AS Physics Report

Introduction

As part of my physics investigation into the physics involved with a rollercoaster I was given the privilege to see some live rollercoaster's at work in Thorpe Park. Although at the end I chose a ride which was not a strictly a rollercoaster, however it did have some key aspects and physics of a normal rollercoaster. I decided to investigate two rides; these were the 'Detonator' and the 'Tidal wave'. Out of the two I decided to base my investigation on the 'Tidal wave'. This ride had more key aspects of physics involved and seemed more plausible for such an investigation in order to gain a stimulus, development and a detailed/analysed conclusionand evaluation.

The physics principles of roller coasters haven't changed much since the original roller coasters. "Most coaster physics comes from Isaac Newton's law of motion. Roller-coaster designs rely on the acceleration caused by forces to make a roller coaster ride both thrilling and safe." (According to the Hyper coaster) The most important factor in designing roller coasters is how to balance out these forces. For example, a large up-force may cause you to faint because your heart can not pump enough blood to your head so balancing the forces is key.

Roller-coasters are a small car lifted or driven to the highest point of the track. When set free it starts rolling down under the force of gravity, and then goes up and down along a fantastically curved line, giving the occupants a thrill by the sudden changes in velocity.

To design a good and safe roller coaster requires a lot of physics principles, such as acceleration (the rate of change in speed or direction), velocity (ratio of change in position to time interval of which change takes place), free fall (the acceleration =9.8m/s/s), projectile (motion of objects given initial velocity that then move only under force of gravity), mass (the amount of material an object contains), gravitation (the force of attraction that every object in the universe has on every other object), friction(force opposing relative motion of two objects that are in contact), Fnorm (the force that perpendicular to surface), centripetal acceleration (acceleration toward centre of circular motion), centripetal force (force that causes centripetal acceleration), Newton's laws of motion (laws relation force and acceleration), kinetic energy (energy of object due to its motion), and potential energy (energy of object due to its position or state), etc. (definition According to Physics glossary)

A roller coaster is a balance between safety and sensation. In order to know that have to understand the difference between velocity and acceleration. Velocity is how quickly an object changes it position. The higher the velocity the quicker an object travels between two locations. "phrases like,'...how fast..., how quickly,' are used to describe velocity." (According to General) Often the word speed is substituted for the word velocity in common usage. But velocity is actually a vector, speed with direction. Acceleration describes how quickly an object changes it velocity. "Phrases like, '...slow down..., ...speed up..., ...change speed... and change velocity...'are used to describe acceleration" (According to General)The cars are pulled by a chain to the top of the highest hill along the track. Then they are released from the chain. As the front car begins its decent, the unpowered cars have almost no speed and only a small acceleration. As more cars reach the downward slope the acceleration increases. The reason is the cars at top of the hill have a high potential energy which means a low kinetic energy. The cars at the bottom of the loop have a high kinetic energy, but a low potential energy. Since the PE depends on height and the KE depends on velocity, so the cars has low speed at top of the hill and high speed at bottom of the loop. The acceleration peaks when all the cars are headed downward. The peak value is the product of the acceleration generated by gravity and the sine of the slope of the track.

Part 1 – Physics involved

There are number of physics aspects I could generate form the ‘Tidal wave’. However I will only discuss the two most relevant and these are the acceleration and the gravitational potential energy.

The acceleration is used to generate a thriller sensation for the riders and the small gravitational potential is used as a source of adrenalin rush and to create anticipation for the riders. The heart pounds much faster as the body

Acceleration gives the forces directly, so it can be used to establish the forces that a structure experiences during an earthquake. Also, acceleration sensors are generally the hardiest of all seismic sensors. In addition, they are usually small, only a few inches on a side, so they are easy to place at key locations in a structure. The acceleration record can be computer processed and integrated to obtain the velocity and displacement records. Acceleration, in physics, corresponds to the force applied to something that causes it to change its position or speed. It is the force you feel when a car accelerates from a stop sign; pushing you back into the car seat (it’s a horizontal force). Similarly, when an elevator starts moving, you feel more weight on your legs (it’s a vertical force). When a roller coaster car makes a hairpin turn, the acceleration may push you to the side, or up or down.

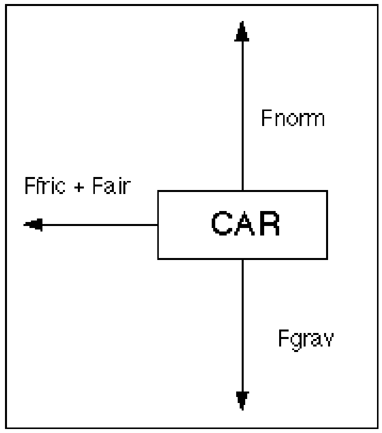
Acceleration is measured in “g”, where 1 g corresponds to the vertical acceleration force due to gravity. Roller coasters experience accelerations of 2.

<u>Force</u>
The Tidal Wave works by some of the most fundamental principles of physics. Newton’s First and Second Laws in particular apply to rollercoaster’s today, they relate force and acceleration.

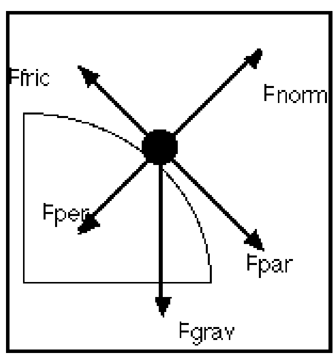
<u>Energy</u>
When a train is pulled up to the top of the lift hill it is gathering potential energy. When it reaches the top, it no longer receives the energy and it is all transferred to Kinetic energy 9gravity) which pulls the train down the drop. If it goes up a hill it loses kinetic energy and slows down.

FORCE:

As the car travels across a horizontal surface, there are three forces acting on the car.(see FBD diagram)



According to Newton's 1st law, when an object stays at rest or moves with a constant velocity, there must be a balance of forces. Since the car is not accelerating vertically, the normal force is balanced with the gravity force which means they are equal. The surface of the track applies the normal force. According to the Newton's 2nd law, when an object accelerates, there must be an unbalanced force. In Newton's 2nd law a = Fnet / m, the acceleration of an object is directly proportional to the net force on it and inversely proportional to its mass, also the net force is directly proportional to the mass. The ball is accelerating through the track, so the unbalanced force is the friction force and small amount of air resistance. The net force is equal to the mass of the cars times the acceleration which is the same as the friction force and air resistance. Friction force and air resistance are always in the opposite direction the object moves. Assume normal force and the mass is constant on a horizontal surface. When the object moves to the right, and the frictional force is to the left, the equation becomes -Fnet = ma. When the cars slides down the decline, there are also three forces acting upon the object. They are normal force, friction force and gravity force (see diagram).



When the object is rolling down the incline, the gravity force has two parts, one is F parallel and the other one is F perpendicular. Fpar = mg sin angle and Fper = mg cos angle. The F perpendicular is balanced with Fnorm, so the ball doesn't move vertically. The frictional force is the force that prevents the car from reaching as high a point which it started.

ACCELERATION

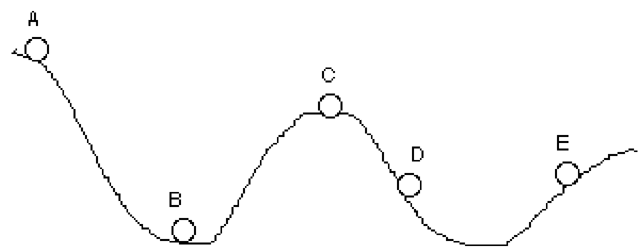
I have decided to talk about the acceleration in detail because this is the main physic principle on the ride and the way the water acts as a stopping force for the large accelerating force coming down.

The cars are pulled by a chain to the top of the highest hill along the track. Then they are released from the chain. As the front car begins its decent, the unpowered cars have almost no speed and only a small acceleration. As more cars reach the downward slope the acceleration increases. The reason is the cars at top of the hill have a high potential energy which means a low kinetic energy. The cars at the bottom of the loop have a high kinetic energy, but a low potential energy. Since the PE depends on height and the KE depends on velocity, so the cars has low speed at top of the hill and high speed at bottom of the loop. The acceleration peaks when all the cars are headed downward. The peak value is the product of the acceleration generated by gravity and the sine of the slope of the track.

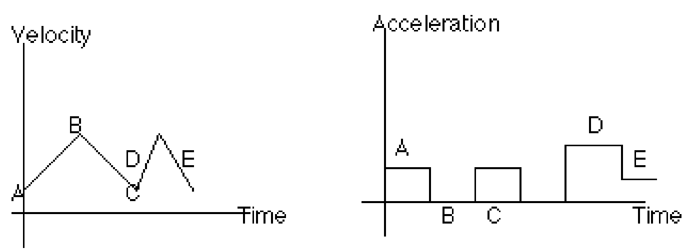
A steeper decent generates a greater acceleration, because if the air resistance and friction force are absent, acceleration will equals

$$a = g \sin ø$$

So angle and acceleration are directly proportional. When the angle of the incline increases, the acceleration of the car will increase, too. "When the coaster reaches the bottom of the valley and starts up the next hill, there is an instant when the cars are symmetrically distributed in the valley. The acceleration is zero. As more cars ascend, the coaster begins to slow, reaching its lowest speed just as it is symmetrically positioned at the top of the hill." (According to The Amateur Scientist, p.162) (See diagram below)



At point A, the car has acceleration and low speed. At B, the car has maximum speed and no acceleration. At C, the car has low speed and no acceleration. At D, the car has the greatest acceleration, because the decline is steeper. At E, the car has the greatest slowing. (See the graph of acceleration and velocity)



The slope of the velocity-time graph is the acceleration. As the graph shows when the velocity increases and the slope of the graph is positive, the acceleration is positive, such as in sections A, D and E When the velocity decreases and the slope of the graph is negative, the acceleration is negative. When the velocity is constant the acceleration is zero, such as sections B and C.

Diagram:

Acceleration and GPE – working out:

The following pieces of data are needed to calculate a number of physics principles:

S – 32.81m , Time – 1.524sec , Start velocity – 21.52ms-1 , End V – 0ms-1 , mass = 2990 kj

First I needed to calculate the starting velocity:

Velocity = displacement/time = 32.81/1.524= 21.52ms-1

From this I could calculate the kinetic and Gravitational potential energy and ignoring friction and air resistance, I assumed these should equal each other:

- Kinetic energy = 0.5 * mass * velocity squared

  = 0.5 * 2990 * 463.1104 = 692350.048J -> 692.350kj

- Gravitational Potential Energy = mass * 9.81 * change in height

  = 2990 * 9.81 * 23.6m = 692232.84j = 692.232 kj

- Acceleration = change in velocity / time taken

  = 21.52 / 1.524= 14.120 ms-2

Below is the force produced:

- Force = mass * acceleration = 2990 * 14.12 = 42218 Newton's

-Below is the work produced/ energy by the ride

Work done = force * distance moved in direction of force

  = 42218 * 32.18 = 1358600.984j= 1358.6 kj

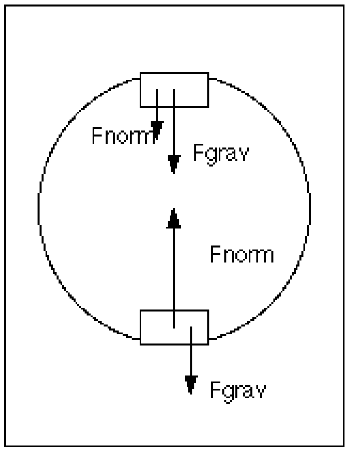
Below is the power produced by the ride :

- Power = work done / time taken = 1358.6 * 1.524 = 2071 Watts

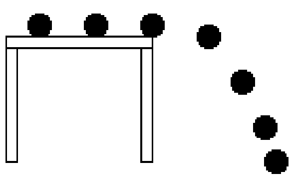
As you can see from the information provided I can understand and show the relevant physics principles involved. The large force and power show me how powerful the ride is. The amount of energy produced to move and stabilize the carriage shows how a lot of energy is required for one of these things to work. Obviously there is chemical energy from the electricity needed to push these things to the top and to generate the stopping force by the brakes system.

Gravitational Energy

Gravity forces accumulate only when the coaster is climbing. As it speeds downhill, the pull of gravity is actually reduced, producing "negative gravity," or a feeling of weightlessness. Weight is the pull of gravity. Typical weight units are pounds(British system) and Newton's(metric system). On the earth, neglecting air resistance and other forces, all objects will speed up at a rate of 9.8m/s every second they fall. That is a speed increase of about 22mph every second it falls. "Many amusement park rides generate the weightless sensation by acceleration down at 22mph every second." (According to Weightlessness) "On a roller coaster we go no lower than 0.2 g . This is enough to give people the thrill of being airborne but, in a worst-case scenario, keeps them in the car if the laps bars or seat belts fail." said Summers. (According to Ticket to Ride, p.79) Any time an object experiences an external force equal to the force of gravity, it is said to be in a "one g" environment. If a car whose weight on the Earth is 100lb was moved to a 2g environment it experiences 200 lbs of external force. In a 9g environment its Fext = 900lbs, so in a 0.2g environment then its Fext = 20lbs. When the car at the bottom of the loop the gravity force is smaller than the normal force, this cause a feel in 2g environment. When the car at the top of the loop, both gravity force and normal force are downward and the normal force is smaller than the gravity force, so this cause a feel of weightlessness. (see diagram below) However, no matter what happens to its external forces of the car's mass would never change. Mass is unaffected by the pull of gravity.

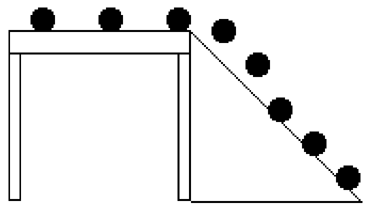


One of the biggest thrills on a roller coaster is the free fall when the rider experiences while travelling over a hill. Free fall also known as the pull of gravity, and all object will speed up at a rate of 9.8m/s/s. Also there is a projectile motion. As a person falls they experience weightlessness. As long as a person travels in the air in a projectile motion they will feel weightless. Suppose a ball travelled off a table as a coaster falls off the horizontal surface, horizontally, at 10m/s. It would look like the path shown below.

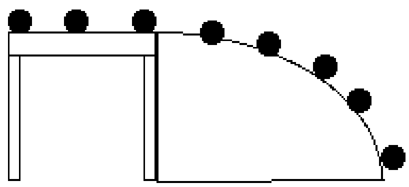


When the ball falls from a table, it has a projectile motion. According to Newton's 1st law, when an object is in motion it stays in motion, unless there is an unbalanced force. When the ball move across the table, it continues its horizontal motion and goes straight until it falls of the table. When the ball falls off the table there is no more normal force to keep the ball up. It only has gravity force to pull it down.

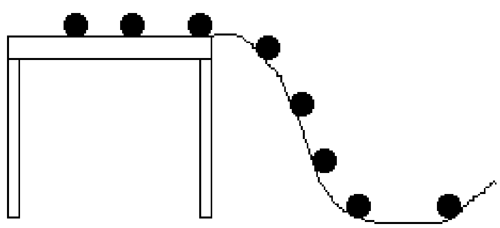
Now suppose the ball travelled off the table top onto a shallow angled ramp as the coaster travels off the horizontal surface and along the decline. It is a horizontal projectile motion would look like the one below.



A straight track is not the answer for a thrilling design. A straight ramp gives the rider a fast safe feeling ride. To give a rider more of a thrill, see the diagram below.



The only problem with the diagram above is the impact with the ground. When the object slides down the curve, it has a great Vy. Therefore, to alleviate this problem another curve scoops the balls as they descend such as a parabolic curve. The incline curve can help to reduce the Vy and increase the Vx, so the riders won't impact with the ground. This makes the ride smooth and survivable. See the diagram below.



To get a weightless sensation the hill is designed to have the same shape as the trajectory of a projectile a being thrown off the top of a hill. Shape is determined by how fast the roller coaster car travels over the hill. The faster the coaster travels over the hill the wider the hill must be. The way to apply projectile motion concepts to design the hill's shape is to calculate the coaster's position as if it drove off a cliff. The position equation is:(According to Hills and Dips)

WEIGHTLESSNESS – due to the acceleration

0Weight is the pull of gravity. Typical weight units are pounds and Newton's. (1 pound a t 4.45 Newton's). On the moon, gravity pulls with $^1/_6$ the force compared to the Earth. Therefore, a student on the moon weighs $^1/_6$ of what she weighs on the Earth.

On the Earth, neglecting air resistance, all objects will speed up at a rate of 9.80 $^m/_s$ every second they fall. That is a speed increase of about 22 mph for every second an object falls.

Time in the Air	Velocity
s	mph
0	0
1	22
2	44
3	66
4	88
5	110

There are two ways to experience weightlessness. **(1)** move far enough away from the planets and sun to where their pull is nearly zero. [Gravity acts over infinite distance. One can never completely escape it.] **(2)** Fall down at a rate equal to the pull of gravity. In other words, accelerate to the Earth speeding up 22 mph every second in the air. In order for a person to feel weight, a person must sense the reaction force of the ground pushing in the opposite direction of gravity.

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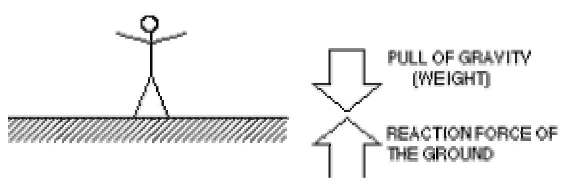


In the absence of the reaction force a person will sink through the ground.
Many amusement park rides generate the weightless sensation by accelerating down at 22 mph every second.

This is what also happens on the 'Tidal Wave' as I calculated the average velocity to be around 21.5 ms-1. This acceleration cause's weightlessness as the car comes down the long ramp.

G's

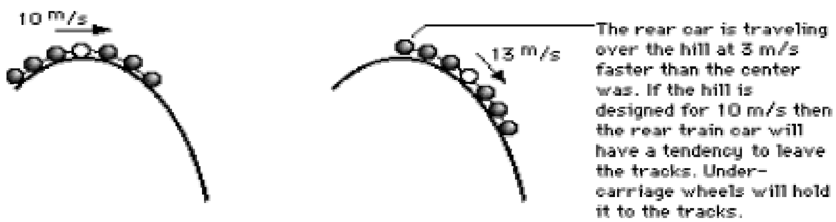
Neglecting air resistance, if a rock is dropped, it will accelerate down at $9.8\ m/s^2$. This means it will speed up by $9.8\ m/s$ for every second it falls. If a rock you drop accelerates down at $9.8\ m/s^2$, scientists say the rock is in a "1 g" environment, [$1\ g = 9.8\ m/s^2 = 22\ mph/s$].

Any time an object experiences the pull equal to the force of gravity, it is said to be in a "one g" environment. We live in a 1 g environment. If a rock whose weight on the Earth is 100 lbs was moved to a 2 g environment then it would weigh 200 lbs. In a 9 g environment it would weigh 900 lbs. In a "NEGATIVE 2 g" environment it would take 200 lbs to hold the rock down on the ground. In a "-5 g" environment it would take 500 lbs to hold the rock down to the ground. If the rock were put into a "zero g" environment then it would be weightless. However, no matter what happens to its weight the rock's mass would never change. Mass *measurement* is unaffected by the pull of gravity.

Most roller coasters keep the g's felt under 5 g's on an inside loop or the bottom of a dip after a hill. When a rider travels over a hill at a high rate of speed, he experiences negative g's. A negative g is the multiple of a person's weight that is needed to keep a rider in his seat. Negative g's also force the coaster car to try to come up off the track. Negative g's are a rider's heaven and a designer's nightmare. Negative g's are avoided as much as possible.

A negative g has a different effect on a rider than a positive g. Both negative and positive g's can cause a rider to pass out. But negative g's cause a rider to "red out." A red out condition occurs when there is too much pressure on the brain caused by too much blood in the head. The extra pressure can cause blood vessels to burst and kill the rider. This is a sure way to limit the number of repeat riders.

There is another way for a rider to experience negative g's. It is related to the length of the train. The roller coaster track is designed for the dynamics at the centre of mass of the coaster train. Negative g's are experienced by the rider at the back of the train as he travels over a hill. For an empty train, the centre of mass is in the middle of the train. Whatever speed is acquired by the centre of the train is the speed for the entire train. After the centre of a train passes over a hill it begins to gain velocity. As the centre speeds up so does the back of the train. This means that the rear of the train will travel over the hill faster than the middle of the train. If the rider travels over the hill faster than the designed velocity of the hill the rear car will be whipped over the hill.



Calculation of the g's felt

To calculate the g's felt, a formula from circular motion will be utilized. Since energy relationships do not utilize time, the circular motion formula used will also not utilize time. To work out the G's felt on a rollercoaster going into a loop I would use the following formula, however because I am doing a ride which does not have a loop and only a downwards slop I calculated the G-Force to be 1, the same as it would be standing stationary anywhere on earth.

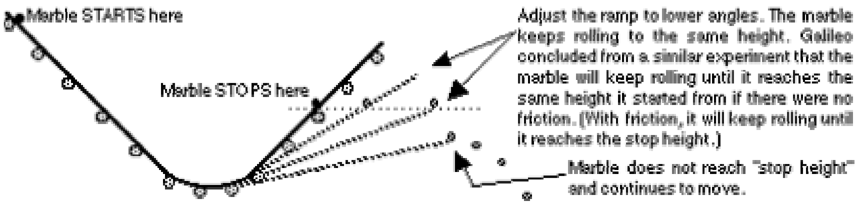
$$a_{CENTRIPETAL} = \frac{v^2}{R}$$

$$g's = \frac{a_{CENTRIPETAL}}{9.8\,\frac{m}{s^2}}$$

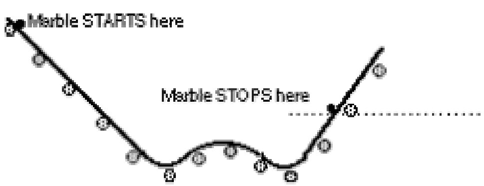
Where **"v"** is the velocity of the body and **"R"** is the radius of the circle travelled. To calculate the velocity a body is travelling, use energy relationships to solve for the kinetic energy and the associated velocity. One more thing. To calculate the g's felt remember that the g's felt by the rider is the normal force on the seat of the rider divided by the mass then converted into g's

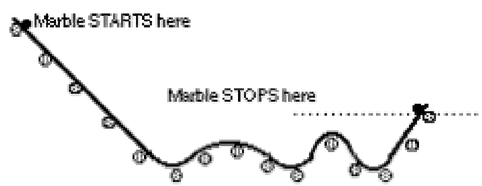
THE SIMPLE ROLLER COASTER - Galileo

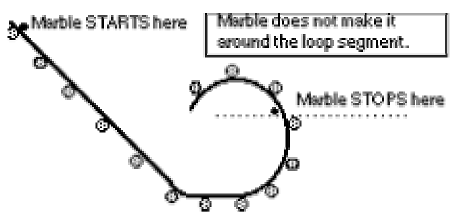
The simple roller coaster started with Galileo Galilei. Below is a description of how to demonstrate Galileo's experiment using the Roller Coaster Simulator. [This experiment could also be duplicated using a HotWheels™ track and a marble.]

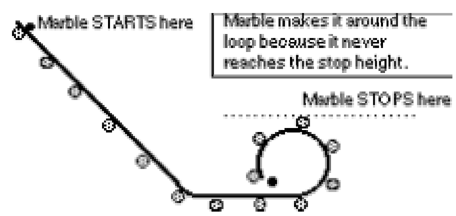


This has far-reaching implications. **(1)** The marble could take any path until it reaches the same height it starts from, assuming no friction. In the previous activity, the marble did not roll to the same height it started from because of friction. But it consistently rolls to the same height. To reflect these implications, the track could be reshaped as shown below.





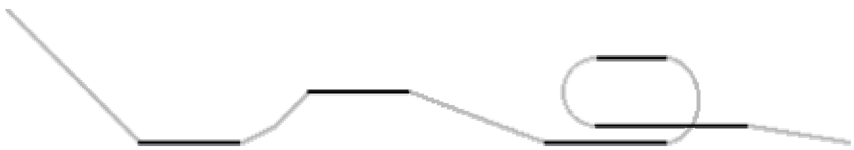




(2) The ball begins to roll down due to the force of gravity. It stops when all the energy gravity gave the ball is used up. The marble accelerates only while a force acts on it *in its direction of motion*.

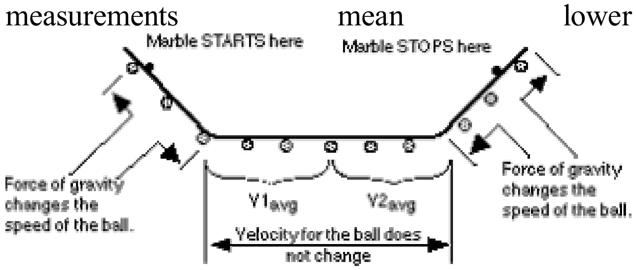
Across which sections of the track would a roller coaster car travel at a constant velocity or accelerate?

ANSWER



- The gray sections of track are where the coaster car accelerates. (Speeds up or slows down.)
- The black sections of track are where the coaster car travels at a constant velocity.

The acceleration can be demonstrated experimentally using the roller coaster simulator or HotWheels™ track. If a long enough section is made horizontal, it can be shown that the average velocities calculated at the beginning and at the end of the horizontal section are equal. Form the track in the shape shown below. Roll a marble or steel bearing down the track. It will accelerate along the drop and move at a constant velocity along the horizontal section and slow down as it climbs up the opposite side. When the marble slows down and speeds up on the hills it is visually obvious. What is not so visually obvious is what happens along the horizontal section of the track. The ball's constant velocity can be shown mathematically. Divide the horizontal section of the track into 2 sections. Calculate the average velocity of the ball along these two sections. If done accurately, the velocities will be nearly equal. To obtain more accurate results, use fairly long sections of horizontal track. The longer the sections of track, the greater the time measurement. Longer time measurements mean lower percent errors.



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Along the horizontal section of the track, ignoring the minimal effects of friction, there are no forces acting on the ball horizontally. Therefore the ball moves at a constant velocity while no force acts on it. This is Galileo's law of inertia!!!

Tidal Wave – how does the ride stop?

The ride is forced to stop using a braking system and the water at the bottom is also used as a stopping force.

For the first few metres the ride speeds up, but for the remainder of its travel through the water it has a steady speed due the drag of the water. However, before this can happen the braking system needs to come into effect.

To break the force of the engine must be equal to the force of air resistance which tends to slow the car down. These two horizontal forces are balanced, just as the two vertical forces (weight and contact force) are balanced.

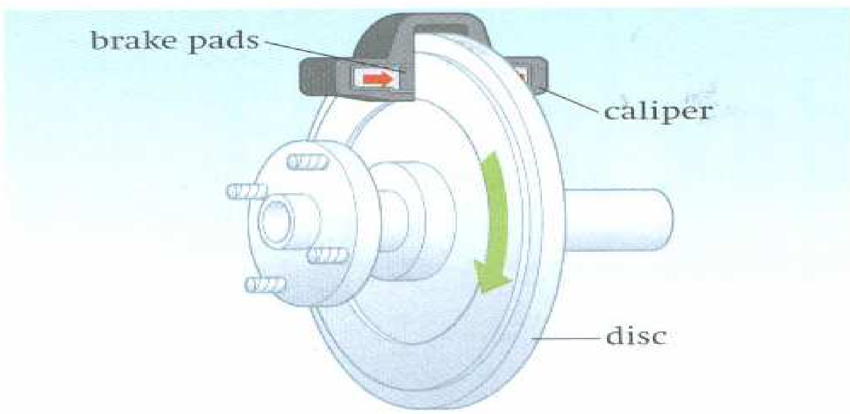

Figure 7.4 Disc brakes: a metal disc is attached to the axle, next to the wheel. When the brakes are applied, hydraulic pistons push the brake pads against the disc. This provides the necessary torque to slow the car.

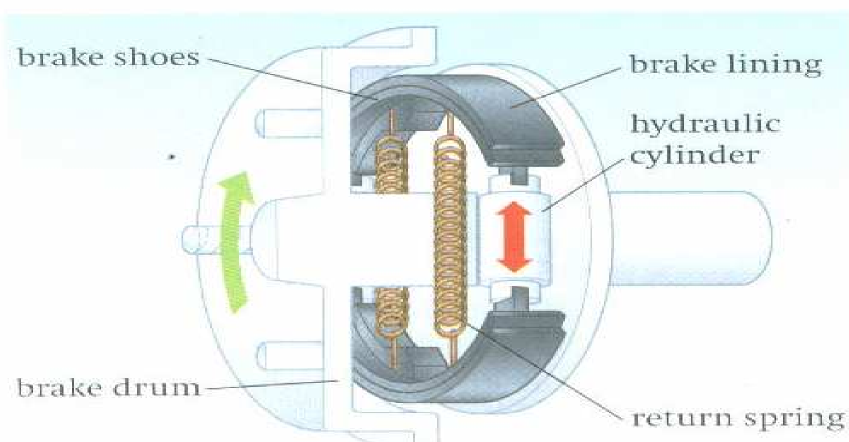

Figure 7.5 Drum brakes: a metal drum is fixed inside the wheel. When the brakes are applied, hydraulic pistons push the brake shoes against the drum. The linings of the brake shoes are gradually worn away by friction.

Future developments:

The Tidal Wave as a ride is thrillingly satisfying and this is only due to the great height and acceleration. This is in turn provides the rider with a great feeling of weightlessness. However if the owners of the ride want to improve this, they should ensure that the Tidal Wave has more hills and slopes to make the ride more thrilling and worthwhile because at the moment the ride has one slope and the feeling of weightlessness is very short and at the end of the ride the rider expects to be very, very wet!

However I cannot suggest anymore improvements because the ride is a 'log' ride and only needs slopes and hills to generate a greater kinetic energy and increase acceleration.

One problem that could arise is a safety problem. The train has no seatbelts or a safety function to make sure the rider will stay put in the train, therefore I suggest that they add waist bands to the carriage to prevent young children with smaller mass from actually falling out. Although this has not happened, and the engineers have carefully calculated out the physic involved in preventing this, but I think this would be a safer thing to do. It will also generate some physiological safety, juts like rollercoaster's with shoulder pads.

BIBLIOGRAPHY

For my project I used a number of resources. These included books, internet and background knowledge

Books used:

Advanced Physics – Salters Hornes
AS/A2 Physics – Chris Mee, Brian Arnold
Cambridge advanced Physics 1 – OCR

URL's used:

http://www.glenbrook.k12.il.us
http://www.vast.org/vip/book/WEIGHTLE/HOME.HTM
http://www.vast.org/vip/book/PHYSIOLO/HOME.HTM
http://www.vast.org/vip/book/MOSTCALC/HOME.HTM