

Lab #1.

A. C. Quillen, PHY141 Fall 2022

Measuring rolling friction using a cart on a track

Equipment list

For each station: Red box of sensors for PHY141. Blue box of equipment for PHY141. Silver track.

Pasco data taking system. Power cords for Pasco system, USB cables. USB adaptors. Cart and Track. Weights for cart. Scale to measure mass of cart and mass of weights that are put on the cart.

Key for using Pasco software. To be given by TA/TIs.

Site for downloading the software!

At the front of the room: spare hardware, extra boxes with spare equipment.

1 Objectives

When a wheel is rolling without slipping, it does not slide where it touches the surface that it rolls over. This means that little energy is lost while the wheel is rolling. However, once the engine is turned off, a train on a level track does eventually come to a stop. Energy is still lost. This is described with the term 'rolling resistance' or 'rolling friction'. Rubber wheels moving on a road tend to dissipate more energy than metal wheels moving along a metal rail. This means that after its engine is turned off, a car with rubber wheels on a level road decelerates more quickly than a railroad car on level rails.

Our goal in this lab is to measure the coefficient of rolling resistance for a cart with metal wheels that rolls on a metal track.

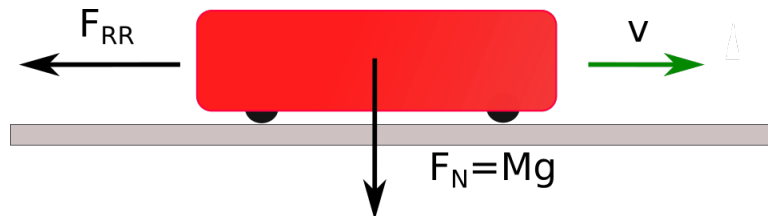


Figure 1: A cart with mass M is moving on level horizontal rails at velocity v . The normal force, exerted by cart onto the rail is equal to $F_N = Mg$. The friction force due to rolling resistance is opposite to the direction of motion and is F_{RR} . The rolling resistance or rolling friction coefficient $C_{RR} = F_{RR}/F_N$.

Consider a cart moving on level, horizontal rails, as shown in Figure 1.

The cart has mass M . Gravitational acceleration is g . The force exerted by the cart onto the rails is equal to Mg and is due to gravity. We call this force the normal force $F_N = Mg$. Rolling friction slows the cart down so it is in the direction opposite to the cart's velocity. The frictional force we denote F_{RR} where RR is short for rolling resistance. The coefficient of rolling resistance, C_{RR} is given by the ratio

$$C_{RR} = \frac{F_{RR}}{F_N}. \quad (1)$$

Since the rolling resistance is a ratio of two forces, it is dimensionless, like most friction coefficients. Since $F = ma$, if the surface is level,

$$C_{RR} = \frac{|a|}{g} \quad (2)$$

where the deceleration a is that experienced by the cart (in the direction parallel to the track) and g is the gravitational acceleration.

Rolling resistance for a railroad steel wheel on steel rail can be as low as 10^{-3} . Rail travel and transport is comparatively **energy efficient**. By comparatively, I mean compared to transport and travel via automobile, truck, or airplane.

What causes rolling resistance? The wheels can sink into the road perturbing it, the wheels can deform as they roll and they might not spring back all the way, and energy can be lost within axles and bearings. Often drag from air is neglected when discussing rolling resistance, but that too slows cars and trains down.

2 Procedures

Help on the Capstone software: <https://help.pasco.com/capstone/>

2.1 Outline

Here is the outline of what we will do in this lab:

- Push the cart, let it roll along the track and use the motion sensor to measure its deceleration.
- Use multiple measurements of the deceleration rate to make an accurate measurement of the coefficient of rolling resistance C_{RR} .

Choose one of the following to explore:

- Vary the cart's velocity to see if the coefficient of rolling resistance depends on velocity.
- Vary the mass of the cart to see if the coefficient of rolling resistance depends on load.

2.2 Measuring deceleration with a motion sensor

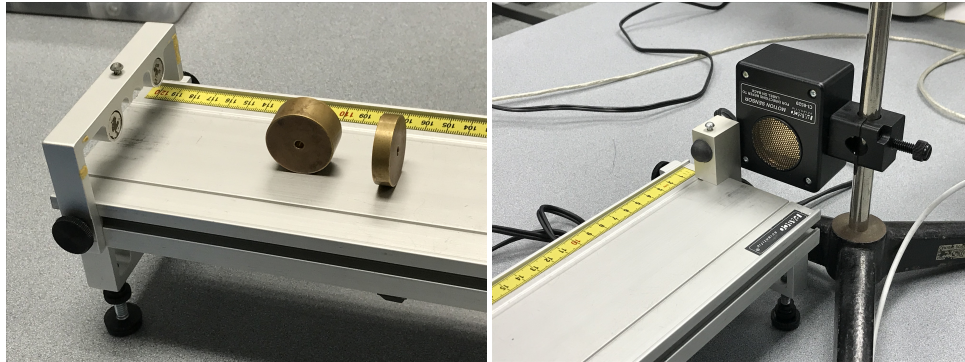


Figure 2: Left: The end of the track, showing mounting bracket, and magnetic bumper. We also show two weights that are used to ensure that the track is level. Right: We show the other end of the cart with bumper and motion sensor.

2.3 Set up

- Set up a track on two adjustable mounts. Level the track. The blue boxes contain round weights. By adjusting the screws on the mounts, you can keep a weight from rolling and ensure that the track is level. See the left panel in Figure 2.
- Attach the magnetic bumper on one side of the track to keep a cart from falling off the track. See the left panel in Figure 2.
- Attach a motion sensor to a lab stand and place it at the other side of the track so that it looks down the track. See the right panel in Figure 2.
- Attach the smaller bumper to the track so that the cart won't smash into the motion sensor.
- Plug in the motion sensor to the Pasco ScienceWorkshop 750 Interface. The yellow connector goes into Digital channel 1 and the black connector goes into Digital channel 2.
- Install the Capstone software on your computer. Alternatively you can use one of the computers in the lab. The lab TA should have a license key for the software.
- Launch the Capstone software. On the left under `Tools` click on `Hardware setup`.

- Click on digital input 1 on the picture of the Science Workshop data acquisition box. In the drop down menu, chose Motion sensor.
- Place a cart on the track.

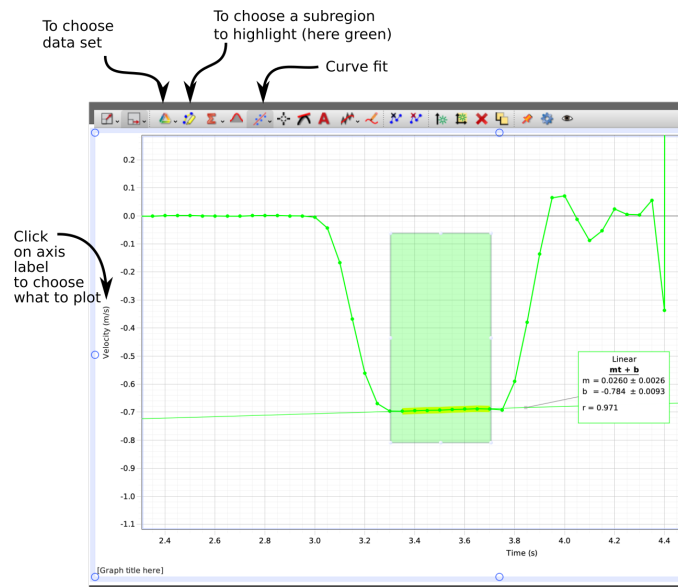


Figure 3: A snap shot of a display from the capstone software. The velocity of the cart is plotted as a function of time. A line is fit to the time interval when the cart is moving. The slope of this line, denoted m gives the deceleration rate in m/s^2 . The green box shows the highlight and active data set.

2.4 Taking data with the motion sensor

- Press record (it's a red button at the bottom of the screen). Now give the cart a push and let it roll down the track. When it nears the end of the track, press pause to stop the recording.
- Click on `Sensor Data` in the main screen.
- Try to see if you can figure out how to display velocity as a function of time as shown in Figure 3. If you click on an axis you can zoom in or out. If you click and hold on the plot you can move the axis. If you click on an axis label you can choose which variable you want to plot.

- Chose a region in the data to highlight. Adjust the position of the highlight box so that it covers the time when the cart is moving along the track. See if you can fit a line to the velocity (you need to click on the curve fit icon that is connected to the highlight box). The slope of this line, denoted m , is the deceleration rate in m/s^2 .
- If you click on the `Data summary` tab on the left you will be able to see different data sets.
- if you click on the triangle icon on the top of a plotting page you will be able to chose which data set you want to plot.
- You can save your data into a file for future analysis.
- You can adjust the data sampling rate by clicking on arrows at the bottom of the screen to the right of the record button. The software automatically sets the sampling rate for the motion sensor at 20 Hz. If the cart is going fast you will need to increase the sampling rate to something like 40 Hz so that there are more data points while the cart is going down the track.
- To the left of Page #1 on the top, you can add pages showing more than one plot.

2.5 The experiments

You have the following goals:

1. By combining a series of measurements, measure the coefficient of rolling resistance.
2. Choose one of the following:
 - A: By comparing a series of runs at different velocities, see if the coefficient of rolling resistance is sensitive to velocity.
 - B: You can increase the mass of the cart by putting two rectangular black weights or the round weights from the blue box on the cart. Each black weight is about 0.5 kg and the cart itself is about 0.5 kg. The other weights are labelled with their weight. By comparing runs with and without the weights you can see if the coefficient of rolling resistance is sensitive to load.

You will need to run a series of experiments for each goal. For each experiment, make sure you write down the name of your data set, an estimate for the cart mean velocity, the cart deceleration rate and whether you have added masses to the cart. When you do a linear fit, you should record the slope and the uncertainty in the slope.

3 Analysis and Discussion

For our first goal: A list of measurements can be combined by computing the mean value of the list. The scatter in the measurements about the mean can be used to estimate the uncertainty of each measurement. The uncertainty of each measurement and the number of measurements can be used to estimate the uncertainty of your mean value (for the list). Your goal is to report something like $C_{RR} = 0.030 \pm 0.005$ where 0.030 is the mean of your list of measurements and 0.005 is your standard error, which is based on the uncertainty of your measurements.

For goal A. Try plotting the coefficient of rolling resistance C_{RR} as a function of cart mean velocity for different runs. You will need to enter a series of numbers into a plotting package (which could be Capstone) to make this plot. Can you find a trend? Do you think C_{RR} increases or decreases if the cart is going faster? If you see a trend, can you describe it with a linear fit?

For goal B. You can discuss whether your measure for coefficient of rolling resistance C_{RR} is meaningfully different for the cart with two different loads. What is meant by meaningful? The difference in the two measurements is larger than a combination of their standard deviations.

On discussion: Do you think your measurements are affected by air resistance or the tilt of the track?

The carts we have in the lab are meant for impact experiments so they are designed to have a low coefficient of rolling resistance. This makes these experiment challenging as we are trying to measure something that is fairly small. Do you feel that the number you have measured for C_{RR} is large or small? Take a look at your cart wheels. Do you have a feeling that they have good or bad bearings?

Relevance to energy efficiency. Railroad wheels have low rolling resistance suggesting that this sets a significant fraction of the transport cost. I think the coefficient of rolling friction for rail is dependent on load which implies that rail freight companies might take it into consideration.

4 Feedback

Don't be afraid to send comments to your professor or lab TAs on the labs.

If you find **broken equipment**, please make sure it is labelled by the TA or TIs so we can fix or replace it. We have spare equipment so you should be able to find a replacement if something is not working. There should be spare hardware available from the TA and TIs that will let you find extra parts that might be missing from your equipment boxes.