# Bikes & Energy

## *Pre-Lab: The Bike Speedometer*

Note that this is a long Pre-Lab. Because of its length, this Pre-Lab is worth 30 points rather than the usual 15.

**A Bit of History**

In this lab you'll use a bike speedometer to make most of your measurements. The Pre-Lab focuses on the basics of how a bike speedometer works. This Bit of History might even motivate you to go out and purchase one of these items for yourself.

Did you know that you can get a speeding ticket on a bike? Obviously, this is a relatively rare occurrence, but the *Seattle Times* has a pretty interesting article about a speed trap set up in a 20-mph school zone that was nabbing bicyclists along with drivers. (See the Pre-Lab Links page on the lab website if you're interested.) According to the article, about 1% of traffic citations meted out by Seattle police go to bicyclists.

These days it may sound ridiculous that a bike could get a speeding ticket considering how fast cars can move. However, the first speeding tickets given to motor vehicles were for speeds that are timid even for a bicycle. In fact, the world's first speeding ticket (given in the UK in 1896) was awarded to a driver moving at 8 mph in a 2-mph zone!

**Understanding the Bike Speedometer**

Most measurements you record in lab this week will come from a bike speedometer. Obviously, the bike speedometer is a natural tool for measuring how fast a wheel on a bike is spinning. What might not be so obvious is how the bike speedometer actually works. The topic of this lab is energy, but that doesn't mean we can't get into some bonus physics by setting up the bike speedometer.

Here are the basics about how the bike speedometer works. Let's say you're riding down the road at 10 km/h. If you have set up your speedometer correctly, it will tell you that you are riding down the road at 10 km/h (~6 mph). But the speedometer is not directly measuring your speed; rather, it directly measures the angular speed of your wheel and then calculates the speed of your bike from there. The speed, $v$, of the center of a rolling wheel is related to its angular speed, $\omega$, through the relationship $v = r\omega$ where $r$ is the radius of the wheel. That leaves us with two new questions. First, how does the speedometer determine the angular speed? Second, how does the speedometer know the radius of the wheel?

Let's answer the first question first. The bike speedometer consists of three big parts: a computer, a magnet, and a sensor. The computer goes on your handlebars. That's where math is done. That's what tells you the speed. That's what most people pay attention to. But there's interesting physics down below, on and around the wheel, where the magnet and the sensor live. When you set up the device, you have to attach a magnet to a spoke of the wheel and you have to attach the sensor to the bike such that the magnet will pass by it as the wheel turns (Figure 1). In the second semester of physics you will learn that moving magnets can create some interesting effects that we won't worry about right now. Using such effects, the sensor can easily see the magnet each time it passes. Calculating the angular speed from that information becomes quite easy. For example, if one second elapses between consecutive sightings of the magnet, the speedometer knows that the angular speed of the wheel is 6.28 rad/s. Now you try!

PL1. What's the angular speed of the wheel if 0.43 s elapses between successive passes of the magnet?

We are now only left wondering how the speedometer knows the radius of the wheel. That's easy! The user simply enters that information. But in our case there is a twist…

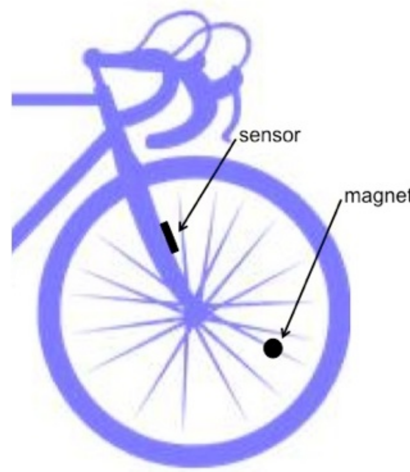

**Figure 1:** The standard arrangement of the sensor and magnet.

**Setting Up the Bike Speedometer**

Under normal circumstances, the instructions for our Schwinn speedometers go like this.

a) Measure the diameter of the wheel in millimeters.
b) Multiply that number by 3.1416 to find what Schwinn refers to as the *wheel factor*.
c) Enter the wheel factor into the computer.

Before we move on, let's answer some questions about that process.

PL2. What is the geometric meaning of the wheel factor?

PL3. What is the wheel factor of a wheel with a diameter of 26 inches?

PL4. Let's say you entered the wheel factor in inches rather than millimeters. How would this affect the reading on the speedometer?

PL5. Why are there not specific instructions regarding the radius at which to place the magnet and the sensor?

PL6. This speedometer can display the distance that the bike has traveled. But the speedometer does not directly measure the distance traveled. Rather, it measures the number of times that the wheel has turned. How can one calculate the distance the bike has traveled given the number of times that the wheel has turned?

**Read This:** Now that you understand the standard installation of the bike speedometer, the twist can be revealed… (Drum roll, please!)

**The Twist**

In order to improve the accuracy of this experiment, the installation of the bike speedometer has been modified slightly. Instead of placing a single magnet on the wheel, we have placed ***three*** magnets equally spaced around the wheel (Figure 2). That is, the sensor sees a magnet three times for each turn of the wheel. This allows us to read slow speeds more accurately than with standard installation, but it also requires a bit of cleverness when entering the wheel factor. The usual instructions just won't work.

> PL7. You will be using a bike with 26-inch diameter tires and three magnets equally spaced around the wheel. What wheel factor should be entered in order to "trick" the speedometer into reporting an accurate speed.

**Figure 2:** The bikes in lab have three magnets on the spokes.

**Getting to Know Our Bikes**

When you get to lab, you will find a bicycle which has been mounted on a stand. Typically these stands are used by cyclists who want to turn their standard bicycle into a stationary bike which they can use to exercise indoors. Other than the stand, the only modification to the bicycle is the replacement of the pedal with a *pedal bar.* This pedal bar will allow us to easily attach weights to the bicycle where the pedal would normally be located.

The basic idea of this lab is to see what the rear wheel of the bike does when you put masses on the pedal bar and let them fall. You'll be thinking about energy the whole time, and you'll use the bike speedometer to take measurements.

**Applying Conservation of Energy to the Bicycle: How and Why?**

We have a closed system (bike, hanging mass, earth). And we want to predict details of a final state given knowledge of an initial state. Conservation of energy can be a wonderful tool for such a problem. Let's look at this example in detail to better understand what we'll be up to in lab.

You have a bike that is on a stand that allows its rear wheel to spin freely. Let's say we hang a 2-kg aluminum disk from the pedal of the bike such that the crank begins horizontal (Figure 3). Initially, everything is static.

Then we let the mass fall, causing the back wheel to start spinning. When the aluminum disk reaches its lowest point, the wheel is spinning at its maximum speed and the aluminum disk has a small velocity to the left (Figure 4). There are other parts of the bike (like the chain and the crank) that are also in motion, but their speeds and masses are small enough to ignore without sacrificing much accuracy.

**Figure 3:** The initial (static) state of the system.

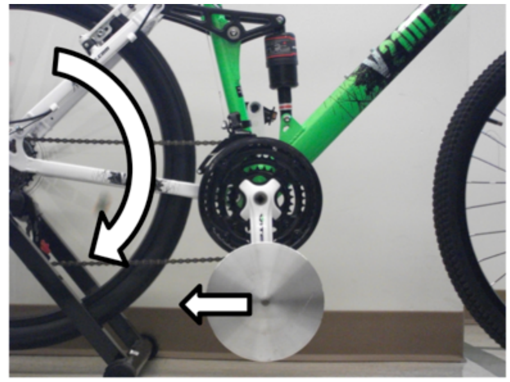

**Figure 4:** The final (dynamic) state of the system.

**Do This:** There is a video on the Pre-Lab Links page that shows the system in motion. Find and watch this video so that the initial and final states are entirely clear.

**Read This:** Now that we have defined the system, its initial state, and its final state, we can start thinking about where the energy is in each state. (All of these definitions are shown in Figure 3, Figure 4, and the video on the Pre-Lab Links page.)

PL8. In the initial state, what parts of the system have kinetic energy (or rotational kinetic energy)?

PL9. In the final state, what parts of the system have kinetic energy (or rotational kinetic energy)? Remember that we are ignoring light parts moving at low speeds like the chain and the crank.

PL10. Which part of the system undergoes a substantial change in gravitational potential energy between the initial and the final state?

PL11. There is a small amount of kinetic friction as the disk falls. Into what form of energy does kinetic friction convert mechanical energy?

PL12. Conservation of energy says that the energy in the system in its initial state is equal to the energy in the system in its final state. Choose the best mathematic expression of this statement, taking into account your responses to PL8 through PL11.

**Read This:** What's incredible is that the details regarding how the initial state evolves into the final state are not especially important. And if there is no friction, the details are not important at all!

**Read This:** But are there other approaches we could take? For example, why not use Newton's laws? Well, such an approach would be very difficult given the surprisingly complicated forces and torques involved in this problem. The torque that the disk exerts on the wheel is constantly changing as the disk falls. And the multiple gears being used can make the mathematics get clumsy quickly. Newton's laws are valid, but they are completely impractical.

**Read This:** In the final state (Figure 4) we realized two things that we will actually decide to ignore for most of this lab.

**Read This:** First, things warmed up due to friction. However, these bicycles do a pretty good job at eliminating friction, so ***we can ignore the effects of friction as the mass falls***. Ignoring friction works better as the size of the falling mass increases. For masses under about 200 grams, the weight of the mass can't overcome static friction and the mass won't even fall!

**Read This:** Second, we noted that the disk is moving slowly to the left in the final state. However, the final kinetic energy of the disk only accounts for approximately 2% to 5% of the final mechanical energy of the system. (Exactly how much depends on the gearing and the mass of the disk. The percentage of energy in the disk increases as the mass of the disk increases. So this approximation gets worse as the hanging mass increases.) The back wheel contains the vast majority of the kinetic energy of the final state. Thus, ***we can ignore the final kinetic energy of the falling mass.***

PL13. Taking into account these two approximations, how can we rewrite the expression from PL12?

**Read This:** These approximations will introduce error that may cause theoretical and experimental results to differ by several percent, but they simplify the problem tremendously. The accuracy that we sacrifice is worth the simplicity that we gain. It is interesting to note that one approximation gets better as the falling mass increases while the other approximation gets worse as the falling mass increases.

**Moment of Inertia**

One of the major goals in this lab will be to determine the moment of inertia of the bike's rear wheel. The moment of inertia is to rotational dynamics what the mass is to linear dynamics. Something with a large moment of inertia is hard to get spinning just like an object with a large mass is hard to get moving. Though the name is cryptic and the formulas occasionally complicated, the moment of inertia is just like the "rotational mass." (A common mistake is to refer to the "moment of inertia" simply as "inertia." This is false. It is the mass of an object that quantifies the inertia. You should not shorten the term "moment of inertia.") Since the moment of inertia is a notorious sticking point for Intro Physics students, we will conclude the Pre-Lab with a couple of relevant calculations.

PL14. What is the moment of inertia of a uniform solid disk with a mass of 500 grams and a diameter of 12 cm rotated about its central axis (Figure 5)? (Draw a picture! It helps!)

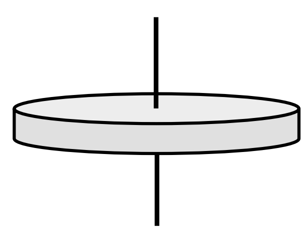

**Figure 5:** The disk from PL14. The vertical black line shows the axis of rotation.

PL15. What is the moment of inertia of a uniform solid sphere with a mass of 2.2 kg and a diameter of 30.5 cm rotated about an axis that passes through its center of mass? (Draw a picture! It helps!)

## *End of Pre-Lab*

# Part I: Max Speed

**The Story**

You have a brand new bike with a brand new speedometer. Plus you have some brand new knowledge regarding the Law of Conservation of Energy that you have just discussed in Introductory Physics. You wonder, "Is there any way that I can put all of these brand new things together?" Well, by some measures, the bicycle is among the most efficient means of transportation that has ever been devised by man or nature. That makes a bicycle a very natural tool to use in order to learn more about energy and its conservation.

**Equipment**

- Bicycle with speedometer
- Disk masses (4 large and 1 small)
- Digital balance
- Measuring tape

STOP

**Read This:** Your bicycle can be dangerous if you are not careful. Please keep your hands and arms away from any moving parts. The aluminum disks can also be potentially dangerous. Please avoid using the portion of the table that is below the crankset.

**1. Effect of Changing Mass and Height on the Max Speed**

This first set of experiments will investigate how the varying properties of the falling mass affects the maximum speed of the rear wheel. But before you begin looking at energy, you need to make sure that the gears are set up correctly.

**Do This:** The gear shifters are located on the handlebars. The left shifter changes the front gear. Make sure the chain is on the **<u>largest gear in the front (#3)</u>.** To change the gear, **SLOWLY** crank the pedals forward using your hand. At the same time, click the gear shifter until the desired setting is achieved. Next, make sure the chain is on the **<u>smallest gear in the back (#7)</u>.** The gear shifter on the right will change the back gear. Ask your TA if you are having trouble.

**Read This:** Now that your bike is properly adjusted, it's time to start learning about energy.

**Do This:** Begin by adding 2 large masses to the pedal. Then raise the mass until the crank is horizontal according to the bubble level on the crank. (You can raise the mass directly or you can use the back wheel.) Let the mass fall. Observe all the moving parts just to make sure that everything matches the pictures and video from the Pre-Lab. No data need to be taken.

**Do This:** Use ***R*** to put the bike speedometer on the MXS setting. **(See Appendix A for details regarding the bike speedometer.)** Reset the maximum speed by holding ***L***. Make sure there are still 2 large masses on the pedal. Raise the mass counter-clockwise such that the crank is horizontal as shown in Figure 3. Then let the mass fall.

**Checkpoint 1.1**: Record the maximum speed achieved by the wheel as the 2 large masses fall. Repeat this measurement two additional times. (Reset the maximum speed by holding ***L*** after each trial.) Finally, compute the average.

**Read This:** What are you measuring here? If your bike were rolling, the speedometer would show you how fast the whole bike is moving forward. Since the bike is on the stand, ***the speedometer is actually telling you how fast a point on the circumference of the wheel is moving***. That information, along with the radius of the wheel, can be used to determine the angular speed of the wheel. (The diameter of each wheel is 26 inches.)

**Read This:** Why did you do multiple trials in Checkpoint 1.1? When possible, conducting multiple trials and using an average value helps you get a more reliable best guess value of a quantity. Further, the variation you see from trial to trial can give you a good idea of the uncertainty in your measurement. This is especially important when the variation from trial to trial is larger than what you might expect by simply looking at the instrument. For example, the last digit that these bike speedometers show is 0.1 km/h. Thus, you might expect the uncertainty in your measurement to be 0.1 km/h. However, when you perform multiple trials of this particular experiment, you may see discrepancies that are larger than 0.1 km/h, suggesting that the uncertainty is not only due to the precision of the speedometer.

**Checkpoint 1.2**: *Predict* what maximum speed will be achieved if the previous experiment is repeated using 4 large masses on the pedal instead of 2. Discuss your reasoning.

**Checkpoint 1.3**: Test the prediction you made in Checkpoint 1.2 with an experiment. Make sure you perform at least three trials. Record each maximum speed and compute the average.

**Checkpoint 1.4**: Given your data from Checkpoint 1.3, was the prediction you made in Checkpoint 1.2 accurate? (Consider the percent difference between your theoretical and experimental values.) If not, discuss why your observations may have differed from your predictions.

**Do This:** Remove 2 large masses from the pedal such that there are 2 large masses remaining.

**Checkpoint 1.5**: *Predict* what maximum speed will be achieved if you raise the mass on the pedal such that the crank is nearly vertical and let the mass fall. Discuss your reasoning.

**Read This:** Please be especially careful when you place the crank arm in a nearly vertical position. If the masses happen to fall left (counterclockwise) they can fall very fast, which could be very dangerous. Ask your TA if you would like clarification.

**Checkpoint 1.6**: Test the prediction you made in Checkpoint 1.5 with an experiment. Make sure you perform at least three trials, and make sure you a very careful. Record each maximum speed and compute the average.

**Checkpoint 1.7**: Given your data from Checkpoint 1.6, was the prediction you made in Checkpoint 1.5 accurate? (Consider the percent difference between your theoretical and experimental values.) If not, discuss why your observations may have differed from your predictions.

S1

**Synthesis Question 1 (30 Points):** Pick one of the two experiments of Section 1 to report on in detail. That is, you can discuss the effects of varying the falling mass or the effects of varying the height from which the mass falls. Your response should include the following:

- Procedure
- Clearly displayed data
- Theoretical value with an explanation
- Quantitative comparison between experimental and theoretical values
- Discussion of specific ***sources of uncertainty*** in your experiment that might lead to differences between your theoretical and experimental values
- Discussion of specific ***approximations*** in your theory that might lead to differences between your theoretical and experimental values

## *Part II: Moment of Inertia*

### 2. Finding the Moment of Inertia of the Rear Wheel

It turns out that this little game we've been playing is a pretty good way to determine the moment of inertia of the bike's wheel. This part of the lab will touch on quite a few topics including energy, rotational motion, unit conversion, and graphical analysis.

**Checkpoint 2.1:** We know that the falling mass loses gravitational potential energy as it falls, energy that is transformed into the rotational kinetic energy of the rear wheel. Do some algebra to show that the potential energy lost by the falling mass should be proportional to the *square* of the final angular speed of the rear wheel.

**Read This:** That means that if you make a plot of $\omega^2$ as a function of the potential energy lost by the falling mass, you should get a straight line that passes through the origin. See the Reference page to find documents that give pointers on plots.

**Checkpoint 2.2:** What should the slope of the line be (algebraically)? How is the slope related to the moment of inertia of the rear wheel?

**Read This:** You are about to make a plot where you fit a curve to data. Instructions for how to use Logger Pro to make a plot can be found on the Reference page of the lab website. These instructions show you how to enter data, label axes, add a title, fit a curve, and make it all legible to your TA. Please do not use Excel to produce your plot.

**S2**

**Synthesis Question 2 (35 Points):** Perform and report on an experiment to determine the moment of inertia of the rear wheel of your bike. Your response should include the following:

- Procedure
- Data table (you may be able to reuse some old data)
- Plot with a linear fit to at least five data points. Make sure the independent variable is on the x-axis.
- A value for the moment of inertia deduced from the slope of the fit
- Discussion of the significance of the y-intercept of the linear fit (alternatively, the x-intercept could be discussed)

**3. Plausibility Arguments**

It's probably not easy to decide whether or not that's a reasonable value for the rear wheel's moment of inertia. The remaining steps in this part will help you figure that out.

**Read This:** The mass of the bike's front wheel is about 2.0 kg. The mass of the rear wheel is about 2.8 kg. The diameter of each wheel is 26 inches.

**Checkpoint 3.1:** Why do the front and rear wheels have different masses? Discuss the main difference between the wheels.

**Checkpoint 3.2:** Calculate an approximate value for the moment of inertia of the rear wheel.

**Checkpoint 3.3:** Compare your calculated value to your experimental value. If they are not within about 20% of each other, you should consult your TA.

**S3**

**Synthesis Question 3 (20 Points):** Comment thoroughly on the plausibility of your experimental value for the moment of inertia of the rear wheel. That is, provide a convincing argument that your experimental value for the moment of inertia of the rear wheel makes sense.

## *Part III: Gears*

In all of the previous experiments you used the combination of gears that led to the disk masses falling as slowly as possible. Such a slow fall allowed us to ignore the kinetic energy of the disks while introducing an error of only a few percent between our theoretical and measured values. However, if we use lower gears, this approximation breaks down.

**4. The Effect of Changing Gears**

Hopefully your chain has been on the largest gear in the front and the smallest gear in the back. If not, this would be a good time to alert your TA so that you can figure out if you need to modify these instructions.

**Do This:** Using the gear shifter on the left side of the handlebars, move the chain to the smallest gear in front. (Keep in mind that you have to pedal forward as you change gears.) Using the shifter on the right side of the handlebars, move the chain to the largest gear in the rear. This should make the crank easier to turn.

**Do This:** Do what you have to do to hang a total of 2 large masses on the pedal.

**Read This:** You are about to repeat the experiment you performed in Checkpoint 1.1 but with this new gear setting.

**Checkpoint 4.1:** *Predict* whether the new maximum speed will be less than, equal to, or greater than the max speed that you found in Checkpoint 1.1. Think about energy. Don't think about forces or torques or anything like that. Discuss your reasoning.

**Checkpoint 4.2:** Test the prediction you made in Checkpoint 4.1 with an experiment. Make sure you perform at least three trials. Record each maximum speed and compute the average.

**Checkpoint 4.3:** Given your data from Checkpoint 4.2, was the prediction you made in Checkpoint 4.1 accurate? If not, discuss why your observations may have differed from your predictions.

**S4**

**Synthesis Question 4 (15 Points):** Using an argument hinging on the Law of Conservation of Energy, explain why the speed found in Checkpoint 4.2 should be slower than the speed found in Checkpoint 1.1. Then cite data that supports your conclusion. The words "force" and "torque" should NOT appear in your response. You should be solving this problem by considering energy. You will get no credit for this question if your response contains "force" or "torque."

## *Time to Clean Up!*

Please clean up your station according to the Cleanup! Slideshow found on the lab website.

# *Appendix A: Operating the Bike Speedometer*

**The Basics**

The bike speedometer has two buttons on it. The button on the left will be referred to as ***L***. The button on the right will be referred to as ***R***. For the most part, ***L*** is used for resetting values and ***R*** is used for switching from mode to mode.

The computer will always display two values. The big number is the instantaneous speed of the bike in km/h. The value below the line in the bottom-right portion of the screen can be lots of different things depending on the setting of the computer. The computer has seven settings. You will only need to use **MXS**. Here are the settings in order of appearance.

- **ODO**: Odometer: It tells you how far the bike has traveled in km since the battery was put in the computer.
- **DST**: Distance: The distance the bike has travelled in km since the last time this feature was reset. Reset by holding ***L***.
- **MXS**: Max Speed: This shows the highest speed that has been achieved in km/h since this feature was reset. Reset by holding ***L***.
- **AVS**: Average Speed: This displays the average speed in km/h since this feature was reset. Reset by holding ***L***.
- **TM**: Time: This is a stopwatch that can be reset by holding ***L***.
- **SCAN**: Scan: This will run through all of the settings, staying on each one for a few seconds.
- [Blank]: This is a clock.

**If the Battery Dies**

If the battery dies, you'll need to re-enter the wheel factor upon replacing the battery. The default setting is *2124*. You want to enter a value of *692*. The *4* in the ones place should be flashing. Pressing ***R*** will cause the flashing digit to increase in value, wrapping around from *9* to *0*. When you change the ones digit to the correct value, press ***L***. This should cause the tens digit to start flashing. Adjust the tens digit with ***R***. Then press ***L*** and set the two remaining digits. If you make a mistake you can remove the battery and start over.

**If Your Speeds Seem Way Off**

If the speeds you measure differ greatly from what people around you are measuring, try resetting the computer by holding down ***L*** and ***R*** at the same time. Then follow the instructions in the above paragraph ("If the Battery Dies").