Aerodynamic Analysis of a Freight Train

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Freight trains are a great choice to transport large quantities of goods over long distances. As a first step in reducing transportation costs, a drag analysis will be conducted to pinpoint areas of aerodynamic issues. Due to drafting effects, it is hypothesized that after a certain number of intermodal carts, the change in aerodynamic drag of the carts decreases the further the cart is from the leading train. This change approaches a small value that could be considered negligible for certain applications. To investigate this phenomenon, a 1/56 scale model locomotive and container/cart assembly will be placed in the Wichita State University 3x4 Wind Tunnel in which a movable metric cart assembly will measure drag forces experienced in that region. It is expected that this change in drag will become small by the fourth and fifth cart in the train. With this data, additional experiments on drag reduction could be conducted by focusing on areas with the highest amount of drag.

I. Nomenclature

A = effective area
CFD = computational fluid dynamics
\( f_d \) = drag force
\( \rho \) = air density
Re = Reynolds number
R = Resistance in N/ton
V = wind velocity
\( V_{rel} \) = relative wind velocity
\( W_{tavg} \) = average weight of train compartment
\( C_d \) = coefficient of drag
\( b \) = an experimental friction coefficient for flanges, shock, etc
\( w \) = weight per axle

Introduction

Trains are a reliable and cost-effective means of transport for goods and services in huge quantities across large distances. Just an average American requires roughly 40 tons of freight each year to support their lifestyle. Although trucks carry goods shipped less than 1200 km, rail is the mostly used for shipments traveling more than 1200 km (Kroll). The train aerodynamic drag consists of pressure drag and viscous drag. Since the length-to-width ratio is larger than any other ground vehicle, the study of aerodynamics in trains is much more complex than any other ground vehicles. The drag of slower moving freight trains has received less attention than that of high-speed passenger trains. This paper consists of the aerodynamic forces and subsequent drag reduction each train car experiences due to the effects of drafting.
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**Literature Review (Background)**

The earliest study of freight train aerodynamics was done at Purdue University in the year 1898. Purdue University built a Locomotive testing plant in the year 1890s. By the late 1800s, the railroad industry encountered many technical issues. A significant amount of research was done during the years 1920s and 1930s. The research done during this time can be linked to many ground breaking designs that are still implemented today. For instance, installation of an air brake system. [Kunz] There have been many others who have taken the challenge to analyze the complex properties of freight trains.

David Soper did his Ph.D thesis on the flow field around a container freight train. Also talking about how the shape and loading of freight trains causes large deformations in the air which can lead to slipstreams severe enough to displace people or cause movement in platform objects. [Soper]

Chris Baker focused his research mainly on the high-speed passenger trains. His research highlighted the issues associated with aerodynamic development around the freight trains, providing a basis for further research. It also emphasized on the development of International safety standards for freight and high-speed trains. [Baker]

Developed by W.J. Davis, the 'Davis equation' (shown below) is a resistance equation that computes the sum resistance of the train by fitting the coefficients to curves obtained from experimental research.

\[
R = 1.3 + \frac{29}{w} + b \cdot V_{rel} + \frac{C_d \cdot A \cdot V_{rel}^2}{Wt_{avg}}
\]

Eq. (1)

Using Eq. (1), Davis extrapolated the data for freight trains at a range of velocities and showed them in the graph (Figure 1). From that graph, it can be understood that the rolling resistances due to the flange and journal of trains remains fairly constant for all speeds. However, the aerodynamic drag rises sharply with the increase in speed. Since a freight trains have a large number of containers, the drag value of each cart compiles up leading to an enormous total drag even at a cruising speed for the train.

![Speed and resistance for conventional freight train](image)

**Figure 1:** Resistances acting on a train with the change in speed [4]
Even with that, trains have been considered to be very effective in transporting large goods mainly because of the relatively lower air resistance experienced by the numerous subsequent train cars [Baker]. The lowered air resistances are brought about due to fact that the latter carriage travels in the slipstream region of the earlier one. Slipstream or wake region is the region of turbulent flow downstream of the solid body. Baker discovered that the first compartment has the highest slipstream velocities at its tail region, producing a low-pressure area behind it [Baker]. So, the following compartment is slightly pushed forward due to the lower pressure. Likewise, the first compartment also gains some advantage since the second compartment fills the firsts ‘eddy’ region. An eddy is the swirling of fluid created when the fluid is in the turbulent flow region, mostly observed behind large emergent rocks in fast flowing rivers. So, in freight trains this phenomenon of drafting happens on each and every compartment, reducing the energy required to cover the distance than if the drafting was not taking place.

Blocken’s work on drafting cyclists group produced numerical estimates on how drafting aims at reducing the aerodynamic drag of cyclists at racing speeds. Their group conducted CFD and Wind tunnel measurement for 8 cyclists cycling behind one another with a gap of 1 cm, and their test results showed that a decreasing drag for each subsequent cyclist [Blocken].

![Image of cyclists group due to Drafting](image2.png)

**Figure 2: Characterization of cyclists group due to Drafting.**

**Method & Apparatus (Experimental Approach)**

1. **Model Design and Constraints:**

   A. **Wind Tunnel and Model Scaling:**

      The experiment was conducted at the 3x4 open section wind tunnel at Wichita State University with a test section of 8 feet. The 3x4 wind tunnel at WSU is capable of operating at up to 24 psf with an external balance fixed in the middle that can measure both forces and moments. The tunnel provides real time data allowing qualitative and quantitative analysis of lift, drag and moments that are obtained. Any aberrant readings that did not match with the engineering estimates could be checked immediately helping save time and money.

      For the experiment, the 53 feet intermodal train containers as the model and scaled down to the required size. For the best possible result, we had to fit in a maximum number of containers inside the wind tunnel. Since the test section was 8 feet long, we decided to have a 1/56th scale model of the train with a locomotive model followed by 5 container models. We decided to use wood as the material to make the model because they were cheap and easy to manipulate.
Figure 3: Container models lined up

B. Drag measurement:

Since our experiment was spread along the entire test section of the wind tunnel, we did not have the option of using the external balance built in the wind tunnel. So, in order to measure the drag on each subsequent cart, we decided to use a load cell that would be fit into a container. A slot was made underneath one of the containers so that the load cell could perfectly fit inside as seen in figure 4. This metric cart could then be used to measure the drag force experienced by it at any particular location.

Figure 4: Underside of Metric Cart Showing Slot

Figure 5: Load Cell with Metal Stake

For our experimental process, this ‘metric cart’ could then be moved from one location to another and be used to measure the drag at that specific location. This metric cart has rolling wheels installed onto it, so it could maintain forward and backward movement.

Before our experiment, we calibrated our load cell using a 1-pound and 2-pound weight. We also looked at the frictional force between the wheels and the platform, but it was almost negligible. Over the course of the experiment, we performed tare before every run (WOZ, Wind-Off-Zero) so as to re-calibrate our load cell. The load cell we chose took the force readings up to the thousandth place taking 50 samples a second for 10 seconds and calculated the average of all those values.

C. Boundary Layer:

After our model scaling, the cross-section area of the model was 2.125 x 1.75 inches. Since we were using the floor of the wind tunnel, we were posed with a new problem during experimentation. Our model sizes were very small, and they would be very close to the boundary layer of the wind tunnel. From previous experimental data, the boundary layer of the wind tunnel was known to be around 1.5 inches which is more than half the height of our model. In order to solve this problem, we decided to raise our entire model onto a wooden platform of 2 inches. This platform would also serve as a plank to make the mounting and unmounting of our models easier. Likewise, we decided to add a splitter plate in front of our model to control the incoming airflow onto our model.
Figure 6: Splitter Plate attached to base. This splitter plate diverts the boundary layer from the tunnel down and out from the model.

The picture above shows all 5 containers along with the locomotive mounted onto the platform inside the wind tunnel. As you can see, the locomotive and the carts were mounted on a wooden platform which was bolted into the floor of the wind tunnel. The container could be moved around very easily during testing as they were held on the platform by a keyhole locking mechanism. In this particular case, the metric cart is in the 5th position and the drag characteristics there were being observed.

2. Test Plan:

For our test, we characterized the drag variation across the different containers of the freight train at zero yaw angle due to the effects of drafting. We used a load cell that is inserted onto a container to measure the drag and moved it from one position to another. The metric container’s position was changed to measure the drag all required position. For our testing purposes, we took the drag readings at different dynamic pressures of 10, 15, 20 and 24 psf.

For ease, the locomotive was bolted onto the platform in front of first container. Our test started with us placing the load cell on the first cart location. The load cell was placed on the slot pertaining to that particular location with the help of the slate, and the metric cart was placed just over it. The remainder of the containers were placed on cart locations onto the platform using key hole locking mechanism. After that, we performed a tare of the load cell at wind-off-zero (WOZ) for load cell calibration. The load cell took 500 readings for 10 seconds and calculated the average of all that. We measured the drag force readings from the load cell at each required q values. This process of computing the drag force was repeated until the metric car was at the last (or fifth) position. After this, we also measured the drag force experienced by a standalone metric cart to use it as a raw data to compare it with the rest of our data.
3. Engineering Estimates

The experimental objective assumed that drag would reduce in each subsequent cart until reaching a normalizing point where drag would no longer be dependent on car position. Thus, engineering estimates calculated show this behavior. The cart in position number one was assumed to have the drag coefficient of a block in freestream flow of 2.1 and consequently the highest amount of drag. This did not include any drafting effects, as there is no analytical formula to calculate the effect of drafting and CFD software was out of reach. From “Numerical study on the aerodynamic drag of drafting cyclist groups” it is seen that the second cyclist saw a 17% reduction in drag. This 17% reduction from baseline drag coefficient was applied to the second cart, giving the second cart a drag coefficient of 1.74. Using the results from this paper for the third, fourth and fifth cyclist where drag was reduced 25%, 30% and 33.5% from baseline, estimates for the drag coefficient of the third, fourth and fifth cart were able to be calculated. It was initially suspected that there was no Reynolds number dependency and therefore all drag coefficients remained the same for all Reynolds numbers. The estimates are tabulated and graphed below in table 1 and figure 8.

<table>
<thead>
<tr>
<th>Q(psf)</th>
<th>Averaged Reynolds Number</th>
<th>Frontal Area</th>
<th>Cd Cart 1</th>
<th>Cd Cart 2</th>
<th>Cd Cart 3</th>
<th>Cd Cart 4</th>
<th>Cd Cart 5</th>
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<td>0.0254</td>
<td>2.1</td>
<td>1.743</td>
<td>1.58</td>
<td>1.47</td>
<td>1.40</td>
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<td>1.743</td>
<td>1.58</td>
<td>1.47</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Table 1

![Theoretical Drag Coefficient of an AP53 Single Stack Car at Various Positions for Different Dynamic Pressures - April 25, 2019](image)

**Figure 8**

**Results and Discussion**

The results were slightly different than what the initial estimates described. Looking at Figure 9, it is seen that the value of drag coefficient for cart number one is significantly lower than 2.1 and close to one of the lowest across all dynamic pressures. It is understandable that the drag coefficient is lower than 2.1 as a drag coefficient of
2.1 was for a block in an unblocked free stream flow, and this case was a shape similar to a block behind a large wake created from a much larger locomotive.

Focusing on the center part of Figure 9, that is, cart 2, 3 and 4, it is possible to draw some similarities between the estimates and results. It is seen that both follow a decreasing trend. In all cases, cart position 3 saw a lower drag coefficient than 2 and cart position 4 saw less drag than cart position 3. Unfortunately, due to test section restrictions, it was not possible to put an additional number of carts. Because of this, the normalizing point was not able to be found. Conclusions on whether the difference in drag decreases the farther back you go on a train cannot be drawn either as there are too little points from which this conclusion could be drawn. It seems as if the little data that was acquired does not contribute to any significant finding. However, this data could be used as a baseline result and motivation to find this normalizing point as it was found that drag decreases and it is impossible for drag to go to zero.

Cart position 5 was higher than what was expected. This was due to the wake not only having to close out on the entire train model, but also having to close the wake of the base. A run with cart number 4 being the last car could have been done to compare what effect the end of the base had on drag. This was not done so as there was very little time to complete the set objectives and procedures. The large wake created large pressure differences, spiking the drag coefficient as seen in Figure 9.

![Figure 9: Measured Drag Coefficient of an AP53 Single Stack Well Car at Various Positions for Multiple Dynamic Pressures - April 25, 2019](image)

In order to look for Reynolds number dependency, results were also plotted against Reynolds number. In figure 10 it is seen that the drag coefficient was dependent on Reynolds number. As the Reynolds number increased, the drag coefficient increased as well. This is due to the turbulent nature of the bluff bodies. Since Reynolds number is a parameter that describes how long it takes for a flow to become turbulent and bluff bodies make airflow become turbulent due to their shape, having a flow that becomes turbulent over a smooth surface sooner has the same effect of flow that takes longer to become turbulent. As soon as the flow turns the sharp corner, the flow becomes turbulent. Because of this, it could be said that the Reynolds number is only describing the velocity of the flow. Further, dynamic pressure is a function of velocity, so a higher Reynolds number yields a higher dynamic pressure, which in turn yields more drag and subsequently gives a higher drag coefficient.

In figure 10, the trend that was found in figure 9 is also followed. It is seen that the drag coefficient values for cart 1 are very close to the lowest for almost all runs. Again, the decreasing drag trend is seen from positions 2 through 4 and once again we see the sharp drag coefficient increase for cart position 5. The drag coefficient for a standalone cart was also plotted as well. The standalone cart data was acquired from placing the metric cart in location 1 and removing the locomotive and non-metric carts from the test section. As expected, the drag coefficient values for
the standalone cart were much higher than all the other carts. This is because there is no drafting effect that is reducing drag for the standalone part proving that drafting is significant in train carts.

![Drag Coefficient of an AP53 Single Stack Well Car for Various Reynolds Numbers at Different Locations - April 25, 2019](Figure 10)

**Figure 10 : Drag Coefficient of an AP53 Single Stack Well Car for Various Reynolds Numbers at Different Locations**

**Conclusions**

After testing the model train in the 3x4 wind tunnel, it was found that the drag at cart 1 is less than the drag at cart 2. From cart 2 to cart 4, a decreasing trend in drag was as expected and at cart 5 the drag increases rapidly. The reason for the high drag at car 5 can be justified by the fact that wake closes behind the last car, creating a low-pressure region. Therefore, leading to a drastic rise in drag at car 5.

This research could have been done in an even better way. Due to the small length of the test section, only five cars and one locomotive were accommodated in the wind tunnel. Performing this test with a greater number of cars could have paved the path for finding the normalization point. It is a point from which the drag difference between adjacent cars become negligible. To get more realistic data, this test should have been performed with different configurations like the double stack, gas tank and so on.

In the future, research can be done in the Beech wind tunnel instead of the 3x4 wind tunnel to better understand the Reynold’s number dependency and to find out the critical point. After performing the experiment, research can be done on minimizing the drag. This can be achieved by finding the normalization point and installing the drag reduction devices like air tabs on the car from where the normalization point begins.

**References**


Blocken, Bert, “Numerical study on the aerodynamic drag of drafting cyclist groups”, 2010


Soper, D., Baker, C., and Sterling, M., “Experimental investigation of the slipstream development around a container freight train using a moving model facility,” Journal of Wind Engineering and Industrial

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