera and processes these images using computer algorithms with the objective of extracting pertinent information. The algorithms, which are the core of the machine vision system, transform or manipulate images to obtain objective and potentially quantifiable results by using the color, texture, geometric, and other attributes of interest within the image (*9*).

Machine Vision Technology in the Railroad Industry

Since the 1980s, machine vision technology has been used to improve railroad safety, efficiency, and reliability through inspection systems that address both civil infrastructure and rolling-stock mechanical components (*10-15)*. The uniform shapes and sizes of intermodal containers and trailers make machine vision a viable technology for evaluating intermodal train loading configurations.

Wayside Machine Vision System Objectives

To reliably capture images and perform aerodynamic analyses on intermodal trains, a wayside machine vision system must be designed with the computational capability to capture, store, and analyze videos with near real–time performance. This is best facilitated through the construction of a permanent, automated installation with multiple processors, such as the one UIUC is developing along BNSF's Southern Transcon intermodal corridor. The design objectives for this machine vision system include the following:

- Automate the video capture and data analysis system.
- Determine the type of each intermodal load (single or double stack container or trailer) and measure its length.
- Consistently and accurately determine slot efficiency and the train's aerodynamic coefficient based on the gap measurements and comparisons of the well or platform size.
- Provide useful results that can be interpreted by intermodal terminal and transportation managers and applied toward improving loading operations.

WAYSIDE SUB-SYSTEMS

To achieve the aforementioned goals, the machine vision system has been designed with several sub-systems, which are integrated through custom automation software. These sub-systems include wayside automation, video acquisition, load monitoring, train scoring, and communications. The wayside automation system detects trains approaching the wayside installation, prepares the system for video acquisition, collects automatic equipment identification (AEI) data, and executes software algorithms with corresponding results from the other sub-systems. AEI data lists the order of rolling stock within the train consist and provides a timestamp for each locomotive and railcar axle. The video acquisition system collects and stores videos, and the Train Monitoring System (TMS) analyzes these videos to determine the train's particular loading. The Train Scoring System (TSS) uses information about the loading configuration from the TMS and AEI subsystems to score the train on how efficient the loading is. The communication system provides a means to interact with and monitor the performance of the system and ultimately submit the results to intermodal terminal managers and other personnel. The subsequent sections describe each of the machine vision sub-systems.

Wayside Automation System

To minimize human supervision, a wayside automation system was developed to integrate each of the sub-systems into a single system as shown in Figure 2. For a wayside installation, the automation system includes various train detectors, signal acquisition electronics, and train detection logic for interpreting the signals and initiating subsystem operations (Figure 3). When the system is idle, it waits for a pulse from a detector signal indicating an approaching train. Once a train activates a detector (see Figure 2), the system initiates video recording. The recording continues until the train clears all of the detectors. After the video is stored, the computer resumes waiting for another train. Within the automation system, there is a contingency for the rare case in which a train stops at the installation, which will pause the video capture. If the signals from the detectors resume, indicating that the train is moving, the system will resume video recording. Whenever the system is idle, it begins analyzing videos to determine the loading configuration using TMS and then calculates the trains' aerodynamic coefficient and slot efficiency using TSS.

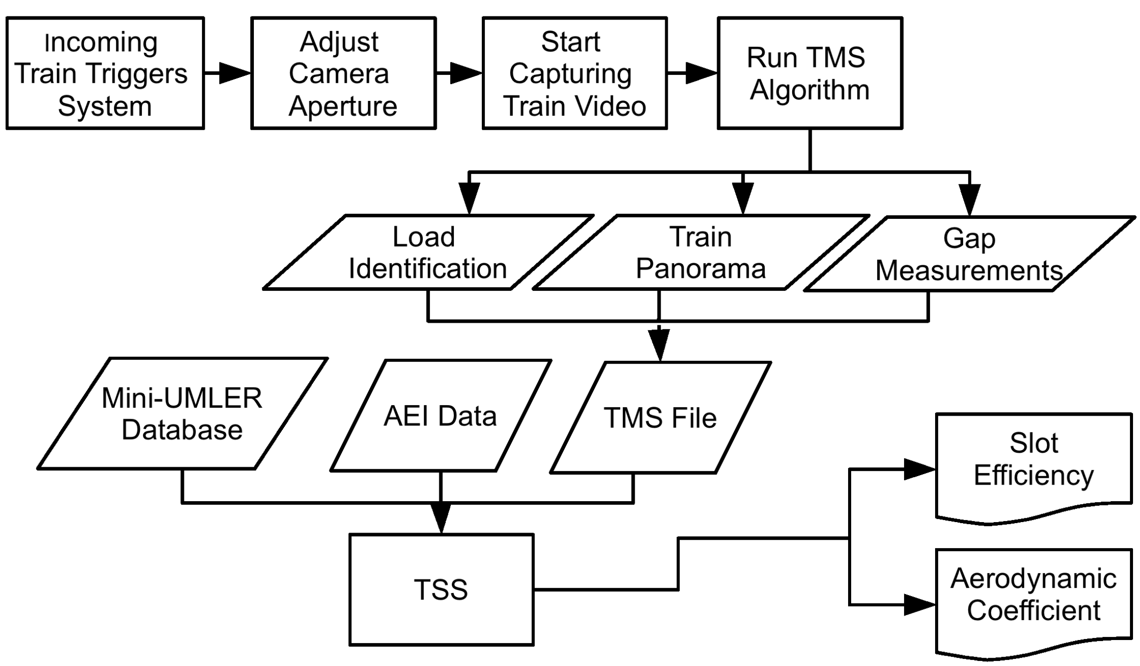

FIGURE 2 Flow chart of the machine vision automation system and sub-systems.

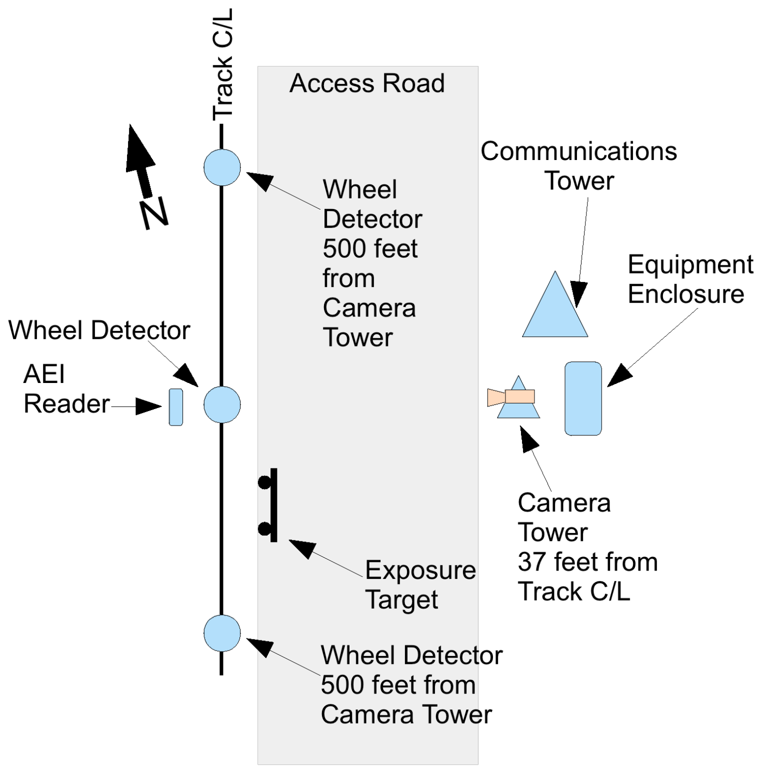

FIGURE 3 Installation layout of the prototype wayside machine vision system at BNSF's Logistics Park Chicago (LPC).

Image Acquisition System

The image acquisition sub-system provides methods for capturing usable images and is directly related to the quality of data that can be obtained from the images. If images are not properly acquired (e.g. appropriate view, proper exposure, etc), little or no useful information can be extracted. To properly acquire an image, the equipment must be capable of capturing videos in the target environment and be able to adjust to any variable environmental conditions. The major factors for obtaining images suited for this project are described in the following sections.

Camera Placement and Orientation

Camera placement and orientation are important considerations when designing the image acquisition system. The optimum location of the camera depends on what object the camera is required to observe and the specific information that needs to be obtained from the images. For detecting intermodal loads, the camera is aligned so it is normal to the side of the train. This is accomplished by adjusting the roll, pitch, and yaw of the camera mount beneath the camera and ensures that the train will not be distorted in any direction. If the image of the train is too distorted, the TMS algorithms will not function properly. Also, the camera setup needs to be placed where there are no obstructions to the camera view, such as another train travelling in front of or behind the train to be recorded. Finally, the camera needs to be placed so that the top of double stack containers are clearly visible and such that the "fish eye" lens effect near the top of the image is minimized.

Video Image Acquisition

Recording videos 24 hours a day in an outdoor setting requires careful consideration of image exposure. Image exposure depends upon the light from the sun and the weather conditions present at the time of the recording. This is also complicated by the need to capture images of the background prior to the arrival of the train, so it can be more easily removed from the individual images (see "Train Monitoring System" section).

The first step in achieving proper exposure is to provide an exposure target placed in front of the camera near the track. This target is designed and positioned to reflect light in the same manner as the side of the train (once the train arrives). Once a detector indicates that a train is approaching, the camera will reduce its field-of-view (FOV) to only the area of the target and adjust all of the camera parameters (with the exception of shutter speed) to obtain a properly-exposed image of the target. The setting for the shutter speed must be short enough so the motion of the train does not cause motion blurring in the image. Once this set of parameters is fixed for the current environmental conditions, the FOV is returned to the entire image, and the system waits for the train to approach the FOV of the camera. Just before the train comes into the FOV of the camera, wheel detectors initiate the capture of the background at the beginning of the video, and the camera continues to record video of the entire train. With a successful exposure of the video, the machine vision algorithms can remove the background and extract each intermodal train's loading configuration.

Train Monitoring System

This section describes the Train Monitoring System (TMS) that uses computer vision and image processing algorithms to analyze intermodal train videos. The first step is to identify the train in each image frame of the video using a background removal algorithm. Background removal is followed by the generation of a panorama of the entire train that is further used to detect intermodal loads and the gaps between them.

Background Removal

Background removal refers to the identification of objects of interest and the elimination of all other objects from a given image frame. All of the objects of interest are termed as "foreground" and everything else is termed as "background." For this system, all the moving objects (i.e. the locomotives, railcars, and intermodal loads) form the foreground and the more static objects (e.g. the ground, trees, clouds, etc.) form the background. Thus, the TMS must correctly identify the foreground objects using their distinct characteristics (e.g. shape and motion) to extract them from all other background objects. While this is being computed on each image frame of the video, the foreground objects are assembled, section-by-section, into a train panorama.

One specific characteristic of foreground objects is their considerable movement between consecutive frames as compared to objects in the background, which have negligible motion. This property can be utilized to distinguish and classify objects into foreground and background categories in a given image frame extracted from a train video. For example, suppose the current image frame requiring background removal is I_c. Let I_p and I_n denote image frames captured before and after I_c. Using a railcar visible in consecutive image frames, an initial estimate of the velocity of the train can be obtained by correlating the railcar in I_c and I_n or I_c and I_p. The initial velocity estimate, v, indicates the number of pixel shifted per consecutive image frame for the objects in the scene. A coordinate system is defined with its origin lying at the bottom left corner of an image where the horizontal direction is along the *x*-axis and the vertical direction is along the *y*-axis. Once the initial estimate of *v* is obtained, the next step is to find regions moving at velocity *v* in the current image frame (I_c). These regions are found by taking a window of size S_z (21 x 41 pixels) in image frame I_c at any location (*x,y*) and correlating it with a window of similar size in image frame I_p at location (*x-v,y*) and at location (*x+v,y*) in I_n. The above calculation assumes that the train only moves horizontally, which is reasonable as there is only a sub-pixel order of vertical movement between any pair of consecutive image frames. The correlation used is known as normalized cross correlation (NCC) (*16*). In this correlation technique, the mean pixel intensity of the image frame window is first subtracted from each pixel value in the window to reduce the effect of small lighting changes. Next, all the pixel values in the window are normalized such that their sum of squares is equal to 1.

At each window patch located at (*x,y*) in I_c, two NCC costs are obtained, NCC_p and NCC_n, corresponding to correlations with previous (I_p) and next image (I_n) frames. In addition to these two correlations, the current I_c window is also correlated with the current background estimate. This allows for static objects in the scene to correlate with high confidence. This value is stored as NCC_{bg}. Finally, all the values are combined together to obtain a foreground value referred to FG_{Cost} as follows:

$$FG_{Cost} = \frac{(NCC_p + NCC_n - 2 \times NCC_{bg})}{4}$$

The denominator normalizes the FG_{Cost} between -1 and 1. This foreground cost is then set as a threshold to obtain the foreground objects as shown in Figure 4.

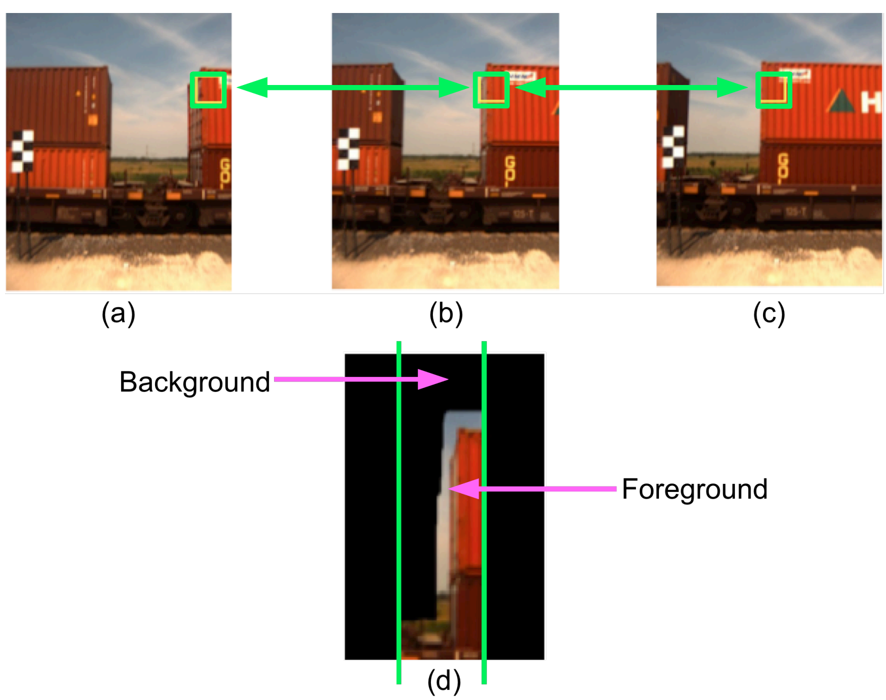

FIGURE 4 Normalized correlation calculated between image frames (a) I_p at *x-v*, (b) I_c at *x*, (c) I_n at *x+v* and (d) the background removed from image I_c.

Mosaic Generation and Load Detection

Once the velocity is obtained, strips having a width equal to the velocity v are taken from I_c and are used to comprise the panoramic image. This is continued for all of the image frames in the video to comprise a seamless panorama. Using the particular velocity calculated for that image frame ensures the panorama will not contain duplicate or missing parts of the train and makes the algorithm responsive to changes in train speed. Thus, a panorama of the complete train, with its background removed, is generated as shown in Figure 5.

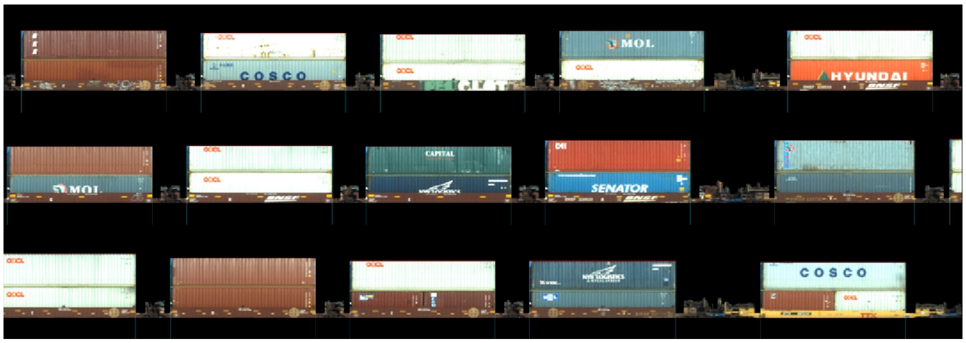

FIGURE 5 Three horizontal strips showing a portion of an intermodal freight train panorama.

In the panorama, the gaps are detected by finding the edges of the containers and trailers. The containers are later classified as single or double stack based on their height above the top-of-rail. The different types of double-stack load configurations (e.g. a smaller container on top of a larger container and vice versa) are identified by detecting the presence of background at the edges of both the top and bottom containers. The trailers are classified by detecting the presence of background near the bottom of the trailer. The sizes of the loads are determined using a pixel-to-foot conversion determined by the camera and lens parameters and the location of the camera relative to the track. Once the container/trailer sizes and gap lengths between loads on the train are determined, the train's loading is then evaluated and scored by the Train Scoring System.

Train Scoring System

The Train Scoring System (TSS) evaluates intermodal train loading efficiency and provides a train-specific aerodynamic coefficient using the gap-length information from the TMS. The aerodynamic coefficient can be used as a proxy for relative fuel consumption and results from the TSS will aid intermodal terminal managers in loading more fuel-efficient trains. In order to attain these results, the TSS needs the following input data: a portion of the Universal Machine Language Equipment Register (UMLER) database pertaining to intermodal rolling stock, AEI data, and TMS result data. Figure 6 describes the flow of data through the major function of the TSS.

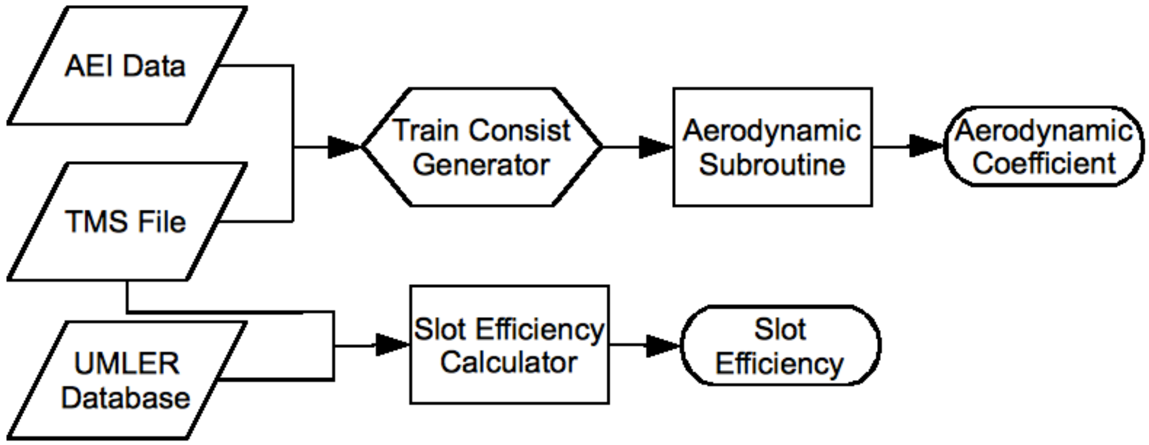

FIGURE 6 Flow Diagram of TSS beginning with the TMS (intermodal load analysis), AEI (intermodal equipment data), and the UMLER database.

TSS Inputs

The UMLER database contains design and loading information on all railcars in unrestricted interchange within North America. We use a subset of the UMLER database pertaining to intermodal rolling stock, which includes the car identification number, outside length, loading attributes, and other geometric and operational parameters. The loading attributes also describe whether the railcar has one, three, or five units (the three or five-unit cars are articulated cars that are connected by drawbars). Additionally, data fields describe whether the railcar can transport containers and/or trailers and what load sizes can be accommodated. The TSS uses the UMLER database to determine the ideal loading configurations for each railcar in the train. The second input is the AEI data that includes the order of the railcars and a timestamp for each axle. The axle timestamps help match the loads identified in TMS with the correct railcar platform or well.

TSS Results Summary

The final result of the TSS is a text file that contains the slot efficiency for each slot in the train (for well cars, it includes both the bottom and top containers) and a value for the average slot efficiency for the entire train. Also, the aerodynamic coefficient is generated so the train's fuel consumption can be computed in the Train Energy Model (TEM). TSS output files will be used to evaluate the loading performance of a particular terminal, train, and/or terminal manager.

Communication System

The communication system is a critical component in the machine vision system because it enables BNSF and UIUC to access the computer and monitor the system to ensure it is functioning properly. In the future, the results will be sent to the appropriate personnel at BNSF using the communication system, but they are presently being transferred manually using external data storage drives.

Wayside Installation Development

Currently, this research project has two field installations: one at BNSF's Logistics Park Chicago (LPC) facility in Joliet, IL and another revenue-service installation along BNSF's Southern Transcon near Kansas City, Missouri. While both installations have the same fundamental task, they differ in terms of their functionality and purpose. Both installations will be described in greater detail in the following sections.

Logistics Park Chicago (LPC) Test Installation Development

A semi-permanent wayside installation location was selected based on frequent intermodal traffic and single-track operation, ensuring no other trains would be visible in the background of the video. LPC was an ideal location for a test installation because approximately eight to ten intermodal trains pass the location per day and it was located within an intermodal terminal providing easy access for developmental work. Figure 3 shows the layout of the LPC installation.

For the image acquisition system, the camera was protected inside an enclosure and the FireWire cable, which transfers images from the camera to the computer, was housed in protective conduit. The computer and the other hardware were stored inside an aluminum enclosure to shield it from the elements. An exposure target was installed to adjust the exposure of the videos and wheel detectors send signals to the computer to begin capturing a video of the train. A communication system allows videos and AEI to be sent over the internet to be analyzed on another (more powerful) computer. The LPC installation has an older AEI reader, which converts the raw data into a format useable by TSS. This installation has been very valuable in proving the feasibility of the wayside-installation concept and to test the TMS background removal algorithms without the use of a backdrop. However, trains from LPC almost exclusively transport international containers thus the location does not reflect the variety of intermodal equipment rolling stock and loading permutations experienced in revenue service. With this being said, a second installation was developed to analyze a higher number of trains in revenue service.

Fully Automated Installation along BNSF's Southern Transcon

Currently, UIUC and BNSF are developing a fully automated wayside system along BNSF's Southern Transcon near Sibley, Missouri. This is an ideal location for a revenue service installation because it has about 40 to 50 intermodal trains a day over a single-track section of the Transcon. Many of the intermodal trains travel to/from Chicago and Los Angeles and loading improvements on these trains would result in substantial fuel savings along this over 2,000-mile (3218 km) corridor. Figure 8 provides a plan view diagram of the Sibley installation.

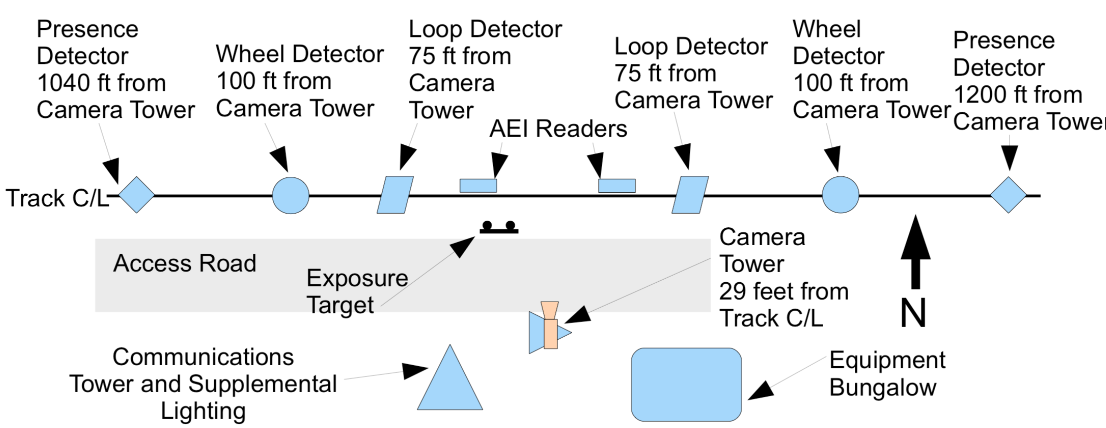

FIGURE 7 Installation layout of the BNSF Railway wayside machine vision system near Sibley, MO.

The installation has three types of train detectors and each detector has different capabilities and functions. The presence detectors are located 1,040 feet west and 1,200 feet east from the camera tower. These detectors use microwave technology to detect trains and send a wireless signal to inform the system that a train is approaching. The wireless detectors also helped reduce installation costs for trenching cables along the BNSF right-of-way.

The wheel detectors, located 100 feet (30.5 meters) to either side of the camera, send a pulse to the computer when a locomotive or railcar wheel passes the detector. These detectors are used to trigger the start of video recording to minimize the effects of variable train speeds. The inductive loop detectors, located 75 feet to either side of the camera, transmit a continuous signal if a train is occupying the loop detector circuit. The purpose of the loop detectors is to verify whether a train has stopped within the installation since no pulses would be emitted from the wheel detectors because they are dependent on motion of the wheels.

The installation at Sibley is similar to LPC in that it has a camera tower with enclosure to house the camera, a bungalow to house the computer and the other electronic equipment, and an exposure target. The installation also has artificial lights to capture videos at night. Because some of the detectors outputs are not digital, a programmable logic controller (PLC) was installed to capture the detector signals and control the high-current outputs, such as the lights.

The installation will soon be capable of analyzing and scoring the train videos on-site. Currently, the communications system uses a wireless internet card provided by a cellular phone provider so it cannot transfer videos for development, as was customary at LPC. Instead, videos are transferred to external hard-drives and shipped to UIUC where the videos are analyzed and scored. In 2010, an AEI reader with redundant transponder detection capabilities was installed and is being integrated with the wayside automation sub-system.

FUTURE WORK

Currently, the TMS is undergoing testing using both video and AEI data from the wayside installation in Sibley. In addition, work continues to integrate and test peripheral equipment and systems such as the artificial lighting and automated exposure adjustment under these conditions. Optimization of the TMS code is underway to achieve a faster run-time while maintaining its current level of accuracy.

Additional research is underway to finalize methods for presenting intermodal loading results to BNSF in a manner conducive to improving their intermodal train energy efficiency. In the future, the aerodynamic coefficient from the machine vision system will serve as an input into the AAR's Train Energy Model (TEM) to compare the predicted fuel consumption to the actual fuel consumption along intermodal corridors. The use of TEM will also allow us to compare an optimally-loaded train's fuel consumption to a train with inefficient loading. Additionally, fuel consumption estimates can be validated through a comparative analysis of actual fuel consumption data and results obtained from the machine vision system and TEM.

In addition to analyzing TSS results, we are currently investigating how the implementation of slot efficiency affects intermodal terminal operations. This investigation will include a review of intermodal equipment utilization methods and load planning software used at railway intermodal terminals and port facilities. In combination with machine vision systems for loading analysis, future research aims to help the railway industry improve intermodal train energy efficiency through the development of improved loading practices that minimize potential impacts on intermodal terminal operations.

CONCLUSIONS

Improving the aerodynamic efficiently of intermodal freight trains has significant potential to reduce operating costs and improve energy efficiency. This paper described the development of an automated machine vision system for analyzing the loading of intermodal freight trains. The development of a fully-automated wayside installation on the BNSF Railway in Sibley, MO is ongoing, and the installation is expected to be fully operational in 2010. This system will allow the BNSF railway to evaluate the loading of intermodal freight trains along the Transcon from Los Angeles to Chicago. Given the high volume of intermodal traffic along BNSF's Transcon, the Sibley installation and machine vision system is capable of analyzing intermodal train loading from multiple intermodal terminals along the corridor. The results from Sibley installation will benefit intermodal terminals along the BNSF's Transcon as well as other railroads interested in improving the energy efficiency of their intermodal freight network operations. If railroads implement improvements to their loading practices, this machine vision system can then serve as a valuable measurement tool to track improvements and consequent fuel savings.

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