Section 7 Impulse and Changes in Momentum: Crumple Zone

TECH LAB

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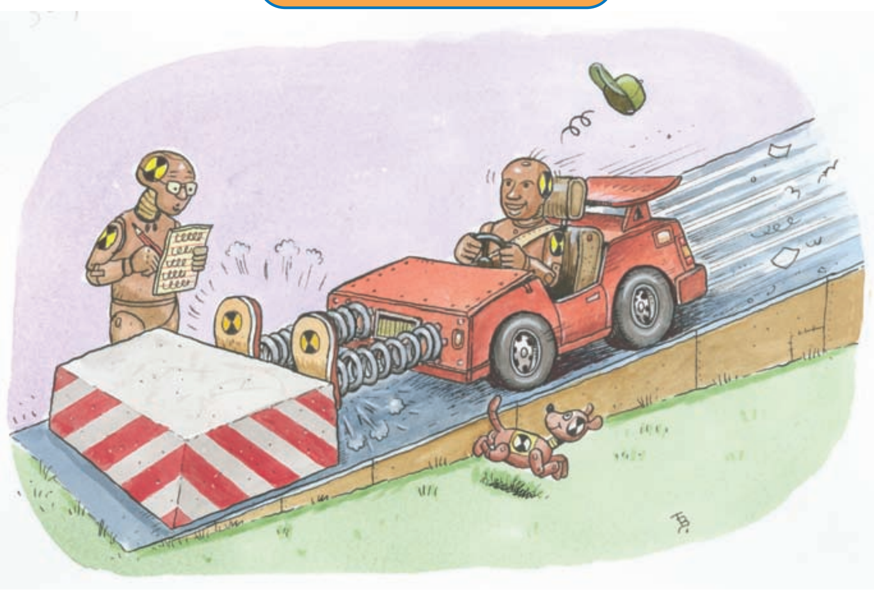
Learning Outcomes

In this section, you will

- **Design** a device that is able to absorb the energy of a collision and reduce the net force on an object in an automobile.
- **Describe** collisions and crumple zones in terms of momentum, impulse, and force.
- **Apply** the concept of impulse in the analysis of collisions.
- **Use** a computer's motion probe (sonic ranger) to determine the velocity of moving vehicles.
- **Use** a computer's force probe to determine the force exerted during a collision.
- **Compare** the change of momentum of a model vehicle before a collision with the impulse applied during a collision.
- **Explore** ways of using cushions to increase the time that a force acts during a primary collision.

What Do You See?



What Do You Think?

When an automobile collides with a wall and is brought to a stop, all of the energy of motion that the automobile had has to go somewhere. Also, a force must act to stop the automobile, and any passengers inside. Automotive engineers design something called a crumple zone to absorb the energy of the collision and to lessen the force on the passengers. (*A crumple zone is part of the body of an automobile that compresses during an impact.*)

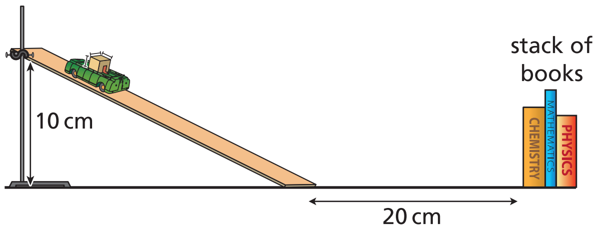
- **What are some of the factors that automobile designers and engineers must consider when designing a crumple zone as a safety feature?**

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

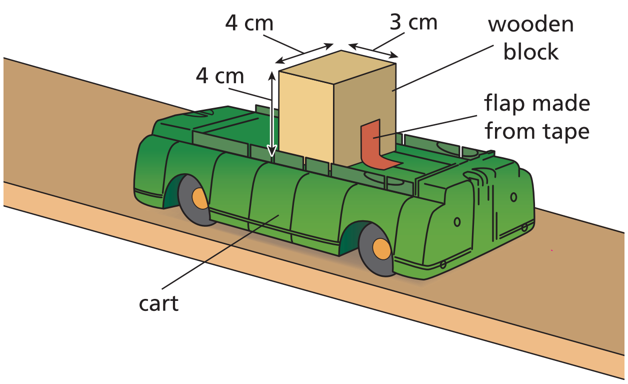
Investigate

Part A: Designing a Crumple Zone

1. Form teams of three to five students. Each team will design a crumple zone that will attach to the front of a cart. You may use one sheet of paper, 30 cm of tape, 2 rubber bands, and 30 cm of string.
2. The task is as follows:
   - Your cart (automobile) will roll down the ramp from a height of 10 cm, cross 20 cm of level ground, then hit a wall of books and come to a complete halt.



   - A 4 cm by 4 cm by 3 cm block (passenger) will be attached to the cart. The wooden block will be held in the automobile by a single 2-cm length piece of tape attached to the front of the block.



   - The crumple zone which you will design must allow the cart to stop without the block falling over.

If the challenge appears too difficult at first, try heights below 10 cm. You can then demonstrate the height below 10 cm that allows the automobile with the crumple zone to stop without disturbing the wooden block. If the challenge appears too easy, you can try heights above 10 cm.

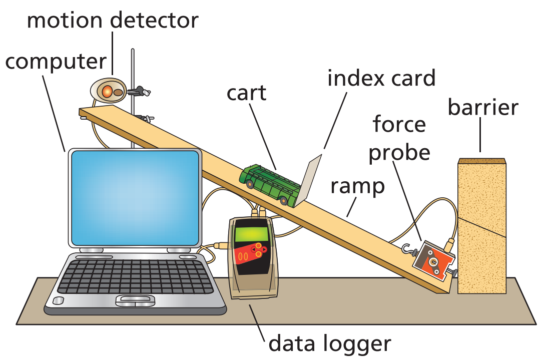
3. Follow your teacher's guidelines for considering the use of time, space, and materials as you design your crumple zone.
4. Begin by discussing why the tape on the front of the block will not help hold the block in place when the automobile hits the books. (Hint: Use Newton's first law.)
5. Demonstrate your design team's crumple zone for the class. Keep a careful record of your *Engineering Design Cycle*. When you make changes, record the changes and the reason for these changes.

Part B: Cushioning Collisions (Computer Analysis)

1. In this part of the investigation, you will be using a force probe that is attached to a computer to determine the effectiveness of different types of cushions for a cart. A force probe is a device that measures the force of an impact. Before beginning the experiments, investigate how the force probe works. Open the computer files that will display a graph of force versus time. Your teacher will help you locate the program. As the computer is recording data, use your finger to move the lever of the force probe. Investigate how the force of your finger on the lever affects the graph that appears on the computer screen.
   a) Draw the graph that you have generated with the detector.
   b) Beneath the graph, describe what you were doing to create that graph.

2. Release a cart at the top of a ramp and measure the force of impact as the cart strikes a barrier at the bottom. A sonic ranger can be mounted at the top of the ramp to measure the speed of the cart prior to the collision. Open the appropriate computer files to prepare the sonic ranger to graph velocity vs. time and the force probe to graph force vs. time.

3. Mount the sonic ranger at the top of a ramp and place the force probe against a barrier at the bottom of the ramp, as shown in the diagram. Attach an index card to the cart to obtain better reflection of the sound waves and improve the readings of the sonic ranger.



4. To ensure that the data collection equipment is working properly, conduct a few runs of releasing the cart down the ramp so that it collides with the force probe.

   a) Make copies of the velocity vs. time and force vs. time graphs that are displayed on the computer.

   b) Some computer probe programs calculate the area between the curve and the x-axis. Record this calculated value. Alternatively, you can use a transparency of graph paper to place over the curve and count the number of boxes that are between the curve and the x-axis.

5. Attach your cushioning material to the front of the cart. Conduct a number of runs with the same type of cushioning. Make sure that the cart is coasting down the same slope from the same position each time.

   a) Make copies of the velocity vs. time and force vs. time graphs that are displayed on the computer.

   b) Record the area between the curve and x-axis.

6. Repeat *Step 5* using other types of cushioning materials.

   a) Record your observations in your log.

7. Using the information from the graphs you obtained in this investigation, answer the following:

   a) Compare the force vs. time graphs for the cushioned carts with those for the carts without cushioning.

   b) Compare the areas under the force vs. time graphs for all of the experimental trials.

   c) Compute the *momentum* of the cart (the product of the mass and the velocity) prior to the collision and compare it with the area under the force vs. time graphs.

   d) Summarize your comparisons in a chart.

   e) The area under the force vs. time graph is called the *impulse*. How can impulse be used to explain the effectiveness of cushioning systems?

   f) Describe the relationship between impulse ($F\Delta t$) and the change in momentum = $\Delta(mv)$.

Physics Talk

FORCES AFFECTING COLLISIONS

By examining the different crumple zones designed by other teams in your class, you can get an insight into the physics of collisions. Probably no team just used the flat sheet of paper. Most teams tried to fold the paper in specific ways. It seemed the goal was to have a "softer" collision rather than have the cart hit the wall without any crumple zone.

By trying to make a "softer" collision, you may have used the physics of work and change in kinetic energy.

$$W = F \cdot d = \Delta KE$$

In this case, as in the air bag, you wanted to decrease the force by increasing the distance to stop the automobile. The work done on the cart then reduced the kinetic energy of the cart.

Impulse and Changes in Momentum

There is an equivalent way of describing the physics of a collision. Rather than focusing on the distance that the force acts, you can look at the amount of time that the force acts. By maximizing the time, you can minimize the force. When creating the crumple zone, you increased the time and thereby minimized the force.

It takes an unbalanced, opposing force to stop a moving automobile. Newton's second law of motion, $F = ma$, lets you find out how much force is required to stop any automobile of any mass with a corresponding *acceleration* (or change in speed with respect to time). For example, if a 1000-kg automobile accelerates at –2 m/s^2, then the force required is

$$F = ma = \left(1000 \text{ kg}\right)\left(-2 \text{ m/s}^2\right) = -2000 \text{ N}$$

Notice that the acceleration is negative because the automobile's **velocity** decreased. Also, notice that the force is negative to indicate that it produces a negative acceleration as it slows the automobile down to a stop.

The overall idea can be shown using a concept map seen at the top of the next page.

Physics Words

velocity: speed in a given direction; displacement divided by the time interval; velocity is a vector quantity; it has magnitude and direction.

$F = ma$
F is force
m is mass
a is acceleration

where →

$a = \Delta v / \Delta t$
Δv is change in velocity
Δt is the time interval

and ↓

$\Delta v = v_f - v_i$
v_f is final velocity
v_i is initial interval

If you know the mass and can determine the acceleration, you can calculate the force using Newtons second law

$$F = ma$$

Suppose a moving automobile has a forward velocity of 15 m/s. Stopping the automobile in 3 s gives it a final velocity of 0 m/s.
The change in velocity

$$= v_{final} - v_{initial}$$
$$= 0 - 15 \text{ m/s}$$
$$= -15 \text{ m/s}$$

(This calculation corresponds to the bottom box in the concept map. Any change in velocity is defined as acceleration. In this case, the change in velocity is -15 m/s.

If the change in velocity occurs in 3 s, the **acceleration** is –15 m/s in 3 s, or –5 m/s every second, or -5 m/s^2. You can look at this as an equation:

$$a = \frac{\Delta v}{\Delta t} = \frac{(v_f - v_i)}{\Delta t} = \frac{-15 \text{ m/s}}{3 \text{ s}} = -5 \text{ m/s}^2$$

(This calculation corresponds to the upper right box in the concept map.)

Newton's second law informs you that unbalanced outside forces cause all accelerations. The force stopping the automobile may have been the frictional force of the brakes and tires on the road, or the force of a tree, or the force of another automobile. Once you know the acceleration, you can calculate the force using Newton's second law. If the automobile has a mass of 1000 kg, the unbalanced force for the acceleration of –5 m/s every second would be –5000 N. The negative sign tells you that the unbalanced force was opposite in direction to the velocity.

If the automobile has a mass of 1000 kg, the unbalanced force for the acceleration of –5 m/s every second would be –5000 N.

Physics Words

acceleration: the change in velocity per unit time; acceleration is a vector quantity.

Newton's second law of motion: if a body is acted upon by a net external force, it will accelerate in the direction of the net force with an acceleration proportional to the force and inversely proportional to the mass.

$$F = ma$$
$$= (1000\ \text{kg})(-5\ \text{m/s}^2)$$
$$= -5000\ \text{N}$$

The same problem can be solved with the same automobile stopping in 0.5 s. The change in speed would still be –15 m/s, and the acceleration can be calculated.

$$a = \frac{\Delta v}{\Delta t} = \frac{v_i - v_o}{\Delta t} = \frac{-15\ \text{m/s}^2}{0.5\ \text{s}} = -30\ \text{m/s}^2$$

There is another, equivalent picture that describes the same collision:

$$F = ma$$

Multiplying both sides of the equation by Δt, you get

$$F\Delta t = m\Delta v$$

then you can rewrite Newton's second law as

$$F = \frac{m\Delta v}{\Delta t}$$

Physics Words

momentum: the product of the mass and the velocity of an object; momentum is a vector quantity.

impulse: a change in momentum of an object.

The term on the right-hand side of the equation is change in **momentum**. The term on the left side of the equation is impulse.

Any moving automobile has momentum. Momentum is represented with a small *p*. Momentum is defined as the mass of the automobile multiplied by its velocity $p = mv$.

A change in momentum is called **impulse**. The impulse-momentum equation tells you that the momentum of the automobile can be changed by applying a force for a given amount of time. The impulse is the force multiplied by the time. So a small force exerted over a long time produces the same impulse (change in momentum) as a large force exerted over a short time. "The small force exerted over a long time" is what you found in the effective crumple zones.

Impulse-momentum is an effective way in which to describe all collisions.

Consider this question: "Why do you prefer to land on soft grass rather than on hard concrete?" Soft grass is preferred because the force on your body is less when you land on soft grass. This can be explained by using the impulse-momentum relation.

Whether you land on concrete or soft grass, your change in velocity will be identical. Your velocity may decrease from 3 m/s to 0 m/s.

On concrete, this change occurs very fast, while on soft grass this change occurs in a longer period of time. Your acceleration on soft grass is smaller because the change in velocity occurred in a longer period of time.

$$a = \frac{\Delta v}{\Delta t}$$

When the change in the period of time gets larger, the denominator of the fraction gets larger and the value of the acceleration gets smaller.

When landing on grass, Newton's second law then tells you that the force must be smaller because the acceleration is smaller for an identical mass, $F = ma$. Smaller acceleration on grass requires a smaller force. Smaller forces are easier on your body and that is why you prefer to land on soft grass.

Change in value of momentum $\Delta p = \Delta mv$	Force F	Change in time Δt	Impulse $F\Delta t$
150 kg • m/s	50 N	3 s	150 N/s (150 kg • m/s)
150 kg • m/s	150 N	1 s	150 N/s (150 kg • m/s)
150 kg • m/s	15,000 N	0.01 s	150 N/s (150 kg • m/s)

You can get this change in momentum with a large force over a short time or a small force over a longer time.

If your mass is 50 kg, the amount of your change in momentum will be 150 kg • m/s when you decrease your velocity from 3 m/s to 0 m/s. There are many forces and associated times that can give this change in the value of the momentum.

If you could land on a surface that requires 3 s to stop, it will only require 50 N. A more realistic time of 1 s to stop will require a larger force of 150 N. A hard surface that brings you to a stop in 0.01 s requires a much larger force of 15,000 N.

On concrete, this change in the value of the momentum occurs very fast (a short time) and requires a large force. It hurts. On soft grass this change in the value of the momentum occurs in a longer time and requires a small force that is less painful and is preferred.

Notice that in the chart above, the change in momentum is always equal to the impulse.

"Work and Energy" or "Impulse and Momentum"

The effective crumple zone decreases the force on the passenger. Using the work-energy theorem the force can be minimized by increasing the distance required to stop. Using the impulse-momentum theorem, the force can be minimized by increasing the time required.

As a physics student, it is your job to decide which of these two approaches is best for explaining a particular collision.

$$W = Fd = \Delta KE$$

or

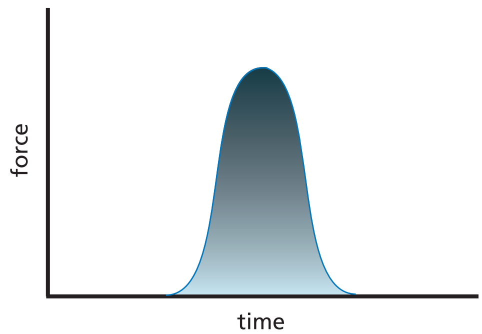
$$F\Delta t = \Delta p$$

Both show that the force can be minimized. In work-energy, force is minimized by an increase in impact distance. In impulse-momentum, force is minimized by an increase in impact time.

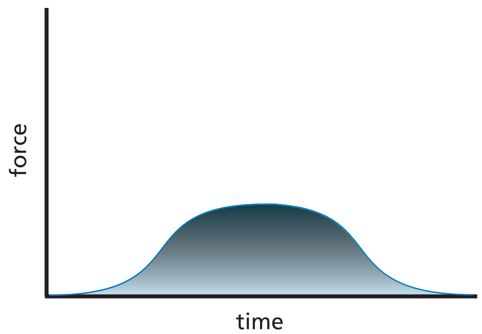
Conserving Momentum

In *Part B* of the *Investigate*, a moving cart was brought to rest. The moving cart had momentum. The force probe was able to record the force that was applied to the cart over time to stop the cart. This force over time changed the momentum of the cart.

The force vs. time graphs for two carts with the same initial momentum are sketched below.



Hard cushion



Soft cushion

As you can see, the cart with the hard cushion had a larger force acting over a shorter time than the cart with the soft cushion. For the safety of passengers, a small force over a long time is what is needed.

Designing a safety device for an automobile is often determined by finding ways to decrease the force and increase the time during an impact. The change in momentum of a cart or an automobile can be identical, but a smaller force over a larger time will be safer.

You know that during a collision, momentum is always conserved. However, confusion may arise because now you find that a force can change the momentum of a cart by bringing it to rest. How can momentum be conserved in collisions but momentum can be changed by a cushion? It may help to view the collision from two different perspectives. It is true that the total momentum before the collision is equal to the total momentum after the collision. However, during the collision the first cart may lose momentum while the second cart may gain momentum. Each cart changed momentum but the total momentum remained the same. A similar thing happens when the force probe stops the automobile. The automobile loses momentum. The probe gains that same amount of momentum. Since its mass is large (it is connected to the lab table), then this large gain in momentum corresponds to a very small gain in velocity.

You may recall that another way in which to describe the same cushion is to say that the larger force acted over a shorter distance. The work done by the force over the distance was the same for both bumpers, and both bumpers decreased the kinetic energy of the automobile.

Change in Momentum and Impulse

Momentum is the product of the mass and the velocity of an object,where p is the momentum,
m is the mass, and
v is the velocity.

Change in momentum is the change in the product of mass and velocity. If the mass remains the same, the change in the momentum is the product of the mass and the change in velocity.

$$p = \Delta mv$$

Impulse is the change in momentum.

$$F\Delta t = \Delta mv$$

Change in Kinetic Energy and Work

Kinetic energy is the product of ½ the mass and the square of the velocity.

$$KE = \frac{1}{2}mv^2$$

Work is the product of the force and the distance over which the force acts.

Work is equal to the change in kinetic energy.

$$W = \Delta KE$$

Checking Up

1. What is a crumple zone?
2. Why is it safer to collide with a soft cushion than a hard surface?
3. What is momentum?
4. What is the relationship between impulse and momentum?

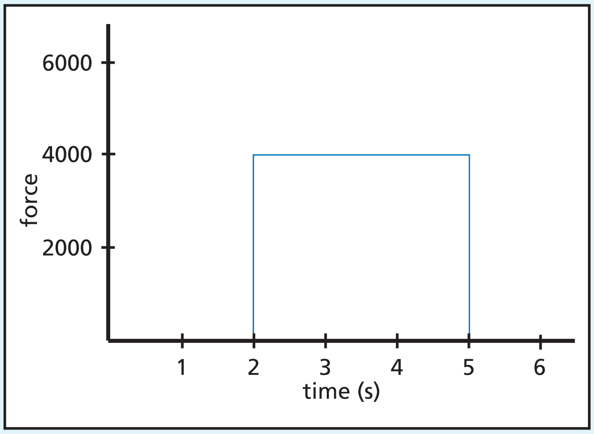
Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
◆◆			

Graphing Momentum Change

An automobile undergoing a collision has a momentum change of 12,000 kg•m/s during a collision. This could occur with a constant force of 4000 N (newtons) over 3 s (seconds).

The graph of the force vs. time for this collision would look like this:



Notice that the area under the graph is the area of the rectangle:

$$A = bh$$

$$A = (3\text{ s})(4000\text{ N})$$

$$A = 12{,}000\text{ N} \bullet \text{s}$$

You can find the units of 1 N by reminding yourself that the newton is defined in Newton's second law:

$$F = ma$$

$$1\text{ N} = (1\text{ kg})(1\text{ m/s}^2)$$

$$1\text{ N} = 1\text{ kg} \bullet \text{m/s}^2$$

The area under the graph has the units of N s. Since 1 N is 1 kg•m/s^2, the area of the graph has the identical units of kg•m/s.

1. Create a graph that shows the same momentum change of 12,000 kg•m/s where the force is a constant 8000 N. You will have to calculate the corresponding time for the collision.
2. Create a graph that shows the same momentum change where the force is a constant 4000 N for 1 s and then 8000 N for the remainder of the required time to bring the automobile to rest.
3. Create a graph that shows the same momentum change where the force is a constant 4000 N for 1 s, then 8000 N for 0.5 s, and then 4000 N for the remainder of the required time to bring the automobile to a rest.
4. Create a graph that shows the same momentum change where the force gradually increases from 0 N to 4000 N, remains at 4000 N for 1 s and then gradually decreases to 0 N when the automobile comes to rest.

What Do You Think Now?

- **What are some of the factors that automobile designers and engineers must consider when designing a crumple zone as a safety feature?**

Now that you have completed this section on crumple zones, what do you think are some of the important considerations in designing a crumple zone? Compare and contrast crumple zones and air bags.

Physics

Essential Questions

What does it mean?

What is the difference between impulse and momentum?

How do you know?

What were the key design features of your crumple zone and why were they important? What were the physics principles that you used?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Forces and motion	Systems	* Good clear explanation, no more complicated than necessary

* The same physics principles can be applied to many situations. Newton's second law $(F = ma)$ can describe the effectiveness of air bags or crumple zones. Another form of Newton's second law $(F\Delta t = \Delta mv)$ provides other insights into the design of air bags or crumple zones. Show how the second equation can be derived from the first equation.

Why should you care?

How could the crumple zone concept be used in your safety system for the *Chapter Challenge?*

Reflecting on the Section and the Challenge

In this section, you found that a crumple zone, as you would find in bumpers or an air bag, is able to protect you by extending the time it takes to stop you. Without the air bags, you will hit something and stop in a brief time. This will require a large force, large enough to injure you. With the air bag (or other crumple device), the time to stop is longer and the force required is therefore smaller.

Force and impulse must be considered in designing your safety system. Stopping an object gradually reduces damage. The harder a surface, the shorter the stopping time, and greater the damage. In part, this provides a clue to the use of padded dashboards and sun visors in newer automobiles. Understanding impulse allows designers to reduce damages both to automobiles and passengers.

You can describe the decrease in force by using work (small force and large distance) or impulse (small force and large time). Which explanation to use depends on whether the stopping distance or stopping time is more easily measured. Work relates to changes in kinetic energy ($KE = \frac{1}{2}mv^2$). Impulse relates to changes in momentum ($p = mv$).

An automobile can be stopped in a very short time or over a longer time. In both cases, there is an identical change in momentum of the automobile. The impulse on the automobile is also identical in both cases since impulse is equal to the change in momentum. However, the potential damage to the automobiles and the passengers is not identical. A large force over a short time can produce severe damage to the automobile and injury to the driver and passengers. Therefore, you will want to consider how you can increase the time (and decrease the force) for your automobile to minimize dangers.

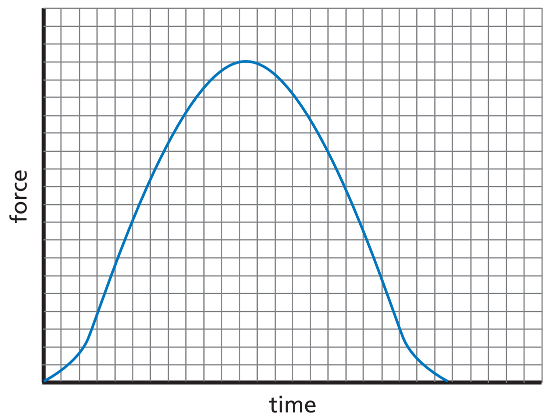
Similarly, an automobile can be stopped in a very short distance or over a longer distance. Although an automobile crashing into a snow bank or a highway barrier can lead to damage and injuries, they are not nearly as severe as what is experienced if the same automobile hits a concrete wall. In this case, you describe the work (force • distance) required to change the kinetic energy of the automobile.

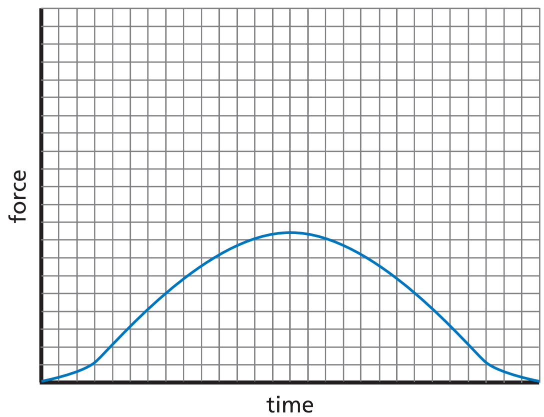
When demonstrating your automobile's safety devices, you may use "momentum and impulse" or "work and kinetic energy" to provide a rationale for your design.

Physics to Go

1. How do impulse and Newton's first law (the law of inertia) play a role in your crumple-zone design?
2. Automobiles today have crumple zones designed into the body of the automobile, and they also have air bags inside the automobile. How do these systems work together to protect the passengers?
3. In automobiles built before 1970, the dashboard was made of hard metal. After 1970, the automobiles were installed with padded dashboards like you find in automobiles today. In designing a safe automobile, why is it better to have a passenger hit a cushioned dashboard than a hard metal dashboard?
   a) Using Newton's second law, explain why the padded dashboard is better.
   b) Using impulse and momentum, explain why a padded dashboard is better.
4. Explain why you bend your knees when you jump to the ground.

5. Helmets are designed to protect cyclists. How would the designers of helmets make use of the concept of impulse to improve their effectiveness?
6. An automobile has a mass of 1200 kg and an initial velocity of 10 m/s (about 20 mi/h). Calculate the change in momentum required to do the following:
   a) Bring it to rest
   b) Slow it to 5 m/s (approximately 10 mi/h)
7. If the braking force for an automobile is 10,000 N, calculate the impulse if the brake is applied for 1.2 s (seconds). If the automobile has a mass of 1200 kg, what is the change in velocity of the automobile over this 1.2 s time interval?
8. A 1500-kg automobile, traveling at 5.0 m/s after braking, strikes a power pole and comes to a full stop in 0.1 s. Calculate the force exerted by the power pole and brakes required to stop the automobile.
9. For the automobile described in *Question 8*, explain why a breakaway pole that brings the automobile to rest after 2.8 s is safer than the conventional power pole.
10. Compare and contrast the two force vs. time graphs shown below.





11. ***Preparing for the Chapter Challenge***

    How can your safety device reduce the force experienced during an impulse? What features of your device increase the stopping time for the passenger? Record a description of how these features work in terms of impulse and momentum.