

## Lab 5.1 – Centripetal Force

### Purpose

To discover and quantify the factors that determine the force required to keep an object in uniform circular motion.  
 To use graphical analysis techniques to derive/verify the equation for centripetal force.  
 To investigate the behavior of friction in circular motion.

**Note: Careful study of Part II of the Lab Guide is essential to your success in this lab. This includes preforming the related activities in that guide.**

### Equipment

Virtual Centripetal Force Lab  
 Grapher  
 PENCIL

### Explore the Apparatus

Open the Virtual Centripetal Force Lab on the website. You'll see a 70's era Technics® direct drive turntable. Surrounding it you should see all its controls and other apparatus.



**Figure 1: Centripetal Force Apparatus**

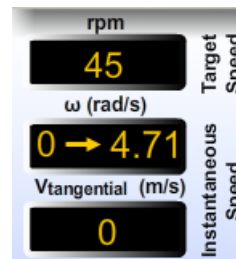
Let's take a trial run. If you're working as a team you'll want to take turns practicing with the apparatus.

## Setting Speeds/Velocities

Click the on/off switch beside the tone arm. It toggles on/off each time you click. You don't have to drag up and down.

With the turntable on, note the three speed indicators. Be sure to experiment with them to learn what each one does.

- When you turn on the motor the **angular speed,  $\omega$**  (radians/sec), changes, indicating an angular acceleration up to the **target angular speed**. (We won't use radians in this lab. And we'll often drop the term "angular" since the context or units are adequate identification.)
- The rpm indicator doesn't reflect this acceleration. It registers the **target angular speed** (in revolutions per minute) set with the speed control knob.
- For now, the **tangential velocity,  $V_T$**  remains at zero since the record as a whole doesn't have a tangential velocity. The tangential velocity is associated with objects (A – D) that you'll put on the record.



If you click on the white dot on the speed adjust knob, you can adjust the target speed from 0-90 rpm. Try it. The record will speed up or slow down to that angular speed when you turn on the turntable.

We want to observe the behavior of small objects in circular motion. We have two types of metal objects to work with – **flat disks**, and **rolling cylinders**. The record is also a disk, but we'll just call it the **record** to avoid confusion.

Turn on the turntable and adjust the target speed to something less than 15 rpm. Drag and drop a disk at a point somewhere near the outside edge of the record. Thanks to friction it should remain in place on the record and revolve at your target speed. Notice that there is now a value in the  $V_T$  display. This is the tangential velocity of the metal disk. We refer to it as a velocity since its direction – tangent to the circular path – is implied in the name. The magnitude of this velocity is the same as the speed in the centripetal force equation,  $F = m \frac{v^2}{r}$ .

Now gradually increase the target speed. At some point you should see the disk fly off the turntable as you'd expect. After three seconds the tangential velocity display changes to read zero, also as expected. Why zero? The tangential velocity is the velocity of an object traveling in a circular path. It's the disk that we're interested in so the  $V_T$  display refers to the velocity of the (center of) whatever disk is on the record. So when the disk slides away, it no longer has a tangential velocity. Why the 3 second delay? In this lab you'll need to know the maximum velocity,  $V_{T, \text{Max}}$  just when the disk slips. For your convenience, that velocity is displayed briefly so that you can write it down. You're welcome.

Later you'll need to adjust the target speed and hence  $V_T$  very precisely. Slow down the turntable and put another disk on the record. Click on the little white knob and try to set the target speed to 15.8 rpm. You'll need to move the knob along a circle such as the one from point 1 to point 2.

Having trouble? Click on the knob again, and then, **with your mouse button still down**, move your mouse radially outward to point 3. Now try setting the speed at 15.8 rpm. That's a bit easier. Try moving farther away from the center of the knob. It's even easier at the greater distance. You can go all the way to the edge of your monitor.

This method works because at greater radii every pixel you move the mouse along the virtual circle corresponds to a smaller change in the angle through which the knob turns. And as long as you keep your mouse pointer down, the knob will remain under your control.

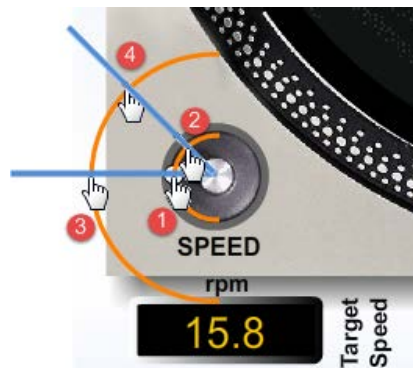


Figure 2: "Chopsticks" Tool

## Disk and Cylinder Masses

You'll need to know the masses of our disks and cylinders. Try the **digital scale** with Disk D. The reading is given in grams. Be sure to convert to kilograms when collecting data. While Disk D is still on the scale, use the Min Mass tool to double its mass. Adjust the Min Mass tool further to see the number of masses available for a given disk.

Drag Disk C onto the scale. Note that when you select a new object, the last one goes back "home."

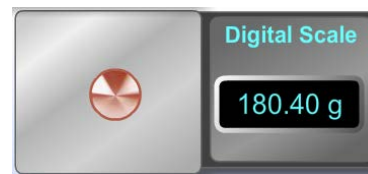


Figure 3: Digital Scale

## Forces

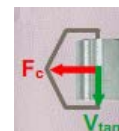
Since this lab is about centripetal force, we'll need some way to determine the amount of that force acting on our disks and cylinders. We can directly measure the force on the rolling cylinders. Turn off the turntable and drag and drop a cylinder onto the record. That's odd. It flies away. It expects to be held in place by the wireless force sensor. (See Figure 1.) Drag and drop the force sensor somewhere near the center of the record. Snap.

Now drag and drop a cylinder onto the record. Like a spider, the force sensor pivots and spits out a length of string to hold it in place.

Turn on the record and note that the sensor rotates with it. The force exerted by the string is recorded on the force sensor display. Try adjusting the speed. The disk doesn't fly off since the string can exert any centripetal force necessary to keep it on the record.

### Dynamic Centripetal Force and Tangential Velocity Vectors

Adjust the speed to between 15 and 20 rpm. Turn off the turntable. Turn the vector display on and off by clicking the toggle switch. (See Figure 4.) Notice the faint green and red plus-shaped image appearing on the cylinder. Turn on the turntable. Turn it back off and then on again. Adjust the speed and note the change reflected in the tangential velocity and the centripetal force vectors.



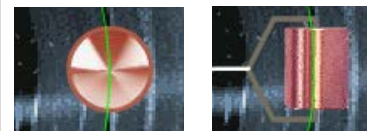
**Figure 4:**  $V_{tan}$  and  $F_c$  vector toggle switch

Reduce the record's target speed to about 15 rpm. Increase the mass of the rolling cylinder with the numeric stepper. When the mass multiplier equals 3 it means that the mass of the object on the record or on the digital scale is three times its initial mass. It's sort of cheating to let you read the mass of the object when it's not on the scale, but this makes changing the mass without changing the radius of revolution a lot easier. You can turn off the vector display now.

So why do we need a rolling cylinder anyway? We need something that can be dragged tangentially by friction with the record so that we can make it move with different tangential speeds. But we don't want friction to act radially. We want the string to exert the radial centripetal force so that we can read its value on the force sensor display. The use of the rolling cylinder eliminates any radial friction force between the cylinder and the record.

### Radius of Motion

Finally, let's see how we measure the radius of the motion of a disk or rolling mass. Stop the record. Turn the radius knob to about 1 o'clock. The green circle's radius is indicated by the radius display. It's in centimeters for convenience, but be sure to convert to meters in your data tables and calculations. It's easy to see the location of the center of a disk. The bright line along the center of a cylinder marks a line through its center of mass. As shown in the figures, you'll measure the radius out to the center of either mass using the green circle. Don't forget that you can zoom in for better precision.

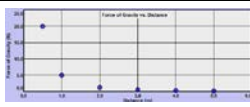
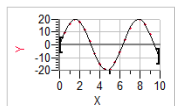


To adjust the radius of the cylinder's path we need to change the length of the string. If you click on the cylinder it will release the string. Drag and drop the cylinder somewhere else and the force sensor and string will readjust.

The disks can be dragged around the same way. Give them a try.

## Part I: Verification of the Equation for Centripetal Force

In your Lab Guide you have detailed information about graphically determining relations between variables. That document includes this summary of the relations often encountered in an introductory Physics course.

Relation between variables	Graph	Equation
1. No relation	Horizontal line	$y = \text{const.}$
2. Linear relation with y-intercept	Straight, non-horizontal line not through origin	$y = mx + b$ m: slope, b: y-intercept
3. Direct proportion	Straight, non-horizontal line through origin	$y = mx$ m: slope
4. Inverse proportion	Hyperbola	$y = 1/x$
5. Quadratic proportion	a. upward opening parabola b. side opening parabola	$y = kx^2$ $y^2 = kx$
6. Inverse square proportion		$y = k/x^2$
7. Sinusoidal		$y = A \sin(x \text{ or } \theta)$ $y = A \cos(x \text{ or } \theta)$ $y = A \tan(x \text{ or } \theta)$

In this lab you'll explore the factors determining the centripetal force acting on a body traveling in a circle. By this point you should have already learned the centripetal force equation relating these factors.

**Your goal in part I of this lab is to use these techniques to verify that  $F_c = m \frac{v^2}{r}$**

As you learned in the Lab Guide and in the Pendulum lab and other labs you can find the relations between  $F_c$  and the mass, for example, by measuring the force for a number of different masses. You'll then plot force vs. mass for this data and if the graph is linear you say that  $F_c \propto m$ . If the graph is not linear you can plot  $F$  vs.  $m^2$  or  $F$  vs.  $1/m$ , etc. until you get a straight line. You'll repeat the process for velocity and radius. The results of this process should verify the proportional relationship found in our  $F_c$  equation. Here's a summary of the process. More details follow.

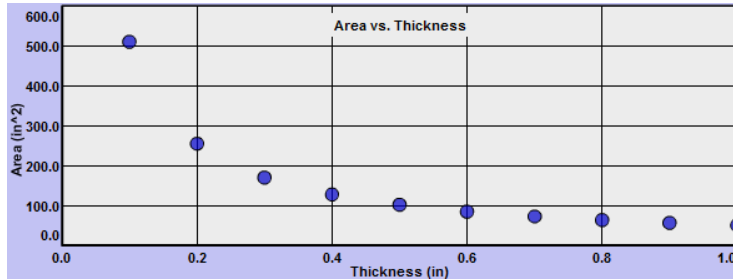
Using the cylinders and force sensor you'll collect and record data for **force vs. mass**, **force vs. (tangential) velocity,  $V_T$** , and **force vs. radius**. In each case you'll need to vary the value of one quantity while controlling (holding constant) the other two. The values you'll use for the controlled quantities are listed below the table number. E.g. velocity and radius I Table 1.

- When investigating the effect of *mass* on  $F_c$  you'll use one cylinder of your choice (A, B, C, or D), one specified velocity, one specified radius, and make measurements for each multiple of its minimum mass ( $M_m \times 1, 2$ , etc.).
- When investigating the effect of *velocity* on  $F_c$  you'll use one cylinder of your choice (A, B, C, or D), a Mass Multiplier of 5, one specified radius, and make measurements for 13 different velocities. Suggested velocities are provided to help you get a good spread of velocities. Just try to get close. Use your chopsticks!
- When investigating the effect of the *radius* on  $F_c$  you'll use one cylinder of your choice (A, B, C, or D), a Mass Multiplier of 5, and make measurements for 10 radii. (Suggested velocities are provided. Just try to get close.)

To determine the relation between each pair of variables (e.g. Force vs. velocity), you'll use the **linearization** technique illustrated in the Lab Manual in section 2.1.4 (area vs. thickness for a given volume of pizza), and 2.1.5 (speed vs. tension for a guitar string). This, of course, won't be necessary in the case of data that is already linear.

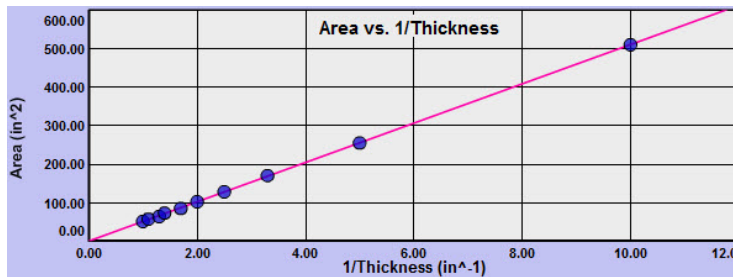
If more than one graph is required be sure to include both the before and after linearization graphs like those shown in Graphs 1 and 2 below. (They're from the Lab Guide.) Only one graph is necessary if the initial data is linear.

Thickness (in)	Area (in <sup>2</sup> )
0.10	510
0.20	255
0.30	170
0.40	128
0.50	102
0.60	85
0.70	73
0.80	64



Graph 1: Area vs. Thickness

1/T (in <sup>-1</sup> )	Area (in <sup>2</sup> )
10.0	510
5.0	255
3.3	170
2.5	128
2.0	102
1.7	85
1.4	73
1.3	64



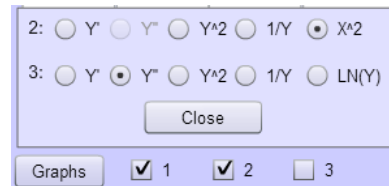
Graph 2: Area vs. 1/Thickness

### Summary

- You are to confirm that  $F_c \propto m \frac{v^2}{r}$
- You should collect and record the **data** and create the graphs necessary to find the relation between **force and mass**, **force and velocity**, and **force and radius**. Include the **original graphs** as well as any successful **linearization graphs** (when needed) to prove each relation.
- Three data tables, along with room to paste your graphs are provided on the three pages that follow.
- Mail in this completed lab when you're finished. You may email your graph images if printing them out is inconvenient. Be sure to use file names that identify each graph clearly.

### Some helpful suggestions

- Remember that when adjusting the speed or radius knobs you need to click and drag away from the knob to make more precise adjustments as illustrated in Figure 2.
- When investigating force vs. velocity you can use the second graph tool to plot force vs. velocity<sup>2</sup>. This eliminates the need to square each velocity value.
- Always click all three Graphs checkboxes to minimize the sizes of the graphs.
- When investigating force vs. radius, you'll have to stop the turntable to make each radius change. Once it's stopped, adjust the radius of the measurement circle to the next radius you want to work with. Then move the mass to center it on the green circle. **Also you'll need to adjust  $V_T$  after each radius change since it must be kept constant.** This is because for a given angular speed, changing the radius also changes the velocity. Don't let your eyes glaze over on that one. It's important. When you arrive at that part of the lab you'll need to experiment with the apparatus to see what this actually means.



### Data and graphs for Part I: Verification of the Equation for Centripetal Force

Table 1 Force vs. Mass		Chosen Cylinder letter: _____	Notes:
Velocity of Cylinder _____ m/s		.383	
Radius of Motion _____ m		.1228	
Trial/Mm $\times$	Mass (kg)	Force (N)	
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

- Enter your data into Grapher. Plot Force vs. Mass. If your graph is linear, you're almost done. Otherwise use your linearization skills to replot it to achieve a linear relationship.
- Check all three Graphs checkboxes to create the smallest possible graph. Be sure and include all labels, units, line of best fit, etc. Take a screenshot of the graph and name it Lab05\_ + some text to identify which graph it is. Ex. Lab5\_Fvsmass.
- Print out and paste your graph in the space below or email it to your teacher along with the rest of the graphs for this lab.

- Look back at the table of seven relations at the start of Part I. What is the relationship between the centripetal force and the mass? State this as an equation using  $k_1$  for the constant of proportionality. No numbers are needed.
-

<b>Table 2 Force vs. Velocity</b>				<b>Chosen Cylinder letter: _____</b>	<b>Mass Mult. = 5</b>
Mass of Cylinder		_____ kg (with Min. Mass set to 5)			
Radius of Motion		.1228 m			
Trial	Sug. Velocity (m/s)	Actual Velocity (m/s)	Force (N)	<b>Notes: (abbreviated)</b> a. Choose a cylinder. Record letter as before. b. Set Mass Mult to 5. Measure and record the cylinder mass. c. Drag and drop the Force Sensor near the center of the record. Place the cylinder on the record. d. Set the radius to approximately the value specified above the table. Adjust the cylinder to that radius. e. Turn on the turntable. Adjust the speed dial until $V_T$ equals approx. the first value listed in the suggested velocity column. Record actual velocity. f. Record the Force Sensor reading. g. With the mass still in place, repeat for a total of 13 trials. h. Create a Force vs. velocity graph with your data. Create and save Screenshot as before. Don't forget labels. i. Use Grapher and your linearization skills to produce a linear graph. Create and save Screenshot. j. Paste both graphs below. Or email.	
1	0.17				
2	0.24				
3	0.32				
4	0.42				
5	0.45				
6	0.5				
7	0.56				
8	0.62				
9	0.69				
10	0.79				
11	0.88				
12	0.96				
13	0.98				

2. Look back at the table of seven relations at the start of Section I. What is the relationship between the centripetal force and the velocity? State this as an equation using  $k_2$  for the constant of proportionality.
-



<b>Table 3 Force vs. Radius Chosen Cylinder letter: _____ Mass Mult. = 5</b> Mass of Cylinder _____ kg (with Min. Mass set to 5) Velocity of Cylinder <u>.3</u> m/s				
Trial	Sug. Radius (m)	Radius (m)	Force (N)	
1	0.060			<b>Notes:</b> (abbreviated) a. Choose a cylinder. Record letter as before. b. Set Mass Mult to 5. Record cylinder mass. c. Drag and drop the Force Sensor near the center of the record. Place cylinder on the record. d. Set the radius to approx. first value listed in suggested radius column. Record actual value. Adjust the cylinder to that radius. Turn on the turntable. e. Adjust the speed dial to set $V_T$ to approx. velocity specified above. f. Record the Force Sensor reading. g. Repeat d-f until all radii have been used. h. Create a Force vs. radius graph with your data. Screenshot and save as before. i. Use Grapher and your linearization skills to produce a linear graph. Screenshot and save. Paste both graphs below. Or email.
2	0.068			
3	0.076			
4	0.084			
5	0.092			
6	0.100			
7	0.108			
8	0.116			
9	0.124			
10	0.132			

3. Look back at the table of seven relations at the start of Section I. What is the relationship between the centripetal force and the mass? State this as an equation using  $k_3$  for the constant of proportionality.

Hopefully you have verified that  $F \propto m$ , and  $F \propto v^2$ , and  $F \propto 1/r$ . It can be shown that if one variable is proportional to several others, it is also proportional to their product. So  $F \propto m v^2/r$ . And  $F = k m v^2/r$   
 In this case, no constant is needed due to the way that we define the Newton in terms the kg, m and s. So we do get the centripetal force equation,  $F_c = m v^2/r$ , that we were seeking.

Let's put this equation to some practical use by using it to help us understand the behavior of cars on slippery roads.



## Part II: Friction Acting as a Centripetal Force

In this course you've learned about several named forces – friction, tension, gravity, etc. What about centripetal force? Is it just another in the list? Consider the string in Part I. Did it exert a tension force or a centripetal force?

Both. When we say that it's a tension force, we refer to the way a stretched string exerts a force on objects attached to each end. When we say that a force is a centripetal force we refer to the way in which the force acts on a body. A centripetal force always acts perpendicular to the velocity of an object. As a result, it causes the body to move in a circle.

We really have two lists.

- Friction, tension, gravity, magnetic, electroweak, strong nuclear...
- Centripetal, normal, conservative, external, internal...

Friction can act as a centripetal force or an external force, but not a normal or conservative force. Gravity is a conservative force and can be a centripetal force.

Get the idea? This isn't some fundamental dichotomy like plants and animals. There are just two different types of terms. The first list contains types of forces. The second describes different ways in which forces are found to act in a given situation.

Let's return to friction and centripetal force. Any body moving in a circle is being acted on by a centripetal force. In the case of a planet in circular orbit (approximately in some cases) the centripetal force is gravitation. Similarly, in one model of the atom, an electrostatic force holds electrons in their orbits around a nucleus. In that situation it's acting as a centripetal force. A car on a curve must be acted on by a sideways force; otherwise it will exhibit its property of inertia by continuing in a straight line into the corn field on the outside of the curve. If the curve happens to be circular, the force required will be a centripetal force. On a level road, the centripetal force is provided by friction between the tires and the road. On a properly banked track less friction or even no friction is required depending on the angle of the track.

There's one last factor to consider when friction acts on a car traveling, without slipping, around a curve – static vs. kinetic friction. The tire is moving, thus it must be kinetic friction, right?

Nope. Let's investigate this using interpretive dance!

1. Place a loose sheet of paper on the table in front of you. Place your palm on the paper. Keeping a little downward pressure, move your hand from side to side, dragging the paper.  
There is *kinetic friction* acting between the paper and the table – they're moving relative to one another.  
What about the friction force between your palm and the paper? That's *static friction*. They're both moving but they aren't moving relative to each other. It's that relative motion that matters.
2. Now starting with your hand above the paper, make a fist, knuckles down. Now again, with enough pressure to grab the paper, slide your knuckles sideways across the table. Same deal.
3. Now instead of dragging your knuckles, roll them back and forth on the paper like a wheel. The paper (sort of) sits still, but your knuckles are moving. Which kind of friction force is this? Neither. Your hand is not exerting a sideways force on the paper. It's just changing which knuckle is pushing down on it. It's the same idea for the idealized case of a wheel rolling at a **constant speed** across a table with no air resistance. The wheel and table exert forces perpendicular to the table – no sideways friction force. Grab a coin and toss it so that it rolls across the paper. There's no relative motion between the paper and the constantly changing point on the perimeter of the coin making contact with the paper.
4. If you now put a motorized toy car on the table and turn it on, it might start from rest and speed up to a constant speed. During startup it needs a forward reaction force to accelerate it. It causes that by exerting a backward force on the table. There's no relative motion between the tire and the table – no slipping. But the tire does push backward on the table. This is a static friction force.  
What about during the motion at constant speed? In order to move against the force of air resistance the car still needs that forward static friction force.  
The only time you'll have a kinetic friction force is if the tires slip – skidding to a halt, sliding around a curve, etc.
5. Finally consider the stresses on the tire.  
First picture how the tire looks when you're at rest – symmetrical from side to side and squashed a bit on the bottom. Now consider the tire when you start to accelerate forward or put on the brakes. We'll not try to describe it, but you can imagine how the tire would be distorted forward or backward respectively. There would be a smaller distortion when traveling at a constant speed against air resistance.

Now how about going around a level curve at a constant speed. It will again have some forward distortion, but there is no net forward or backward force on the car. The road's friction force exactly balances the resistive forces such as air resistance. But it will also be distorted sideways in response to the sideways static friction force exerted by the road.

**When the curve is circular, this component of the friction force will be perpendicular to the velocity, toward the center of the curve. When it just static friction, all's well. But when it's kinetic, we have trouble as you'll see.**

We're going to investigate friction as a centripetal force by looking at a few important issues related to driving on slick roads. If you live in a location that doesn't offer this thrill, count yourself lucky. In any case, "learn and live."

**Important Note: The discussions that follow corresponds to what you might find in a drivers manual and other references. However, a deeper investigation will show that such factors as front wheel, rear wheel, and all-wheel drive will make a difference in some cases. So this information provides just general guidelines. The most important rule for any type of driving is to drive slowly enough that you will not go into a skid when trying to turn or slow down.**

**Disclaimer – this is not intended to be a driver's manual. The intention is to help you understand why your car behaves the ways it does so that you can make safe decisions on normal and slippery roads. The best advice is to err on the side of slower speeds.**

**Driving Question 1.** When driving on a level (flat) curve is your traction affected by the **mass** of your car?

More specifically, if you were rounding a slick curve and you sensed that your car was going to skid would it help to throw some massive object overboard?

In reality this is a very complicated problem since the tires will increasingly distort under greater stress as you take on passengers. Also the car will tip a bit as you go around a curve, putting more of the stress on the outside tires. So a more reliable answer would come from extensive testing under different conditions. But we can reach an approximate answer by ignoring these effects and just assuming that the friction force is given by

$$f_s = \mu_s F_N = \mu_s mg.$$

OK, let's make a prediction.

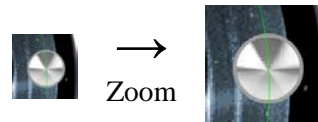
6. A car is rounding a level curve at too high a speed and about to lose traction and slide off the road. If the car had more passengers on board would this happen at the same speed, a lesser speed or a greater speed? Assume that the passengers are evenly distributed within the car. (Circle one.)
- same speed    lesser speed    greater speed

To find out the approximately correct answer we'll let disk A represent our car and vary its mass to see how the maximum tangential velocity,  $V_T^{\max}$  varies with mass. (We're finished with the rolling masses. We need some friction.)

7. Set the Min Mass multiplier to 1. Place disk A on the digital scale. Record its mass in Table 4. Repeat for multiplier values 2 and 3.

Adjust the turntable speed to a very low value and then turn off the turntable so that it will be at rest.

8. Set the Min Mass multiplier to 1.
9. Adjust the radius indicator to 13 cm. (As close as possible.)
10. Place disk A on the record, centered on the green circle. Zooming in helps.



11. Turn on the turntable. You now want to gradually increase  $V_T$  until the disk slips. Remember how you learned to adjust this in very gradual increments by clicking and dragging away from the speed knob and then start to gradually increase the speed? As soon as the disk slips check the red speed value in the  $V_T$  box and record it in Table 4. Reduce the speed and turn off the turntable.
12. Record  $V_T^{\max}$  for two more trials for disk A. Calculate and record their average,  $\overline{V_T^{\max}}$ .
13. Increase the Min Max multiplier to 2 using the numeric stepper. Repeat steps 10-12.
14. Increase the Min Max multiplier to 3 using the numeric stepper. Repeat steps 10-12.
15. For our disk, the centripetal force,  $F_c = mv^2/r$ . Calculate and record  $F_c$  for each mass. Use  $\overline{V_T^{\max}}$  for your velocity.

Table 4 $V_T^{\max}$ vs. mass					
Fixed radius <u>    .13    </u> m					
Min Mass #	mass (kg)	$V_T^{\max}$ (m/s)		$\overline{V_T^{\max}}$ (m/s)	$F_{\text{centripetal}}$ (N)
1					
2					
3					

16. Based on your data, does  $V_T^{\max}$  depend on the mass of the object under our ideal circumstances? \_\_\_\_\_

17. Does  $F_c$  depend on the mass of the object? \_\_\_\_\_

So why aren't both answers the same? Let's get this straight.

- Place your disk at the fixed radius you used above. Set the mass multiplier to 1. Gradually speed up to a bit below your lowest  $V_T^{\max}$ . The disk should stay on the record.
- Increase the mass multiplier from 1 up to its maximum value of 10. The disk still doesn't slide away! The disk was just at the point of slipping and you added 9 times as much mass and you know that more mass requires more centripetal force. But still it doesn't slip.

So how is this possible? How is the centripetal force able to just increase as needed?

18. It keeps increasing because it's a centripetal force and a \_\_\_\_\_ force.

If you're having difficulty with that question go back to the discussion in the first several paragraphs in Part II. After some review you should be able to answer the following question too.

19. Starting with  $F_s = F_c$ , explain why the mass does not matter in this situation.

---



---



---

So let's have a second look at our initial question for this section.

20. A car is rounding a curve at too high a speed and about to lose traction and slide off the road. If the car had more passengers inside would this happen at the same speed, a lesser speed or a larger speed? Assume that the passengers are evenly distributed so that that's not a factor. (Circle one.)

same speed    lesser speed    greater speed

**Driving Question 2.** When you feel that your car may begin to skid on an **icy curve**, what should you do to maintain control of your car?

We just found that ejecting a passenger won't work since mass is not an issue. And it's rude. What other factors are there?

At any given radius and speed there's a specific centripetal force required to keep you in your circular path:  $F_c = mv^2/r$

**So if the radius of your path gets small enough, or your speed gets large enough, the centripetal force required will become greater than the maximum static friction force available.**

If you change your path or speed so that you don't have enough static friction what will happen?

21. If your new motion requires that  $F_c > f_s^{\max}$ , you will begin to \_\_\_\_\_. When this happens, the friction force changes from \_\_\_\_\_ friction to \_\_\_\_\_ friction. Since  $\mu_k$  \_\_\_\_\_  $\mu_s$ , you will have much less friction available than before. So you'll probably slide along out of control until some new force acts. Gulp.

So, if you sense that you're about to go into a skid why not just put on your brakes? Slowing down will result in your needing less centripetal force so wouldn't that be a good idea? If you're right at the skidding point and you put on your brakes, the tires will almost certainly skid, since you've changed their speed relative to the road. So they're no longer acting like your

rolling knuckles. As you hopefully said above, the friction force changes from static to kinetic friction. And of course, hitting the accelerator would be worse. You'll again slide and may pick up a bit more speed. Not what you want!

There are a number of factors to consider **before** and **after** you begin to skid and they depend on such things as front wheel, rear wheel, or four wheel drive, etc. So there are no one size fits all answers to how to drive on slick surfaces. But a clear understanding of how friction works may help us be a more proactive driver. Again, there is no foolproof advice, but there are some general guidelines that are worth knowing about. Here's one that's often cited for dealing with slippery curves. See if you can follow the logic.

*"If your car starts to skid, turn the steering wheel in the direction of the skid. Let your foot off the gas pedal but don't hit the brakes. Keep your wits and in many cases you can regain control of the car before you hit anything."*

Turning in the direction of the skid sounds counter-intuitive. What exactly does it mean? And how can that work? For starters, let's consider why you're about to slip? Suppose you're traveling along a straight stretch (Point A in Figure 5) and the road starts to bend into a counter-clockwise circular turn. Everything is fine at Point B, but at Point C the road has become icy – maybe the road is shaded and the sun has not prevented ice from forming. You feel that the car is not responding the same as it was at point B. The wheels are pointed a bit to the left, parallel to center line, but the car is starting to move toward the side of the road. It's like you've lost your ability to steer. Yikes! What to do?

In Figure 5 the hollow box at point C represents your sliding car. Its wheels are still turned a bit to the left as they always would be to make the turn. But that's not working now since you're sliding already. Here are your other two choices.

- Turn your wheels more to the left (which would produce the red curve, #1) to try to keep the car on the road. This is what everyone's brain suggests the first time it confronts this dilemma.
- At point C your wheels are pointed somewhat counterclockwise of the direction the car is aimed. Turn them a bit to the right to align with the direction the car is headed. This would produce the green curve which is obviously irrational. Right?

Choice 1 is a terrible idea since it aims for a tighter turn than the one that's already failed. Choice 2 takes you in the direction you want to avoid. But it has two possible advantages.

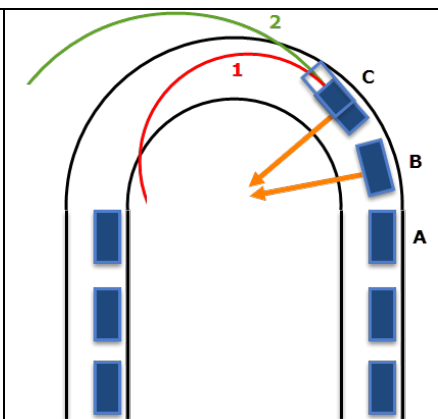


Figure 5

- Your car can maintain traction in this larger circle because you aren't trying to turn in such a tight circle. (Larger  $r$ , less  $F_c$  required.) And this buys you a little time. And if you take your foot off the gas, air resistance, and other non-brake-related forces can slow you down a bit without the use of your brakes. So you have a larger radius and decreasing speed. Both of these require less centripetal force, which means less required friction force. Once you've slowed down a bit you have a better chance that you can turn in a tighter circle, like #1, and head back toward the path you need to be on.
- Often the apron of the highway will have a rougher surface which provides some additional friction. So seemingly irrational choice #2 can **sometimes** improve the outcome of this dangerous situation.

**But...** You can't take advantage of this maneuver if it would endanger anyone on the side of the road or take you into worse danger such as a big drop off beside the road. But in the second case there would generally be a guard rail. How about the three car snapshots on the left side of the Figure 5? Would it work for the driver of that car? Think about it. For two-way traffic this maneuver would send the car on the inside lane into the outside lane! This would be very dangerous unless there is clearly no oncoming traffic. Note also that this car is already at a disadvantage due to the smaller-radius inside lane. **This driver should be going slower than the other driver. I'd bet that you couldn't find one person who knows that!**

Hopefully, having read this, you're smarter already about driving on slick roads. Fortunately engineers take this sort of information into consideration when designing modern highways. But the key take-away is that this is really dangerous business. Stay off of slick roads if you can. If you can't, just take your time. And remember, the slickness is not uniform.

Let's give the two choices a try with our apparatus. You'll use Disk B for this part. The combination of Disk B and the vinyl record have a specific static friction coefficient. So there is a maximum amount of static friction that they together can provide. And this maximum amount does not depend on the particular situation. It's fixed at

$$f_s^{\max} = \mu_s F_N = \mu_s m_{\text{disk}} g.$$

You'll be asked to determine  $\mu_s$  for this disk a little later. So be thinking about how to find it.

22. Measure and record the mass,  $m_{\text{disk}}$ , for Disk B in Table 5.
23. We'll start with Path 0 – the middle path that follows the curve of the road. Adjust the radius to about 10 cm. Record the actual value in Table 5 in the Path 0 row.
24. Center Disk B on the green circular line.
25. Experimentally determine  $V_T^{\text{max}}$  for this case by speeding up until the disk slips. Record your  $V_T^{\text{max}}$  in Table 5. This represents the path where you stay in your lane rather than taking a smaller or larger radius path. **Note also that  $V_T^{\text{max}}$  is the maximum speed you can have along that path. That's important in what follows.**
26. Consider a path like Path #1. That is, one a bit smaller in radius than Path 0. Maybe 8 or 9 cm in radius.
27. Will  $V_T^{\text{max}}$  be larger or smaller this time with the smaller radius? \_\_\_\_\_
28. Experimentally determine  $V_T^{\text{max}}$  for this case. Record  $V_T^{\text{max}}$ . Think about how this compares to Path 0.
29. Consider a path like Path #2. That is, one a bit larger in radius than Path 0. Maybe 11 or 12 cm in radius.
30. Will  $V_T^{\text{max}}$  be larger or smaller this time with the larger radius? \_\_\_\_\_
31. Experimentally determine  $V_T^{\text{max}}$  for this case. Record  $V_T^{\text{max}}$ . Think about how this compares to Path 0.

Table 5 $V_T^{\text{max}}$ 3 curvatures			
Disk B mass _____ kg			
Path	Radius (m)	$V_T^{\text{max}}$ (m/s)	Static Friction Coefficient $\mu_s$
0			
1			
2			

32. Using your data from **one** of the three trials, determine the static friction coefficient of the vinyl/disk B material combination. Enter your value in the appropriate space in the table above. (Path 0, 1, or 2.)
33. Show your calculations of this  $\mu_s$  value in the space below. You should be able to figure that given that you've learned that static friction provides the centripetal force on non-banked roads... and vinyl records. You will have to think about this one, but here's a good starting point.

$f_s = F_C$	$F_C = mv^2/r$	$f_s^{\text{max}} = \mu_s F_N = \mu_s m_{\text{disk}} g$
-------------	----------------	--