How Roller Coasters Work

by Tom Harris

Roller coaster history can be traced back to 16th century Russia where people rode sleds down ice covered slides. Learn more about roller coaster history.

Introduction to How Roller Coasters Work

If you're studying physics, there are few more exhilarating classrooms than a roller coaster. Roller coasters are driven almost entirely by basic inertial, gravitational and centripetal forces, all manipulated in the service of a great ride. Amusement parks keep upping the ante, building faster and more complex roller coasters, but the fundamental principles at work remain the same.

In this article, we'll examine the principles that keep coaster cars flying around on their tracks. We'll also look at the hardware that keeps everything running, as well as the forces that make the ride so much fun.

The amusement-park industry has experienced a coaster boom of sorts in the past 15 years or so. New **catapult launching** techniques, **hanging-train designs** and other technological developments have opened up a world of options for designers. In recent years, designers have introduced coasters that have you lying flat against the train car so you feel as if you are flying, and coasters that shoot you down long stretches of spiraled track. "Fourth dimension" coasters spin or rotate your seat as the ride twists, turns and free-falls. In this article, we'll also keep you in the loop on all the newest features and innovations.

Roller Coaster History

Roller coasters have a long, fascinating history. The direct ancestors of roller coasters were monumental ice slides -- long, steep wooden slides covered in ice, some as high as 70 feet -- that were popular in Russia in the 16th and 17th centuries. Riders shot down the slope in sleds made out of wood or blocks of ice, crash-landing in a sand pile.

Coaster historians diverge on the exact evolution of these ice slides into actual rolling carts. The most widespread account is that a few entrepreneurial Frenchmen imported the ice slide idea to France. The warmer climate of France tended to melt the ice, so the French started building waxed slides instead, eventually adding wheels to the sleds. In 1817, the **Russes a Belleville** (Russian Mountains of Belleville) became the first roller coaster where the train was attached to the track (in this case, the train axle fit into a carved groove). The French continued to expand on this idea, coming up with more complex track layouts, with multiple cars and all sorts of twists and turns.

The first American roller coaster was the **Mauch Chunk Switchback Railway**, built in the mountains of Pennsylvania in the mid-1800s. The track, originally built to send coal to a railway, was reconfigured as a "scenic tour." For one dollar, tourists got a leisurely ride up to the top of the mountain followed by a wild, bumpy ride back down. Over the next 30 years, these scenic rides continued to thrive and were joined by wooden roller coasters similar to the ones we know today. These coasters were the main attraction at popular amusement parks throughout the United States, such as Kennywood Park in Pennsylvania and Coney Island in New York. By the 1920s, roller coasters were in full swing, with some 2,000 rides in operation around the country.

With the Great Depression and World War II, roller-coaster production declined, but a second roller-coaster boom in the 1970s and early 1980s revitalized the amusement-park industry. This era introduced a slew of innovative tubular steel coasters. Some of the most popular ride variations -- such as the curving corkscrew track -- saw their heyday around this time.

In the next section, we'll look at the coaster components that get the train rolling and bring it to a stop.

Roller Coaster Components

At first glance, a roller coaster is something like a passenger train. It consists of a series of connected cars that move on tracks. But unlike a passenger train, a roller coaster has no engine or power source of its own. For most of the ride, the train is moved by gravity and momentum. To build up this momentum, you need to get the train to the top of the first hill (the lift hill) or give it a powerful launch.

Chain Lift

The traditional lifting mechanism is a long length of chain (or chains) running up the hill under the track. The chain is fastened in a loop, which is wound around a gear at the top of the hill and another one at the bottom of the hill. The gear at the bottom of the hill is turned by a simple motor.

This turns the chain loop so that it continually moves up the hill like a long conveyer belt. The coaster cars grip onto the chain with several **chain dogs**, sturdy hinged hooks. When the train rolls to the bottom of the hill, the dogs catches onto the chain links. Once the chain dog is hooked, the chain simply pulls the train to the top of the hill. At the summit, the chain dog is released and the train starts its descent down the hill.

Catapult-launch Lift

In some newer coaster designs, a catapult launch sets the train in motion. There are several sorts of catapult launches, but they all basically do the same thing. Instead of dragging the train up a hill to build up potential energy, these systems start the train off by building up a good amount of kinetic energy in a short amount of time.

One popular catapult system is the linear-induction motor. A linear-induction motor uses electromagnets to build two magnetic fields -- one on the track and one on the bottom of the train -- that are attracted to each other. The motor moves the magnetic field on the track, pulling the train along behind it at a high rate of speed. The main advantages of this system are its speed, efficiency, durability, precision and controllability.

Another popular system uses dozens of rotating wheels to launch the train up the lift hill. The wheels are arranged in two adjacent rows along the track. The wheels grip the bottom (or top) of the train between them, pushing the train forward.

The Brakes

Like any train, a roller coaster needs a brake system so it can stop precisely at the end of the ride or in an emergency. In roller coasters, the brakes aren't built into the train itself; they're built into the track.

This system is very simple. A series of clamps is positioned at the end of the track and at a few other braking points. A central computer operates a hydraulic system that closes these clamps when the train needs to stop. The clamps close in on vertical metal fins running under the train, and this friction gradually slows the train down.

Roller Coaster Physics

The purpose of the coaster's initial ascent is to build up a sort of reservoir of potential energy. The concept of **potential energy**, often referred to as energy of position, is very simple: As the coaster gets higher in the air, gravity can pull it down a greater distance. You experience this phenomenon all the time -- think about driving your car, riding your bike or pulling your sled to the top of a big hill. The potential energy you build going up the hill can be released as **kinetic energy** -- the energy of motion that takes you down the hill.

Once you start cruising down that first hill, gravity takes over and all the built-up potential energy changes to kinetic energy. Gravity applies a constant downward force on the cars.

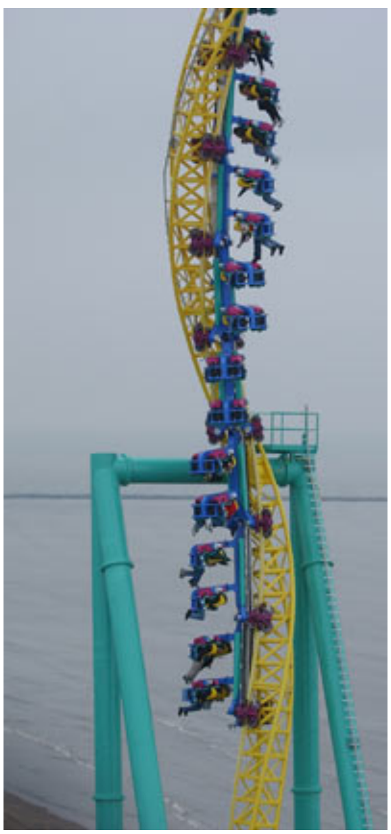
Click **play** to start the animation, which demonstrates how a roller coaster's energy is constantly changing between potential and kinetic energy. At the top of the first lift hill (a), there is maximum potential energy because the train is as high as it gets. As the train starts down the hill, this potential energy is converted into kinetic energy -- the train speeds up. At the bottom of the hill (b), there is maximum kinetic energy and little potential energy. The kinetic energy propels the train up the second hill (c), building up the potential-energy level. As the train enters the loop-the-loop (d), it has a lot of kinetic energy and not much potential energy. The potential-energy level builds as the train speeds to the top of the loop (e), but it is soon converted back to kinetic energy as the train leaves the loop.

The coaster tracks serve to channel this force -- they control the way the coaster cars fall. If the tracks slope down, gravity pulls the front of the car toward the ground, so it accelerates. If the tracks tilt up, gravity applies a downward force on the back of the coaster, so it decelerates.

Since an object in motion tends to stay in motion (Newton's first law of motion), the coaster car will maintain a forward velocity even when it is moving up the track, opposite the force of gravity. When the coaster ascends one of the smaller hills that follows the initial lift hill, its kinetic energy changes back to potential energy. In this way, the course of the track is constantly converting energy from kinetic to potential and back again.

This fluctuation in acceleration is what makes roller coasters so much fun. In most roller coasters, the hills decrease in height as you move along the track. This is necessary because the total energy reservoir built up in the lift hill is gradually lost to friction between the train and the track, as well as between the train and the air. When the train coasts to the end of the track, the energy reservoir is almost completely empty. At this point, the train either comes to a stop or is sent up the lift hill for another ride.

At its most basic level, this is all a roller coaster is -- a machine that uses gravity and inertia to send a train along a winding track. Next, we'll look at the various sensations you feel during a roller coaster ride, what causes them and why they're so enjoyable.



Roller Coaster Forces

In the last few sections, we looked at the forces and machinery that send roller coasters rocketing around elaborate courses. As you move over the hills, valleys and loops of the track, the forces on you seem to change constantly, pulling you in all directions. But why is this rollicking movement so enjoyable (or, for some people, so nauseating)?

To understand the sensations you feel in a roller coaster, let's look at the basic forces at work on your body. Wherever you are on Earth, gravity is pulling you down toward the ground. But the force you actually notice isn't this downward pull -- it's the upward pressure of the ground underneath you. The ground stops your descent to the center of the planet. It pushes up on your feet, which push up on the bones in your legs, which push up on your rib cage and so on. This is the feeling of weight. At every point on a roller-coaster ride, gravity is pulling you straight down.

The other force acting on you is acceleration. When you are riding in a coaster car that is traveling at a constant speed, you only feel the downward force of gravity. But as the car speeds up or slows down, you feel pressed against your seat or the restraining bar.

You feel this force because your inertia is separate from that of the coaster car. When you ride a roller coaster, all of the forces we've discussed are acting on your body in different ways.

Newton's first law of motion states that an object in motion tends to stay in motion. That is, your body will keep going at the same speed in the same direction unless some other force acts on you to change that speed or direction. When the coaster speeds up, the seat in the cart pushes you forward, accelerating your motion. When the cart slows down, your body naturally wants to keep going at its original speed. The harness in front of you accelerates your body backward, slowing you down.

Roller Coasters and Your Body

Your body feels acceleration in a funny way. When a coaster car is speeding up, the actual force acting on you is the seat pushing your body forward. But, because of your body's inertia, you feel a force in front of you, pushing you into the seat. You always feel the push of acceleration coming from the opposite direction of the actual force accelerating you.

This force (for simplicity's sake, we'll call it the acceleration force) feels exactly the same as the force of gravity that pulls you toward the Earth. In fact, acceleration forces are measured in g-forces, where 1 g is equal to the force of acceleration due to gravity near the Earth's surface (9.8 m/s2, or 32 ft/s2).

A roller coaster takes advantage of this similarity. It constantly changes its acceleration and its position to the ground, making the forces of gravity and acceleration interact in many interesting ways. When you plummet down a steep hill, gravity pulls you down while the acceleration force seems to be pulling you up. At a certain rate of acceleration, these opposite forces balance each other out, making you feel a sensation of weightlessness -- the same sensation a skydiver feels in free fall. If the coaster accelerates downward fast enough, the upward acceleration force exceeds the downward force of gravity, making you feel like you're being pulled upward. If you're accelerating up a steep hill, the acceleration force and gravity are pulling in roughly the same direction, making you feel much heavier than normal. If you were to sit on a scale during a roller coaster ride, you would see your "weight" change from point to point on the track.

At the top of a hill in a conventional coaster, inertia may carry you up, while the coaster car has already started to follow the track down. Let go of the safety bar, and you'll actually lift up out of your seat for an instant. Coaster enthusiasts refer to this moment of free fall as "air time."

That Sinking Feeling

"Air time" has a strange effect on your body because your body is not completely solid -- it is composed of many loosely connected parts. When your body is accelerated, each part of your body is accelerated individually. The seat pushes on your back, the muscles in your back push on some organs and those organs push on other organs. This is why you feel the ride with your whole body. Everything inside is being pushed around.

Normally, all the parts of your body are pushing on each other because of the constant force of gravity. But in the "free-fall" state of plummeting down a hill, there is hardly any net force acting on you. In this case, the various pieces of your body are not pushing on each other as much. They are all, essentially, weightless, each falling individually inside your body. This is what gives you that unique sinking feeling in your stomach -- your stomach is suddenly very light because there is less force pushing on it. The same thing happens when you drive down a dip in the road in your car or descend in an elevator moving at high speed.

On a roller coaster, this full-body sensation is complemented by all sorts of visual cues -- the upside-down turns, dizzying heights and passing structures. Visual cues are an important part of the ride because they tell you that you are going fast. Your body can't feel velocity at all; it can only feel change in velocity (**acceleration**).

The only reasons you know that you are moving quickly on a coaster is that the support structure is whipping past you at top speed, and the air is rushing in your face. Roller-coaster designers make sure to create plenty of tight fits and near misses to make you feel like you're rocketing through the structure at out-of-control speeds.

One of the most exciting elements in modern coasters is the loop-the-loop. These structures turn the whole world upside down for a few seconds. Let's take a closer look.

Loop-the-Loops

As you go around a loop-the-loop, your inertia not only produces an exciting acceleration force, but it also keeps you in the seat when you're upside down.

A roller coaster loop-the-loop is a sort of **centrifuge**, just like a merry-go-round. In a merry-go-round, the spinning platform pushes you out in a straight line away from the platform. The constraining bar at the edge of the merry-go-round stops you from following this path -- it is constantly accelerating you toward the center of the platform.

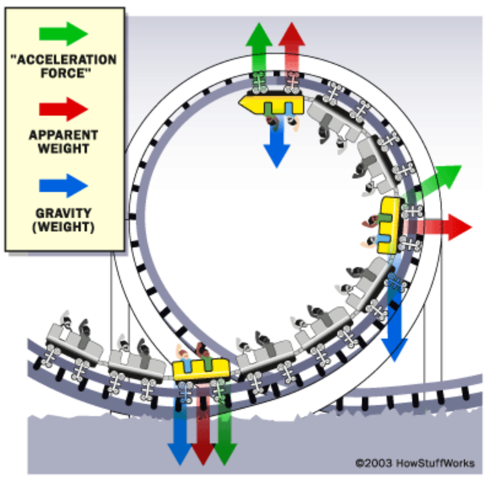
The loop-the-loop in a roller coaster acts exactly the same way as a merry-go-round. As you approach the loop, your **inertial velocity** is straight ahead of you. But the track keeps the coaster car, and therefore your body, from traveling along this straight path. The force of your acceleration pushes you from the coaster-car floor, and your inertia pushes you into the car floor. Your own outward inertia creates a sort of false gravity that stays fixed at the bottom of the car even when you're upside down. You need a safety harness for security, but in most loop-the-loops, you would stay in the car whether you had a harness or not.

As you move around the loop, the net force acting on your body is constantly changing. At the very bottom of the loop, the acceleration force is pushing you down in the same direction as gravity. Since both forces push you in the same direction, you feel especially heavy at this point. As you move straight up the loop, gravity is pulling you into your seat while the acceleration force is pushing you into the floor. You feel the gravity pulling you into your seat, but (if your eyes are still open) you can see that the ground is no longer where it should be.

At the top of the loop, when you're completely upside down, gravity is pulling you out of your seat, toward the ground, but the stronger acceleration force is pushing you into your seat, toward the sky. Since the two forces pushing you in opposite directions are nearly equal, your body feels very light. As in the sharp descent, you are almost weightless for the brief moment when you are at the top of the loop.

As you come out of the loop and level out, you become heavy again. The loop-the-loop is amazing because it crams so much into such a short length of track. The varying forces put your body through the whole range of sensations in a matter of seconds. While these forces are shaking up all the parts of your body, your eyes see the entire world flip upside down. To many coaster riders, this moment at the top of the loop, when you're light as a feather and all you can see is the sky, is the best part of the whole ride.

In a loop-the-loop, the intensity of the acceleration force is determined by two factors: the speed of the train and the angle of the turn. As the train enters the loop, it has maximum kinetic energy -- that is, it is moving at top speed. At the top of the loop, gravity has slowed the train down somewhat, so it has more potential energy and less kinetic energy -- it is moving at reduced speed.



Originally, roller-coaster designers made circle-shaped loops. In this design, the angle of the turn is constant all the way around. In order to build an acceleration force strong enough to push the train into the track at the top of the loop, they had to send the train into the loop at a fairly high rate of speed (so it would still be going pretty fast at the top of the loop). Greater speed meant a much greater force on the rider as he entered the loop, which could be fairly uncomfortable.

The **teardrop** design makes it much easier to balance these forces. The turn is much sharper at the very top of the loop than it is along the sides. This way, you can send the train through the loop fast enough that it has an adequate acceleration force at the top of the loop, while the teardrop shape creates a reduced acceleration force along the sides. This gives you the force you need to keep everything running, without applying too much force where it might be dangerous.

Types of Roller Coasters

There are two major types of roller coasters, distinguished mainly by their track structure.

The tracks of **wooden** roller coasters are something like traditional railroad tracks. In most coasters, the car wheels have the same flanged design as the wheels of a train -- the inner part of the wheel has a wide lip that keeps the car from rolling off the side of the track. The car also has another set of wheels (or sometimes just a safety bar) that runs underneath the track. This keeps the cars from flying up into the air.

Wooden coaster tracks are braced by wooden cross ties and diagonal support beams. The entire track structure rests on an intricate lattice of wooden or steel beams, just like the beam framework that supports a house or skyscraper.

They can even flip the train upside down (though this is rare in modern wooden coasters). But, because the track and support structure are so cumbersome, a wooden track is fairly inflexible. This makes it difficult to construct complex twists and turns. In wooden coasters, the exhilarating motion is mainly up and down.

The range of motion is greatly expanded in **steel** roller coasters. The world of roller coasters changed radically with the introduction of tubular steel tracks in the 1950s. As the name suggests, these tracks consist of a pair of long steel tubes. These tubes are supported by a sturdy, lightweight superstructure made out of slightly larger steel tubes or beams.

Tubular steel coaster wheels are typically made from polyurethane or nylon. In addition to the traditional wheels that sit right on top of the steel track, the cars have wheels that run along the bottom of the tube and wheels that run along the sides. This design keeps the car securely anchored to the track, which is absolutely essential when the train runs through the coaster's twists and turns.

The train cars in tubular steel coasters may rest on top of the track, like the wheels in a traditional wooden coaster, or they may attach to the track at the top of the car, like in a ski lift. In **suspended** coasters, the hanging trains swing from a pivoted joint, adding an additional side-to-side motion. In an **inverted** coaster, the hanging train is rigidly attached to the track, which gives the designer more precise control of how the cars move.

A tubular steel track is prefabricated in large, curved segments. The steel manufacturing process allows for a smoothly curving track that tilts the coaster train in all directions. A wooden roller coaster rattles as it rolls over the joints that connect the pieces of the wooden track. In a tubular steel coaster, the track pieces are perfectly welded together, making for an incredibly smooth ride. As any coaster enthusiast will tell you, each sensation has its own distinctive charm.

According to the Roller Coaster DataBase, there were 2,088 coasters in operation around the world in 2007 -- 1,921 of them steel, 167 wooden. The RCDB identifies eight main coaster types:

- **Sit-down**
- **Stand-up**
- **Inverted**
- **Suspended**
- **Pipeline:** The track is attached to the middle of the train, instead of above or below it.
- **Bobsled:** Wheeled trains slide down a U-shaped tube instead of being fixed to a track.
- **Flying:** Riders start out in a seated position but are rotated to face the ground as the ride starts, giving the feeling of flying.
- **Fourth Dimension:** Two seats from each car are positioned on either side of the track. The seats spin or rotate on their own axis - either freely or in a controlled motion. In 2007, there were only four Fourth Dimension coasters in operation.

Never been on a coaster before? In the next section we'll give you some advice on your first ride.

Safety Tips for a First-timer

So, you're finally taking the plunge. For years, you've been playing it safe on the bumper cars and kiddie rides, but now you're ready to try the real deal -- a coaster. Once you're in line, though, the bloodcurdling screams coming from the ride could make you think you're about to put your life at risk. You might want to turn around and head back to the carousel. But really, how dangerous are roller coasters?

First of all, it's important to know that the numbers are on your side. According to the International Association of Amusement Parks and Attractions, 335 million people visited U.S. theme parks in 2006 [Source: IAAPA]. A study that year by the Consumer Product Safety Commission found that around 6,500 people seek medical attention every year for injuries at theme parks (this includes non-ride injuries). Of that number, about 130 required overnight hospitalization, making your risk of serious injury -- just from stepping into the park -- about one in 25 million. The chance of a fatal injury at a theme park is one in 1.5 billion [Source: CPSC]. By comparison, the chance of fatal injury in a car crash is almost 15 in 10,000 [Source: U.S. Department of Transportation].

In 2003, the Brain Injury Institute of America released a study that concluded, in part, that "The risk of brain injury from a roller coaster is not in the rides, but in the rider" [Source: Brain Injury Institute of America]. Of the six fatal injuries the study examined, all had been caused by previously undetected brain conditions.

Basically, use common sense. If you have, or think you might have, any of the conditions posted on the warning signs (i.e., high blood pressure, heart disease or heart condition, pregnancy) don't get on the ride. If you've been consuming alcohol or if you don't meet the height and weight requirements, you are putting yourself at risk by riding a roller coaster.

Once you've made it into the coaster car, you'll be secured by one of two basic restraint systems: a lap bar or some variation of an over-the-shoulder harness. Don't be alarmed if you're getting on a loop-the-loop coaster with a lap bar -- as we saw earlier, inertia would keep you in your seat even with no restraints!

The restraint system -- and everything else on a roller coaster -- is completely computer-controlled. **Programmable logic controllers**, usually three of them, monitor every aspect of a coaster's operations. They regulate the ride's speed, ensure that trains never come too close to one another, and alert human operators to technical glitches or track obstructions. There is no possibility that, say, the ride would leave the station with an unsecured safety belt or that an attendant would forget to apply the coaster's brake. All coasters are carefully inspected on a daily basis and completely worked over during the park's off-season. Even armed with all these facts, you'll probably still be a little nervous. Just remember that roller coasters are designed to give you a thrill -- to make you feel like you're in danger, if only for a few seconds. So just sit back, relax and enjoy the ride!