Section 10 Safety Is Required but Thrills Are Desired

What Do You See?

Learning Outcomes

In this section, you will

- **Calculate** the speed of the roller coaster at different positions using conservation of energy.
- **Calculate** the acceleration of the roller coaster at turns.
- **Determine** if the acceleration is below 4 *g* for safety.
- **Determine** if the speed at the top of a loop is sufficient for safety concerns.
- **Construct** sounds and scenery to enhance the thrills of a roller-coaster ride.

What Do You Think?

Occasionally, people are severely injured or killed on a roller coaster. However, these type of accidents are rare.

- **Does the knowledge that people can get hurt or die on a roller coaster change the thrill of the ride?**
- **Would your answer change if you found out that one-half of all roller-coaster rides ended in the death of its passengers?**

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

1. Safety is one of the criteria that you must meet in designing your roller coaster.

   a) List three reasons why safety is a major concern for roller-coaster designers.

   b) How safe is safe? Your answer may depend on what injuries you describe for the roller coaster. Nausea and vomiting are one type of injury, broken bones are a second type of injury, becoming unconscious is a third type of injury, and death is the greatest injury. For the four types of injuries listed, make an estimate of how many people could get injured on a roller coaster ride before it would be closed to the public. Be sure to include whether these are injuries in a day, a month, or a year.

2. Astronauts going into space have to withstand very large accelerations during rocket launch. After many tests of test pilots and race-car drivers, it was determined that people will become unconscious if the acceleration is greater than about 9 *g* (or 9 times the acceleration due to gravity, that is, $9 \times 9.8\ m/s^2$). Some people black out at 5 *g* or 6 *g*. This unconsciousness results from the blood leaving the brain during the high acceleration.

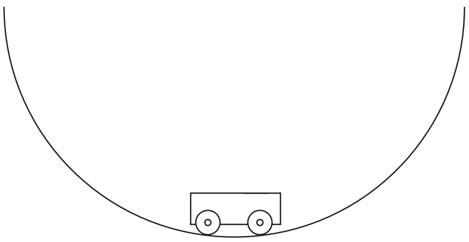
   The roller-coaster manufacturer has indicated that the maximum acceleration at any place on the roller coaster should not exceed 4 *g* (or 4 times the acceleration due to gravity, that is, $4 \times 9.8\ m/s^2$).

   a) At what locations on the roller coaster are there accelerations?

   b) If the roller coaster were to fall straight down, what would be the acceleration?

   c) Is this a safe acceleration?

   d) If you find that your roller coaster accelerations are greater than 4 *g* at the position shown, what changes in speed or shape of the curve can be made to decrease the acceleration?



3. The roller-coaster designer can play all sorts of tricks to produce extra thrills on the same roller coaster.

   a) Describe how you can add suspense to the trip up to the top of the first hill.

   b) Describe how you can use sounds during the roller-coaster ride to add to the thrills.

4. The choice of scenery surrounding the roller coaster can also add to the thrill. The roller coaster can look like it will dive into water when it is descending. The roller coaster can look like it will hit a building when it rounds a curve.

   a) Describe three visual effects through the use of scenery that will add to the thrill of your roller coaster.

5. Thrills can come from high speeds. Thrills more often come from acceleration (changing velocity with respect to time). Change in velocity can be a change in speed or direction.

   a) Describe three ways in which you can add thrills to a roller-coaster design by having changes in velocity.

   b) Describe three ways in which you can add thrills to a roller-coaster design by having changes in acceleration.

6. The photo shows a roller coaster at an amusement park.

   a) Using what you have learned in this chapter, describe the different parts of the roller-coaster ride shown in the picture. Where are you likely to experience the most thrills? Why?

b) In the vertical loops you will notice that the track is more sharply curved at the top than in the curved sections between the loops? Why is the track designed that way? (Hint: Think about speed and the *g*'s you would pull on various parts of the loop.)

Physics Talk

ROLLER-COASTER SAFETY

The roller coaster has to be safe in order to be fun. Analysis of the safety requirements of the roller coaster is a valuable way of reviewing some of the physics in earlier sections. Your class and teacher can decide the level of mathematics that will be required for your challenge. In each of the examples below, there is both a qualitative and quantitative discussion.

You know from research with test pilots that people will not be safe if their acceleration is greater than 4 *g*. A free fall provides an acceleration of 1 *g*. Roller coasters may have steep inclines but they are generally not in free fall and therefore have an acceleration less than 1 *g* on straight inclines.

When the roller coaster rips around a corner or moves through the bottom of a vertical loop, the acceleration can be much more than 1 *g*. Analyze the acceleration at the bottom of a loop. The acceleration can be computed by recognizing that the roller coaster at this location is moving in an arc of a circle. The centripetal acceleration must be toward the center of the circle and can be calculated by using the equation

$$a = \frac{v^2}{r}$$

By varying the speed or the radius of the circle in the roller-coaster design, you can limit the acceleration to less than 4 *g*.

Qualitative (no numbers): Decreasing the speed at that point will lower the acceleration. This can be accomplished by changing the height from which the coaster descends. Less gravitational potential energy, *GPE*, will result in less kinetic energy, *KE,* and therefore a lower speed. Alternatively, you can make the curve gentler. This increases the radius of the curve and decreases the acceleration as well.

Sample Problem 1 (Quantitative – with numbers)

A roller-coaster car with a mass of 800 kg is traveling at 15.0 m/s at the bottom of a loop. The loop has a radius of 5.0 m.

a) What is the centripetal acceleration required to keep the car moving in a circle?

Strategy: Use the equation for centripetal acceleration.

Given: $v = 15.0$ m/s

$r = 5.0$ m

Solution:

$$a = \frac{v^2}{r}$$

$$= \frac{(15.0 \text{ m/s})^2}{5.0 \text{ m}}$$

$$= 45 \text{ m/s}^2$$

This acceleration is greater than 4 g ($4 \times 9.8 \text{ m/s}^2 = 39.2 \text{ m/s}^2$) and is therefore unsafe.

b) One way to lower this acceleration would be to lower the speed. Assume that the new design gives the coaster car a speed of 12.0 m/s. Calculate the centripetal acceleration if the car is moving in a circle.

Strategy: Use the equation for centripetal acceleration, again.

Given: $v = 12.0$ m/s

$r = 5.0$ m

Solution:

$$a = \frac{v^2}{r}$$

$$= \frac{(12.0 \text{ m/s})^2}{5.0 \text{ m}}$$

$$= 29 \text{ m/s}^2$$

This acceleration is now less than 4 g ($4 \times 9.8 \text{ m/s}^2 = 39.2 \text{ m/s}^2$) and is therefore safe.

c) Another way to lower the acceleration is to make the loop larger. Using the original speed of 15.0 m/s, calculate the centripetal acceleration if the radius of the loop were 7.0 m.

Strategy: Use the equation for centripetal acceleration, again.

Given: $v = 15.0$ m/s

$r = 7.0$ m

Solution:

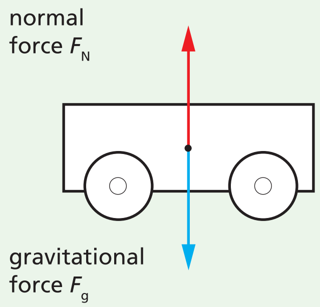
$$a = \frac{v^2}{r}$$

$$= \frac{(15.0 \text{ m/s})^2}{7.0 \text{ m}}$$

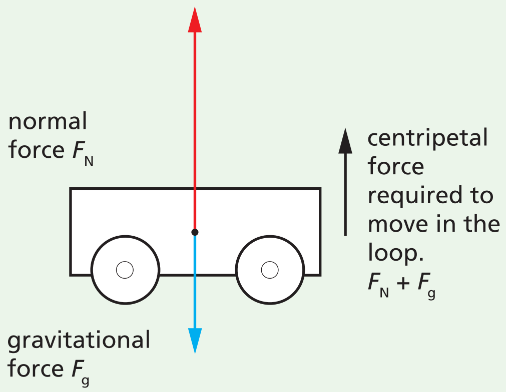
$$= 32 \text{ m/s}^2$$

This acceleration is now less than 4 g ($4 \times 9.8 \text{ m/s}^2 = 39.2 \text{ m/s}^2$) and is therefore safe.

The largest centripetal acceleration (at the bottom of the loop) also requires the largest centripetal force. This maximum force will inform you as roller-coaster designer of the strength of materials required to build this part of the roller coaster. The force acting on the coaster car is a combination of its weight and the normal force from the track. The normal force required when the coaster car is moving in a circle at the bottom of the loop is much greater than the normal force that would support the car at rest at the bottom of the incline. The at-rest cart requires no net force. The normal force up (provided by the track) must equal the gravitational force (weight) down. This is shown with the first vector diagram to the right.



When the car is moving in a vertical circle, a centripetal force is required. The sum of the normal force from the track and the gravitational force must equal the centripetal force required. Since the gravitational force is down, the normal force, must be greater at the bottom of the loop to provide the additional upward force needed. This is shown in the second vector diagram to the right.



The centripetal force required can be calculated using Newton's second law:

$$F_{net} = ma.$$

In this case $F_{net} = \dfrac{mv^2}{r}$.

In this section, you equated an acceleration with the concept of pulling "*g*'s." Pulling 4 *g*'s is actually different that experiencing an acceleration of 4 x 9.8 m/s^2. For example, when you stand still on Earth your acceleration is 0 *g*'s, but you are experiencing 1 *g*. Here, 1 *g* means you feel normal. The support force under your feet is equal to your weight. Experiencing 2 *g*'s means that you feel twice as heavy as normal, because the support force (often normal force) is twice your weight. The heaviness that you experience is strictly based on the support force. When you are in free fall, your acceleration is 1 *g*, but you feel weightless because there is no support force.

In the chapter, it indicates that an acceleration of greater than 4 *g*'s (as produced by $a = v^2/r$) is the maximum acceptable. Actually, if you are at the bottom of the loop, an acceleration of 4 *g*'s will require a support of 5 *g*'s (five times the rider's weight) and you will feel five times as heavy as normal. At the top of the loop, an acceleration of 4 *g*'s only requires 3 *g*'s of support force, because gravity is providing a force toward the center as well.

Sample Problem 2

A roller-coaster car with a mass of 800.0 kg is traveling at 15.0 m/s at the bottom of a loop. The loop has a radius of 5.0 m.

a) What is the centripetal force required to keep the car moving in the circle?

Strategy: Use Newton's second law to relate net force and acceleration.

Given:

$$v = 15.0 \text{ m/s}$$
$$r = 5.0 \text{ m}$$
$$m = 800.0 \text{ kg}$$

Solution:

$$F_{net} = ma = \frac{mv^2}{r}$$
$$= \frac{(800.0 \text{ kg})(15.0 \text{m/s})^2}{5.0 \text{ m}}$$
$$= 36{,}000 \text{ N}$$

This net force of 36,000 N up will allow the car to move in the vertical circle.

b) What is the normal force that the track exerts on the car?

Strategy: The normal force must be 36,000 N greater than the gravitational force to provide a net force of 36,000 N as required.

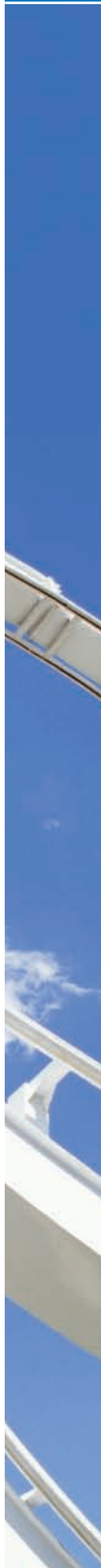
Solution: The gravitational force (weight) is:

$$F_w = mg = (800.0 \text{ kg})(9.8 \text{ m/s}^2)$$
$$= 7840 \text{ N}$$

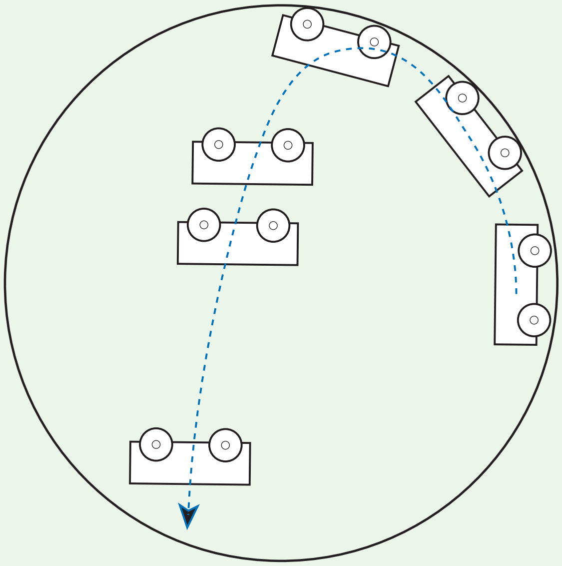
Therefore, the normal force must equal 36,000 N + 7840 N = 43,840 N or about 44,000 N.

This indicates that the track and support structure of the roller coaster must be able to exert a force of at least 44,000 N or the track will break.

Similar calculations can be completed with the force required to make a turn on a horizontal part of the roller coaster and a turn where the roller coaster banks on its side as it whips around a turn.



Another safety feature requires that the speed at the top of the loop is great enough to complete the loop. A cart that has too little speed will not make it to the top of the roller coaster and will not be able to move in the circle. It will fall to the ground, as shown in the diagram at the right.



If gravity were the only force acting at the top of the roller coaster, then the car must require a centripetal acceleration equal to that of free fall.

Sample Problem 3

What is the minimum speed required at the top of the loop to ensure that the coaster car does not leave the track? The car has a mass of 800.0 kg. The loop has a radius of 5.0 m.

Strategy: The minimum speed pertains to the centripetal acceleration of 9.8 m/s². Using the equation for centripetal acceleration, you can find the required speed.

Given: $a = 9.8 \text{ m/s}^2$

$r = 5.0 \text{ m}$

Solution:

$$a = \frac{v^2}{r}$$

$$v = \sqrt{ar}$$

$$= \sqrt{(9.8 \text{ m/s}^2)(5.0 \text{ m})}$$

$$= 7.0 \text{ m/s}$$

A coaster car traveling with a speed of 7.0 m/s will be able to complete the upper part of the loop. A speed greater than 7.0 m/s will also be able to make the loop. The greater speed will require a larger centripetal force. The additional force will be provided by the track pushing down on the car. In real roller coasters, the cars have special attachments under the wheels to keep the cars on the track if, for some reason, the speed gets too low near the top of the loop.

Checking Up

1. What is the maximum safe acceleration for a roller coaster?
2. List two ways to keep the acceleration of coaster cart low enough to be safe.
3. At what part of the loop is the acceleration the greatest on a roller-coaster cart?
4. At what part of the loop is the normal force the greatest?

Active Physics **Plus**

+Math	+Depth	+Concepts	+Exploration
◆◆			

More Quantitative (with numbers) Analysis

1. A roller-coaster car is traveling at 30.0 m/s at the bottom of a circular loop. The radius of the loop is 9.0 m.

   a) Using the conservation of mechanical energy,

   $KE + GPE = \text{constant}$

   $$mgh + \frac{1}{2}mv^2 = \text{constant}$$

   calculate the initial height of a roller-coaster car to give it a speed of 30.0 m/s at the bottom of a loop. At the highest point of the roller-coaster ride, the velocity is 0 m/s. At the bottom of the loop of the roller-coaster ride, the height h equals 0 m.

   b) Using the equation $a = \frac{v^2}{r}$,

   calculate the acceleration at the bottom of the loop.

   c) Is this a safe acceleration?

   d) At what speed would this loop with a radius of 9.0 m begin to be a safety concern?

   e) At what speed would a loop with a smaller radius of 7.0 m begin to be a safety concern?

   f) How fast would the roller-coaster car be traveling at the top of the loop? (Because the loop's radius is 9.0 m and the top of the loop is 18.0 m above the ground, the diameter is 18.0 m.) You must use the initial height of the roller coaster that you calculated above to solve this problem.

   g) Using the equation $a = \frac{v^2}{r}$,

   calculate the acceleration at the top of the loop.

   h) Is this a safe acceleration?

   i) There are two safety concerns regarding accelerations in a loop. The acceleration cannot exceed 4 g. This excessive acceleration would occur at the bottom of the loop, if at all. The acceleration at the top must be greater than 1 g (9.8 m/s^2). If the acceleration required for circular motion at the top of the loop is less than 1 g, the roller-coaster car will leave the track and plummet to the ground. The speed at the top of the roller coaster must be large enough to require acceleration at least as great at 9.8 m/s^2.

   j) Describe if the results you found in *b) – g)* fit these safety limits.

2. The track must be strong enough to hold the roller-coaster car without breaking. You can calculate the minimum strength of a track by assuming that the roller-coaster car is filled with big football players or Sumo wrestlers.

   What force would a roller-coaster track on a horizontal section of track have to supply to hold up a car filled with passengers if the total mass were 1000.0 kg? (Remember the equation for weight is $F_w = mg$ where $g = 9.8$ N/kg.)

3. When the roller-coaster car makes turns, there must be a centripetal force pushing the roller-coaster car toward the center of the circle.

The following are three types of turns that will be analyzed:

- a sharp left turn on a flat track,
- a sharp left turn where the car is turned on its side and the track is vertical, and
- a loop where the car is moving in a vertical circle.

a) For each of the three turns, identify the direction of the force keeping the car moving in a circle.

b) For each of the three turns, identify the source of this force. (The force could be the force of friction, the gravitational force, the normal force, the force of tension on a rope, the force of the wheels in the track or any combination of these forces.)

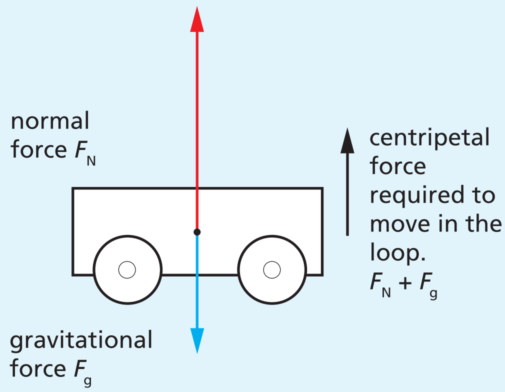
4. A roller-coaster car has a mass of 1000.0 kg and takes a sharp left turn where the car is turned on its side and the track is vertical with a radius of 12.0 m and the car is moving at 15.0 m/s. Calculate the centripetal force required to keep the car moving in the curve.

5. A roller-coaster car has a mass of 1000.0 kg and takes a sharp left turn on a flat track with a radius of 12.0 m and the car is moving at 15.0 m/s. Calculate the centripetal force required to keep the car moving in the curve.

6. A roller-coaster car has a mass of 1000.0 kg and is about to enter a vertical loop that has a radius of 12.0 m. The car is moving at 15.0 m/s.

   a) Calculate the centripetal force required to keep the car moving in the curve.

   b) This centripetal force that you calculated is the sum of the normal force of the track up toward the center of the roller-coaster car and the force of gravity down to the ground. Copy the following diagram into your log:



   c) Calculate the force of gravity on the car.

   d) Calculate the normal force on the car. This is the magnitude of the force that the tracks and frame of the roller-coaster structure must be able to exert on the car to keep it moving in a circle.

What Do You Think Now?

At the beginning of this section, you were asked the following:

- **Does the knowledge that people can get hurt or die on a roller coaster change the thrill of the ride?**
- **Would your answer change if you found out that one-half of all roller-coaster rides ended in the death of its passengers?**

Record you ideas about these questions now. What aspects of the roller-coaster ride are most likely to be dangerous if the ride is not properly designed? Describe how you would use what you have learned about the physics of roller coasters to make sure your roller-coaster ride is safe.

Physics

Essential Questions

What does it mean?

Scientific concepts are often useful in helping you understand safety issues. Explain why 4 g is the maximum acceleration that should be designed into the roller coaster. If a given design exceeded this acceleration, how could you alter the design?

How do you know?

Cars, trains, and planes can all go much faster than a roller-coaster ride, but don't produce the thrills of the roller-coaster ride. How do roller coasters produce the thrills?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Forces and motion	* Models	Experimental evidence is consistent with models and theories

* Different scientific principles can explain the same phenomenon. Compare and contrast the use of forces and energy as ways to describe roller-coaster rides.

Why should you care?

Safety is a primary concern of any roller-coaster ride. How can you increase safety and increase thrills through the use of scenery surrounding your ride?

Reflecting on the Section and the Challenge

There is lots of creativity in designing a roller coaster. There is lots of creativity in designing a bridge, a building, and a table. All designs are constrained by the physics of the world.

A beautiful bridge must also be a bridge that does not collapse. In this section, you learned about the safety features that you must take into account in your design for the roller coaster. You have to ensure that the accelerations are never above 4 g. This will require you to design the curves and loops with radii that limit the accelerations. You must also make sure that if your roller coaster does have a loop, the cart will be able to complete the loop. You can vary the radius of any part of the track in the design. You can vary the velocity of the car by changing the launch height for the roller coaster. The higher the first hill, the more speed the coaster will have at the bottom. Safety is required, but thrills are desired. The section also discussed ways in which you can use sound and scenery to improve the thrills of your design.

Physics to Go

1. An engineering company submits a plan for a roller coaster. What factors will you check to ensure that the roller coaster is safe?

2. Active Physics *Plus* A roller-coaster car is traveling at 20.0 m/s at the bottom of a loop. The radius of the loop is 12.0 m.

   a) Using the conservation of mechanical energy ($KE + GPE = \text{constant}$) $\left(mgh + \frac{1}{2}mv^2 = \text{constant}\right)$, calculate the initial height of a roller-coaster car when it starts from rest to give it a speed of 20.0 m/s at the bottom of a loop.

   b) Using the equation $a = \frac{v^2}{r}$, calculate the acceleration at the bottom of the loop.

   c) Is this a safe acceleration?

   d) At what speed would this loop with radius of 12.0 m begin to be a safety concern?

   e) At what speed would the acceleration in a loop with a smaller radius of 7.0 m begin to be a safety concern?

3. A roller-coaster car is traveling at 25.0 m/s at the bottom of a loop. The radius of the loop is 10.0 m.

   a) Calculate the acceleration of the car at the bottom of the loop.

   b) Is this a safe acceleration?

4. Active Physics *Plus* A roller coaster has an initial height of 50.0 m above the bottom of an incline.

   a) What will be the speed of the roller-coaster car at the bottom of the incline?

   b) The roller-coaster car goes into a loop with a radius of 10.0 m. What is the acceleration required to keep the cart moving in the circular loop?

   c) What will be the speed of the roller-coaster car at the top of the loop?

   d) What will be the acceleration of the car at the top of the loop if the car is moving in a circle?

   e) Explain whether this roller coaster is safe at the bottom and the top of the loop.

5. Active Physics *Plus* A roller coaster has a loop with a radius of 8.0 m (diameter = 16.0 m).

   a) What speed must the roller-coaster car have at the top of the loop if the only force acting on the car at the top is the force of gravity and the acceleration is therefore 9.8 m/s^2?

   b) How high must the first hill be to provide this speed at the top of the loop?

6. A roller-coaster car, when filled with people, has a mass of 900.0 kg. The roller-coaster car rounds a curve on the ground with a radius of 18.0 m at a speed of 12.0 m/s.

a) What is the centripetal acceleration of the car?

b) What is the centripetal force on the car?

c) What will provide this centripetal force?

7. A roller-coaster car, when filled with people, has a mass of 900.0 kg. The roller-coaster cart rounds a curve on the ground with a radius of 15.0 m at a speed of 20.0 m/s.

a) What is the centripetal acceleration of the car?

b) What is the centripetal force on the car?

c) The wheels in the tracks can provide a force of 25,000 N. Is the roller coaster safe?

8. A roller coaster is able to complete a loop when the car has two passengers. The car is loaded with six people.

a) Will the centripetal acceleration change as a result of the change in mass?

b) Will the roller coaster be going faster, slower, or the same speed at the bottom of the loop with the extra passengers?

c) Will the roller-coaster track require a stronger material because of the increased number of riders?

Inquiring Further

Amusement-park physics

Visit an amusement-park physics site as directed by your teacher and explore some of the safety factors in designing roller coasters. Report your findings back to your team.