**Investigating Thrust and Rolling Resistance**

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***Introduction***

The concept of ***thrust***, typically encountered when studying rockets and jet engines, can be investigated in the physics laboratory using the Encoder Fan Cart (CART-FEC). Other examples of thrust sources include the spinning blades of an airplane’s propeller, a bird flapping its wings, and a motor boat’s propellers. The Encoder Fan Cart has been designed to provide a constant force by expelling a mass of air in one direction causing a force of equal but opposite direction on the cart. Thrust is, therefore, a reaction force that is related to Newton’s second and third laws of motion.

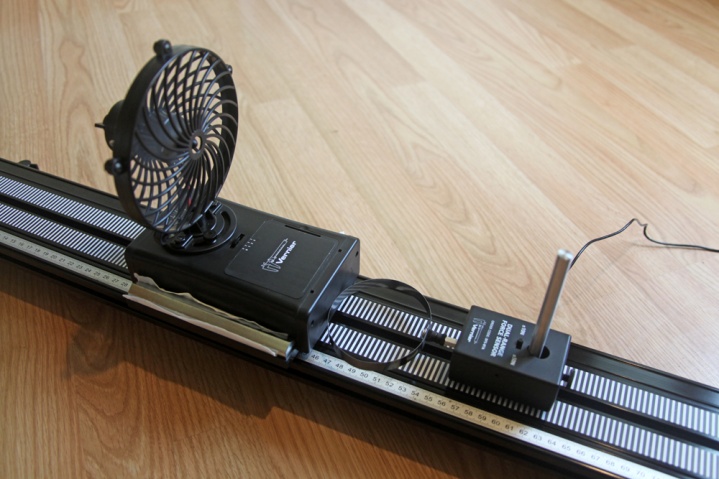
***Rolling resistance*** is the force opposing the motion for rotating wheels and rolling balls. Common examples of items having rolling resistance include automobile tires, bicycle wheels, skateboard wheels, steel railroad wheels, ball bearings, bowling balls, and carts rolling on a dynamics track. Numerous factors can affect the magnitude of the force of rolling resistance. To mention a few, these include the wheel’s material, the surface on which the wheel is rolling, surface adhesion, wheel diameter, pressure on the wheel created by the load it may be carrying, and bearings that hold the wheel to its axle.

The Vernier Motion Encoder System (VDS-EC), Encoder Fan Cart (CART-FEC) and Dual-Range Force Sensor (DFS-BTA) can be used to introduce students to the concepts of thrust and rolling resistance in the physics laboratory in a way that is both educational and fun. This is accomplished in an experiment involving six steps.

***Step 1: Determine the Cart Fan’s Thrust***

During the experiment it is suggested that students run the fan only when collecting data, in order to keep the thrust as constant as possible throughout the duration of the experiment. Doing so will minimize possible reduction in thrust as the fan’s batteries discharge.

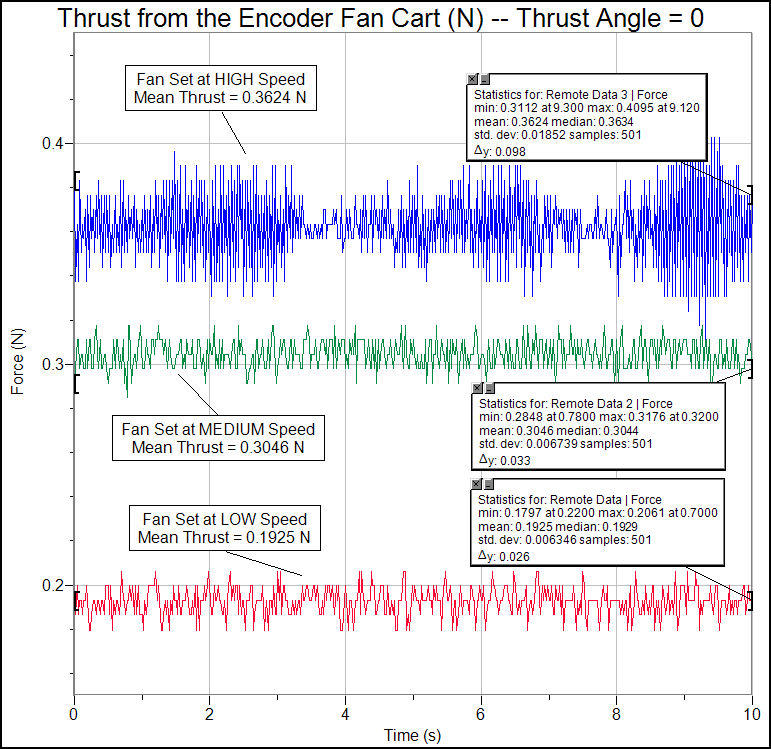
Figure 1 shows an easy setup for obtaining data on the thrust from the fan. The fan angle is kept at 0° for the entire investigation in order to keep the thrust along the track as high as possible. The stiff hoop bumper from the Bumper and Launcher Kit (BLK) is attached to the Dual-Range Force Sensor. Use of the stiff hoop is encouraged as it helps to smooth and reduce variance in force readings. In order to further reduce vibrations and thrust variance, the hex weights are resting on a thin piece of facial tissue in their holders on the cart. The Dual-Range Force Sensor is attached to the dynamics track (properly leveled!) and the switch is set to ±10 N. You may want to select the “Reverse Direction” option for the Dual-Range Force Sensor so that the force readings will be positive. The Force Sensor is zeroed when no pressure is on the stiff loop. The fan is turned on and allowed to be thrust into contact with the Force Sensor. After several seconds have passed, allowing the fan cart to settle down, thrust data is obtained for 10 seconds for each of the three fan speeds. Statistics can then be computed in your data-collection software, and the average thrust noted for each of the three fan speeds.



*Figure 1*

Figure 2 shows a Logger *Pro* graph of the thrust force (in newtons) produced from the fan, with text annotations detailing the mean thrust obtained for the three fan speeds. You will notice that the values for force seem to occur at only specific discrete values. This is especially noticeable as the thrust from the fan is small enough that all values are very close to the low end of the the Dual-Range Force Sensor’s ±10 N range. The distance from one step to the next in these discrete values is about 0.006 N, which rounds to the 0.01 N resolution indicated in the Dual-Range Force Sensor User Manual. **Although the thrust is small and near the low end of the ±10 N range , it is measurable, and we can clearly distinguish the forces for the three fan speeds.**

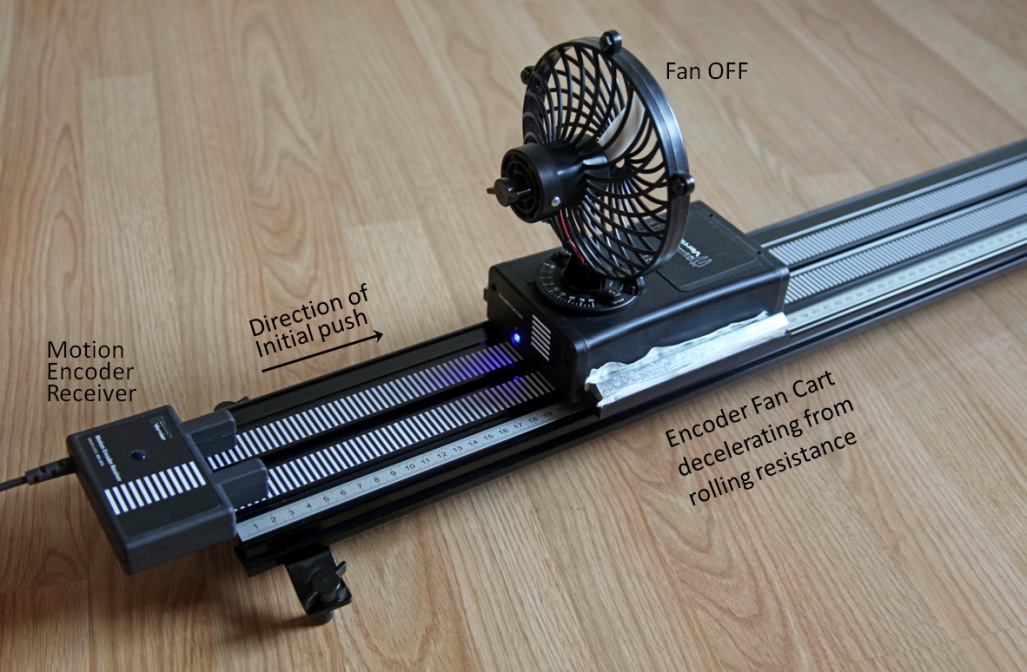
***[****If you are using the discontinued two-speed Cart Fan (FAN-VDS) that attaches magnetically to a dynamics cart, you can still do this investigation. However, the thrust from this fan, even at the higher speed, will likely be somewhat less that the thrust from the lowest speed with the fan on the Encoder Fan Cart. In addition, the thrust will be more highly dependent on the extent to which the smaller AAA batteries on the Cart Fan are discharged.****]***



*Figure 2*

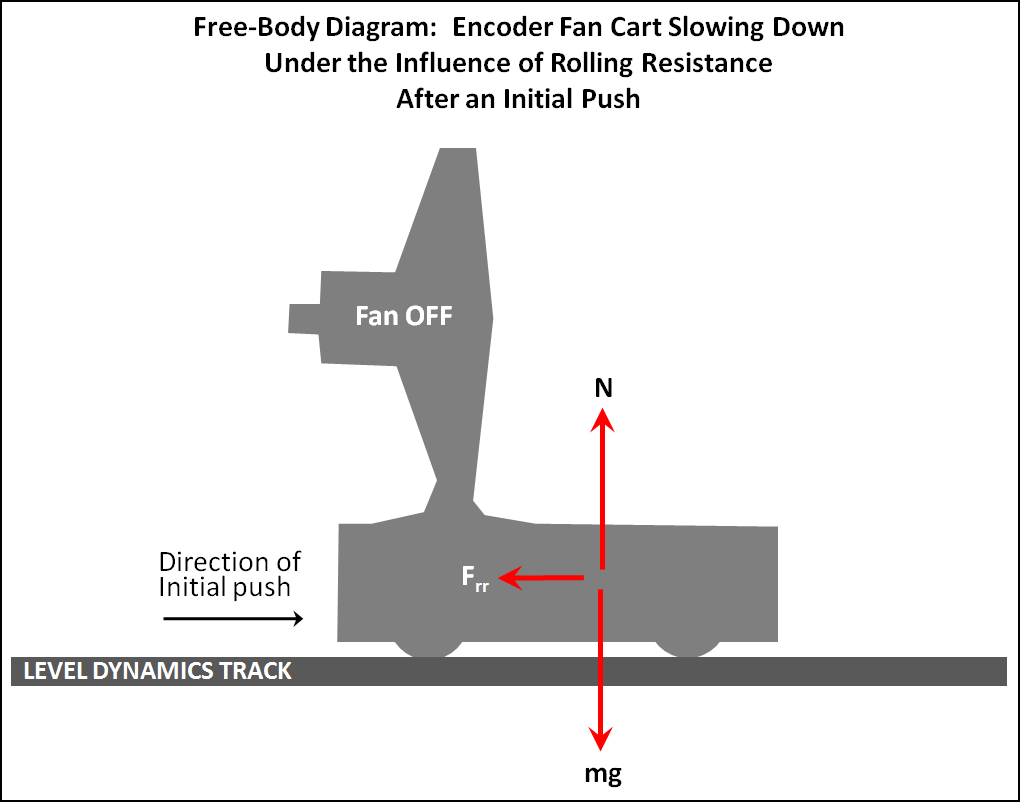
***Step 2: Determine the Force of Rolling Resistance***

As shown in Figure 3, with the fan turned off, the Encoder Fan Cart is given an initial push down the track and allowed to come to rest just before reaching the end of the track. As mentioned in the Encoder Fan Cart User Manual, the cart is rugged but not indestructible, so be careful not to allow the cart to fall off the track. Meanwhile, the Motion Encoder Receiver captures data allowing one to determine the deceleration, *a,* of the cart. You will want to set the zero position when the fan cart is near the left end of the track. It is also helpful to enable triggering and start data collection when the Motion Encoder Cart is increasing across 0.1 meter. Doing this will avoid collection of data while you are giving the cart and initial push down the track.



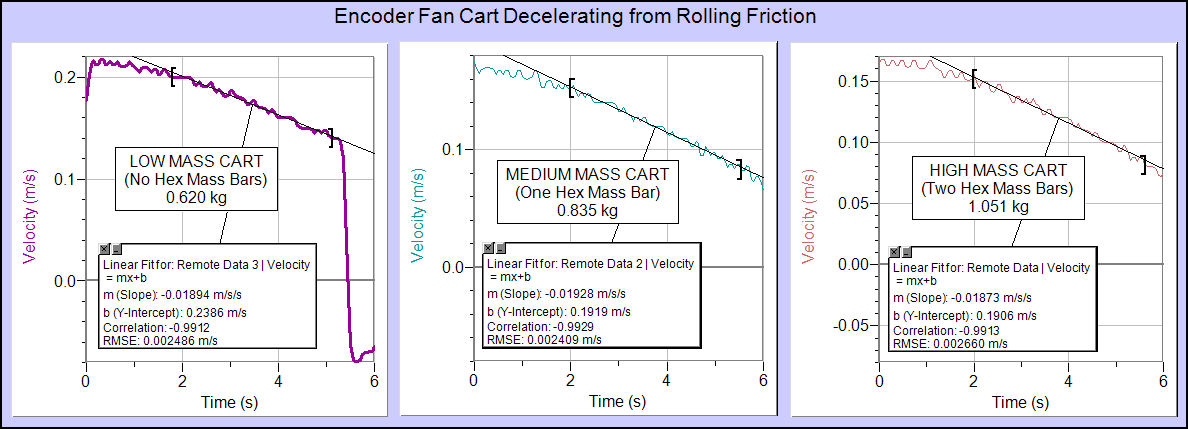
*Figure 3*

By measuring the mass, *m,* of the Encoder Fan Cart system, students can then determine the force of rolling resistance using Newton’s second law of motion. As shown in the free-body diagram in Figure 4, the Normal force, *N,* and the force of gravity, *mg,* cancel one another on the level track, leaving a net force equal to the force of rolling resistance *Frr*. Therefore, *Fnet = Frr = ma*.



*Figure 4*

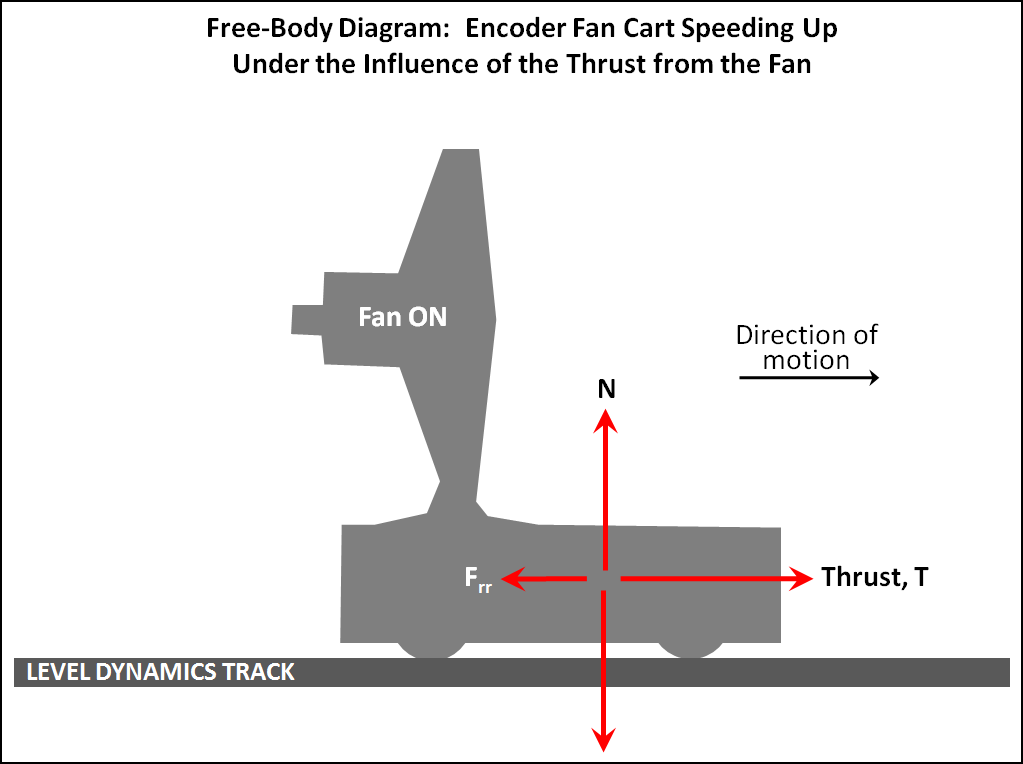
Figure 5 shows the velocity *vs*. time graphs for the cart slowing down under the influence of the force of rolling resistance for each of the three possible masses of the cart system. The acceleration is obtained from the slope of the velocity *vs*. time graph using a linear model over the region where the deceleration is most constant. We observe from the slope that the rate of deceleration *a*, 0.019 m/s2, is independent of the mass of the cart system. The force of rolling resistance can then obtained from the second law of motion as *Frr* = *ma*, since we know both the mass of the cart system and the rate of deceleration, *a*.



*Figure 5*

***Step 3: Predict Acceleration of Encoder Fan Cart System Under the Thrust of the Fan***

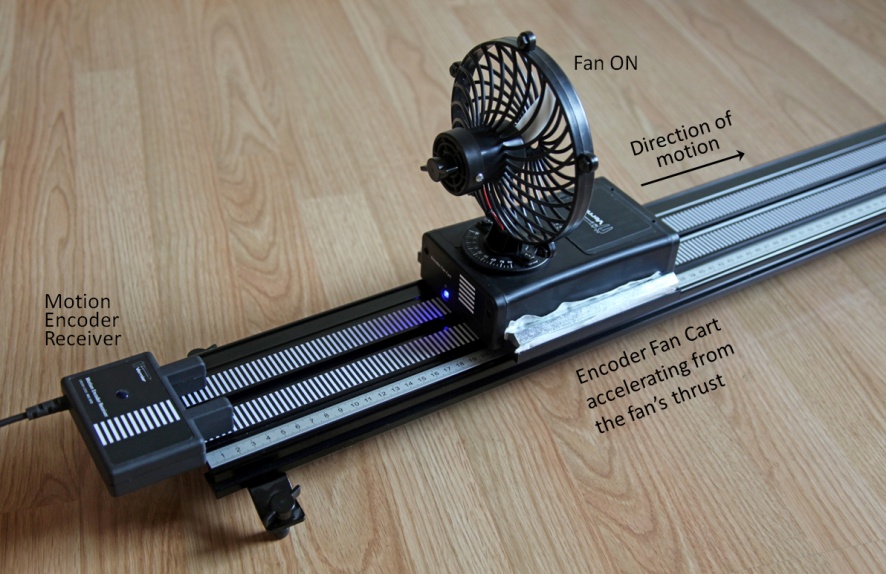
Knowing the fan’s thrust from Step 1 and the force of rolling friction from Step 2, the student can then calculate the predicted acceleration of the cart system under the thrust of the fan. From the free-body diagram of Figure 6, it is seen that the net force is the thrust minus the force of rolling resistance. Therefore, *Fnet* = *T – Frr = ma* and the acceleration of the cart can be easily predicted by using the equation *a = (T – Frr)/m*.



*Figure 6*

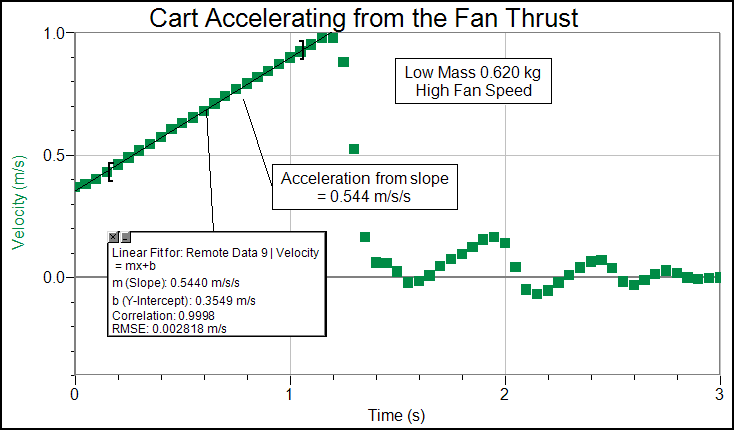
***Step 4: Obtain the Actual Acceleration of the Encoder Fan Cart System under the Thrust of the Fan***

The actual acceleration of the Encoder Fan Cart system under the thrust of the fan is then determined from data captured by the Motion Encoder Receiver as shown in Figure 7. As was done back in Step 2, you will again want to set the zero position when the fan cart is near the left end of the track, and enable triggering so that data collection begins when the Motion Encoder Cart is increasing across 0.1 meter. It is especially important to make sure that the accelerating cart does not undergo damage by falling off the right end of the track. You could hold a small pillow at the right end of the track to help stop the accelerating cart if you wish.



*Figure 7*

Figure 8 shows a velocity graph for the cart system under the influence of the fan at the highest speed and lowest mass. Note that the cart only takes on the order of a second to accelerate the length of the track, so care must be made to stop the cart at the end of the track. Following the same procedure as back in Step 2, the acceleration is obtained from the slope of the velocity *vs*. time graph using a linear model over the region where the cart is accelerating before reaching the end of the track. The region of irregular velocity after reaching the end of track is the result of stopping the cart and is not included in the linear model analysis.



*Figure 8*

***Step 5: Determine the Percentage Error in the Predicted Accelerations***

The predicted accelerations from Step 3 can then be compared to the actual accelerations from Step 4 by calculating percentage errors of the predicted accelerations:

***Step 6: Determine the Coefficient of Rolling Resistance***

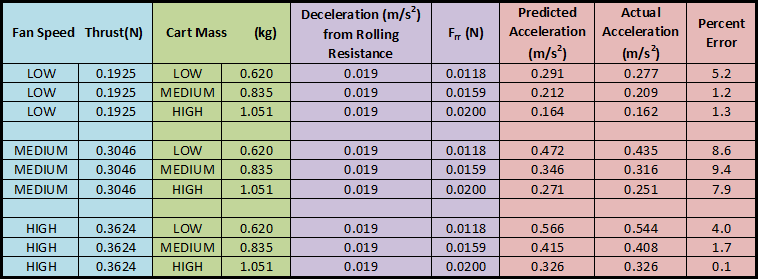
Analogous to sliding friction, the *coefficient of rolling resistance* *Crr* is determined from its defining equation:

where *Frr*is the force of rolling resistance and *N* is the normal force, perpendicular to the surface on which the object is rolling. *Crr* is, therefore, a dimensionless quantity that describes the force required to push an object with wheels per unit weight of the object on a level surface with constant speed and negligible air resistance. Since *Frr* equals mass times the rate of deceleration, *a*, and the normal force *N = mg*, an alternative expression for the coefficient of rolling resistance is given by

In Step 2 of our investigation, we found *a*= 0.019 m/s2. Using 9.8 m/s2 as the acceleration due to gravity, the coefficient of rolling resistance for the Encoder Fan Cart system on the dynamics track is approximately 0.0019.

***Typical Results***

The table in Figure 9 shows typical results that students may get for each of the nine permutations of (thrust, mass) pairs. If desired, each student lab group could be assigned a subset of the nine (thrust, mass) pairs. The Excel file used to create this table is one of the attachments for this investigation. Students should also be encouraged to think about possible sources of error.



*Figure 9*

***Additional Student Investigations***

1. Suppose that you wanted to keep the cart, with the fan running at high speed, stationary on the dynamics track. What angle, θ, in degrees would the track need to be set at to accomplish this? First derive a formula for this angle by considering the free body diagram of this situation. Then check your formula out by setting the track at this angle and see if the cart with the fan running at high speed will remain stationary. (There are a number of apps for the iPhone or Android devices that can be used to easily measure angles of tilt. You can simply rest the device on the track and measure tilt directly from the app.) **[Solution: sin θ = T/mg].**
2. Do some research on the web to find values for the coefficient of rolling resistance for a variety of wheel types and surfaces on which the wheels move. How does the coefficient of rolling resistance that you obtained in Step 6 for the cart and dynamics track compare to similar values that you found on the web.
3. Assuming that the coefficient of rolling resistance for a car with ordinary tires on concrete is 0.012, how hard would you have to push on an average mid-size car with a curb weight of 3500 lbs to keep it moving at a constant speed on a level surface?
4. Using the Vernier ***Video Physics*** app, design an experiment to determine the coefficient of rolling resistance for a properly inflated basketball rolling on a basketball court.

***Attachments***

Investigating Thrust and Rolling Resistance.docx *(this document)*

Encoder Fan Cart Thrust.cmbl *(Example data for Step 1)*

Encoder Fan Cart Decelerating from Rolling Friction.cmbl *(Example data for Step 2)*

Encoder Fan Cart Accelerating with Fan On.cmbl *(Example data for Step 4)*

Thrust and Rolling Resistance.xlxs *(Summary spreadsheet)*