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Mechanics behind Roller Coasters

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Abstract: *This paper aims to explain the intricacies of the application of a wide range of mechanical physics concepts utilised in the construction of roller coasters. The topics under consideration in this article are the Law of Conservation of Energy, Newton's Laws of Motion, functioning of clothoid loop - the - loops and effects along with utilisation of aerodynamic drag. The researchers have taken some of the conventional concepts of classical mechanics, describing how one of the most well - renowned amusement park rides arose from the building blocks of physics*

Keywords: conservation of energy, laws of motion, clothoid loops, air drag, safety mechanics

I. INTRODUCTION

Roller coaster is very popular amusement ride. It is famous for different types of excitement which varies with its design. Our problem requires an exciting and safe track for roller coaster. The motion of the train along the track will result from the initial potential energy. A precise analyze of the path and orientation of the train along the track and its dynamics is required. A good amount of background work was done on this topic. Many of them ([1]) used simulator games and software to design and inspect the dynamics and orientation of the track which is really a good method Instruction in an introductory mechanical engineering dynamics course is typically focused on key concepts and applying these concepts to different types of problems. The goal is to dispel misconceptions and develop in students the knowledge, intuition, and skills necessary to analyze particle and rigid body motion. The need for practice and for exposure to a wide variety of problems in order to ensure student competence means typical classes' centre on solving textbook-style problems.

Roller coaster rides are an exhilarating experience for people across the globe. This much sought - after ride comprises a sequence of controlled turns, loops, hills and dips which are painstakingly designed for maximum safety, while simultaneously maintaining the thrill level for the riders. Mechanical physics plays the most essential role during the drawing of the blueprint of roller coasters.

II. LITERATURE SURVEY

The blueprints and origin of roller coasters, as written in the article by Neil J. Meridith (1) about their history depicts its gaining popularity in America after the establishment of the Gravity Pleasure railway at Coney Island by LaMarcus Thompson. In an article by American Experience, called "A Century of Screams: A History of Roller Coasters" (2), it is expressed how a coal mine in eastern Pennsylvania was later converted to a tourist attraction, utilising the lurching up and down motion of the cart created by railway proprietors. We can see that the physics utilised in the creation of roller coasters was not necessarily used initially as amusement, but as necessary concepts for building machinery which revolutionised industrial concepts like mining. Various textbooks on mechanical physics have described the concepts

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used in creation of roller coasters, but between the screams and laughter, one hardly ever admires the physics behind this creation.

III. METHODOLOGY

The methodology used for the creation of this article was the qualitative reviewing of several published papers on the history of the construction of roller coasters, along with articles on fundamental concepts of classical mechanics. Observing modern day roller coasters and linking the data from these areas, the researchers have formed links between all the concepts mentioned. Law of Conservation of Energy The law of conservation of energy states that energy cannot be created nor destroyed. It can be transformed from one form to another. With respect to roller coasters, this law plays a crucial role in the ride experience At the start of a roller coaster ride, the coaster car is pulled up a hill to a high point, which stores potential energy in the form of the car's position relative to the ground. As the car begins its descent down the hill, this potential energy is converted into kinetic energy, which is the energy of motion. As the car moves through the twists, turns, and loops of the coaster, the law of conservation of energy ensures that the total amount of energy in the system remains constant.

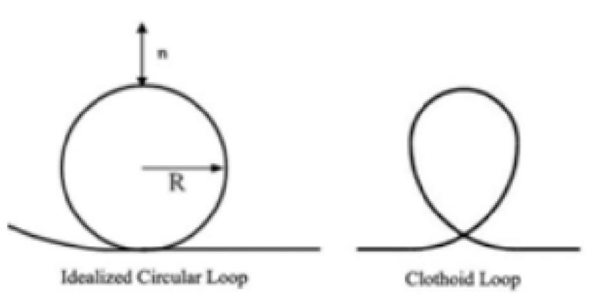
Newton'S Laws of Motion

First law: The Law of Inertia states that an object at rest will remain at rest, and an object in motion will continue in motion with a constant velocity, unless acted upon by a net external force. When a roller coaster is at the top of a hill and comes to a stop, it remains at rest until an external force, such as the release mechanism or gravity, acts upon it to set it in motion. Once in motion, the coaster continues to move until an external force, such as friction or the brakes, slows it down and brings it to a stop.

Second law: The law of acceleration states that the acceleration of an object is directly proportional to the net external force acting on it and inversely proportional to its mass. In a roller coaster, the external force is provided by gravity and the track's structure, which exert a force on the coaster, causing it to accelerate as it moves down the track. The amount of acceleration depends on the mass of the coaster and the net external force acting upon it.

Third law: The law of action and reaction states that for every action, there is an equal and opposite reaction. In a roller coaster, this law is observed when the coaster travels through a loop or turns. As the coaster goes through the loop, it exerts a force on the track, and the track exerts an equal and opposite force on the coaster, keeping it on the track through various turns and preventing it from falling off.

Clothoid Loop - The - Loop Design The loop - the - loop is a type of inversion, which occurs when the track of the roller coaster is designed to go upside down and then return to an upright position. Contrary to popular belief, roller coaster loops are not usually circular since the gravitational forces experienced by riders is unsafe in that design. The more common loop design is the teardrop shaped clothoid loop, which is a section of a spiral with regularly changing radii, making it safer for the public due to the manner of descent.



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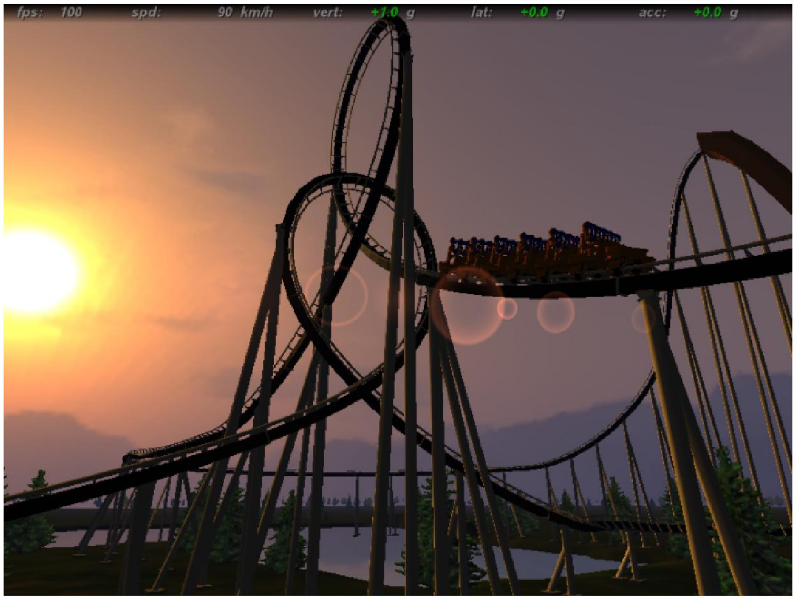

Figure 1: A student-designed roller coaster as rendered in the NoLimits software

When a roller coaster enters the loop - the - loop, it is travelling at a high speed and must maintain enough speed and momentum to complete the loop without losing velocity. As the coaster continues to travel through the loop, the angle of descent gradually decreases until the coaster reaches the end of the loop and returns to an upright position. There are four primary forces acting on a roller coaster as it travels through a loop - the - loop:

• Gravity:

This is the force that pulls the coaster and its riders downwards towards the centre of the earth which is necessary for maintaining the momentum of the coaster. As it enters the loop, gravity pulls the riders towards the bottom of the loop, which creates the sensation of weightlessness at the top

• Centrifugal force:

This is the force that pushes the riders outwards as the coaster travels through the loop. At the bottom of the loop, the centrifugal force is greater than gravity, which helps to keep the coaster and its riders moving in a circular motion. Inertial force: This is the force that opposes changes in motion, and it comes into play as the coaster transitions from the bottom of the loop to the top. The inertia of the riders' bodies wants to keep them moving in a straight line, but the track of the coaster keeps them moving in a circular path

• Friction:

This is the force that acts between the coaster and the track, and it helps to keep the coaster moving along the track without slipping or losing traction. In a loop - the - loop, friction is particularly important to ensure that the coaster maintains enough speed and momentum to complete the loop without losing velocity.

• Air Drag Application and Reduction

As a roller coaster train moves through the air, it encounters resistance from the air molecules, which can slow down the train and affect its motion. It experiences hindrance caused by the air particles colliding with the train's surface and the resulting force opposes the train's motion. The effects of air drag on a roller coaster depend on various factors such as the shape and size of the coaster train, the speed at which it's moving, and the density of the air. The faster the roller

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coaster is moving, the more significant the drag force becomes. Roller coaster designers try to minimise the impact of air drag by designing trains with streamlined shapes that reduce the amount of resistance the train experiences. Additionally, roller coaster tracks are often designed with banked turns and other features that allow the train to maintain its speed through the turns, reducing the amount of deceleration due to air drag. In some cases, designers intentionally create roller coasters with elements that produce a lot of air resistance, such as corkscrews or loops. These elements can add excitement and thrills to the ride by creating moments of weightlessness and rapid changes in direction.

IV. ROLLER COASTER TRACK

A Cartesian coordinate system with origin at the ground, 30 meter bellow the highest point of the track is considered. For a person sitting at the origin keeping horizontal segment behind, X-axis is along horizontal direction in front of him, y-axis is along vertical direction and z is found by right hand rule, along the right side. Another Cartesian coordinate system is at the center of mass of the train. For a passenger sitting at it, X, Y and Z is ,as before, along front, up and right side of him respectively.

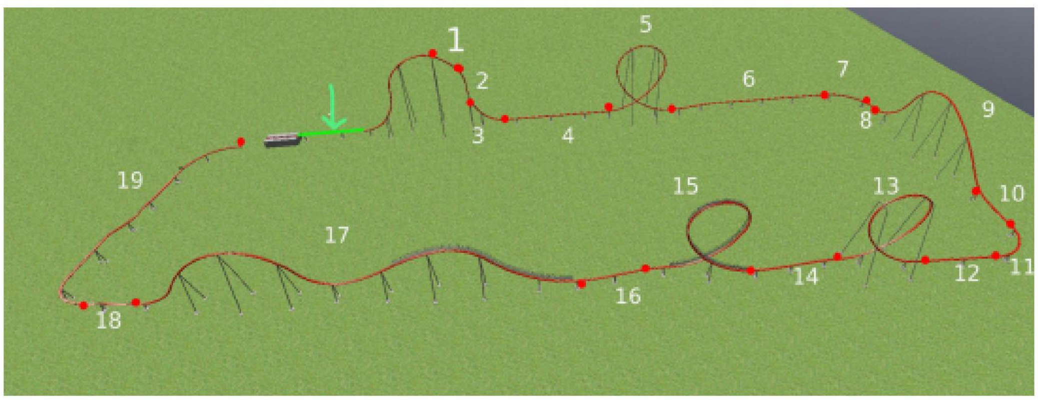

Figure 2: Track of the roller coaster

Figure 2 shows a rough modeling of a roller coaster track. It contains loops, hills and banking curves. For simplicity, we assume that loops and hills are in two dimensional x-y plane. The ride start at 30 meter height on the hill. At time t=0, the train is on top of hill. This is the point of highest potential. The total motion of train is caused by this energy. So no other point in the track can be higher than this point. Leaving this point, the train undergoes free fall after passing part 1 in Figure 1 which is a part of circle. Part 2 is free fall of the train, where passengers will feel zero G-force. The velocity of the train down the track will depend on the length of this part. Part 3 is a portion of clothoid, which ensure smooth transition of g-force to 1 after free fall. Then part 4 is a linear portion before entering loop. Initial velocity of every part will depend on its height and arc length of track passed by the train before reaching it. Part 7 is banked curve after a liner portion part 6. The train make 90 degree angle with x-axis by this banked curve and starts to move along z-axis. Part 8 is a linear iportion and Part 9 is a gaussian hill following part 10 a linear portion. Then part 11 is second banked curve which bring back the train along x-axis. Then comes two loops, one after another. Height of second loop will be lower than height of the first one because of energy lost due to friction, if two loops are to be same. After a small linear portion then comes double Gaussian hill. The track end with a banked curve which rotates the train 180 degree and bring back to the starting station.

G-force

The forces per unit mass that riders undergo as a result of changing acceleration or direction called G force. G-force is measurement of force per unit mass typically acceleration hat causes a perception of weight. A rider undergoes three G-force in three directions.

• Vertical G force

Vertical G forces act perpendicular to the track. It is the cause of pushing the riders into their seat(positive) or feeling of lifting the riders out of their seat(negative). During vertical G forces, positive g's act on head to toe and negative g's act on toe to head.

• Linear G force

Linear G force act parallel to the track. In the time of acceleration or deceleration linear g force felt by the riders. it push against a rider's front, pressing them into the back of the seat or push the rider forward

• Lateral G force

Lateral G forces typically act perpendicular to the track. It occurs on turns and curves. Lateral g's are the forces that squish one rider against the other on fast turns. 4 Friction The train undergoes generally two types of frictional forces.

• Rolling frictional force

The train contains three wheels at a point (figure 2).

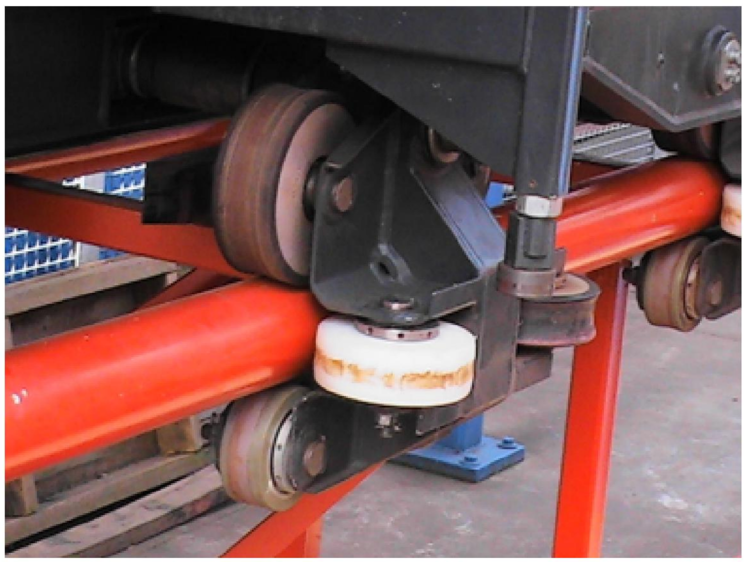

Figure 3: Roller coaster wheel

• Safety Standards

Safety is the most important consideration during designing a roller coaster. In a ride, the rider's experience mostly G forces and velocity. Variation in g force make the ride uncomfortable and enjoyable. But high value of g force can causes danger. High value of vertical G force will rush the blood out of the head and it may cause the person to pass out. If the negative G forces reach too large of values then too much blood will go towards the brain also having detrimental effects on the person. ASTM International Technical Committee imposed regulations on designing roller coaster.Regulations also conclude electrical, mechanical and partitioning systems, such as the placement of fencing. Figure 3 is a graph of the acceptable vertical G forces depending on the duration time.

But rider can tolerate much higher linear and lateral G forces compared to vertical G forces.

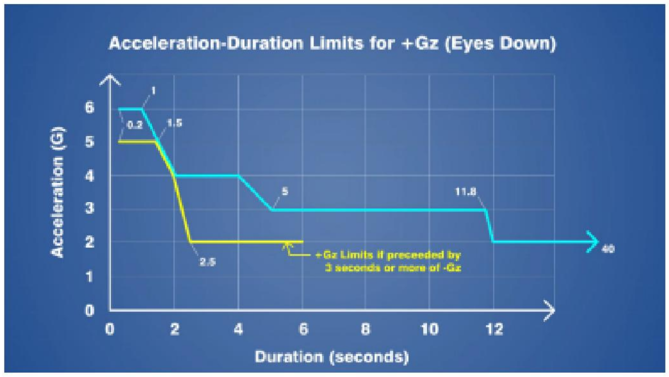

Figure 4: ASTM standard for G-force

V. RESULT

The article concisely explains some of the most essential concepts of mechanical physics. The level of safety required in roller coaster designing is of utmost importance and requires modification according to budget, environmental characteristics and several other factors. Utilising these concepts to reduce the number of roller coaster accidents can be accomplished, increasing the public's trust and enthusiasm in riding a coaster without hesitation. Improvement in designs of the tracks, carts, wheels and safety belts are some of the primary advancements which can be made utilising classical mechanical concepts in engineering.

VI. CONCLUSION

The article has defined the mechanical aspects of roller coasters, bringing to light the concepts, laws and theories which have been studied since the 17th Century when Isaac Newton gave the Laws of Motion. It consolidates the thought process involved in creating new and exciting amusement park rides, utilising these postulations to enhance safety and thrill, while also involving the enhancements of science to create new experiences and better machine efficiency. These new technologies will continue to go hand in hand with the mechanical aspect of the roller coaster, making it an amalgamation of multiple fields of physics.

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