Busch Gardens®

Physics Day

Introduction

The principles of kinematics, dynamics and energy come alive at Busch Gardens. You can experience forces similar to the space shuttle astronauts on the Kumba, feel the effects of inertia as you rapidly decelerate on the Tidal Wave, feel close to weightless as your log plunges down the incline on the Log Flume, or confuse your senses as you turn upside down on the Montu.

General Guidelines:

1. Students should work in groups. Each group should have a Vertical G Force Meter, a Horizontal G Force Meter, and a Stopwatch. **These instruments can not be taken on the Montu, Kumba, Phoenix, Gwazi or SheiKra.**
2. Each ride has a Basic and an Advanced section. (The Bumper Cars have only a BASIC section, and the Phoenix only has an ADVANCED section. There are a couple of Advanced questions on the SandSerpent.) The Basic section is designed to use less mathematics than the Advanced section and is appropriate for middle school students as well as high school students. Students may be assigned to do both Basic and Advanced sections of a particular ride, or they may do only the Basic or only the Advanced. There is no duplication if students do both. (If they do only the Advanced, there is a section entitled "What to do if you didn't do the Basic," and it indicates how to compensate for not doing the Basic section.)
3. Except for the height measurement on the Scorpion, which requires a Horizontal Force Meter, the Advanced sections require only the use of a stopwatch. If you want your students to be able to use the Horizontal and Vertical Force Meters, then assign them some Basic sections:

   Vertical Force Meters are used on the following Basic rides:

   Scorpion, SandSerpent

   Horizontal Force Meters are used on the following Basic rides:

   Log Flume, Tidal Wave, Bumper Cars, SandSerpent

   Hand-held instruments are not allowed on the Kumba, Montu, Phoenix, Gwazi or SheiKra.
4. If the students do not have Force Meters, they still can benefit from doing the Basic sections. Only a few of the questions in each section require Force Meter measurements. These questions can be made qualitative or left out. On Physics Days there also will be G Force Meters mounted on the Montu, Kumba, Phoenix, and Gwazi.
5. An electronic accelerometer (a Vernier Low G accelerometer or a 3-axis accelerometer that is attached to a TI Calculator/CBL/Lab Pro) may be used on any of the rides in this workbook, as long it is contained in an approved vest, such as the Vernier Data Vest.
6. Please be courteous and obey all of the park rules. You will be allowed to carry the hand-held G Force Meters on rides indicated, but the Meters should be equipped with hand-straps for the safety of yourself and others.
7. No one will be able to complete the entire workbook in one day. Choose which rides to do and what level (Basic, Advanced or both) before coming to the park. Generally, four or five rides are sufficient to give the students a positive experience in the park.
8. Students are supposed to make three measurements of every data point. This could mean either a student making all three measurements or each student in the group making

a measurement and combining results. It may be easy to make three time measurements while watching the ride from the side, but it may not be easy for each student to make three G Force measurements, as that would require riding the ride three times.

What to do before coming to the park:

1. Have the students complete the WHAT TO DOING BEFORE COMING TO THE PARK section for each ride that they are going to do. They will do sample problems and make predictions.
2. In class, go over the physics principles and do some of the pre-activities.

Making Measurements

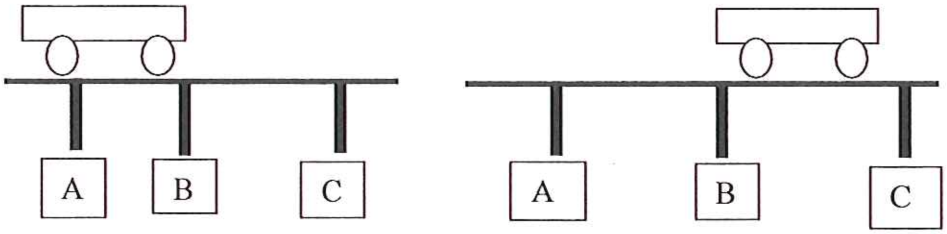
Three Measurements

The workbook calls for three measurements of most quantities, because a single measurement can be in error. The three may be a combination of three students making one measurement each or one student making three measurements. All three measurements should be consistent with each other. All of the calculations should be made with the average of the three measurements.

Speed

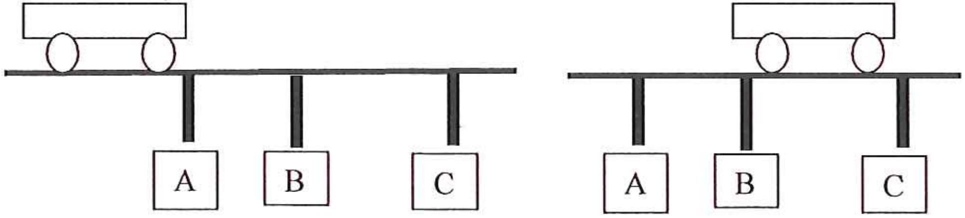
Usually the average speed of a coaster at a point (usually a post or pole) is determined by timing the coaster passing by that point. The stopwatch is started as the front of the coaster arrives at Post B, and the stopwatch is stopped as the back of the coaster passes the same post. If the length of the coaster is known, then:

Average Speed = (Length of coaster)/(time)



Sometimes, if the speed is large and the car (or log) is small, this method of measuring speed will not be precise enough. The car then can be timed between two points of known separation. The stopwatch is started when the front of the car passes post A and stopped when the front of the car passes post C.

Average Speed=(Distance between A and C)/(time)



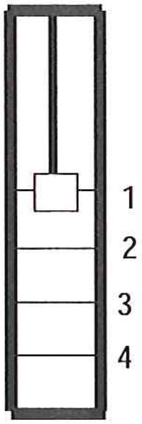
G Force

Forces that are experienced while on the rides can be measured with a G Force Meter.

When standing still on the surface of the earth or traveling at a constant speed in a straight line, the G Force is 1. This is called 1 "g." If riders are accelerating, then they will experience a G Force other than 1. The G Force can be computed by taking the support force and dividing it by the weight. Support force is whatever force is preventing an object from falling. This could be the force of the track on the coaster divided by the weight of the coaster or the force of the seat on the rider divided by the rider's weight. In each case the G Force will be the same.

A Vertical G Force Meter indicates forces due to accelerations that are parallel to your backbone, which is perpendicular to the track. The Meter is held or mounted so as to be parallel to your backbone. A reading of 2 g's means you are experiencing a force equal to twice your weight. Thus, you will feel twice as heavy as normal. A force of 0.5 g's means that the force that you feel is one-half of your weight, and you will feel lighter. If you are in free fall (meaning only the force of gravity is at work), then the support force will be zero, and you will experience zero g's, or weightlessness.

The G Force Meter illustrated below is at rest, and the G Force is 1. An upward G Force will cause the weight to go down the tube, with the location of the weight indicating the G Force. If the Meter reads less than 1, this indicates that the rider appears to weigh less than normal.



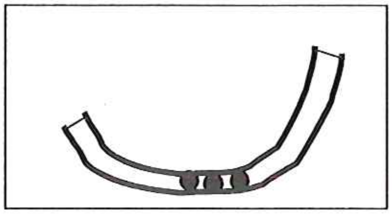
If you are traveling in a straight line at a constant speed, you will be experiencing 0 g's horizontally. If the coaster car or other ride slows down or speeds up, and the Horizontal G Force Meter reads 1, this means that you are experiencing a force equal to your weight, but pushing on you horizontally. The Horizontal G Force meter should be held parallel to the coaster car or boat and braced against the side of the car. A reading of 0.5 means that a force of one-half of your weight is pushing on you horizontally.

If the coaster car turns a corner quickly in an unbanked turn, a lateral G Force is experienced and can be measured by holding the Horizontal Force meter perpendicular to the direction of motion.

A Horizontal G Force Meter is often calibrated in degrees. As illustrated below, when acceleration is experienced, BBs will roll up a tube. The highest angle achieved relates to the G Force in the following way:

G Force = Tangent of the Angle
(i.e. Tan (60 degrees) = 1.7, so 60 degrees corresponds to 1.7 g's.)

The chart below can be used to determine the G Force from the angle on the Horizontal G Force Meter. A G Force to the right will cause the BBs to roll to the left.

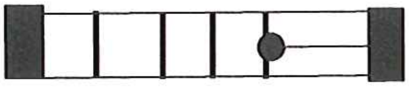


Angle	10	15	20	25	30	35	40	45	50	55	60	65
G's	.18	.27	.36	.47	.58	.70	.84	1.00	1.19	1.43	1.73	2.14

Force Meter Construction

Vertical and Horizontal G Force Meters (sometimes called accelerometers) are available from Pasco Scientific (1-800-772-8700). Pasco sells a set of 15 vertical and horizontal accelerometers for about $70 (ME-9426). Sargent Welch (1-800-727-4368) also sells a set of 15 of each type of accelerometer for about $94 (CP32513-00).
These commercially purchased accelerometers come with a hand-strap. This hand-strap is required when using the G Force meters on the rides.
Meters may not be used on the KUMBA, MONTU, GWAZI, SHEIKRA or PHOENIX!!!
You may also create your own G Force meters, but they must have no sharp edges or exposed heavy objects. The Horizontal G Force meters which are sold by Pasco and Sargent Welch are ideal in that they are made of cardboard, with BBs in a plastic tube. You will not be able to use a homemade meter made of a protractor with a hanging weight.

As long as it has a hand-strap, homemade Vertical G Force meters will be allowed. They must conform to the standards of not being hard and of having no sharp edges or exposed weights. A Force Meter described in the Exloratorium Quarterly (Vol. 11, Issue 2) conforms to these standards. It is made of flexible plastic tubing with furniture end caps on the ends and a fishing weight hung from a rubber band in the middle.



You may also take a TI Calculator with CBL/LabPro and an accelerometer probe on any ride as long as it is contained properly in an approved vest (such as the Data Vest available from Vernier for $26). A complete description of how to use this electronic accelerometer probe is available at the Vernier website (www.vernier.com/cmat/datapark.html) by clicking on the "Download the

Data Collection at the Amusement Park Manual" link. Graphs similar to those found at the end of this workbook can be produced and analyzed. Schools must provide their own computers to download the data from the Calculators/Lab Pros.

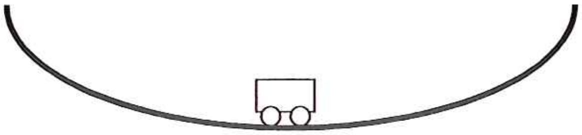
Problems

Finding the G Force for Vertical Acceleration

At the tops and bottoms of coaster hills, centripetal force (force acting in toward the center of a circle) is required to cause the acceleration of the coaster. Two forces act upon the coaster: the track and gravity. The resultant force of those two factors must provide the centripetal force, $F_c=mv^2/r$. Toward the center of the circle is considered to be the positive direction. The G force will be equal to the support force of the track divided by the weight of the coaster.

G Force at theBottom of a Hill

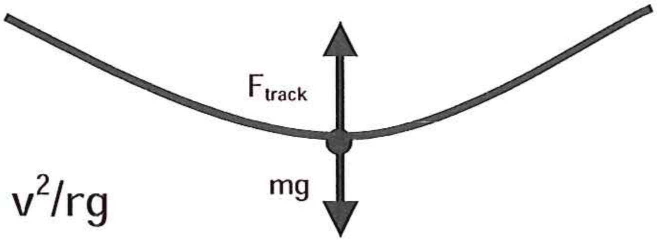
The force of the track is in toward the center of the circle and is therefore positive. The weight of the coaster, mg, is negative, since it is away from the center of the circle.



$$F_{track} - mg = mv^2/r$$

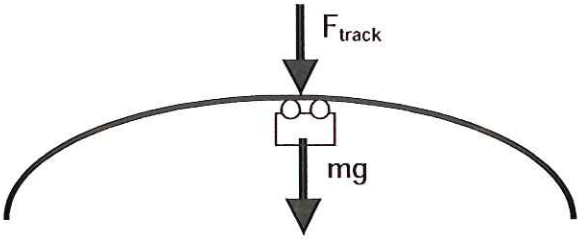
$$F_{track} = mg + mv^2/r$$

$$\text{G Force} = F_{track}/mg = 1 + v^2/rg$$



The force depends upon the velocity of the coaster and the radius of the turn, where $g=9.8\ m/s^2$. The velocity must be expressed in m/s and the radius in m.

G Force Upside Down at the Top of a Loop



At the tops of the loops, the procedure is similar, except that the track's force and the weight are in the same direction. Since both point toward the center of the circle, both are positive.

$$F_{track} + mg = mv^2/r$$

$$F_{track} = mv^2/r - mg$$

$$\text{G Force} = F_{track}/mg = v^2/rg - 1$$

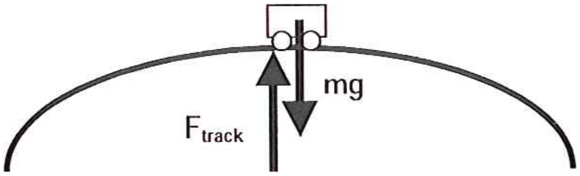
G Force at the Top of a Hill, When Right Side Up

The forces are in opposite directions, but the gravitational force now points in toward the center of the circle and is therefore positive.

$$mg - F_{track} = mv^2/r$$

$$Ftrack = mg - mv^2/r$$

$$\text{G Force} = Ftrack/mg = 1 - v^2/rg$$



Finding the G Force for Horizontal Acceleration

Acceleration can be computed by use of the kinematic equations:

$v^2 - v_o^2=2ax$ $v = v_o + at$ $d = 1/2 at^2 + v_ot$

The horizontal force will then be given by "ma," and then the G Force can be computed by dividing the Horizontal Force by the weight (mg).

$$\text{G Force} = ma/mg = a/g$$

2. Energy Conservation. Assume the energy is the same at the beginning as at the end and solve for the speed at the end.

$\frac{1}{2} mv^2 + mgh$ at top = $\frac{1}{2} mv^2 + mgh$ at bottom
initial energy final energy

Energy Losses

Measure the speed and height at both the beginning and at the end and find out what percentage of the energy is lost or turned to heat.

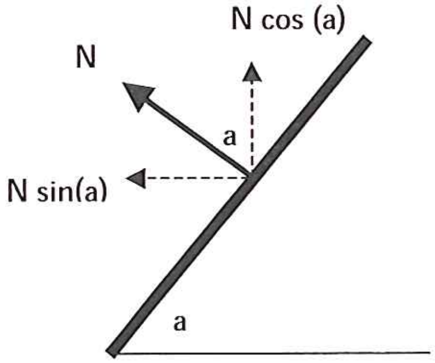
$$(\text{Initial energy} - \text{Final Energy})/(\text{Initial Energy}) \ * \ 100\%$$
$$(\tfrac{1}{2}\, mv_0\hat{}2 + mgh_0 - \tfrac{1}{2}\, mv\hat{}2 + mgh)/(\,(\tfrac{1}{2}\, mv_0\hat{}2 + mgh_0)\ * \ 100\%$$

Since there is an "m" in every term it cancels, therefore the mass of the coaster is not needed to find the energy loss. The lowest point in the ride is taken as the reference for the height. The final equation is:

$$(\tfrac{1}{2}v_0^2 + gh_0 - gh - \tfrac{1}{2}\, v^2)/(\,(\tfrac{1}{2}v_0^2 + gh_0)\ * \ 100\%$$

Banking Angle and G Force in Horizontal Circles

Horizontal circles are usually banked. If properly banked, the track will only exert a perpendicular force, called a normal force. The passengers are not thrown to the side. The vertical component of the normal force supports the weight of the coaster, and the horizontal component makes the coaster go in a circle



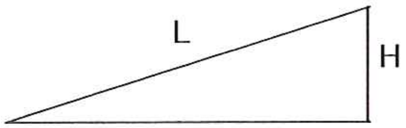
Horizontal component will be equal to the centripetal force ($N \sin(a) = mv^2/r$) and the Vertical component will be equal to the weight ($N \cos(a) = mg$) Dividing the first equation by the second yields an expession for the banking angle:

$$\tan(a) = v^2/rg$$

The G Force is given by: $1/\cos(a)$

Power

P=Work/time. The work done is equal to the increase in potential energy as a coaster is pulled to the top of an incline by the chain drive. W = mgh



H may be computed by using trigonometry: H = L * sin (angle)

Pre-Activities

Practice Using the Force Meters

a. Go to the playground. The swings are a great place to experience 2 g's using the Vertical G Force Meter. A merry-go-round can be used to experiment with the Horizontal G Force meter.

b. On an elevator, the Vertical G Force Meter can show both greater than or less than 1 g. A bathroom scale also indicates how heavy or light the students feel in a elevator.

c. In a car or bus, the Horizontal G Force Meter can be used to measure the forces in stops and starts and also in the turns. The Force Meter should be perpendicular to the motion in a turn or parallel to the motion while speeding up or slowing down. The same thing can be experienced by speeding up, slowing down or turning a corner while running.

Practice Using a Stopwatch

a. Make measurements as a car drives by. Start the stopwatch when the front of the car passes a point, and stop the stopwatch when the back of the car passes the same point. A typical car is 15 feet long. Thus, if the car drives by at 10 miles/hour, the time for the car to pass a point will be close to 1 second. If it drives by at 15 miles/hour, then the time will be about 0.7 seconds. The coasters will be going four times faster than 15 miles/hour, but they will also be about four times as long, so the times will be comparable.

b. Have a chain of people walk by, and time them from front to back.

c. Time a student running between two points. Have several students time the same event and compare times. This will lead to a great discussion about the need to make multiple measurements.

Roller Coaster Video

Show the video entitled "Roller Coaster." This was a Nova presentation that deals with the construction and desirgn of roller coasters along with some of the physics of roller coasters. This video may be obtained from WGBH at 1-800-255-9424. It sells for approximately $20.

Physics Principles

a. Upside down:
Hang one of the class members upside down for a few seconds (only with their permission). Pick someone who is not very heavy, and use caution. Have the person who was held upside down indicate as many ways as possible that he could tell that he was upside down. Possible answers might include: hair fell down; blood rushed to the head; everyone looked upside down; the student felt the force of the hands holding them up.

b. Centripetal Acceleration:
Bucket of water is swung in a vertical circle, and the water does not leave the bucket. The water tries to go in a straight line, and the bucket keeps applying a force toward the middle that makes it go in a circle.

c. Banking Angle:
Hold a string with an object tied onto it at arm's length and spin around. The angle at which the weight hangs is the banking angle for that speed and radius of turn. Or take a book and place an object such as a pencil on it. Hold the book at arm's length with the object on top of the book. Start to spin slowly at first, and as you speed up, slowly incline the book, giving it a banking angle. Have students pay attention to how the banking angle depends on how fast you spin and how far out you hold the book.

Principles of Physics

WEIGHTLESSNESS

According to Einstein's Principles of Equivalence, an observer cannot tell the difference between the absence of gravitational forces and being in a state of free fall. In both situations, observers would experience "weightlessness."

If the force of gravity alone acts on an object, the object is in a state of free fall. Diving off a high dive or bungee jumping produce this sensation. When an upside-down cup of water is dropped, the water will not fall out. The water appears weightless, because it is falling, just like the cup.

After a football is kicked, it is in a state of free fall. It follows the path called a parabola. NASA trains astronauts to deal with weightlessness by putting them in a plane that flies in a parabolic path. A roller coaster can also achieve "weightlessness" if the track follows a parabolic path, like a Camelback hump. A steep coaster hill, which has the shape of a half-parabola, also produces a near-weightless sensation. The Camelback on the Kumba and the zero-g roll on the Montu produce near weightlessness for about 2.5

The information from the Physics Day program collateral is not based on any scientifically acc
accelerometer testing of the amusement rides. In fact, the testing was done solely for the purp
providing this program with information necessary to complete vital academic experiments, and does

seconds. A steep coaster hill would have to be four times as high as the Camelback hump to produce the same weightless sensation for the same period of time.

WHICH WAY IS UP?

As the students ride the roller coaster, they may have a hard time telling which way is up. When they are upside down in a loop, they will not feel like they are falling out, and up seems like down. When going around a turn that is steeply banked, students will not fall to the side, and up now seems to be sideways. Going over a parabolic hill, there seems to be no "up," as students experience weightlessness.

Think of sitting in a chair. If you concentrate, you will notice the force of the chair pushing up on your seat. You can't feel the gravitational force acting on any particular part of your body, but you know from experience that it exists. You know that you need this "up" chair force to keep you from falling "down." "Up" is the direction of the felt force, which keeps you from falling down. This direction of "up" is therefore the same as the direction of the "chair force" or support force. This could also be the floor pushing up on your feet. The G Force that you feel is really a measure of the strength of the "chair force" or other support force. The G Force is equal to the support force (chair, floor, etc.) divided by the weight of the object.

FORCES AND ACCELERATIONS

Acceleration is a change in speed or a change in direction. Accelerations are produced by forces. Newton's Laws of Motion describe the relationship between acceleration and forces.

Newton's First Law

Objects at rest remain at rest and objects in motion remain in motion unless acted upon by an external force. A tablecloth can be pulled out from underneath a set of dishes if it is pulled quickly. This is because the dishes have what is called inertia, or a tendency to remain at rest. A bowling ball, on the other hand, once set in motion will continue in a straight line forever, unless it hits the pins or friction eventually supplies the force to slow it down.

Newton's Second Law

Every acceleration, or change in speed or direction, requires a force. The greater the acceleration, the greater the required force. If two objects undergo the same acceleration, the more massive of the two will require a greater force.

At the bottom of a roller coaster hill, a force is required to accelerate the coaster cars and passengers back up the hill. Two riders side by side will experience the same acceleration, but if one has more mass than the other, they will experience a greater force. When we say that they experience a force of 3 g's, this means that the force is three times their normal weight.

A horizontal acceleration of 9.8 m/s^2 requires a horizontal force equal to the weight of the object (1 g). A vertical acceleration of 9.8 m/s^2 requires a force equal to twice the weight

of the object (2 g's) since an upward force of 1 g is required simply to keep the object from falling through the floor.
A Dodge Viper can accelerate from 0 to 60 mph in 4.1 seconds. This is an acceleration of 6.4 m/s^2. Passengers in the car therefore experience a horizontal force of 2/3 g, and the car must produce a force equal to 2/3 the weight of the car to produce this acceleration.
A dragster has a much larger acceleration, and consequently the driver experiences a force of 3.5 g's. A passenger in a commercial jet airplane which is taking off experiences only a force of 0.2 g's.
A space shuttle astronaut will experience a maximum force of 3.5 g's, whereas the Apollo astronauts experienced 7.5 g's.

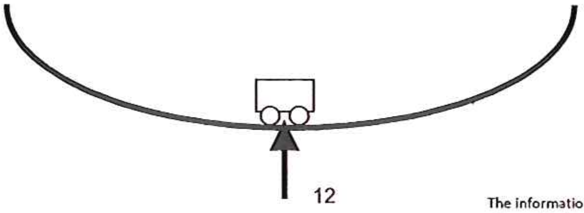
Newton's Third Law
For every action there is an equal and opposite reaction. If two people are engaged in a tug of war, the rope pulls the same on each one, but in opposite directions. The loser is the one with the poorest footing. In order for a person in an elevator to accelerate upward, the elevator floor must push up on the feet with a force greater than the weight of the person, and the feet must push back on the floor with the same force. The person will feel heavy. (If the upward force were 1.5 g's, then the person would feel 1.5 times heavier than normal.)

Application of Newton's Three Laws

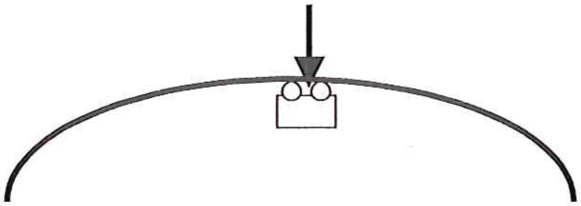
On a roller coaster, it is the acceleration that produces the thrills. Accelerations can be either changes in speed or changes in direction. While experiencing accelerations, passengers feel heavy or light, feel pushed back into their seats or thrown forward, or feel like they are thrown to the left or to the right.

A force is required to make a coaster slow down. If the change in speed occurs quickly, the seat of the coaster car can't produce enough force, and the passengers feel as if they are thrown forward. Actually, the coaster car stopped, and the passengers didn't. Such forces are generally less than 1 g.

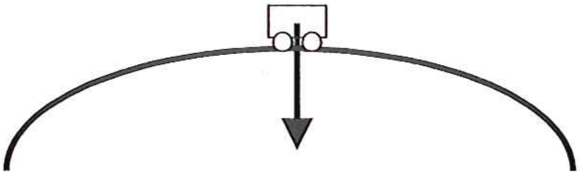
If the speed along the horizontal is increased, the back of the seats must push the passengers. They in turn feel pushed back into their seats. This sensation occurs for passengers in the last coaster car at the top of hills.
As a coaster train descends a hill, gravity provides the force to cause the acceleration. The closer the incline is to being vertical, the closer to weightless the passengers will feel. The passengers also feel weightless if the coaster track follows the same parabolic path in its descent that a freely falling coaster would naturally go.



An upward force is required to make the coaster change direction at the bottom of a hill. The coaster car seat pushes up on the passenger, so the passenger pushes down on the seat and feels heavy. On the Kumba and the Montu, this force exceeds 3 g's on many of the hill bottoms. The maximum force experienced is generally around 4 g's.



A downward force is required to make the coaster change its direction at the top of a loop. Gravity provides part of the force, but generally the coaster is designed to move fast enough at the top so that the track must also push down on the coaster. If the track does not push down at all, then the passengers would feel weightless at the top. On some loops the passengers feel light, less than 1 g, but never leave their seats. On other loops, the passengers will actually feel heavy at the top. Either way, down now seems to be up. If the riders keep their eyes closed on a loop, they will never know that they were upside down. Kumba riders experience seven inversions (the Vertical loop, the Dive loop, the Camelback Hump, twice on the Cobra Roll and two corkscrews).



At the top of a hill, a down force is needed to cause the change in direction. If the coaster is moving slowly enough, gravity can provide sufficient force to cause the change in direction. As a result, however, the passengers feel light. This is the same sensation experienced when a car goes over a large bump in the road, causing passengers to experience a tummy lifter. The Camelback humps on both the Montu and Kumba are designed so that the force experienced is very close to zero for over two seconds. If the coaster is traveling so fast that a force greater than gravity is required, then the shoulder harness holds the people in the car, and the second set of wheels below the tracks keeps the car on the tracks.

To turn a corner to the left requires a force to the left. The passengers feel like they are thrown to the right. In reality their inertia carries them forward as the coaster turns the corner. This makes it appear as if passengers were thrown to the right. The greater the speed or smaller the radius of the turn, the greater the force required. In the carrousel on the Kumba, the forces are between 2 g's and 3 g's. When g forces are high, the turns are banked to keep passengers from being thrown to the left or the right.

Sometimes several kinds of acceleration are occurring at the same time. On the first drop of the Kumba and the Montu, the coaster cars are dropping but are at the same time turning a very tight corner at a high speed. As a result, the passengers feel heavy, even though they are dropping.

ENERGY

Roller coaster cars do not have a motor. Rather, a heavy-duty motor attached to a chain pulls them up the first hill. At the top of the first hill, the roller coaster cars have what is called Gravitational Potential Energy (GPE). It is computed with the equation: mgh. The cars have the greatest GPE when they are at their highest. After the center of mass passes over the top of the hill, the coaster cars begin to speed up. They begin to lose their GPE as gravity pulls them down the hill, and they gain Kinetic Energy (KE) or energy of motion
($KE = \frac{1}{2} mv^2$). The total amount of energy remains the same. As the cars go up the next hill, they slow down and lose Kinetic Energy while gaining Gravitational Potential Energy.

If the coaster had 10 units of GPE at the top of the hill, then it should have 10 units of KE at the bottom of the hill. This is called Conservation of Energy. The sum of GPE and KE should add up to the same number. In actual operation, however, the coaster may lose 10 units of GPE and gain only eight units of KE. It may appear that energy has been lost. What actually happened is that part of the energy has been changed into heat. As the coaster cars move over the track, friction between the wheels and the track and air friction produces heat energy. The coaster hills must become smaller as the ride progresses because of this heat production. The Kumba loses well over half its initial energy due to friction before it brakes at the end of the ride. Brakes must then convert any remaining energy of motion into heat at the end of the ride, or it will not stop at the station. Even through the coaster is traveling slower at the end of the ride because of friction, the ride can still be made exciting, by having sharper turns.

In order to find the percentage of energy converted to heat, the following equation can be used:

$$\Big((GPE + KE)\ \text{beginning} - (GPE + KE)\ \text{end}\Big)\ /\ (GPE + KE)\ \text{beginning} \quad \times 100\%$$

For example, the height of the first hill on the Kumba is about 40.9 meters (134 feet). If we assume no friction and a fairly slow speed at the top, then the speed at the bottom of this coaster would be about 28.3 m/s (63 mph). In actuality, friction makes this maximum speed of 27.0 m/s, or an energy "loss" of about 9 percent.