



Name: _____

Date: _____

Student Exploration: Crumple Zones

Vocabulary: acceleration, airbag, collision avoidance system, crash test dummy, crumple zone, force, kinetic energy, Newton’s laws of motion, safety cell, seat belt, work, work-energy theorem



Prior Knowledge Questions (Do these BEFORE using the Gizmo.)

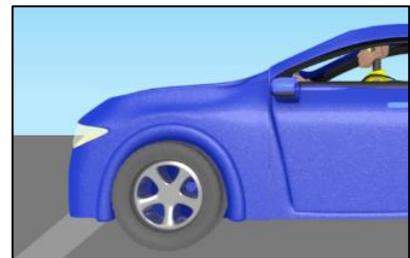
Two burglars run down an alley at night, trying to escape the cops. Jack is carrying a rigid metal safe. Jill is carrying an armful of antique quilts. In the pitch dark, they both collide headlong into a concrete wall.

1. Who do you think will be hurt more in the collision, and why?

2. During a car crash, what features of the car might act like either Jack’s safe or Jill’s quilts?

Gizmo Warm-up

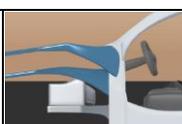
When cars were first invented, the safety of passengers was not a great concern. As vehicles grew larger and faster, accidents became more deadly. Safety features went from being a rare luxury to a legal requirement. In the *Crumple Zones* Gizmo, you will design cars that will help a **crash test dummy** survive a collision.



1. To begin, do not make any changes to the DESIGN tab of the Gizmo. Select the CRASH TEST tab, and click **Play** (▶). After the crash, click **Slo-mo replay**. What happens?

2. Select the RESULTS tab to read about the results of the crash. Do you think a passenger would have survived this car crash? Explain. _____



Activity A: Surviving a crash	<u>Get the Gizmo ready:</u> <ul style="list-style-type: none"> Click Reset (↺). On the DESIGN tab, check that Sedan is selected. 	
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Introduction: Modern vehicles contain features designed to keep passengers safe in a crash. The **crumple zone** in the front of the car slows the car gradually and increases stopping time. The **safety cell** is a rigid cage that prevents passengers from being crushed. Inside, **seat belts** and **airbags** prevent the driver from hitting the windshield, steering wheel, or dashboard.

Question: How does a crumple zone help protect a passenger?

- Make a hypothesis: On the DESIGN tab, look at the parameters you can control. What settings do you think will make the safest car? Set up the Gizmo, and then fill in below.

Crumple zone length: _____ Crumple zone rigidity: _____ Safety cell rigidity: _____

Seat belt present? _____ If present, seat belt stiffness: _____

Air bag present? _____ If present, air bag rigidity: _____

- Test: On the CRASH TEST tab, check that the **Car 1 speed** is 16 m/s, or about 35 miles per hour (mph). Click **Play**. After the crash, select the RESULTS tab.

A. By what percentage did the crumple zone deform? _____ Safety cell? _____

B. Did the dummy hit the steering wheel? _____

C. What was the maximum **force** on the dummy? _____

D. How likely was the dummy to survive? _____

In this simulation, forces are measured in kilonewtons (kN). One kilonewton is equal to 1000 newtons, or the force of a 225-pound (102 kg) person standing on your chest. While many factors affect survival, only the maximum force and safety cell collapse are considered here.

- Experiment: On the DESIGN tab, set the **Crumple zone length** to 100 cm and the **Safety cell rigidity** to 2000 kN. Set the **Seat belt stiffness** to 50 kN/m and turn off the **Airbag**. For each **Crumple zone rigidity** setting, run a 16 m/s crash test and enter the results below.

Crumple zone rigidity	Crumple zone deformation	Dummy displacement	Max. force on dummy	Likelihood of survival
100 kN				
200 kN				
300 kN				
400 kN				

(Activity A continued on next page)



Activity A (continued from previous page)

4. **Evaluate:** Look at the results of your experiment. What was the relationship between crumple zone rigidity, crumple zone deformation, and maximum force on the dummy?

5. **Infer:** For a 1.00 m (100 cm) crumple zone, how much deformation do you think is needed in order to keep the passenger the safest? _____

Explain your answer: _____

6. **Explore:** In the U.S., all cars are evaluated using a frontal 35 mph (~16 m/s) crash test. Using the variables on the DESIGN tab, try to design a car that produces the lowest possible force on the dummy and does not injure the dummy in a 16 m/s crash. If you like, record your data on the provided blank data tables on the next page.

When you have finished, describe your car and your results below.

Car parameters (CZ = crumple zone, SC = safety cell, SB = seat belt, AB = airbag)

CZ length	CZ rigidity	SC rigidity	SB stiffness	AB rigidity

Crash results

CZ deform.	SC deform.	Dummy disp.	Max. force	Survival %

7. **Test:** Click **Reset**. On the CRASH TEST tab, change the **Car 1 speed** to 22 m/s (about 50 mph). Run a crash test at this speed, then look at the summary data.

A. What did you find? _____

B. What is a possible disadvantage of designing a car for only one crash speed?



Blank data tables for car experiments (make as many copies as you need)

Key

CZL = Crumple zone length (cm)
 CZR = Crumple zone rigidity (kN)
 SCR = Safety cell rigidity (kN)
 SBS = Seat belt stiffness (kN/m)
 ABR = Air bag rigidity (kN)

CZ def = Crumple zone deformation (m)
 SC def = Safety cell deformation (m)
 Dum d = Dummy displacement (m)
 Max F = Maximum force on dummy (kN)
 Surv% = Likelihood of survival

Car parameters					Crash results				
CZL	CZR	SCR	SBS	ABR	CZ def	SC def	Dum d	Max F	Surv%

Car parameters					Crash results				
CZL	CZR	SCR	SBS	ABR	CZ def	SC def	Dum d	Max F	Surv%



Activity B: Modern safety features	<u>Get the Gizmo ready:</u> <ul style="list-style-type: none"> • Click Reset. • On the DESIGN tab, check that Sedan is selected. 	
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Introduction: The idea of a crumple zone was conceived by Béla Barényi in 1952 and first used in the 1959 Mercedes W111. Seat belts were also first widely used in the late 1950s. More recently, airbags and **collision avoidance systems** (CAS) were introduced.

Question: How do modern safety features and body types help keep passengers safe?

1. Experiment: Set the **Crumple zone length** to 90 cm, the **Crumple zone rigidity** to 1000 kN, and the **Safety cell rigidity** to 1000 kN. Turn off the seat belt and the airbag. These settings represent a 1950's car with no crumple zone, seat belt, or airbag.

A. On the CRASH TEST tab, set the **Car 1 speed** to 16 m/s. Click **Play**. What happened to the dummy? _____

B. Turn on the seat belt and set the **Seat belt stiffness** to 100 kN/s. Run another crash. What happened? _____

C. Set the **Crumple zone rigidity** to 250 kN and run another test. What happened? _____

D. How did the crumple zone and seat belt work together to keep the driver safe? _____

2. Test: An airbag is designed to quickly inflate on impact, then deflate as the passenger hits the bag. Invented in the early 1970s, airbags did not become widespread until the 1990s. Using the crumple zone and safety cell settings above, experiment with the seat belt to find the lowest possible force on the dummy. Then, experiment with just the airbag. Finally, include both the seat belt and airbag. Report your findings below.

Setup	Seat belt stiffness	Airbag rigidity	Max. force
Seat belt only		(No airbag)	
Airbag only	(No seatbelt)		
Seat belt and airbag			

How did the seat belt and airbag work together to keep the driver safe? _____

(Activity B continued on next page)



Activity B (continued from previous page)

3. Experiment: Another modern safety innovation is the collision avoidance system, or CAS. A CAS will apply the brakes when it senses an imminent collision. The brakes can slow the car by about 8.8 m/s for each second they are engaged.

Click **Reset**. On the CRASH TEST tab, select **Enable collision avoidance system (CAS)**. Drag the car to the far right of the track at the bottom of the Gizmo, then click **Play**.

What were the results of this test? _____

4. Explore: Click **Reset**. In some cases, there will not be enough time for the car to completely stop before the crash occurs. However, the CAS can still be useful. On the CRASH TEST tab, set the **Car 1 speed** to 23 m/s (about 50 mph). Play a crash without the CAS, and then run another test with the CAS on. What did you find?

5. Challenge: You work in the safety engineering department for a large auto manufacturer. Your job is to create the safest possible vehicle given each of the following design criteria. Using the Gizmo, try to create a vehicle that meets each description.

- Design the safest possible SUV with a crumple zone length of 85 cm, no CAS, and a speed of 20 m/s (45 mph). (Note: Injuries such as broken legs are not allowed.)

CZL	CZR	SCR	SBS	ABR	Max. F	Surv%
85 cm						

- Design the safest possible subcompact (no injuries) with a crumple zone length of 80 cm, no CAS, and a speed of 18 m/s (40 mph).

CZL	CZR	SCR	SBS	ABR	Max. F	Surv%
80 cm						

- Design a sedan with a crumple zone length of 110 cm that can give passengers a greater than 50% chance of surviving a 27 m/s (60 mph) crash *and* give passengers a greater than 80% chance of surviving a 16 m/s (36 mph) crash.

(Note: Crumple zone length in both experiments is 110 cm.)

Speed	CZR	SCR	SBS	ABR	Max. F	Surv%
27 m/s						
16 m/s						



Activity C: Force and acceleration	<u>Get the Gizmo ready:</u> <ul style="list-style-type: none"> • Click Reset. • On the DESIGN tab, select the SUV. 	
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Introduction: To understand the physics of a car crash, it is helpful to consider **Newton's laws of motion**:

- First law: An object in motion will stay in motion unless acted on by an unbalanced force.
- Second law: The **acceleration** (a) of an object is directly proportional to the net force (F) on the object and inversely proportional to its mass (m). In equation form: $F = ma$.
- Third law: For every action there is an equal and opposite reaction. If object A exerts force F on object B, then object B exerts force $-F$ on object A.

Question: In a car crash, how are force, mass, acceleration, and velocity related?

1. **Observe:** On the DESIGN tab, check that **SUV** is chosen. Turn off the seat belt and airbag. On the CRASH TEST tab, set the **Car 1 speed** to 10 m/s and click **Play**. Observe the crash, then observe the dummy in slow motion by clicking the **Slow-mo replay** button.

How does Newton's first law explain the motion of the dummy? _____

2. Select the TABLE tab. On the table, scroll down to where the **Dummy v** changes. The velocity change occurs when the dummy hits the steering wheel.

A. What maximum force did the steering wheel exert on the dummy? _____

Notice that this force is negative. In this Gizmo, the positive direction is right to left. A negative force pushes the dummy from left to right, opposite its velocity.

B. According to Newton's third law, what force did the dummy exert on the steering wheel? _____

3. **Calculate:** On the DESIGN tab, set the **Crumple zone length** to 100 cm, the **Crumple zone rigidity** to 200 kN (200,000 N), and the **Safety cell rigidity** to 4000 kN. These settings will result in the crumple zone exerting about 200,000 N of force on the wall during the crash.

A. If the crumple zone exerts +200,000 N of force on the wall, how much force will the wall exert on the crumple zone? _____

B. The SUV has a mass of 2,000 kg. According to Newton's second law, what will be the acceleration of the SUV during the crash? _____

(Activity C continued on next page)

Activity C (continued from previous page)

4. Test: Select the TABLE tab and click **Play**. Look at the **Car a** column. Note where the SUV hits the wall and starts to slow down. What is the acceleration of the SUV? _____

You may notice that the acceleration of the car is not exactly what you predicted. The SUV's acceleration depends on the rigidity of the crumple zone and the safety cell. If the safety cell were perfectly rigid, the acceleration would only depend on the rigidity of the crumple zone.

5. Predict: On the DESIGN tab, select the **Subcompact**. A subcompact has the engine in the back, so the entire front of the car is part of the crumple zone. (Engines do not compress easily, so having the engine in the front of the car reduces the length of the crumple zone.)

Set the **Crumple zone length** to 80 cm, the **Crumple zone rigidity** to 190 kN, and the **Safety cell rigidity** to 4000 kN. Turn off the seat belt, turn on the airbag, and set the **Airbag rigidity** to 15 kN.

- A. Based on the crumple zone rigidity, approximately what force will the wall exert on the car during the crash? _____
- B. Based on the mass, estimate the acceleration of the car: _____
- C. Like the crumple zone, the airbag in this Gizmo exerts a constant force on the dummy. What force, in newtons, does the airbag exert? _____
- D. The dummy has a mass of 50 kg (110 lb). When the dummy hits the airbag, what will be the acceleration of the dummy? _____
6. Test: On the CRASH TEST tab, set the **Car 1 speed** to 16 m/s. Click **Play**. Select the TABLE tab. What is the car's acceleration and the dummy's acceleration during the crash?

Car acceleration during crash: _____ Dummy acceleration during crash: _____

How do these values compare to your predictions? _____

7. Summarize: How do Newton's laws help to explain the acceleration of the car and dummy during a crash? _____



Activity D: The work-energy theorem	<u>Get the Gizmo ready:</u> <ul style="list-style-type: none"> • Click Reset. • On the DESIGN tab, select the SUV body type. 	
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Introduction: In designing a safe vehicle, the goal is to minimize the force on the passenger during a crash by maximizing the stopping time and distance. In this process, it is helpful to know the minimum force that is possible. One way to find this force is to consider how the kinetic energy of the dummy relates to the work done in stopping the dummy.

Question: How can you determine the minimum possible force that acts on a passenger?

1. Calculate: The energy of a moving object is described by its **kinetic energy**, in which $KE = \frac{1}{2} mv^2$. **Work** is the product of force and distance: $W = Fd$. The **work-energy theorem** states that work changes the kinetic energy of an object: $W = \Delta KE$. This means that the work required to stop an object is equal in magnitude to the kinetic energy of the object.

A. Work is equal to Fd , and work is also equal to ΔKE . Combine these relationships to write an equation that relates force and distance to the change in kinetic energy. Then, rearrange this equation to solve for force.

B. If the goal of a safety system is to minimize the force, should the distance the dummy moves during the car crash be very large or very small? Explain your answer.

C. Suppose a car has a 1.00 meter crumple zone. The distance from the dummy to the steering wheel is 0.50 m (50 cm). After impact, if the crumple zone collapses completely, how far could the dummy go before hitting the steering wheel?

Maximum distance dummy could be displaced: _____

D. The dummy has a mass of 50 kg (110 lb). If the dummy is traveling 16 m/s at the time of the crash, what is the dummy's initial kinetic energy? _____ joules (J)

E. $\Delta KE = KE_{\text{final}} - KE_{\text{initial}}$. If the dummy comes to a stop, what is ΔKE ? _____

F. The work-energy theorem can be rewritten as $F = \Delta KE \div d$. If the distance and kinetic energy change are known, you can solve for the force. Based on your answers to questions C and D, what constant force will stop the dummy?

$F =$ _____ N

G. Convert the force to kilonewtons. $F =$ _____ kN

(Activity D continued on next page)



Activity D (continued from previous page)

2. **Test:** In the Gizmo, set the **Crumple zone length** to 100 cm. On the CRASH TEST tab, set the **Car 1 speed** to 16 m/s. Click **Play**, wait for the end of the crash, then look at the **Summary** data on the RESULTS tab.

A. What is the lowest possible maximum force on the dummy? _____

B. The RESULTS tab shows the magnitude of the force on the dummy. (Since magnitude does not deal with direction, it has no sign.) How does the magnitude of this force compare to the magnitude of the force you found in question 1G?

C. Suppose the dummy had a velocity of 24 m/s before the crash and the crumple zone had a length of 1.20 m. What is the lowest possible force on the dummy in this case? Show your work and check your answer with the Gizmo.

Minimum force on dummy: _____ kN

3. **Calculate:** In the simplified situation shown in the Gizmo, the exact design of the crumple zone is not considered. Instead, the crumple zone is modeled as a semi-rigid structure that exerts a constant force on the car as it collapses. (This model is similar to how real-world crumple zones act.) The more rigid the crumple zone, the greater this constant force will be.

You can use the work-energy theorem to determine the ideal constant force the crumple zone exerts. On the DESIGN tab, select the **SUV** body type and set the **Crumple zone length** to 100 cm. Note the mass of the SUV is 2,000 kg. On the CRASH TEST tab, set the starting speed to 16 m/s.

A. What is the kinetic energy of the SUV, in joules? _____

B. How far can the crumple zone collapse, in meters? _____

C. What force (in kN) must the crumple zone exert in order to stop the car as it collapses completely? _____ Check your answer in the Gizmo.

4. **Think and discuss:** No matter what you do, you will not be able to get the maximum force on the dummy exactly equal to the lowest possible maximum force because of the design of the airbags and seat belt. In the Gizmo, the seat belt is modeled as a spring, so the force of the belt increases as it is stretched. The airbag takes a few milliseconds to get into position. As a result, the dummy does not hit the airbag right away.

How do these limitations affect how well the safety system can protect passengers in the car? What aspects of these systems can be improved? Write down your thoughts in your notes, and then if possible discuss these questions with your classmates and teacher.

