MEASUREMENT OF THE AERODYNAMIC PRESSURES PRODUCED BY PASSING TRAINS

Robert A. MacNeill and Samuel Holmes
2672 Bayshore Parkway, Suite 1035
Mountain View, CA 94043

Harvey S. Lee
Volpe National Transportation Systems Center
55 Broadway, Kendall Square
Cambridge, MA 02142

ABSTRACT
This paper describes measurement of the aerodynamic pressures produced by a Bombardier High-Speed Non-Electric Locomotive (HSNEL) on an adjacent stationary double-stack freight car. Static pressures are measured on the near and far-side faces of the freight containers over a range of locomotive speeds from 60 to 130 mph. This data is also compared with the pressures predicted by computational fluid dynamics (CFD) simulations.

INTRODUCTION
It is well established that passing trains can exert aerodynamic loads on each other. These loads can produce stress on passenger car windows and can produce reduced wheel/rail loads on the train being passed. These effects are of greater concern at higher train speeds.

A sensible approach to studying the aerodynamic loads for passing trains is to use CFD to analyze a variety of scenarios. However, the changing geometry of the passing trains (due to their relative motion) and the unsteady airflow makes numerical solutions difficult. Holmes and Schroeder [1] simplified the problem by assuming that viscous forces on the passing trains are small and that the aerodynamic loads are determined mostly by the shape of the trains (the form of drag). Furthermore, special methods such as mesh movement, sliding interfaces or moving boundary conditions (as in Reference 1) must be used to make the numerical methods tractable. Thus, it is important to verify these techniques by comparing the CFD solutions with experiments wherever possible.

There has been interest in passing train effects for a number of years, and many studies have been conducted on this subject [2]. The focus for many of these studies has been to determine the localized effects such as potential damage to windows. This study was undertaken to obtain a broader measurement of aerodynamic forces along the length and height of a tall, large surface area double-stack container car.

Testing of the HSNEL at the Transportation Technology Center (TTC) in Pueblo, Colorado provided a unique opportunity to gather useful data for comparison with analysis.

This paper describes a set of experiments designed to gather pressure-time histories on a stationary freight car as a high-speed train passes. The experiments recorded transient static pressure at several locations on the stationary car, thus allowing partial verification of the total forces on the car predicted by CFD simulations using the commercial code Acusolve™.

TEST SETUP
The test was designed to simulate a moving train passing a stationary double-stack freight car on an adjacent set of tracks. The moving train—a HSNEL (BBRX2200) pulling two Horizon class AMTK 54011 cars—traveled speeds up to 130 miles per hour. A close track spacing of 12 feet, center to center, was used to simulate the closest track spacing experienced in the United States Northeast Corridor. The stationary freight car, consisting of a well car and two empty stacked freight containers, was instrumented with ten pressure gauges on the near-side in a 3x3 pattern (the center location had two gauges, totaling 10 gauges). The far-side was instrumented with two more sensitive gauges. Each container weighed approximately 8800 lbs empty and the well car weighed approximately 55,000 lbs. HSNEL position was synchronized with the pressure measurements by redundant trigger methods, arbitrarily using the north face of the freight containers as a zero-time reference plane. Figure 1 below provides a sketch of the overall test setup.
Two types of gauges were used for the test. Piezoresistive Endevco 8510B-2 differential pressure gauges, on which the reference tube was sealed, were used primarily on the near-side of the containers. Higher sensitivity piezoelectric PCB 103A02 gauges were used on the container far-side. Because the expected near-side peak pressure was estimated to be an order of magnitude higher than the corresponding far-side pressure, the less sensitive Endevco gauges were selected for measuring the stronger near-side pressure histories while the more sensitive PCB gauges were used for far-side measurements. In addition, a single PCB gauge was collocated with an Endevco at the center near-side position for comparison between the gauge types.

Some pretest CFD calculations were made to determine an adequate transducer mounting scheme that would minimize the localized pressure effects from ribs along the side of the freight container. These calculations were undertaken because it was feared that static pressure measurements could be adversely affected if the flow parallel to the container side was so high that eddies being shed from ribs adjacent to the pressure transducers strongly influenced the pressure measurements. To minimize these effects, the transducers were mounted into 13"x13"x1/2" 6061-T6 aluminum plates that were rigidly screwed to the 1/16" steel container wall. The transducers were isolated with latex rubber tubing to minimize interference from vibrations in the aluminum plate. The aluminum plates were surrounded by a 36"x36"x1/2" foam panel with a square hole cut out of the center for the aluminum plate. The foam panels were glued to the container with the edges taped to the container walls and to the aluminum plate providing a large, smooth surface with a flush mounted gauge.

A 3x3 pattern spanning the whole front face of the two containers was selected for maximum coverage with a limited number of gauges. The positions of the transducer facing the train are shown below.
The rail mounted strain-gauges used as a position and speed detector were installed 10 feet away from the northern end of the double-stack container car. Speed was measured using strain gauge peak amplitude signals that occurred when the HSNEL wheel was centered over an individual gauge. Train speed was measured by using the detection of these peaks and by knowing the distance between the pair of strain gauges. Speed measurement accuracy is on the order of 0.2 mph or less for a train speed at or below 130 mph. The optical sensor functioned in a similar way but was triggered when the passing train broke the beam. It was used as a means for verifying the strain gauge measurements.

Figure 6 and Figure 7 below illustrate the spacing between the cars and show some critical overall dimensions.

Figure 7. Dimensional Schematic of Freight Car and HSNEL Proximity

**TEST DESCRIPTION**

Data was collected during seven passing events: five at successively higher speeds from 60 to 120 mph and two at the highest speed of 130 mph. The two passes were made at 130 mph to verify consistency and repeatability between data sets. As shown in the results section, recorded pressure histories from both high-speed runs were practically identical. Since weather conditions were nearly unchanged between all passes, direct comparison can be made between different HSNEL speeds without having to compensate for wind speed and air density. Average air density was 0.0633 lb/m^3 for all seven tests. The test matrix is given below in Table 1, showing HSNEL speed and air density for each pass. HSNEL speed was calculated using both track mounted strain gauges.

<table>
<thead>
<tr>
<th>Run</th>
<th>HSNEL Speed</th>
<th>Air Density (lb_m/ft^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>61.8 mph (27.6 m/s)</td>
<td>0.0636</td>
</tr>
<tr>
<td>3</td>
<td>79.4 mph (35.5 m/s)</td>
<td>0.0634</td>
</tr>
<tr>
<td>4</td>
<td>100.5 mph (44.9 m/s)</td>
<td>0.0634</td>
</tr>
<tr>
<td>5</td>
<td>109.8 mph (49.1 m/s)</td>
<td>0.0633</td>
</tr>
<tr>
<td>6</td>
<td>120.4 mph (53.8 m/s)</td>
<td>0.0632</td>
</tr>
<tr>
<td>7</td>
<td>129.9 mph (58.1 m/s)</td>
<td>0.0631</td>
</tr>
<tr>
<td>8</td>
<td>129.6 mph (57.9 m/s)</td>
<td>0.0631</td>
</tr>
</tbody>
</table>

Data was collected using a 12-bit analog-to-digital converter (ADC) sampling at 100 microsecond intervals for 52 seconds. The ADC was manually triggered with approximately 10% of the data recorded prior to train arrival. All pressure signals were subjected to a 2 pole low-pass Bessel filter set at 1 kHz in order to prevent signal aliasing. All data have been baseline shifted to remove effects of amplifier drift. Also, all data have been time shifted so that zero time corresponds to the instant in time that the leading portion of the southbound
moving train breaks the plane created by the north surface of the stationary storage containers. This was obtained by using both strain gauge and optical methods.

TEST RESULTS

In this section, results from the test are presented. General comparisons between pressure data are made including relations between train speed and pressure. Since high-speed aerodynamics is the focus of this study, we concentrate here on the results at the highest test speed (130 mph).

The signal-to-noise ratio of the collected pressure data was generally very good. The transducers facing the train during the 130 mph runs had a signal-to-noise ratio greater than 1000:1. The weakest signals occurred with the transducers opposite the HSNEL during the slowest 61.8 mph run with a signal-to-noise ratio of 10:1.

The relative pressures at the various gauge locations on the car were similar regardless of speed. For example, the magnitude of the pressure pulses increases with decreasing gauge mount height. This is because the container stack is substantially higher than the HSNEL and attached cars (see Figure 6). The upper transducers are above the locomotive and are, therefore, influenced less by it. Figure 8 below illustrates the trend for those transducers mounted in the center of the container stack on the side facing the HSNEL. The data is from pass 8, an 130 mph high-speed run.

One can see that each pressure history shows an initial positive gauge pressure followed by a period of negative gauge pressure. The period of positive pressure corresponds to the time that the HSNEL nose is approaching the transducer. The negative pressure phase occurs as the nose passes the gauge location. Next, this pulse settles out somewhat for approximately one second as the locomotive and its two attached cars pass. Finally, a reverse wave (negative then positive pressure) is seen at the transducer as the end of the last car passes. A close-up of the initial pulse is shown below in Figure 9.

As stated previously, time zero seconds corresponds to the HSNEL nose passing the plane defined by the north (upstream) end of the freight container. Looking at the figure above, one can see that pressure is increasing substantially well before the HSNEL reaches the transducer positioned at mid-span on the container. Based on the speed of 130 mph, the HSNEL nose passes the transducers in the above figure at 0.10 seconds, which corresponds to the initial positive pressure peak. Of course, this behavior is consistent with expectations for subsonic flow, where the arrival of pressure waves from traveling vehicles precedes the generating body.

Figure 10 through Figure 12 below show the trend along the length of the car from the highest to the lowest row of transducers, respectively. Pressure increases with lower transducer locations, as shown above in Figure 8, throughout the 9 near-side positions. Another trend is that pressure pulses along a given row are all similar in magnitude and duration but shifted in time corresponding to the arrival times of the HSNEL.
Channel 4 in Figure 11 above shows unusually low readings (by approximately a factor of six) for all passes. The post-calibration data showed no change in the gauge performance. After measurements were made, the transducer was tested by raising its temperature to approximately 110 degrees F and re-calibrated, resulting in no significant change in performance. The amplifier gain and excitation were checked to verify that everything performed as expected. One possible explanation of the reduction in signal size is that there was a leak in the seal for the reference tube on the differential pressure gauge. Indeed, that seems the most likely cause because after post test calibrations, one of the transducer plugs was missing. Unfortunately, the problem with the channel 4 data was not known until after all the plugs were removed from the gauges, making it difficult to say with certainty that plug loss was the cause. However, we conclude that the data from channel 4 is not realistic.

We also noted that channel 7 in Figure 12 above shows a longer period of negative pressure compared to the other two locations along the bottom row. Figure 13 below, which compares channel 7 from both 130 mph passes, suggests that this is a real effect and not a measurement anomaly. The pronounced and sustained low pressure region is most likely due to more highly accelerated airflow at the junction of the well car and the downstream end of the freight container.
Also of interest in the figure above are the two pressure spikes in the sustained negative portion of the pressure curve. These are due to disturbances generated by the inter-car gaps of the passing train. Also indicated on the graph is the time at which the nose and tail pass the transducer.

A high sensitivity PCB transducer (channel 10) was collocated with an Endevco transducer (channel 5) at the center position on the near-side of the freight container. The PCB gauges were also used to measure the pressure histories on the far-side of the freight container. Channels 5 and 10 were mounted together to compare the response between the two gauges. Figure 14 below shows the two histories for the second high-speed pass (pass 8). They agreed within 0.007 psi (or approximately 0.4% of full-scale). Because the piezoelectric gauges (channels 10-12) were newly purchased, the manufacturer's calibration values were used for the pre-cal values. However, there is an 8% difference between the pre-cal and post-cal values. If the post-cal value for channel 10 were used, a difference of less than 0.004 psi would occur between the two gauges. The PCB data, however, is presented using the pre-test calibration.

As expected, pressure histories are considerably lower on the container side opposite the passing HSNEl. Though collecting near-side pressure histories was of primary importance for this test, far-side histories were collected for correlation with CFD models. The pressures can also be beneficial in calculating moments on the freight car about the vertical axis as well as overall forces on the containers. Figure 15 shows the far-side histories for the 130 mph pass 8. Signal-to-noise ratio is down compared to the near-side but the collected data is still quite good, especially considering the far-side pressure pulses are approximately an order of magnitude lower. The far-side histories mimic the near-side in that there is an initial pulse corresponding to the nose passing the gauge, followed by a quasi-static region, which is followed by a reverse pulse as the rear of the HSNEl passes the gauge.

To illustrate the consistency between the PCB gauges from pass to pass, Figure 16 is included below, which shows pass 7 and 8 pressure histories (both at 130 mph) for channel 12. The traces are in good agreement.

Figure 17 below illustrates the relationship between initial pulse peak-to-peak pressure (difference between max and min pressure) and train speed. From Bernoulli's principle, one might expect the relationship to be quadratic (pressure is proportional to speed squared) while, at first glance, Figure 17 seems to indicate linear behavior. However, we believe that this may be an effect of the limited range of investigated speeds, which is too small to show a large amount of the parabolic curvature. Turbulence and flow separation and other nonlinear

![Figure 14. Comparison Between PCB and Endevco Gauges at Center of Middle Row on Side Facing Locomotive](image)

![Figure 15. Pressure Histories on Far-side of Freight Container](image)

![Figure 16. Comparison of Far-Side Pressures at Channel 12 for Both High-Speed Passes](image)

![Figure 17. Relationship between Initial Pulse Peak-to-Peak Pressure and Train Speed](image)
effects may also affect the pressure. We recommend that if other non-tested conditions are of interest, extrapolation to different speed conditions be done with caution.

Figure 17. Peak-to-Peak Static Pressure as a Function of Train Speed for Each Channel

COMPARISON TO CFD RESULTS

A CFD simulation based on the model in Reference 1 (using Acusolve\textsuperscript{TM}) was made to replicate the 130 mph test conditions. In this simulation, the motion of the container relative to the HSSEL is modeled as a moving boundary condition. In this approach, the container is moved through the mesh while the mesh remains fixed [3]. As nodes enter the container volume, the boundary condition is applied so that the fluid velocity within the container is constrained to be the container velocity. Thus the momentum of the fluid within the moving boundary is constant and the pressure distribution on the boundary surface is the same as would occur if the boundary condition (i.e. the container velocity) were applied to the nodes defining the container surface.

The model was set up to predict the initial pressure wave induced on the stationary freight car. An interpolation algorithm was employed to extract the pressures at each transducer location along the containers. Figure 18 through Figure 21 below show comparisons of calculated and measured pressure histories for each transducer location. Near-side records are separated by row in Figure 18 through Figure 20 from top to bottom, respectively. Far-side pressure comparisons are shown in Figure 21.

The agreement between the measured and calculated pressures is generally very good. The peak-to-peak pressure magnitude is very well predicted for most transducer locations. The shape and timing of the pressure pulse is closely predicted as well. However, the measured data consistently exhibits quicker pressure recovery past the negative pressure peak. This may be due to the lack of a turbulence model in the CFD calculation.

Figure 18. Comparison of Calculated and Measured Pressures at Top Row Transducer Locations

Figure 19. Comparison of Calculated and Measured Pressures at Middle Row Transducer Locations

One can see in Figure 20 below, that the sustained negative pressure seen during testing at transducer 7 was not seen in the CFD calculation. This effect may be due to subtle differences between the modeled geometry in the calculation and the actual geometry. On the tested freight car, there is an approximate 6 inch gap between the freight container wall and the well car side that was not modeled in the CFD mesh. Airflow in this gap may have caused the sustained negative pressure at gauge 7. The CFD model can be modified in future calculations to account for this geometry detail. Also, future calculations could include the effects of turbulence in an effort to more closely match pressure recovery as the HSSEL passes the gauge location.

Figure 20. Comparison of Calculated and Measured Pressures at Bottom Row Transducer Locations
CONCLUSIONS

The primary objective of this effort, to collect pressure data on the near-side of a double-stack freight car, was successfully realized. The secondary objective of collecting far-side pressure data was also successful. Both sets of data at 130 mph (pass 7 and 8) were very consistent for all measured channels. With the exception of Channel 4, all the pressure data for all passes showed similar trends and signal-to-noise ratios were quite high given the relatively low pressure wave magnitudes, especially on the far-side. The loss of channel 4 data due to gauge problems is not of major concern since trends in the data were so clear and uniform.

The CFD model from Reference 1 was modified to predict the 130 mph tested conditions under this program. The calculated results were very similar to the measured waveforms in all respects. Even the low amplitude far-side pressure histories were closely predicted. Some improvements in the CFD simulation could be made by more closely modeling the tested geometry and by including a turbulence model in the CFD calculation. On the whole though, the CFD prediction as it stands provides a very good means for predicting the loads produced by passing trains.

ACKNOWLEDGMENTS

This work was supported by the Federal Railroad Administration through the Volpe National Transportation Systems Center. The authors especially wish to thank James H. Lamond of the Volpe National Transportation Systems Center for his guidance and support during the course of this work.

REFERENCES