## Section 7

## Centripetal Force: Driving on Curves



## Learning Outcomes

In this section, you will

- Recognize the need for a centripetal force when rounding a curve.
- Predict the effect of an inadequate centripetal force.
- Relate speed to centripetal force.


## What Do You Think?

You are driving along a road at the posted speed limit of $50 \mathrm{mi} / \mathrm{h}$ $(80 \mathrm{~km} / \mathrm{h})$. A road sign warns that you are approaching a curve and tells you to slow down to $25 \mathrm{mi} / \mathrm{h}(40 \mathrm{~km} / \mathrm{h})$.

- Why is the sign indicating to slow down?
- How is the amount you should slow down determined?

Record your ideas about these questions in your Active Physics log. Be prepared to discuss your responses with your small group and the class.

## Investigate

In this Investigate, you will model some of the problems a driver faces when driving around curves. You will investigate how speed and the tightness of a curve can affect what happens to a vehicle on a curve.

1. Driving around a curve produces some unique problems. Physics lets you model some of these problems.
دa) Imagine that you have a toy car at the end of a string, and it is moving in a circle. If you let go of the string, which way would the car travel? The diagrams on the following page show several possibilities.


In which direction do you think the car will travel? Write your choice and how you made your decision in your log.
2. The best way to check your answer is to try out the model. That is what it means to do science. Tie a motorized toy car to one end of a string. If you do this on a table, the string should be a little less than half the width of your table. (You can use a longer string if you do this on the floor.) With a finger, hold the other end of the string fixed to the tabletop. Turn on the car's motor, so that the car travels in a circle with your finger at the center, as shown in the diagram.


دa) The string makes the car travel in a circle. In which direction does the string pull on the car? This pull is referred to as a force in physics. Understanding forces is a topic that you will return to many times in this course and every future physics course.

Db) Now release the string. Which way does the car travel when it is released?
3. As you know, there is no string attached to a real automobile when it makes a turn, but there must be a force (like the force of the string) that keeps it moving in a circular path. The pull or force toward the center of a circular curve is the friction between the tires and the road. On an icy road, there is very little friction and the automobile cannot move in a curve and continues in a straight line. You can learn more about friction and how to measure friction in another chapter.
(a) Draw a diagram of an automobile traveling north and making a right turn. On your diagram, draw the direction of the frictional force that keeps the car moving in a circular curve.
4. To further investigate the factors that determine whether an automobile will stay on the road as it goes around a curve, you will do a second investigation. Place a block of wood near the edge of a turntable (or revolving tray).
(a) Record the distance from the block to the center of the turntable. This is the radius of the curve.
5. Spin the turntable. As it spins, the block is held on the spinning surface by friction. (In other words, the block is prevented from sliding off the turntable by friction. If the friction suddenly disappeared while the block was rotating, it would be similar to letting go of the string of the motorized toy car.) This friction between the block and the surface of the turntable
is not identical to the friction that holds an automobile on the road, but it is similar to the friction between the surface of the road and an automobile's tires.

6. Gradually increase the rotational speed of the turntable until the block just begins to slide. To repeat the experiment after the block slides, place it back on the turntable at the original distance from the center. Now practice until you find the fastest speed that allows the block to stay in place.
دa) Measure and record the time required for 10 revolutions.
b) Record the number of revolutions per minute made by the block when the friction is strong enough to keep the block going in a circle.
دc) How much time goes by during one revolution?
d) How fast (revolutions per second) is the turntable turning when friction can no longer hold the block in place?
7. To calculate the speed of the block, divide the distance traveled by the time needed to go that distance.
When an object moves in a circle, the distance traveled in one revolution is the circumference (distance around the outside) of a circle.
Circumference $=2 \pi \times$ radius of circle

$$
C=2 \pi r
$$

دa) What was the speed of the block when it stayed on the turntable?
B) What was the block's speed when it slid off the turntable? Record your results in a table in your log.
Note: You may not be able to find the exact speed at which the block leaves the turntable. You can find a maximum speed at which the block stays in place. You can call this a safe speed. Any speed lower than the safe speed will also be safe. You can also find the minimum speed at which the block is not able to stay on the turntable. You can call this an unsafe speed. Any speed higher than this will also be unsafe.
8. Tape some sandpaper or place a rubber mat on top of the turntable. Place the block on the sandpaper or the mat. Repeat the entire investigation. Keep the distance between the block and the turntable's center the same as it was previously.
a) Record all the necessary data.
b) Calculate the greatest speed at which the block can stay on the sandpaper or rubber mat.
dc) Compare the maximum safe speed with the sandpaper or mat to the maximum safe speed without it. How does the surface affect the maximum speed?
9. In addition to the speed and the road surface, you also need to look at the curvature of the road (how tight the turn happens to be). Curves come in many shapes. The arc of a circle is a good approximation for at least a segment of any curve. The arc of a large circle (a circle with a large radius) can represent a gentle curve. The arc of a small circle (a circle with a small radius) can represent a tight curve.
a) Investigate the effect of the amount of curve by placing the block at various distances from the center of the turntable.

B) At each radius, find the maximum safe speed of the block. Record your data and results in your table.
(c) As the radius of the turntable decreases (becomes tighter) what happens to the maximum speed?
10. Get an accelerometer from your teacher. An accelerometer is a device used to measure accelerations.
(a) For example, a necklace hanging from the rearview mirror of an automobile acts as a simple accelerometer. How can something such as a hanging necklace tell you if the automobile is accelerating, even if you are not looking out the windows for other clues?
$\Delta$ b) Hold an accelerometer in your hands and observe it as you either sit on a rotating stool or spin around while standing. What is the direction of the acceleration indicated by the accelerometer? (For a "cork" accelerometer, you can find out how the cork indicates acceleration by holding it and noting its behavior as you accelerate forward.)

©c) In your log, make a sketch that simulates a snapshot photo taken from a horizontal position as the accelerometer was moving along a circular path. Show the circular path, the accelerometer "frozen" at one instant, the cork "frozen" in a leaning position, and an arrow to represent the velocity of the accelerometer at the instant represented by your sketch.
11. Start a ball rolling across the floor. While it is rolling, catch up with the ball and use a rolled-up newspaper or magazine to push the ball sideways or perpendicular to the motion of the ball with a fixed amount of force. Carefully follow alongside the ball and keep adjusting the direction of push so that it is always perpendicular to the motion of the ball.


』a) Make a top-view sketch in your log that shows:

- A line that represents the straightline path of the ball before you began pushing sideways on it.
- A dashed line to represent the straight-line path on which the ball would have continued moving if you had not pushed it sideways.
- A line of appropriate shape to show the path taken by the ball as you pushed perpendicular to the direction of the ball's motion with a constant amount of force.
B) When you pushed the ball perpendicular or sideways to its motion, did you cause the ball to move faster or slower? Explain your answer.
Dc) Assuming that friction could be eliminated to allow the ball to continue moving at constant speed, describe what you would need to do to keep the ball moving on a circular path.
dd) If you stop pushing the ball, how does the ball move? Try it, and make a sketch in your $\log$ of what happens.

12. Repeat Step 11 when the ball is moving faster, and continue using the rolled-up newspaper to keep the ball moving in the same-sized circle.
da) How is the force you need to exert on the faster ball different from the force exerted in Step 11?
13. Repeat Step 12 when the ball is moving at the same speed but in a smaller circle.
(a) How is the force you need to exert to keep the ball moving in a smaller circle different from the force exerted in Step 12?
b) Compare driving around a curve on dry pavement to driving around the same curve when it is covered with ice.

## Physics Talk

## CIRCULAR MOTION

## Centripetal Force

In the Investigate, you observed a toy car moving in a circle. The car required the force of the string to keep it moving in a circle. When you let

Physics Words
force: a push or a pull. go of the string, the car traveled in a straight line. There was no longer a force on the car to keep it moving in a circle. This motion can be explained using Newton's laws, which you will study in more detail in other chapters.


Physics Words
centripetal force: a force directed toward the center to keep an object in a circular path. centripetal acceleration: a change in the direction of the velocity with respect to time.

## Checking Up

1. What is the direction of the force that keeps an object moving in a circle?
2. What is the name of the force that keeps an object moving in a circle?
3. Name the force that keeps an automobile moving in a circular path on a road.
4. Explain how the velocity of an object can change even if the speed is not changing.
5. Describe three situations in which acceleration can take place.
6. What is the force that keeps Earth moving in a circle around the Sun?

Newton's first law of motion states that an object in motion will stay in motion at a constant speed and travel in a straight line unless a force acts on it. When you let go of the string, the car traveled in a straight line, since no force was acting on it. Any time you observe something moving along a curved path, you should recognize that there has to be a force acting on the object.
The force of the string keeps the toy car moving in a circle. This force of the string is always toward the center of the circle. In a similar way, the force of friction between the block and the turntable kept the block moving in a circle. This force of friction is also always toward the center of the circle.
When an automobile makes a turn, it is traveling along part of a circle. There is a force of friction between the tires and the road that keeps the automobile moving in the circle.
Eliminate this friction, which is what happens on an icy road, and the automobile will move in a straight line and will not be able to turn (regardless of what you do with the steering wheel). This force of friction is toward the center of the circular curve.
The force that keeps an object moving in a circular path is called a centripetal force. The centripetal force can be the tension in the string, the friction between the block of wood and surface of the turntable, or the friction between an automobile and the road. For Earth moving in a circle around the Sun, the centripetal force is gravity. (You will learn more about the forces of friction and gravity in later chapters.) For a baseball bat moving in a circle during a swing, the centripetal force is the force of the muscles in the batter's arms.
As the toy car moves in a circle, its speed remains the same. It does not appear to go faster or slower. Its velocity does change because the direction is changing. The car is changing its direction. For a moment it is moving east, then it is moving south, then it is moving west, then north, and then east again as it starts its next revolution. Changes in velocity with respect to time are called accelerations. In the previous sections, you associated accelerations with changes in speed as a vehicle speeded up or slowed down.

A vehicle that is changing directions is also accelerating. The acceleration associated with an automobile changing directions is referred to as centripetal acceleration.
Acceleration is the change in velocity with respect to time. Velocity can change when an object speeds up, slows down, or changes direction.

## Active Physics

| + Math | +Depth | +Concepts | +Exploration |
| :---: | :---: | :---: | :---: |
| $\bullet$ | $\bullet$ |  |  |

## Calculating Centripetal Acceleration and Centripetal Force

You learned that the force of the string on the toy car or the force of friction between the tires and the road cause an automobile to move in a circle. The direction of the force is toward the center of this circle. The size of the force depends on the mass of the automobile, the speed of the automobile, and the radius of the curve. You can use the following equations to calculate the centripetal force and the corresponding centripetal acceleration.

$$
\begin{aligned}
& a=\frac{v^{2}}{r} \\
& F=\frac{m v^{2}}{r}
\end{aligned}
$$

where $a$ is acceleration
$F$ is force
$v$ is velocity
$m$ is mass
$r$ is the radius of the curve

## Sample Problem

Calculate the centripetal acceleration and centripetal force of a $1000-\mathrm{kg}$ automobile traveling at $27 \mathrm{~m} / \mathrm{s}(60 \mathrm{mi} / \mathrm{h})$ that turns on an unbanked curve having a radius of 100 m .
Strategy: Because the automobile is moving along a circular path, the centripetal acceleration must be directed toward the center of the curve. The magnitude can be found because the speed and radius are given.

Given:
Mass $(m)=1000 \mathrm{~kg}$
Speed $(v)=27 \mathrm{~m} / \mathrm{s}$
Radius of curve $(r)=100 \mathrm{~m}$

## Solution:

This acceleration changes the direction of the velocity of the automobile.

$$
\begin{aligned}
a & =\frac{v^{2}}{r} \\
& =\frac{(27 \mathrm{~m} / \mathrm{s})^{2}}{100 \mathrm{~m}} \\
& =\frac{729 \mathrm{~m}^{2} / \mathrm{s}^{2}}{100 \mathrm{~m}} \\
& =7.29 \mathrm{~m} / \mathrm{s}^{2} \text { or } 7.3 \mathrm{~m} / \mathrm{s}^{2}
\end{aligned}
$$

The speed of the automobile remains the same.
Because the automobile is moving along a circular path, the centripetal force must be exerted toward the center of the curve. The magnitude can be found because the mass, speed, and radius are all given.

$$
\begin{aligned}
F & =\frac{m v^{2}}{r} \\
& =\frac{1000 \mathrm{~kg} \times(27 \mathrm{~m} / \mathrm{s})^{2}}{100.0 \mathrm{~m}} \\
& =\frac{1000 \mathrm{~kg} \times 729 \mathrm{~m}^{2} / \mathrm{s}^{2}}{100 \mathrm{~m}} \\
& =7290 \mathrm{~kg} \cdot \mathrm{~m} / \mathrm{s}^{2}=7300 \mathrm{~N}
\end{aligned}
$$

If the centripetal force, which in this case is the force of friction, cannot cause sufficient acceleration, the automobile will not follow the curve and will skid in the direction of its velocity at the instant the tires break loose. Your experiment with the block sliding off the turntable demonstrated this. For a given $v$ and a given $r$, the centripetal force must be enough to provide the acceleration $\frac{v^{2}}{r}$.

For a given road surface, there is a maximum frictional force that can provide this centripetal force. Hence, there is a maximum $\frac{v^{2}}{r}$ that a road surface can provide. If your speed is too fast, or the curve too sharp, then the maximum $\frac{v^{2}}{r}$ will be exceeded, and off the road you go - perhaps to disaster...
A curve with a radius of 40 m has a warning sign that limits the speed to $30 \mathrm{mi} / \mathrm{h}(14 \mathrm{~m} / \mathrm{s})$. Assume that an automobile has a mass of 1000 kg .
a) What is the frictional force of an automobile that is driving the speed limit?
b) How much additional frictional force does the automobile need if the driver decides to exceed the speed limit and travel at $20 \mathrm{~m} / \mathrm{s}$ ?
c) If the frictional force were reduced by half due to wet leaves and water on the road, what speed would you recommend for drivers?

## What Do You Think Now?

At the beginning of this section, you were asked the following:
You are driving along a road at the posted speed limit of $50 \mathrm{mi} / \mathrm{h}(80 \mathrm{~km} / \mathrm{h})$.
A road sign warns that you are approaching a curve and tells you to slow down to $25 \mathrm{mi} / \mathrm{h}(40 \mathrm{~km} / \mathrm{h})$.

- Why is the sign indicating to slow down?
- How is the amount you should slow down determined?

After having investigated the effect of speed on centripetal force, why should you slow down? Use the results of your investigations to support your answer.


## Physics

## Essential Questions

## What does it mean?

What is a centripetal force? Draw a sketch of an automobile making a turn. Show the direction of the velocity and the direction of the centripetal force.

## How do you know?

What evidence do you have that circular motion requires a force toward the center of the circle?
Why do you believe?

| Connects with Other Physics Content | Fits with Big Ideas in Science | Meets Physics Requirements |
| :--- | :--- | :---: |
| Forces and motion | Change and constancy | * Good, clear, explanation, no more <br> complex than necessary |

* In physics, a few simply stated principles explain a large variety of phenomena. How can an automobile be accelerating if it does not speed up or slow down?


## Why should you care?

What are the consequences of exceeding the physical speed limit imposed by the road-tire interface and the radius of the curve?

## Reflecting on the Section and the Challenge

In this section, you learned that friction between the road and the tires helps keep an automobile on the road when it goes around a curve. More friction allows you to move faster and still stay on the road.
A tight turn requires more friction or a slower speed than a wider turn. Because you cannot change or control the friction between the road and tires (other than keeping good tires in good condition), a slower speed will keep the automobile on the road.

Part of your challenge requires you to explain why it is necessary to drive at a slower speed around a curve than on a straight section of the road. You also may want to explain what happens if the road conditions change, if the friction is reduced because the tires are worn out, or if the curve in the road is very tight.

## Physics to Go

1. A person at the equator travels once around the circumference of Earth in 24 h . The radius of Earth is 6400 km . How fast is the person going? Compute the speed in kilometers per hour ( $\mathrm{km} / \mathrm{h}$ ) and in meters per second $(\mathrm{m} / \mathrm{s})$. Recall that 1 km is equal to 1000 m .
2. Earth travels in a circular motion around the Sun. The radius of Earth's motion is about $1.5 \times 10^{8} \mathrm{~km}$. What is the speed of Earth around the Sun? Compute the speed in $\mathrm{km} / \mathrm{h}$ and $\mathrm{m} / \mathrm{s}$.
3. A fan turns at a rate of 60 revolutions per second. If the tip of the blade is 15 cm from the center, how fast is the tip moving?
4. Friction can hold an automobile on the road when it is traveling at $20 \mathrm{~m} / \mathrm{s}$ and the radius of the turn is 15 m . What happens if:
a) the curve is tighter?
b) the road surface becomes slippery?
c) both the curve is tighter and the road is slippery?
5. Think about other examples in which objects travel in curved paths, such as the clothes in a spin dryer, or the Moon traveling around Earth. For each example, explain what produces the force that is constantly being applied to the object toward the center of the curve.
6. Sketch a graph that shows the radial distance and the maximum speed at which the block remains on a turntable for one type of surface.
7. Explain the following statement: "The driver may turn the wheels but it is the road that turns the automobile."
8. Active Physics A jet pilot in level flight at a constant speed of $270 \mathrm{~m} / \mathrm{s}(600 \mathrm{mi} / \mathrm{h})$ Plus rolls the airplane on its side and executes a tight circular turn that has a radius of 1000 m . What is the pilot's centripetal acceleration? Draw a sketch of the acceleration's direction relative to the ground.
9. Below you will find alternate explanations of the same event given by a person who was not wearing a seat belt when an automobile went around a sharp curve.
"I was sitting near the middle of the front seat when the automobile turned sharply to the left. A force made my body slide across the seat toward the right, outward from the center of the curve, and then my right shoulder slammed against the door on the passenger side of the automobile."
"I was sitting near the middle of the front seat when the automobile turned sharply to the left. My body kept going in a straight line while, at the same time due to insufficient friction, the seat slid to the left beneath me, until the door on the passenger side of the automobile had moved far enough to the left to exert a centripetal force against my right shoulder."
Are both explanations correct? Explain your answer in terms of both explanations.
10. Race cars can make turns at $150 \mathrm{mi} / \mathrm{h}$. What forces act on a race car as it moves along a circular path at constant speed on a flat, horizontal surface?
11. Why are highway curves that have radii that decrease as you go into them especially dangerous? In other words, curves that start out as gentle turns but become tighter and tighter as you get into them.
12. In the United States, vehicles drive on the right-hand side of a two-lane road. If the curve bends to the right and you lose traction in the turn, would you end up in the ditch on your side of the road, or into the lane of oncoming traffic? What if the curve bends to the left?

## 13. Preparing for the Chapter Challenge

Write a few sentences telling your parents that you know how to apply the physics from this section to drive safely around curves. You should include information about why you need to slow down around curves in rainy or icy weather.

## Inquiring Further

## 1. Banking a curve

Design an investigation to determine the effect of banking a curve on the speed at which the curve can be safely negotiated. After your teacher approves your procedure, conduct your investigation.

## 2. Mass and speed on a curve

Design an investigation to determine if the mass of an automobile has an effect on the safe speed around a curve. After your teacher approves your procedure, conduct your investigation.




Top speed.................................est 143 mph
Skidpad............................................... 0.83 g Slalom........................................... 61.9 mph
Brake rating................................. excellent


Temperature ................................................ $70^{\circ} \mathrm{F}$

Elevation............................................ 1010 ft


(SAE)...................... 195 bhp @ 6625 rpm
Bhp/liter.....................................................
Torque ........................... $165 \mathrm{lb}-\mathrm{ft}$ @ 5625 rpm Maximum engine speed ......................... 6750
Fuel injection..................elect. sequential port Fuel.......................prem unleaded, 91 pump oct

## CHASSIS \& BODY

Layout..................... front engine/front drive Body/frame...................................nit steel Brakes Front..........................9-in. vented discs
Rear......................in. vented discs
Assist type...............................vacuum; ABS
Total swept area ......................... 366 sq in.
Wheels.........................................cast alloy, $16 \times 6^{1 / 2}$
Tires................................steel-belted touring, P205/55ZR-16
Steering....................................ack \& pinion power assist
Overall ratio.........................................5:1
Turns, lock to lock.................................. 2.7
Turning circle ................................. 38.4 ft
Suspension
Front........struts, lower A-arms, coil springs, tube shocks, anti-roll bar
Rear.......... struts, trailing links, dual lower lateral links, coil springs, tube shocks, anti-roll bar


| GENERAL DATA |
| :---: |
| Curb weight................................... 3055 lb |
| Test weight............................... 3180 lb |
| Weight dist (with driver), $f$ fr, \%..............63/37 |
| Wheelbase................................ 106.5 in . |
| Track, f/r............................ 59.2 in .588 .5 in . |
| Length .................................... 183.9 in. |
| Width ........................................69.1 in. |
| Height.......................................... 54.5 in . |
| Ground clearance .........................8/2 in. |
| Trunk space......................... $18.0+7.0$ cu ft |
| MAINTENANCE |
| Oil/filter............................... $5000 \mathrm{mi} / 5000 \mathrm{mi}$ |
| Tuneup...................................100,000 mi |
| Basic warranty................... $36 \mathrm{mo} / 36,000 \mathrm{mi}$ |


| ACCELERATION |  |
| :---: | :---: |
| Time to speed | Seconds |
| $0-35 \mathrm{mph}$ |  |
|  |  |
| $0-50 \mathrm{mph}$. |  |
|  |  |
|  |  |
|  |  |
| $0-90$ mph........................................... 14.8 |  |
|  |  |
| Time to distance |  |
| 0-100 ft |  |
| $0-500 \mathrm{ft}$ |  |
| $0-1320 \mathrm{ft}(1 / 4 \mathrm{mi})$................ 15.4 @ 91.5 mph |  |
| FUEL ECONOMY |  |
|  |  |
|  |  |
|  |  |
|  |  |
| BRAKING |  |

From 60 mph ................................... 135Control........................................excellentPedal effort for 0.5 g stop.............................naFade, effort after six 0.5 g stops from

60 mph . $\qquad$ ......na
Brake feel......................................excellentOverall brake rating..........................excellent
HANDLING

Lateral accel (200-ft skidpad) ................. 0.83 g Balance........................moderate understeer Speed thru 700 -tt slalom ................... 61.9 mph Balance................................... Lateral seat support.. $\qquad$
Subjective ratings consists of excellent, very good, good, average, poor, na means information is not available


