# PHYSICS DAY
# **STUDENT MANUAL**

**Six Flags St. Louis**
**4900 Six Flags Road**
**Eureka, Missouri 63025**

**(636) 938-5300**
**https://www.sixflags.com/stlouis**

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**Thank-you to Ms. Sheri Donovan for reviewing this manual.** **2023b**

# CONSCIOUS COMMUTING

As you ride to Six Flags St. Louis, be conscious of some of the PHYSICS on the way.

## I. Starting Up – Things to Measure:

As the bus pulls away from a stop sign, find the time it takes to go from rest to 20 miles per hour. *You will have to put someone up front to read the speedometer.*

t = __________ seconds

*Things to Calculate: Always Show Equations Used and Substitutions*

1. Convert 20 miles per hour to meters per second. V = __________ m/s
   (1.0 MPH = 0.44 meters/second)

2. Find the acceleration of the bus. a = __________ $m/s^2$

3. Using your mass in kilograms and Newton's Second Law, find the average forward force on you as the bus accelerates from rest.

   F = ____________ N

4. Is this force greater or less than the at rest force gravity exerts on you (your weight)?

5. Calculate the force factor that you felt.

$$\textit{force factor} = \frac{\textit{force calculated (Question I.3)}}{\textit{weight}} = \frac{\_\_\_\_\_\_\_\_\_\_\ N}{\_\_\_\_\_\_\_\_\_\_\ N} = \_\_\_\_\_\_\_\_$$

(NOTE: The force factor has no units.)

## II. Things to Notice as You Ride:

1. As you start up, which way do you FEEL thrown (forward or backward)?

2. If someone were watching from the side of the road, what would that person see happening to you in relation to the bus?

3. How can you explain the difference between what you feel as the bus starts up and what the observer sees? (You may want to use the ideas of *frames of reference*).

## III. Going at a Constant Speed

1. Describe the sensation of going at a constant speed. Do you feel as if you are moving?

2. Are there any forces acting on you in the direction you are moving?
   Explain what is happening in terms of the Principle of Inertia.

## IV. Rounding Curves

1. If your eyes are closed:

   A. How can you tell when the bus is going around a curve?

   B. What do you feel when you are seated facing forward?

   C. What do you feel when you are seated with your back against the side of the bus?

2. Before the bus starts around a curve, concentrate on a tree or a building that is directly in front of you. From the Law of Inertia, you know that your body should continue straight ahead unless an unbalanced force acts on it. See if you can sense the force that causes you to go around the curve.

   A. What is the direction of the force as you go through the curve?

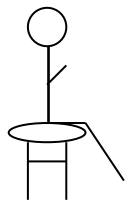
   B. If the turn were tighter (smaller radius) how would the force be different?

   C. How is this force applied to your body? Please explain your answer.
      (A) the friction of the seat
      (B) your seatmate
      (C) the wall
      (D) the arm of the seat
      (E) a combination of these.

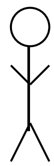
      Explanation:

3. Many rides in the amusement park involve going around curves. Be prepared to compare what you are feeling on the bus with sensations on the rides. Predict some differences you expect to feel.

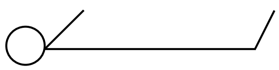
# SENSING SENSATIONS and FORCE FACTORS



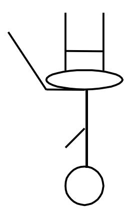
1. Here, you are in a chair. Show the size and direction of the force the chair is exerting you.
   On what part of your body is this force exerted?



2. Here, you are standing up. Show the size and direction of the force the ground is exerting on you. On what part of your body is the force exerted?



3. Here, you are lying on the ground. Show the size and direction of the force the ground is exerting on you.



4. Here, you are upside down and strapped into a chair. Show the size and direction of the force that keeps you from falling out. What is exerting this force and on what part of your body is it exerted?

5. Based on your answers to the previous questions, how could you tell what position you were in if your eyes were closed?

## Force Factor

A force factor enables you to express the size of a force you are experiencing as a multiple of your gravitational force (mg).

To calculate the force factor, divide the force being applied to a person or object by the normal (rest) weight of that person or object.

$$\textit{Force factor} = \frac{\textit{Force being applied}}{\textit{Gravitational force at rest}}$$

# EXAMPLES OF HOW TO USE *FORCE FACTORS*

When you are experiencing a force factor:

> *Equal* to 1, you feel *normal*. Right now, you feel a force on your seat exactly equal to your weight as the seat supports you.
>
> *Greater* than 1, you feel *heavier* than normal and feel pressed into the chair. In reality, the chair is pressing up on you, which you interpret as being pushed down.
>
> *Less* than 1, you feel *lighter* than usual and can feel as if you are almost lifting out of the chair. This is how you feel when an elevator starts going down suddenly.

At a given point on a ride, everyone, regardless of mass, experiences the same force factor.

On a certain ride, a 50-kilogram teenager is being pushed with a force of 1500 Newtons.

A. What force factor is she experiencing?
If we round **g** off to 10 m/sec$^2$ her gravitational force is 500 Newtons.

$$\textit{Force factor} = \frac{\textit{Force being applied}}{\textit{Force due to gravity}} = \frac{\textit{1500 Newtons}}{\textit{500 Newtons}} = 3$$

B. If her friend weighs 120 pounds, what force (in pounds) is her friend feeling?
They will feel the same force factor. This time, the number given is the person's weight. Her normal (rest) weight is 120 pounds, but she is experiencing a force factor of 3 and is therefore feeling a force of 3 times her normal (rest) weight. The force on her must be:

3 x 120 pounds = 360 pounds.

## Practice

An 80-kilogram boy is on a ride where he is feeling a force of 2000 Newtons.

A. What force factor is he experiencing? Force factor =________

B. What force is his 500 Newton girlfriend feeling? Force felt = __________ Newtons

If your answers were a force factor of 2.5 and 1250 Newtons, you have it!!

# ELECTRONIC DATA COLLECTION

Data may be collected with mechanical devices or electronic devices. A discussion of mechanical devices is found on pages 12 – 17. Three-axis accelerometers with altimeters are available from Pasco Scientific and Vernier Software and Technology. Many classrooms employ these sensors, and we assume familiarity with their use. Several smartphone apps exist, as well. There are other apps that make the same measurements. Be sure to test them, including downloading data, before going to the park.

**Regardless of what device is used, it is of critical safety importance that the device be secured by a belt, vest; or wrist, arm, or waist protective carrier.**

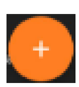
*Figure 1 Sample carriers for smartphones and sensors.*

Whatever app or device is used, do a test run to understand the orientation of the x, y, and z axes. Know how to activate and deactivate data recording, save, and export the file. Most apps will save the file as a .CSV. When taking data on a ride, orient the device as orthonormal as possible to the motion. Start taking data before the ride starts, as data outside of the actual ride cycle can be deleted in post-ride analysis.

## Physics Toolbox Suite

Open the app and using the hamburger icon (≡) select the Rollercoaster data collection. For most phones, the screen will be pointing away from you for the positive z-axis. The file is stored on your phone. If your phone does not have a necessary sensor, the experiment will not show.

## *phyphox*

Open the app and using the plus  icon, select Accelerometer and Pressure to be able to perform experiments. It is recommended to name this multi-sensor experiment something like Amusement Park. It should now show up in your Simple Custom Experiments. If a sensor is not available, it will be grayed out.

## Altitude (barometer reading) Irregularities

There are many electronic 3-axis accelerometers with altimeters on the market. There is a phone app, *Physics Toolbox* by Vieyra Software, *phyphox*, among others. Many phone devices pose challenges. The altitude readings are often accurate but show errors on rides with large acceleration spikes or featuring tunnels that create a back-pressure. This is due to the membrane on the internal electronic sensor deforming or bulging, giving an erroneous reading. Two examples of problematic data artifacts are shown here.

## Strong Accelerations

The following graph shows data collected on The Buccaneer.

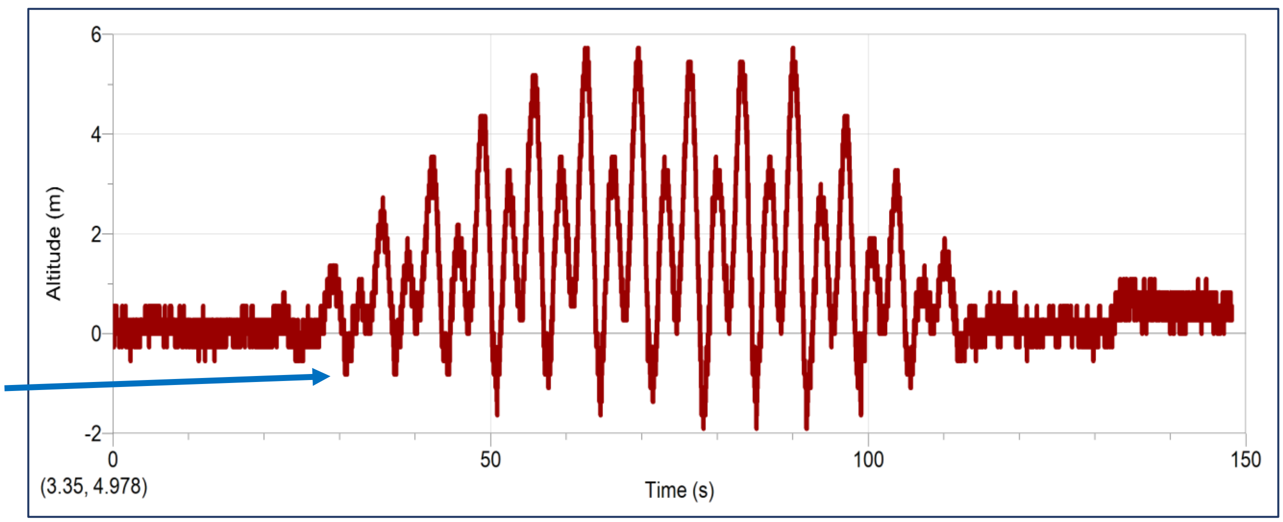



*Figure 2 Altitude versus Time graph for The Buccaneer. Note that during the ride erroneous negative altitude readings are recorded (arrow).*

The student was sitting in a center seat, approximately 0.3 meters above the lowest point of swing. From this graph, it seems that the student swung some 2 meters below the center point when compared to the initial position, at rest. This would place the rider significantly below the cabin's seat. This does not happen.

## Tunnels

Another example of instrumentation error is the tunnel on Raging Bull (at sister park, Great America). The backpressure from the tunnel at the bottom of the first drop gives the impression of a small but sharp hill, instead of a continuous descent. The negative values for height elsewhere in the graph are correct, since zero height is the loading station, and many parts of the rollercoaster track are below the platform level.

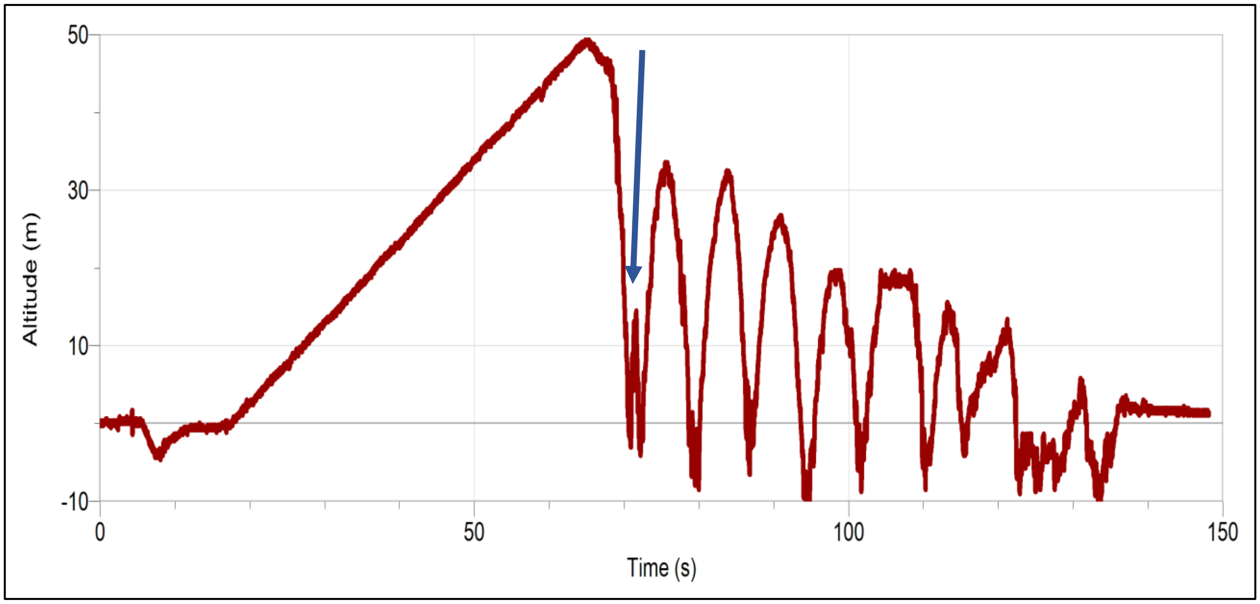



*Figure 3 Altitude versus Time graph for Raging Bull at Six Flags Great America. Note that during the ride an erroneous positive altitude reading is recorded (arrow).*

The anomaly occurs at about 72 seconds as shown in Figure 3 (arrow). A motion of 15 meters up and then down in 3 seconds is not part or the ride design.

## Accelerations

Accelerations can be a difficult problem, especially when one considers that the electronic accelerometer is not always orthonormal to the ride, and the rider may bounce around a bit. Figure 4 shows the $a_x$, $a_y$, and the $a_z$ acceleration plots for American Thunder, an out and back, non-looping wooden rollercoaster.

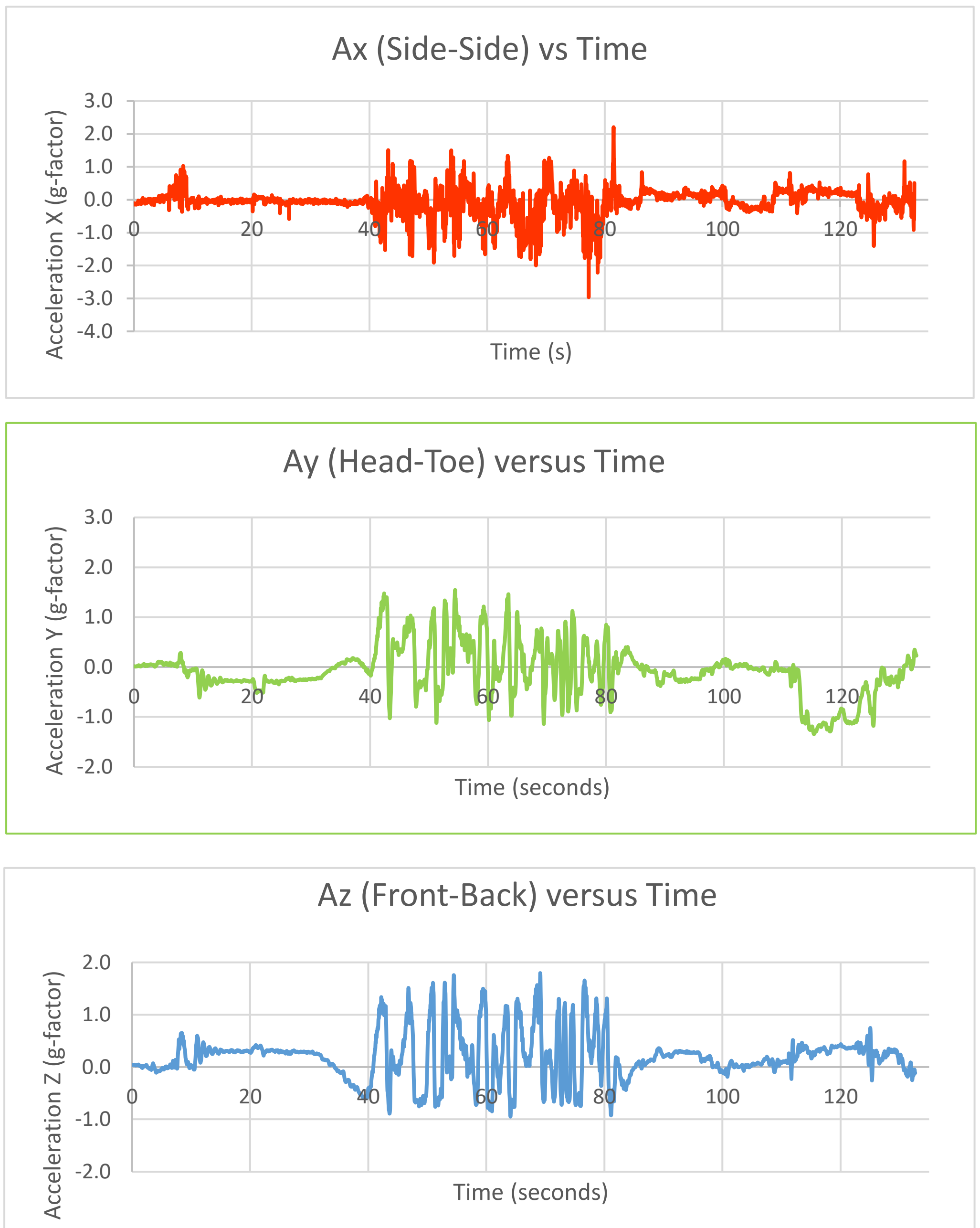



*Figure 4 Component accelerations for a non-looping rollercoaster.*

These data may be difficult to analyze because: i) the sampling rate may not be optimal; ii) vibrations add noise; iii) the device may slip, changing its position on the rider; and iv) the y-axis does not stay vertical as the rider's position changes. It is often more useful to consider the scalar acceleration of the motion. This can be easily calculated with a spreadsheet.

$$a_{scalar} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

The directional components are lost but can be inferred from the track layout and position of the rollercoaster on the ride. In this example, see the track plot for American Thunder on page 25. If the acceleration at a specific place is needed, this method does not work well for vertical loops, particularly barrel rolls. Since the accelerometer is really a force meter, deconstructing the force due to gravity at different angles is difficult. Without compensating for the force due to gravity, this equation will not give meaningful results. The scalar plot is shown in Figure 5.

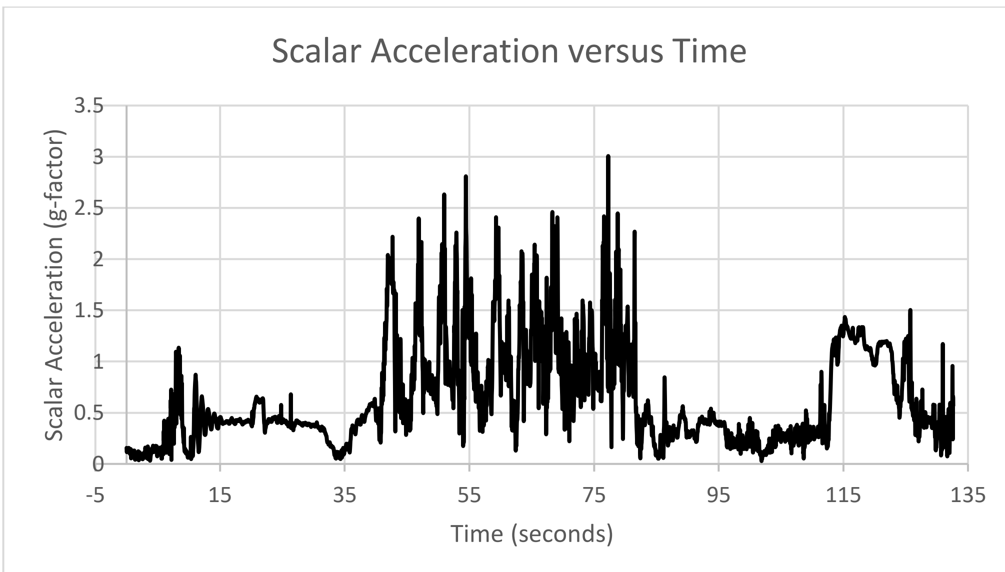



*Figure 5 Scalar acceleration, combining the component accelerations in Figure 4.*

There are mathematical techniques for reducing noise by employing 3-point averaging. This is discussed in the Fireball section, page 48.

## Dual Axis Turning Ride

Shazam! (Page 57) has an interesting set of graphs. The right-left and the forward-back plots are phase shifted. This can be seen when they are plotted together in Figure 9. What is unusual is that there is a small vertical acceleration for a seemingly planar ride. This is owed to the flexing of the arm due to the large loading. In advanced classes, Fourrier Transform analysis can be applied to find the frequencies.

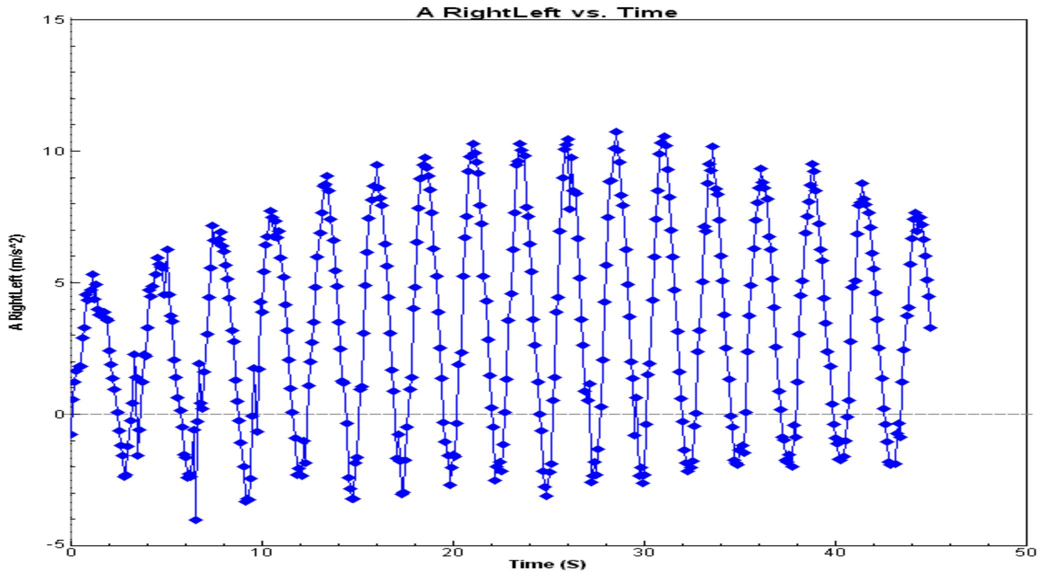



*Figure 6 Plot of right - left motion versus time. Since this is a dual axis turning ride, there are moments of retrograde motion. For a more detailed discussion, see J. Walker, "The Amateur Scientist" Scientific American Vol. 249 No. 4 pp 162-169 Oct. 1983*

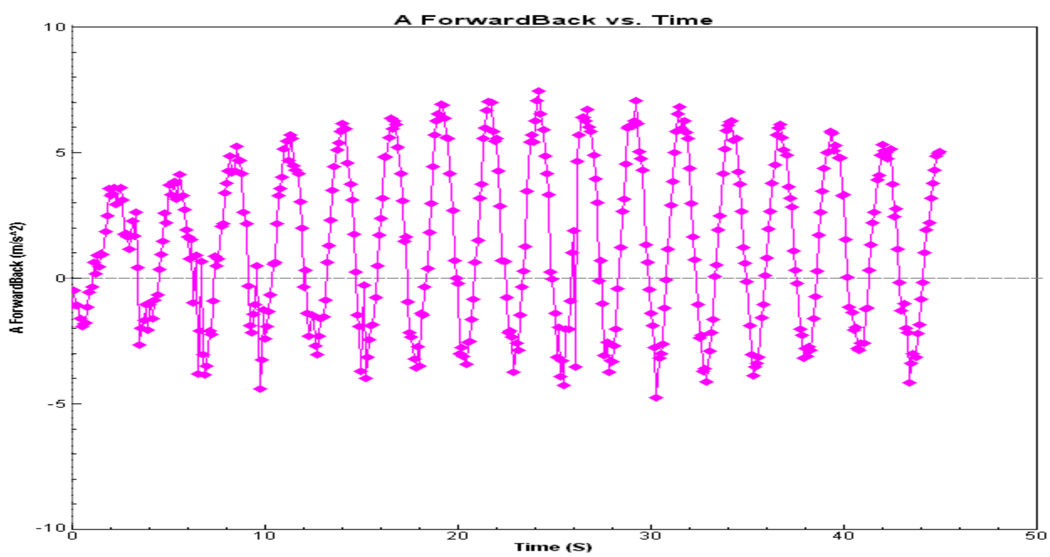



*Figure 7 Plot of forward - back motion versus time. Since this is a dual axis turning ride in counter-clockwise -- counterclockwise mode, some retrograde motion is shown in the region below the axis.*

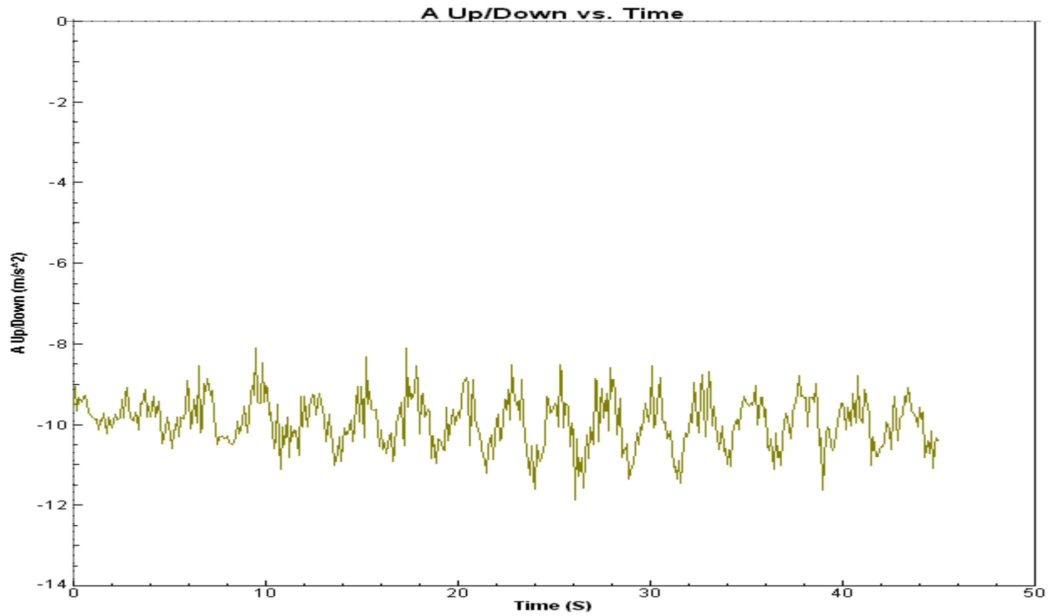



*Figure 8  Plot of vertical motion versus time. Although a constant background of -9.8 N/kg is expected, there is some vertical variation during high acceleration stress moments.*

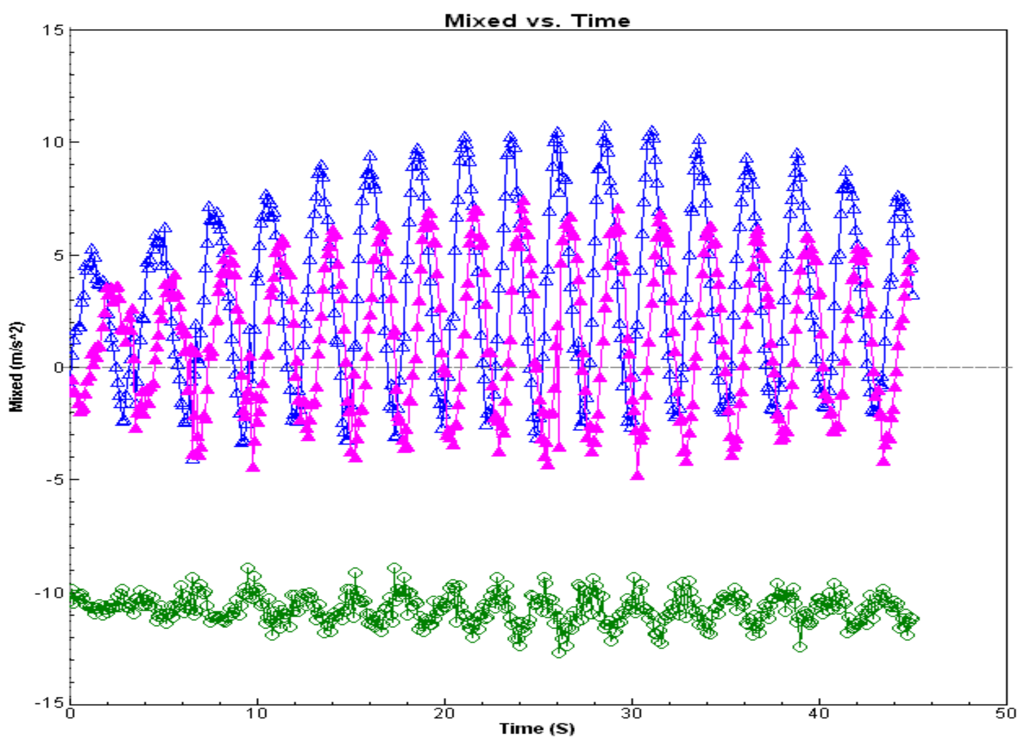



*Figure 9  An overlay of right-left (blue), forward-back (magenta), and vertical (green) motions.*

# SUGGESTIONS FOR TAKING MEASUREMENTS

## Time

The timings that are required to work out the problems can easily be measured by using a watch with a second hand, a digital watch with a stopwatch mode or a smart phone app. When measuring the period of a ride that involves harmonic or circular motion, measure the time for several repetitions of the motion. This will give a better estimate of the period of motion than just measuring one cycle. You may want to collect multiple measures of the time and then average trials.

## Distance

Since you cannot interfere with the normal operation of the rides, you will not be able to directly measure heights, diameters, etc. Most of the distances can be measured remotely using the methods described below. They will give you a reasonable estimate. Try to keep consistent units, i.e., meters, centimeters, etc., to make calculations easier.

*Pacing*: Determine the length of your stride by walking at your normal rate over a measured distance. Divide the distance by the number of steps and you can get the average distance per step. Knowing this, you can pace off horizontal distances.

My pace = __________ m

*Ride structure*: Distance estimates can be made by noting regularities in the structure of the ride. For example, tracks may have regularly spaced cross-members as shown in Figure 10. The distance *d* can be estimated, and by counting the number of cross members, distances along the track can be determined. This method can be used for both vertical and horizontal distances.

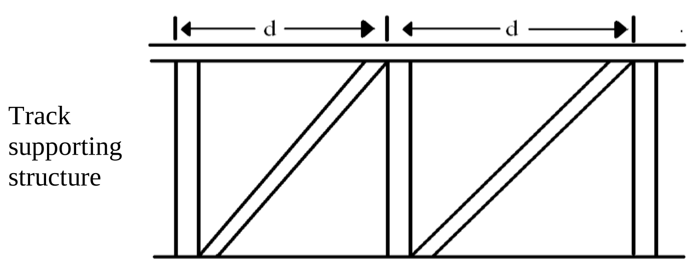



*Figure 10 Detail of cross-members of a rollercoaster structure.*

*Triangulation*: For measuring height by triangulation, a sextant (Figure 11) can be constructed. Practice this with the school flagpole before coming to Six Flags St. Louis.

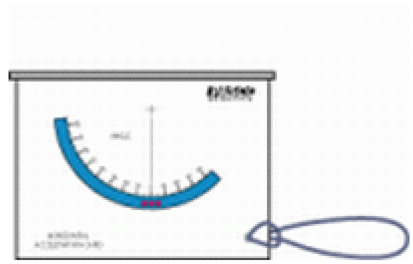


*Figure 11  Protractor accelerometer and sextant.*

Suppose the height *h* of the SkyScreamer® must be determined. *Notice that this shows the height of the tower,* not *the final height of the ride ascent*. Since you cannot measure the distance of baseline all the way to the tower structure, a local baseline, *b*, is needed. You will need to employ the Law of Sines as in Figure 12.

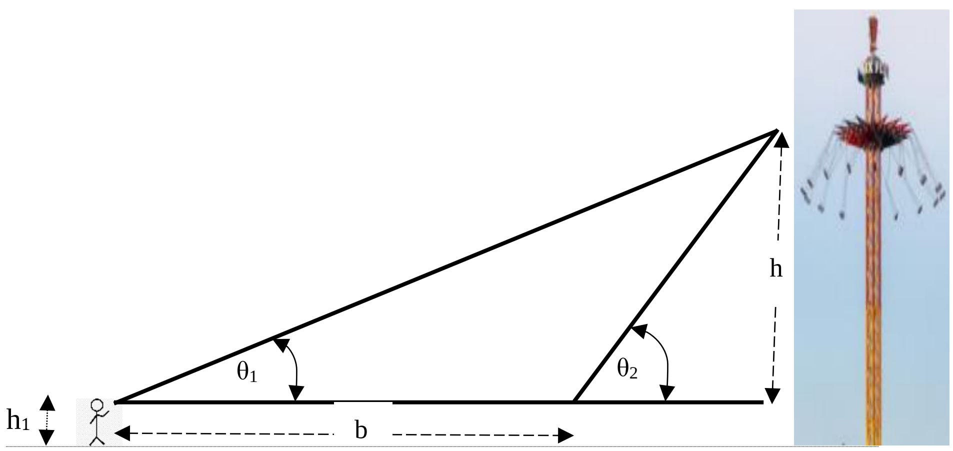



*Figure 12  Drawing of geometry for finding height.*

Knowing $\theta_1$, $\theta_2$, and *b*. the observer's eye to ground height, $h_1$, the height *h* can be calculated using the expression:

$$h = \frac{\sin\theta_1 \sin\theta_2}{\sin(\theta_2 - \theta_1)} b + h_1$$

# UNDERSTANDING A SPRING ACCELEROMETER (FORCE-METER)

The spring accelerometer indicates the rider's acceleration in the direction in which the device is pointing as a multiple of the acceleration due to gravity. This number can be called a $g$-factor. If the accelerometer when pointing **forward** on a ride registers 0.5 $g$, the rider is experiencing an acceleration equal to half the acceleration due to gravity. In this situation, a force corresponding to an acceleration of 0.5 $g$ is pushing on his or her back. A 60 kg rider would experience a force of about 300 newtons.

$$(F_{net} = ma = (60 \text{ kg} * 9.8 \text{ N/kg}) * 0.5 \approx 300 \text{ N})$$

For the vertical situation, we can use a force diagram to guide our thinking:

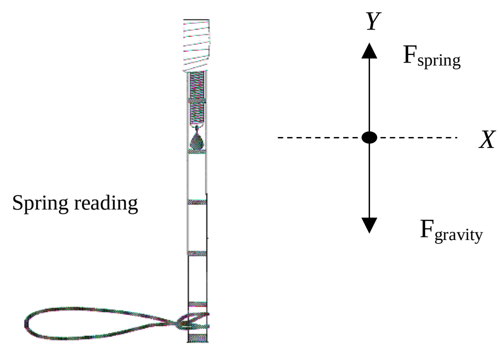



*Figure 13 Vertical accelerometer and accompanying force diagram.*

Using Newton's second law, $F_{net} = F_{spring} - F_{gravity}$, we can find the acceleration. Since the mass of the plumb does not change, this simplifies to: $a_{net} = \frac{F_{spring} - F_{gravity}}{m}$. The accelerometer is calibrated in $g$'s, making for simple computations.

What is happening when the spring accelerometer reads 0 $g$? This would mean that the force of the spring is 0 newtons. Applying the equation, $F_{net} = F_{spring} - F_{gravity} = ma_{net}$, we have $F_{net} = 0 - F_{gravity} = ma_{net}$. This means that the rider's acceleration is equal to the acceleration due to gravity. When the rider is not supported by the seat, both the rider and the seat are in freefall. This happens when a rollercoaster is cresting over a hill, on a freefall ride, and some compressed air rides found in other parks. The sensation is often called *airtime*.

Another interesting case is when the rider is upside down. If the ride goes through the inverted part of a loop fast enough, the accelerometer will read anywhere from 0.2 $g$ to 1.5 $g$. The rider is being forced into a curved motion smaller than the curve a ball thrown into the air would follow. The rider may feel lighter than usual but does not feel upside down. This is particularly evident where the repetitive motion gives riders a chance to get used to the motion and start to notice sensations.

Upside down, on rides that go slowly enough, riders can pull "negative" force-factors. This means that without some sort of harness contraption riders would fall out of the ride. They feel decidedly upside down, as they feel the harnesses holding them in. On most rides, however, riders pass through the inverted loops with large enough acceleration to convince them that they are still right side up.

# SPEED and VELOCITY

In linear motion, the average velocity of an object is given by:

$$v_{ave} = \frac{\Delta x}{\Delta t}$$

In circular motion, where tangential velocity is constant:

$$v_{ave} = \frac{\Delta x}{\Delta t} = \frac{2\pi r}{\Delta t}$$

If you want to determine the speed at a particular point on the track, measure the time that it takes for the length of the train to pass that point. The train's speed then is given by:

$$v_{ave} = \frac{\Delta d}{\Delta t} = \frac{Length_{train}}{t_{passage}}$$

In a situation where it can be assumed that total mechanical energy is conserved, the speed of an object can be calculated using energy considerations. Suppose the speed at Point B is to be determined (Figure14). From the principle of conservation of total mechanical energy, it follows that:

$$E_{Total} = GPE_A + KE_A = GPE_B + KE_B$$

$$E_{Total} = mgh_A + \frac{1}{2}mv_A^2$$
$$= mgh_B + \frac{1}{2}mv_B^2$$

Since mass is constant, solving for $v_B$

$$v_B = \sqrt{2g(h_A - h_B) + v_A^2}$$

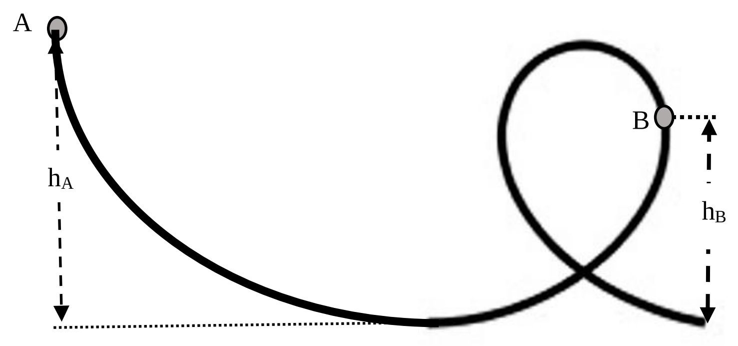



*Figure 14 Velocity calculation at a point in a clothoid loop.*

Thus, by measuring the speed of the train at Point A and the heights $h_A$ and $h_B$, the speed of the train at Point B can be calculated.

# ACCELERATION

Accelerometers are designed to record the "*g* accelerations" felt by a passenger. Accelerometers are usually oriented to provide force data perpendicular to the track, longitudinally along the track, or laterally to the right or left of the track (Figure 15).

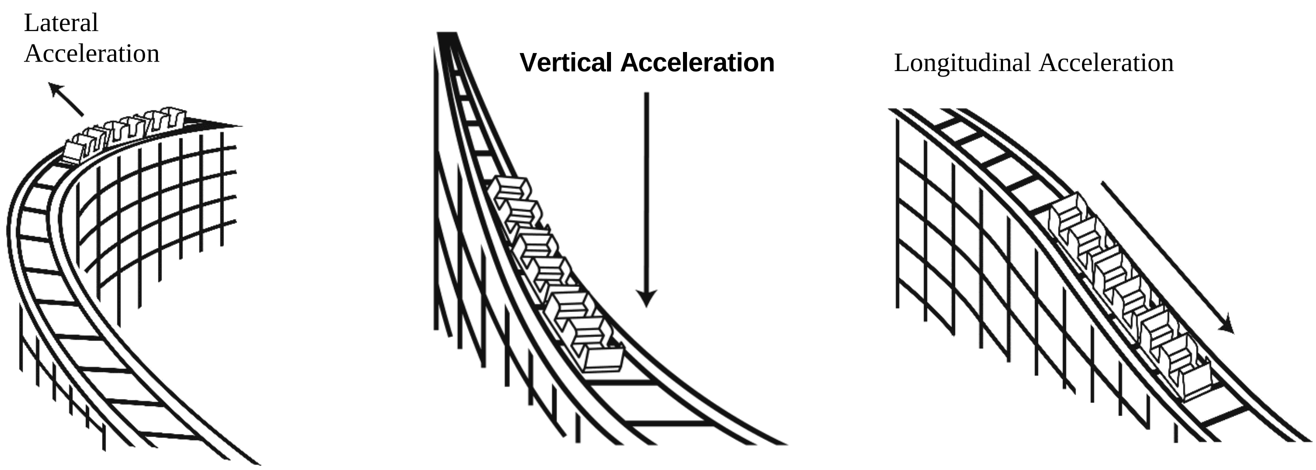


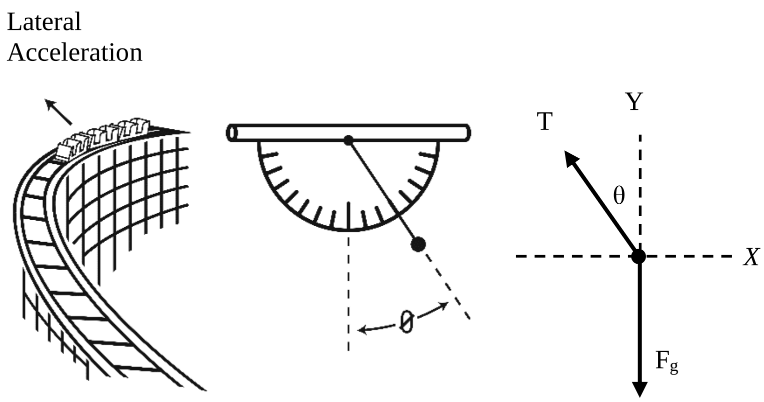

*Figure 15 Acceleration terms.*

Accelerometers are often calibrated in *g*'s. A reading of 1 *g* equals the acceleration due to gravity, 9.8 $m/s^2$. This is also the *force factor*. Since we live on Earth, we normally experience the sensation of 1 *g* of gravitational field intensity vertically (no *g*'s laterally or longitudinally). Listed below are the sensations of various g accelerations or force factors. These are rough estimates but may be helpful in estimating accelerations on the various rides.

| **Accelerometer Reading** | **Sensation** |
|---|---|
| 3 *g* | 3 times heavier than normal (close to maximum *g*'s experienced by astronauts during launch) |
| 2 *g* | twice normal weight |
| 1 *g* | normal weight |
| 0.5 *g* | half-normal weight |
| 0 *g* | weightlessness (no force between rider and coaster) |
| -0.5 *g* | Half-normal weight - but directed away from coaster seat (the shoulder harness is supporting the rider's weight when upside-down.) |

## Lateral Acceleration

The sextant (protractor) discussed earlier as a triangulation instrument, may also be used to measure lateral accelerations. The device is held with sighting tube horizontal toward the center of the turn, and the weight swings to one side (Figure 16).




$$\sum F_Y = 0 = T\sin\theta - mg$$

$$\Sigma F_x = ma = T\cos\theta$$

Since the mass in all terms is the same bob, it divides out, leaving:

$$\boldsymbol{a = g\tan\theta}$$

*Figure 16 Pictorial and diagrammatic representations of using the sextant as a horizontal accelerometer.*

## Centripetal Acceleration

Using the protractor accelerometer pointing toward the center of the circle, the centripetal acceleration can be measured directly. The acceleration can also be calculated by first measuring *r* and *T* and then analyzing as follows:

With uniform circular motion remember that: $v_{\text{tangential}} = \dfrac{2\pi r}{T}$

and the centripetal acceleration is given by: $a_c = \dfrac{v^2}{r} = \dfrac{4\pi^2 r}{T^2}$

where *r* is the radius of the circle and *T* is the period of rotation.

# RADIUS – ROLLERCOASTER DIP

To determine the radius of a rollercoaster dip, one can first use the spring accelerometer to measure the centripetal acceleration experienced on the dip. The velocity of the car can be approximated using the methods mentioned above. From there, the radius of the dip can be calculated from the centripetal acceleration equation:

$$\boldsymbol{a_c = \frac{v^2}{r}}$$

# FORCE DIAGRAMS

Force diagrams, also known as free body diagrams, help with understanding force problems.

To draw a force diagram:

1. Depict the object as a dot (often associated with the center of mass).
2. Use vectors, starting on the dot, to depict all long-range forces. Long range forces include electricity, magnetism, and gravity.
3. Use vectors, starting on the dot, to depict all contact forces.
4. Select a useful frame of reference.


*Figure 17 Force Diagram example SkyScreamer, left. Force Diagram rollercoaster on hill, right.*

# ENERGY FLOW DIAGRAMS

Energy is a conserved quantity that flows when there is a change. We use energy charts as a representation of the flow. To illustrate this, we will use a shuttle or surf-type rollercoaster.

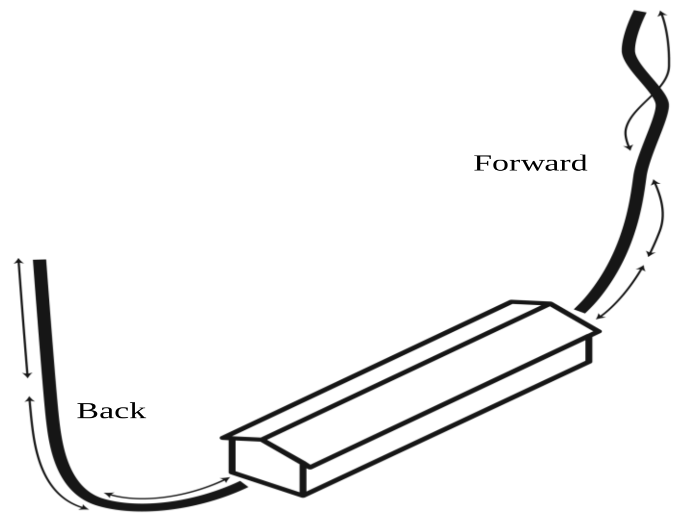



*Figure 18 Shuttle rollercoaster example for Energy Flow Diagrams.*

This ride is launched by a linear induction motor (magnetics) going to a forward tower, coming back through the station to go up a rearward tower, and then returning to the station. Many ride patterns will go through this oscillation two or three times. For the sake of this example, only one cycle will be shown here. The positions used in this example are launch, forward tower peak, passing the station, rearward peak, and stopping back at the station.

The following energy flow diagram represents energy transformations for the situation

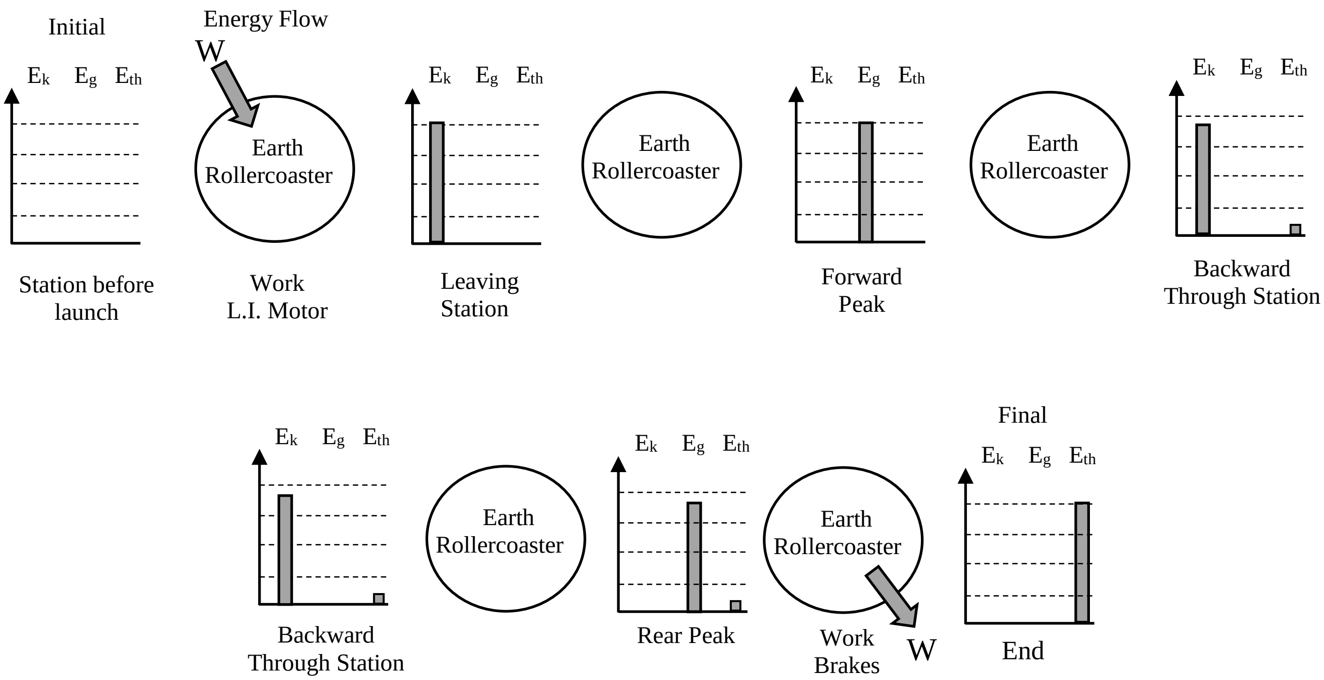



*Figure 19 Energy Diagram of a shuttle rollercoaster at various positions.*

Initially, the Earth-Rollercoaster system has no stored or kinetic energy. When external work is done on the rollercoaster by the linear induction motor like that for Mr. Freeze Reverse Blast, the rollercoaster gains kinetic energy ($E_k$). When the train reaches the forward peak, all the kinetic energy is transferred to the gravitational field and is stored as gravitational potential energy ($E_g$). When the train descends backward through the station, a small amount of thermal energy ($E_{th}$) due to friction has become noticeable. If the energy transfer to thermal energy is large enough, the linear induction motors will give a boost to the train. In our example above, such as boost is not given, and no additional work is done on the system. If we add the bars in each chart together, they show the same total energy in each position, because energy is conserved in a closed system. On the backward peak, the kinetic energy is transferred to the gravitational field then back to kinetic energy as the train descends. Finally, the brakes are applied, and the work done by the brakes transfers energy to the environment as thermal energy. The diagrams lead to the following equation:

$$W_{induction\ motor} = E_k + E_g + E_{th}$$

# FRICTION AND AIR RESISTANCE

## Track Friction

Friction plays a significant role in rides. This is most critical in rollercoasters. Rollercoaster wheels are usually made of steel, nylon, or one of two kinds of polyurethane. Two different polyurethanes are used (hard and soft) as per temperature specifications. The coefficients of friction for polyurethane and nylon are similar. The table below can be used in coefficient of *static friction* problems.

$$F_f = \mu F_N$$

| Materials | $\mu_s$ |
|---|---|
| Steel on steel (dry) | 0.7 |
| Nylon (approximate for polyurethane) on steel | 0.4 |

Coefficients of *rolling friction* vary by lubricants and temperature. Values range:

0.009 to 0.018

## Air Resistance

Air resistance is more complicated. The force due to air resistance depends on the drag coefficient ($C_d$), frontal cross-sectional area (A), density of air (ρ), and velocity of the train. The force due to *aerodynamic drag* is characterized by the equation:

$$F_D = \frac{1}{2} C_d \, A \, \rho \, v^2$$

The drag coefficient differs due to design differences among trains, wings, suspension cars, etc. For a traditional toboggan-type train, the typical drag coefficient is 0.8. Some trains have values twice this. It is recommended to use a drag coefficient of 0.8 for the purposes of this activity.

Approximate the cross-sectional area by measuring the width and height of the car when it is stopped in the station. For many two-across seating trains, the width is often 1 meter, and the height (including seated passenger) is about 1.5 meters.

The density of air depends on barometric pressure, altitude, temperature, and humidity. The middle of Six Flags St. Louis is 184 meters above sea level. Average barometric at the park is 985 millibars. Temperature in the spring season varies, but we will choose $20^oC$. Relative humidity of 70% is common. Note that these quantities are average values and may be different on the day of visit. For these values, the density of air is 1.163 $kg/m^3$.

## Amusement Park Ride Design Challenge

Names of Group Members: ________________________________________

________________________________________

Class Block/Module/Period: ______________

Ride Grouping: ________________________________________

Decide, with your teacher, what grouping of rides is to be chosen for this assignment. Your teacher may have different requirements of what you need to turn in. It is very important that you have a plan for data collection well in advance of your trip. Considerations are the timing of rides, seating capacity, velocities, accelerations, forces, energy and energy transfers, momentum, motor size, physical size, etc.

***Scenario**:*

Six Flags St. Louis has decided to build a new attraction near the SkyScreamer area of the park. The ride may be a duplicate of another in the park if there are long lines at those rides necessitating a duplicate attraction, or it may be an entirely new ride for the park. Once you select the category of ride you will design, determine the placement, footprint, cost, stress levels, age appeal (young, teenage, adult, etc.), theme, capacity, energy transfers, and other considerations deemed important for this ride. A needs assessment, an engineering overview of the proposed ride, and engineering comparisons of existing rides must be included in your final proposal. Be sure to include pictorial, graphical, mathematical, diagrammatic, and narrative depictions for your measurements, calculations, etc. of existing rides to support your final proposal.

## Amusement Park Ride Design Challenge (continued)

- Generate the criteria for the new ride. Elements include creating specifications suggested in the *Scenario* paragraph, above. Great detail is required in this section as it is the heart of the proposal, from which the remainder of the activity flows.

- State your predictions, hypotheses, and testable ideas for this design task.

- Cite ride design resources (URLs, print material, periodicals, etc.).

- Create pre-trip data tables and proposed measurements to be completed at the park.

- State equations or other information that might be desired.

- Itemize the needed equipment (stop watches, string, calculators, accelerometers, protractors, cameras, etc.).

- List the specific responsibilities for each member.

- Incorporate final report elements. This may include abstract, purpose, data, calculations, pictures, diagrams, graphs, design sketch(es) and specifications of proposed ride, discussion of predictions and hypotheses, error analysis, biological and psychological considerations, safety requirements, etc.

# RIDE GROUPINGS

NOTE: Only the rides that are data-collection-friendly are footnoted.

- Rollercoasters
  - Non-inverting[1]
  - Inverting[2]
  - Shuttle[3]
  - Water[4]

- Spinning Rides
  - Single axis[5]
  - Dual axis[6]

- Pendulum Rides
  - Single axis[7]
  - Dual axis[8]

---

[1] American Thunder, River King Mine Train, Rookie Racer, Screamin' Eagle, and The Boss
[2] Batman The Ride, Boomerang, and Ninja the Black Belt of Rollercoasters
[3] Mr. Freeze: Reverse Blast
[4] Log Flume
[5] Colossus, (uniform circular motion); Fireball, and SkyScreamer (non-uniform circular motion)
[6] Shazam!, Supergirl Sky Flyer
[7] The Buccaneer
[8] Spinsanity

# HOW TO USE THE HISTORICAL QUESTION BANK

This historical question bank has been designed to give ideas of ranges and kinds of questions that would support appropriate learning. Your teacher would be the best guide for which questions are most appropriate for you and your group. Be sure to allot time for multiple trials allowing for deeper analysis into the science and engineering of the thrill-inducing machines. The majority of the question bank is arranged by categories of rides (Page 23), not by specific ride.

We encourage students to keep a journal of measurements, diagrams, sketches, etc. A student report might contain a written description of the procedure used to collect the necessary data and then sample calculations showing pertinent equations with the correct units. Pictures, diagrams, and graphs (where appropriate) help tell a complete story.

The questions are grouped by the following types: narrative, engineering, velocity, heights, forces and accelerations, centripetal forces and accelerations, friction and air resistance, and energy. Some questions for a category of ride may not apply due to poor sight lines.

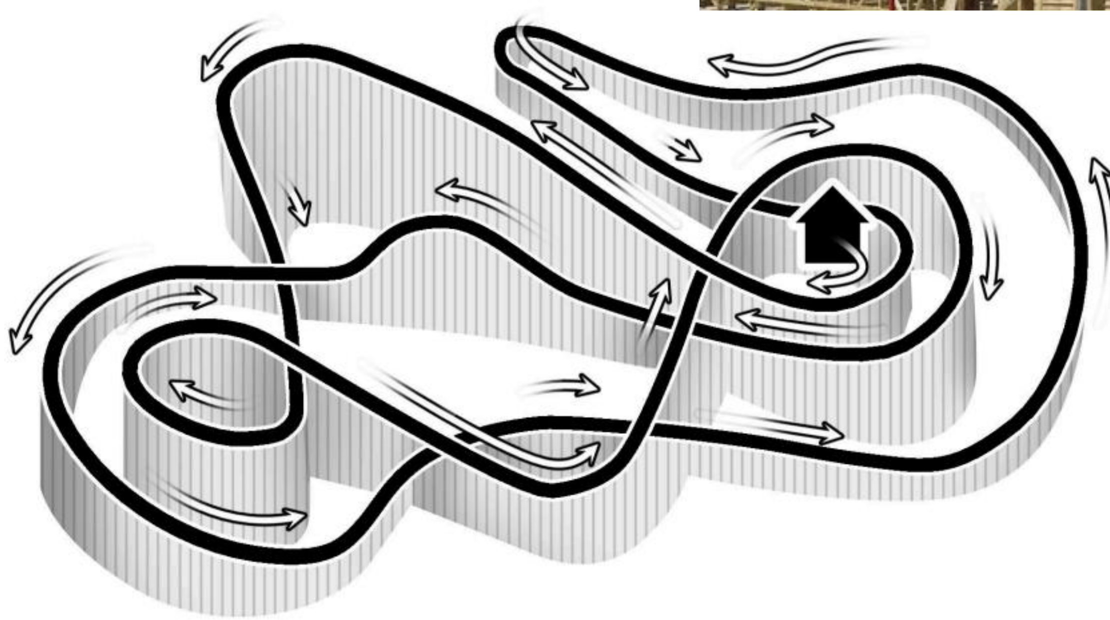
## Approximating Mass

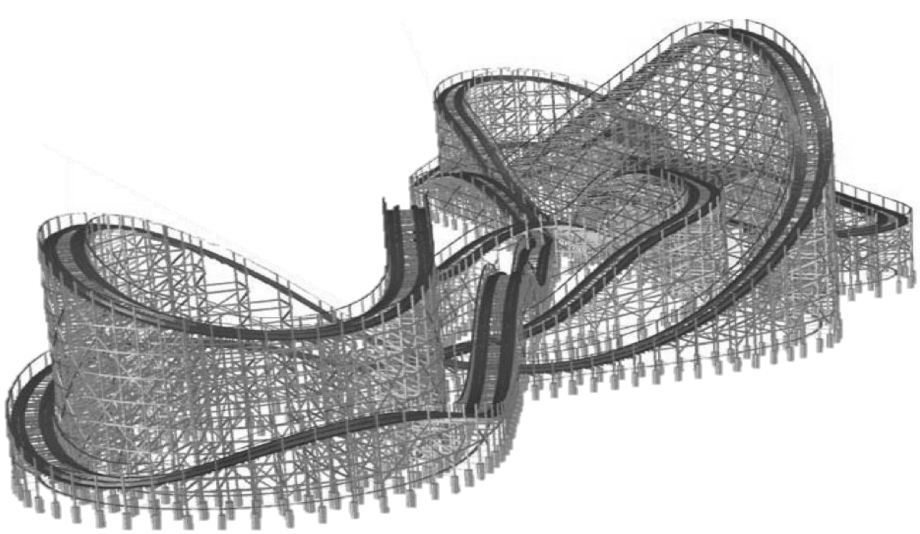
When calculating forces, momenta, energy, and other quantities requiring a *rider's* mass, we recommend using an agreed-upon mass, say 65-kilogram, the mass of a typical rider. This will allow for more meaningful class discussion of results.

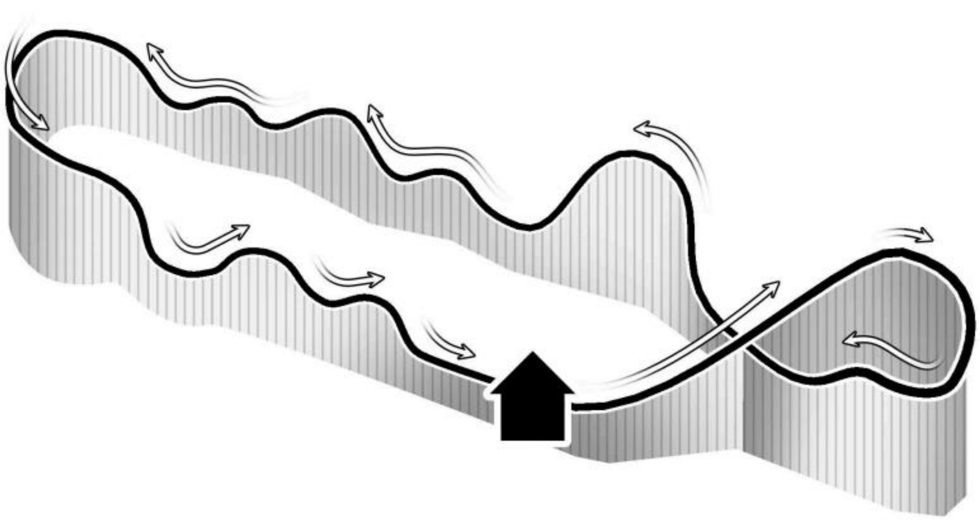
*Rollercoaster* car masses range from 450 kilograms to 1000 kilograms. If rollercoaster car masses are needed, such as when calculating lift motor specifications, a reasonable value to use would be 600 kilograms per car, depending on design and seating.

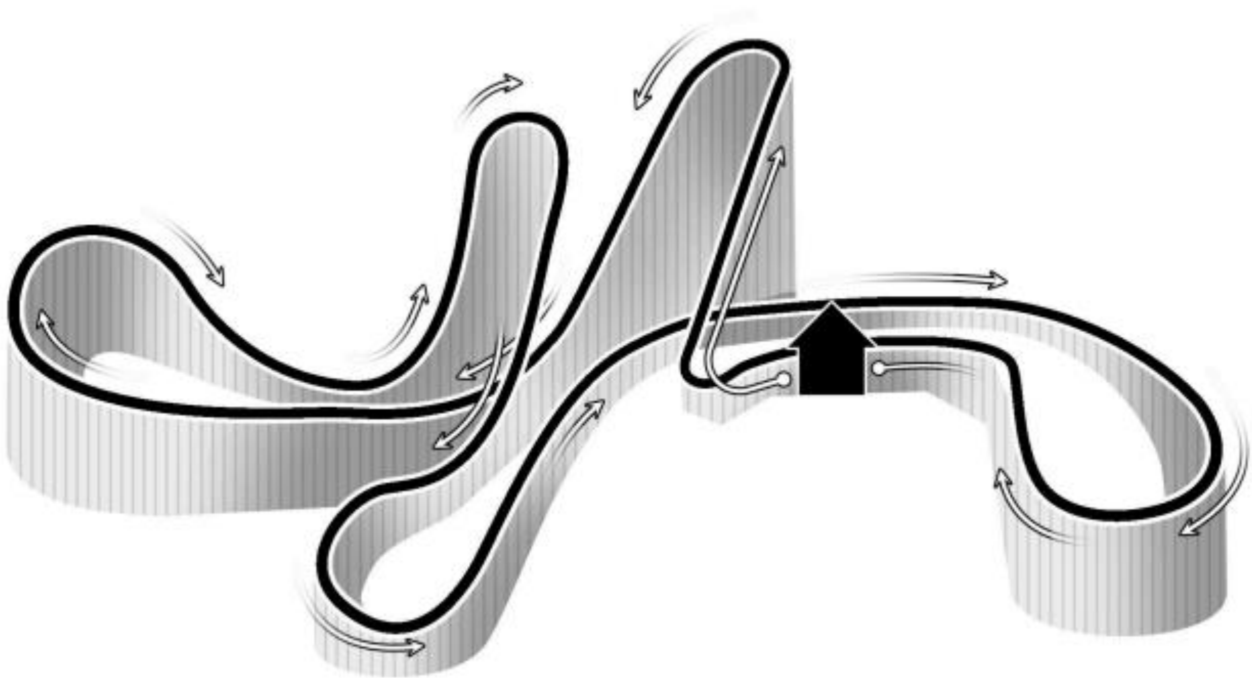
# NON-LOOPING ROLLERCOASTERS

American Thunder









## Narrative

1. Why is the first hill of the rollercoaster the tallest?

2. Why is the operator of a rollercoaster NOT concerned about the mass of the passengers?

3. Describe the sensations experienced while riding over and down the "hills". At which point(s) do you experience a sensation of weightlessness? Label these points on the track layout with the letter '**W**'.

4. Why do the heights of successive "hills" decrease when moving from the beginning to the end of the ride?

5. Where on the ride did you feel lifted off your seat? How did the ride cause this feeling? Label these points with the letter 'L' on the track layout. Be sure to state where you were sitting (front, middle, or rear).

6. When and where is the speed the least during the entire ride (not including the lift hill, and being at rest at the start and finish)?

7. List the locations of energy that are utilized by the rollercoaster. The energy may be in the gravitational field, the coaster, the track, etc.

8. From an energy perspective, how is a rollercoaster like a simple pendulum?

9. Use the track layout to label the following (please use the symbols provided):

| | |
|---|---|
| **S** Maximum speed | **K** Maximum kinetic energy |
| ⓢ Minimum speed | ⓚ Minimum kinetic energy |
| **P** Maximum potential energy | **W** Weightless sensation |
| ⓟ Minimum potential energy | **H** Heavy sensation |

10. Some rollercoaster enthusiasts claim the first rollercoaster car offers the most thrilling ride; others insist that the last car provides the biggest thrills. Discuss the merits and disadvantages of each position. Be sure to explain your answers based on the physics involved. Show mechanical or electronic data to support all claims.

11. Describe where the rollercoaster's track is banked. Explain the purpose of banking rollercoaster track.

## Engineering

12. List at least five safety features (or as many additional as you can) that are used in rollercoasters. This includes both passive and active design components.

13. Measure the amount of time that elapses from when the train leaves the station until the next time the same train leaves the station. This includes loading and unloading time. Count the total number of seats on the train. How many passengers per hour can ride this train? If there is only one train, this is the *capacity* for the ride. If there is more than one train, explain how to calculate the capacity of the ride and determine its value.

14. Using the capacity of the ride (number of guests per hour), determine the length of line needed for an hour's worth of guests. How does this compare to the queue length (including all of the snaking back and forth) for the ride being evaluated?

## Velocity

| RIDE | TRACK LENGTH (meters) |
|---|---|
| American Thunder | 827 |
| River King Mine Train | 723 |
| Screamin' Eagle | 1180 |
| The Boss | 1412 |

15. Measure the amount of time that elapses from when the train leaves the station until it returns. Using the supplied data table, calculate:
    A. The average speed of the trip.
    B. The average velocity of the trip.
    C. Why are the answers for Part A and Part B different?

16. Measure the length of the train while it is at rest in the station. As the train rises on the lift hill, measure the time it takes the train to pass a fixed point on the hill. Use these values to calculate the speed of the lift chain.

17. Measure the velocity of the train at the following positions:
    A. The top of the lift hill.
    B. The bottom of the lift hill.
    C. The top of the second hill.

18. The typical size for a running wheel of a rollercoaster is about 200 millimeters. Use the track lengths in the table above to find these interesting values:
    A. How many times does a wheel rotate in one complete cycle?
    B. What are the maximum revolutions per minute (RPM) of a wheel?
    C. Determine the average RPM of a ride cycle.
    D. Using data from Question 13, how many revolutions does a wheel make in an hour?
    E. What is the maximum tangential velocity of the wheel?

## Heights

19. Measure the angle of the lift hill. Measure the amount of time it takes the train to go up the lift hill. Measure the angle of the lift hill. Calculate:
    A. The height of the lift hill. (This may be done using trigonometry or a scale drawing.)
    B. The length of the lift hill using the speed of the train (Question 16.) Verify this knowing the angle and height of the lift hill.

20. Measure the height of the train at the following positions. (This may be done electronically or by triangulation.)
    A. The top of the lift hill.
    B. The bottom of the lift hill.
    C. The top of the second hill.

## Forces and Accelerations

21. Consider the rollercoaster you have chosen for analysis, and draw a force diagram of each of the following:
    A. The train being pulled up the lift hill at constant velocity.
    B. A passenger at the bottom of the lift hill.
    C. A passenger at the top of the second hill.
    D. The train in the process of stopping, just before reaching the end of the ride.

22. Calculate the force the lift motor exerts through the chain for a fully loaded rollercoaster. Use the mass of each car as 600 kilograms, and each passenger as 65 kilograms. Use the force diagram in Question 21A to guide your answer.

23. Measure the accelerations in each position described in Question 21. This can be done mechanically or electronically. If done both ways, what is the percent of difference?

24. Calculate and compare the normal forces on a 65-kilogram rider in the positions described in Question 21.

25. Draw and label a force diagram of a train on the lift hill. Calculate the force due to the track, force due to the chain, and the force down the inclined plane of the track due to gravity for a ride up the lift hill.

## Centripetal Forces and Accelerations

26. Use an accelerometer to measure your acceleration at the bottom of the first hill. Knowing the velocity (Question 17), calculate the radius of this dip.

27. Draw a force diagram for a person at the bottom of the first dip. Calculate the size and state the direction of each of the forces at this point of the ride. Ask your teacher if friction should be considered.

28. Use an accelerometer to measure your acceleration at the top of the second hill. Knowing the velocity (Question 17), calculate the radius of this crest.

29. Draw a force diagram for a person at the top of the second hill. Calculate the size and state the direction of each of the forces at this point of the ride. Ask your teacher if friction should be considered.

30. Measure your acceleration in the first lateral (horizontal) curve. Calculate the velocity of the train in the curve. Draw a force diagram for a person in this curve. Determine:
    A. The lateral force on a passenger in the curve.
    B. The radius of the curve.
    C. Whether the bank of the curve is such that there is no lateral friction.

## Friction

31. What is the difference between the force due to air resistance at the top of the lift hill and that at the bottom of the first drop?

32. Determine the values of the force of rolling friction and force of static friction on the lift hill.

33. Calculate the force due to static friction at the bottom of the first drop. Compare this to the force due to static friction at the top of the second hill.

34. Calculate the maximum aerodynamic drag at the bottom of the first drop.

## Energy

35. Draw an energy flow diagram for the rollercoaster system starting the moment the train catches the lift chain and ending as the train moves up the third hill. Capture key locations along the way.

36. Draw qualitative energy bar charts to account for the energy of the car at the following locations:
    A. At the start of the ride when attaching to the lift chain.
    B. At the top of the lift hill.
    C. One third the way down from the top of the lift hill.
    D. At the bottom of the lift hill.
    E. At the top of the second hill.

37. Using an electronic altimeter on the ride to record heights (see Figure 3), measure the overall slope of each declining altitude peaks. How does this relate to the anticipated friction of the coaster design?

38. Draw an energy flow diagram for a whole ride cycle on Mr. Freeze Reverse Blast. Draw energy bar charts for the entire ride cycle for Mr. Freeze Reverse Blast.

39. Using information from Question 21, determine the minimum power of the lift motor. Assume each train car's mass is 600 kilograms, and each person's mass is 65 kilograms.

40. If the lift motor is 97% efficient, how much energy is transferred from the electric motor to the train? How much energy is transferred to the environment as heat?

41. Determine the kinetic and gravitational potential energies of the train at the top of the lift hill.

42. Measure the velocity of the train at the bottom of the first drop. Next use conservation of energy to calculate the velocity of the train in this position. Do these velocities match? What is the kinetic energy difference between these two measurements? Where is the missing energy?

43. Estimate the work done on the Mr. Freeze Reverse Blast rollercoaster during launch. What is the cost of electricity for each launch? Assume electricity costs 7.5 cents per kilowatt-hour and that the linear induction motor is 92% efficient.


*Since most of River King Mine Train is not visible from a public space in the park, questions here will concentrate on analysis of electronic accelerometer and altimeter data.*

- *An electronic vest or phone app to record data for this activity is required.*
- *Record your seat position.*

Mine Train is unusual since it has three lift hills along its route. A lift hill is characterised by a less steep linear increasing line on an altitude versus time graph. In Figure 20, a ficticious graph of *Fe Canus Lupus*, we see the lift hill between 20 seconds and 45 seconds. From this information, we can find the train's speed (lift chain speed), change in potential energy, and other quantities.

At 45 seconds and 53 seconds, we see a significant change in height between the lift hill and the second hill. Most of the loss of gravitational potential energy is due to friction. Knowing the speeds at these two peaks and knowing the sum of the gravitational potential energy and the kinetic energy at each point, the missing energy can be found. This can be calculated for successive peaks.

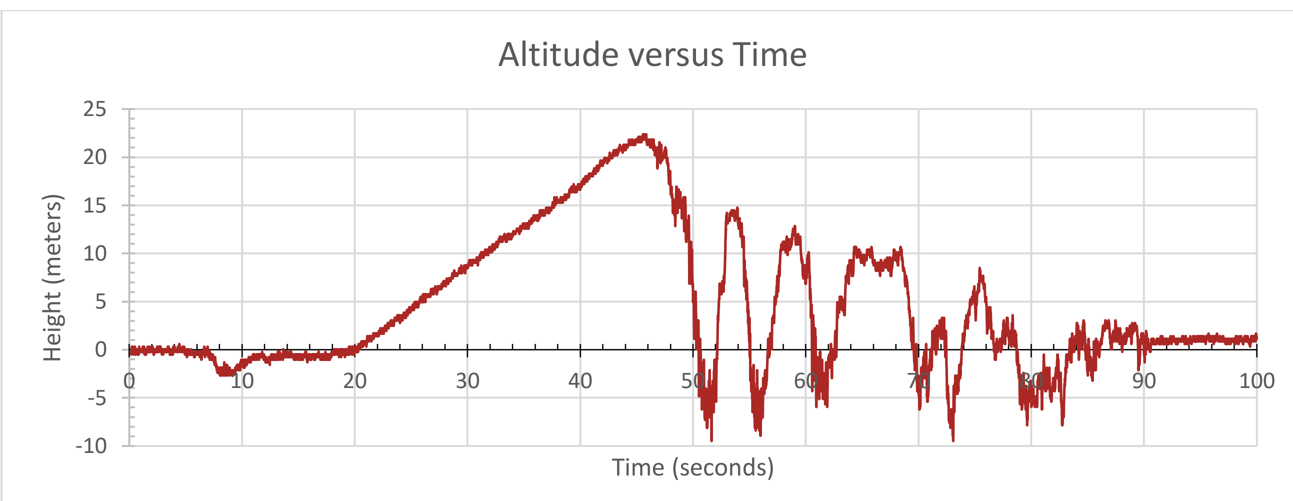



*Figure 20 Fe Canus Lupus, a fictional rollercoaster.*

## Altitude Versus Time

1. On the altitude versus time graph, label the three lift hills.
2. Compare the chain velocities on each of the lift hills.
3. What is the change in gravitational energy of a passenger at each lift hill? What is the work done to lift a passenger up each hill?
4. Power can be expressed as $P = mgv$. Estimate the mass of the rollercoaster and passengers. What is the minimum power rating of the motors of each lift.
5. At specific points of the ride, why are some of the altitude readings negative?
6. Estimating the velocity of the train at the peak of each hill, find the total of the kinetic and gravitational potential energy at each peak. The missing energy is that lost due to friction. In each section of lift hills, plot the loss of energy due to friction versus time (at peaks). This is sometimes referred to the friction profile. Are the negative trends similar? Cite evidence for your answer.

## Acceleration Versus Time

*The electronic accelerometer-force meter is directional. Do a sample test ahead of time so that you know which is the x, y, and z axes of the device. Some devices account for the background gravitational field, others do not. One way to test this is to jump vertically. While airborne, you are weightless, but gravity is still present. During the weightless phase of your test jump, if the accelerometer shows zero meters per second squared, but you are accelerating at -9.8 m/s$^2$, then you need to make an adjustment in the vertical data.*

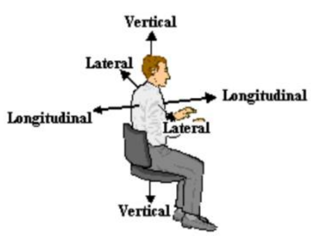



*Figure 21 Orientation of motion axes.*

7. Assuming that the very tops of hills, bottoms of valleys, and middle of curves are arcs of circles,
   A. Calculate the radii of each element from the acceleration measurements. (You will need to know the elapsed time in the curve, since you do not have the velocity. Note that this time is only the time you were in the arc, not the period.)
   B. Draw the force diagrams for each curved element of the ride.
   C. Which element has the greatest centripetal force? The least centripetal force?

8. Use force diagrams and narrative explanation to explain why the rider feels lighter going over the tops of some hills.

9. Some rollercoaster enthusiasts have a favorite seat. It may be front, middle, or rear. They claim the ride is different. But is it? Ride the same rollercoaster three times, once in each seat position. Graph the results on the same axes and compare. The starting times of the trials will need to be coordinated. This can be done by taking some early landmark point, such as jiggling the sensor at the instant the ride begins, and setting all times to zero at that point. Compare the three trials on a single altitude versus time graph. Check peaks and valleys of each graph to the corresponding accelerations. Describe the different experiences felt by the front versus the rear rider at an altitude maximum and altitude minimum.

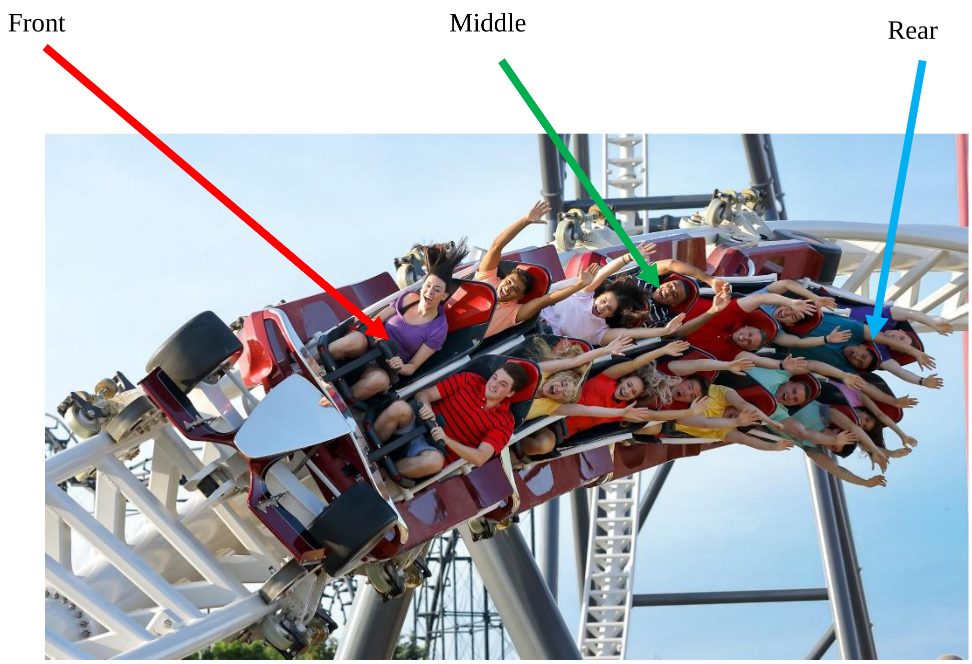
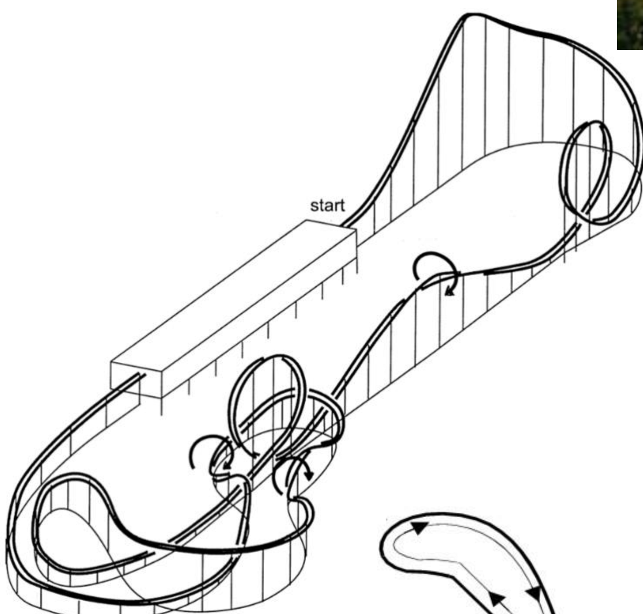
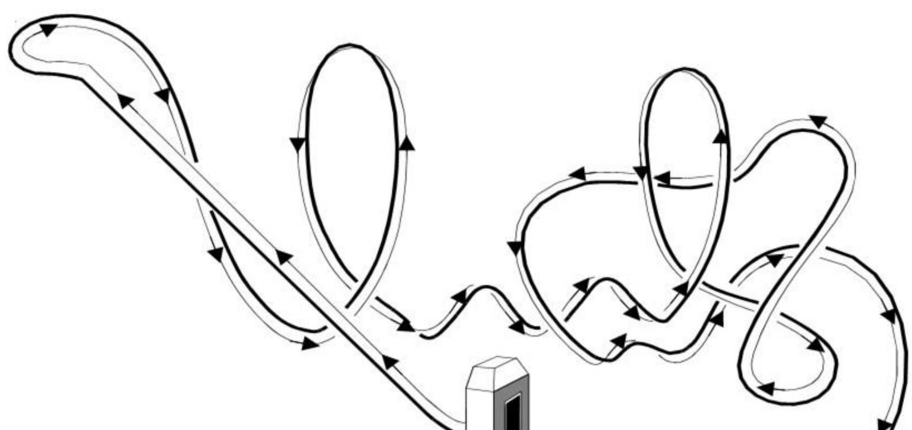
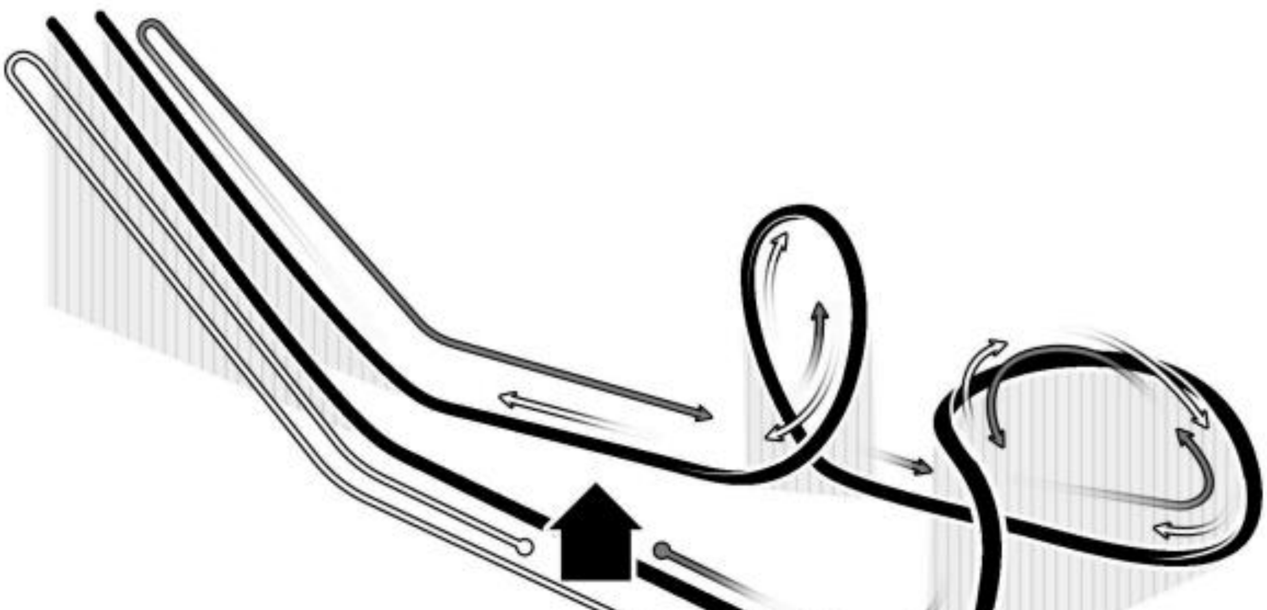


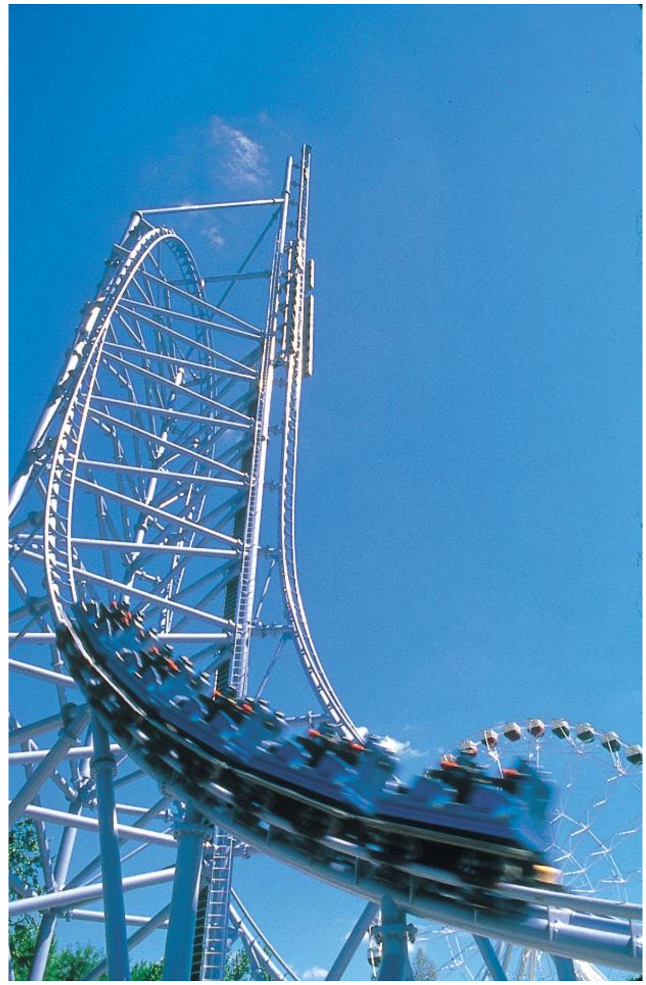

*Figure 22 Front, middle, and rear passenger positions.*

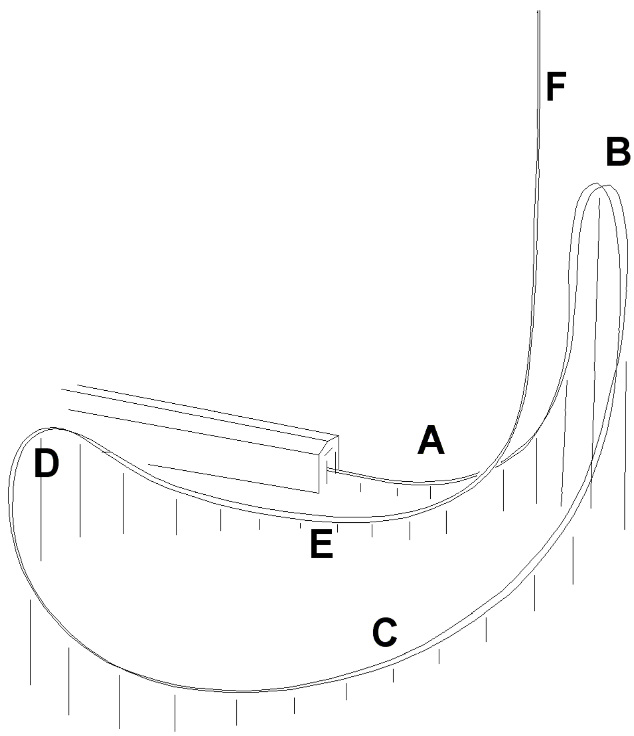
# LOOPING ROLLERCOASTERS








F
B
A
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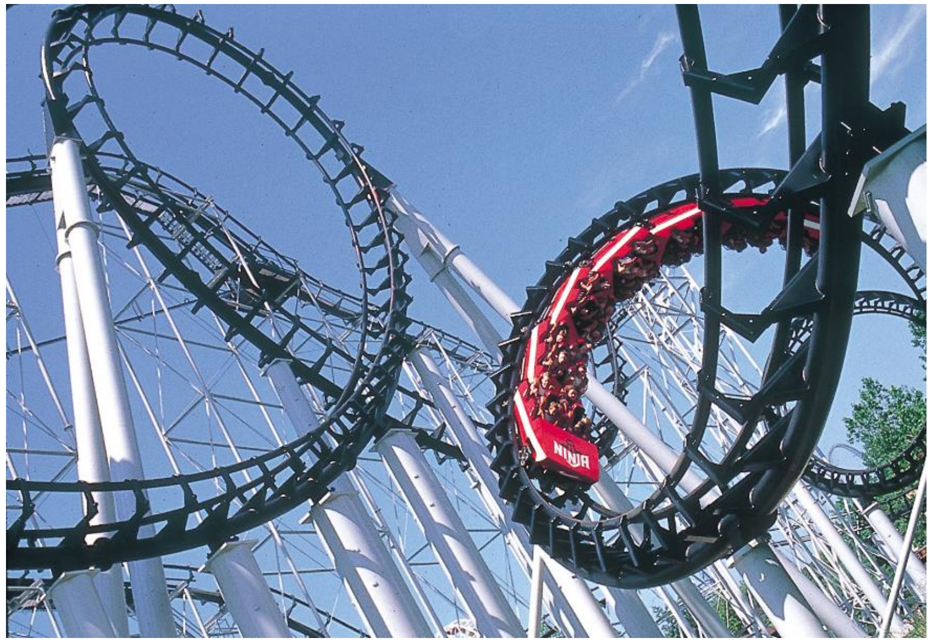
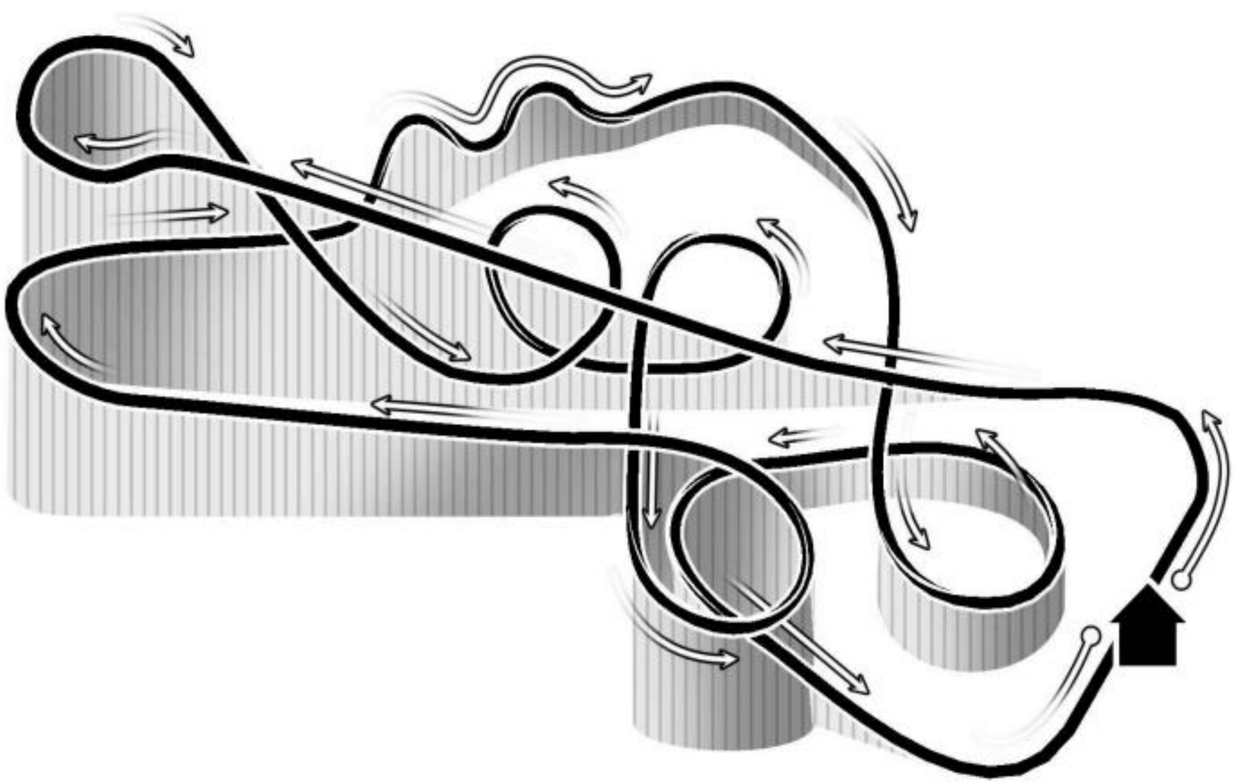
NINJA





*Many of the questions asked on non-looping rollercoasters may be applied to this ride grouping. Specific questions to looping rollercoasters are in this section.*

## Narrative

1. Why do the heights of successive "hills" and loops decrease as the passenger moves from the beginning to the end of the ride?
2. The wheels on these looping rollercoasters employ Urethane® wheels on a metal track anchored to the ground. The train picks up a sizeable electrostatic charge that is periodically discharged. How does the train pick up charge, and how is it discharged?
3. Why is it **not** necessary to carefully monitor the mass of the passengers that board the rollercoaster?
4. Why are the vertical loops on Batman, Ninja, and Boomerang teardrop-shaped? How does this type of loop, known as clothoid loop, differ from a circular loop?
5. In a clothoid loop, what happens to the speed and angular momentum of the rollercoaster car as the radius of the loop shrinks? (Use the laws of conservation of energy and conservation of angular momentum to support your answer.)

## Engineering

6. List at least five safety features that are used in looping rollercoasters. Include both passive and active design components in your list.
7. Most people begin to lose consciousness at about 4 $g$'s of acceleration. If a vertical loop were circular, the minimum entering acceleration would be 6 $g$'s. How does a clothoid loop reduce the acceleration to a safe level?

## Velocity

8. Draw motion maps of the center of mass of the train first going through a vertical loop and then around a horizontal turn.
9. If the ride time were cut in half, how would this change the average velocity of the coaster? How would this change the rider's experience in the vertical loops?
10. Measure the speed of the rollercoaster immediately before the first vertical loop. Measure the accelerations at these points, and use these values to calculate the radius of the curve. Repeat this analysis halfway up the loop and at its peak. Are these radii consistent with a clothoid loop? (See also Question 14.)
11. Use the track layout to label the following (please use the symbols provided):

| | |
|---|---|
| **S** Maximum speed | **K** Maximum kinetic energy |
| ⓢ Minimum speed | ⓚ Minimum kinetic energy |
| **P** Maximum potential energy | **W** Weightless sensation |
| ⓟ Minimum potential energy | **H** Heavy sensation |

## Heights

12. Compare the height of the lift hill to the height of the primary clothoid loop on Batman, Ninja, and Boomerang. Compare and contrast the ratios of their heights.

## Forces and Accelerations

13. Draw and label a force diagram of a train on the lift hill. Calculate the force due to the track, force due to the chain, and the force down the inclined plane of the track due to gravity for a ride up the lift hill.

14. Produce a force diagram for the train in the first vertical loop at the following positions, where $0^{\circ}$ is at the bottom: $0^{\circ}$, $90^{\circ}$, $180^{\circ}$, and $270^{\circ}$. Is the force of the track on the train at $180^{\circ}$ the same magnitude as the force of the track on the train at $0^{\circ}$? Please explain. Calculate the normal force (the upward force of the seat) for a 65-kilogram person at $0^{\circ}$, $90^{\circ}$, $180^{\circ}$, and $270^{\circ}$. (See also Question 10.)

15. Compare the average radius of the first vertical loop of Batman to the average radius of the first vertical loop of the Ninja. Does each vertical loop have the same average radius? Explain any differences. Even though a passenger is riding on the outside of the vertical loop for the Batman ride, does one experience the same sensation on both the Batman and Ninja vertical loops?

## Centripetal Forces and Accelerations

16. It has been said that one can easily lose their shoes during this ride. Where would this most likely to happen? If you lost your shoes at your predicted location, where should a shoe catcher be placed along the ground?

## Friction and Air Resistance

17. Compare the kinetic energy of the rollercoaster as it enters the first clothoid loop to its kinetic energy as it leaves the loop. How much energy was lost due to friction? How does this effect the height of the next hill?

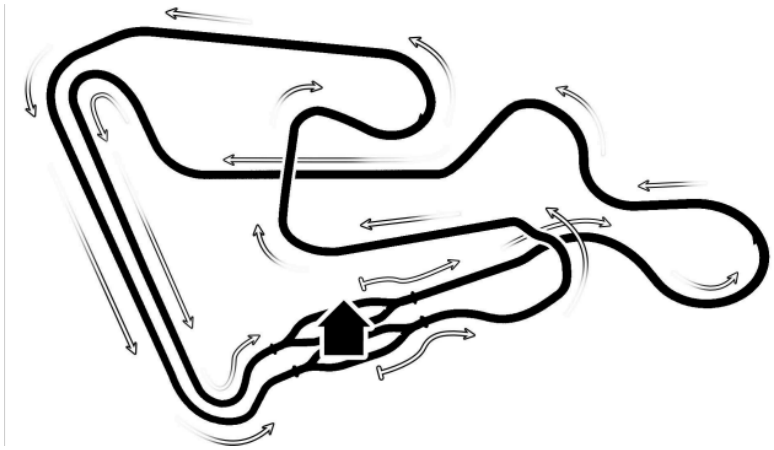
18. Calculate the maximum aerodynamic drag at the bottom of the first hill. Compare it to the drag at the bottom of the first vertical loop.

19. Measure the speed of the rollercoaster immediately before and immediately after the first vertical loop. Estimate the amount of kinetic energy lost due to friction.

## Energy

20. Measure the heights of the lift hills and next three hills of Batman, Ninja, and Boomerang. Compare the percent of decrease of gravitational potential energy at each of these points on the respective rides. Are they similar decreases? Why or why not?

21. Draw an energy flow diagram for the points labeled on Mr. Freeze Reverse Blast. Draw energy bar charts for the points labeled on Mr. Freeze Reverse Blast.

*The mass of the boat is about 227 kilograms and use 65 kilograms for the mass of each person.*

## Narrative

1. Describe the energy transfers that occur to you and your boat between the time leaving the boarding area and the time starting to ascend the inclined plane.

2. Why do passengers lunge ahead when they reach the bottom of big slide?

## Engineering

3. What is the capacity per hour for this ride?

4. At night, the electric pumps that lift the water to the top troughs of the ride are turned off. Where does the water go? Give supporting evidence. Take a picture and annotate it to support the answer.

5. Identify at least 4 safety features on this ride.

## Velocity

6. Compare the velocities of logs on the two lift hills.

7. Measure the maximum velocity of the log on the second drop. How does this compare with the velocity calculated using energy conservation?

8. Does the maximum velocity of the log on the second drop depend on loading (number of passengers)?

9. Draw a motion map of the log 5 seconds before the final drop until 5 seconds after the log reaches the bottom.

## Height

10. Measure the height of the second drop.

## Forces and Accelerations

11. Calculate the acceleration of a boat as it slides down the big slide. Express the answer in $m/s^2$ and "*g*'s."

12. Measure the time it takes the log to stop at the bottom of the last hill. Using the Impulse-Change in Momentum relationship, determine the average force acting on the log.

13. This is one of the few rides in amusement parks in which the average stopping force can be found by using the Impulse-Change in Momentum relationship. Calculate the change in momentum for a passenger during braking. What is the average braking force?

14. Draw a force diagram of the log:
    A. Going up the lift ramp.
    B. As it moves along the level part of the ride.
    C. During the drop.
    D. During the time of splash at the bottom.

## Friction

15. Measure the angle of the last drop. Calculate or measure the log's acceleration and use this to determine the coefficient of friction of the log.

## Energy

16. Determine the minimum amount of work the electric motor must do to lift a loaded boat to the top of the second lift (big ramp). Assume negligible frictional forces are acting. Consider the angle of the lift ramp in your analysis.

17. Determine the minimum power of the lift motor.

18. Determine the net work done on a boat and its passengers for one complete trip around the ride.

# UNIFORM CIRCULAR MOTION RIDES

THE GIANT WHEEL
COLOSSUS

## Narrative

1. Sketch a diagram of Colossus. Label the points of minimum and maximum acceleration and force. Where does the rider feel lightest? Heaviest?

2. Describe the relative motion between you and the wheel when getting on and off the ride. How does this compare to your motion relative to the ground?

## Engineering

3. Determine the hourly capacity of the ride.

4. Estimate the maximum passenger mass for this ride (total number of passengers possible).

## Heights

5. Measure the height of the wheel using triangulation and compare it to the height found with an electronic sensor. Account for any differences and find the percent of difference.

6. Calculate the radius and circumference of this ride.

## Velocity

7. Compute the tangential velocity of Colossus.

8. Determine the rotational velocity of Colossus.

9. Measure the cabin height. At the top of the ride, the cabin lies inside the supporting wheel, closer to the center hub than at the bottom. Calculate the velocity at the top and bottom and find the percent difference.

## Centripetal Forces and Accelerations

10. Draw a motion map showing both velocity and acceleration vectors for this ride.

11. If the bottom is zero degrees, using a spring or electronic accelerometer, *measure* the acceleration every 45 degrees.

12. *Calculate* the net acceleration of the ride at each of the points depicted in Question 11. State the direction of this acceleration.

13. Compare the measurements on a spring accelerometer with that of an electronic accelerometer at top and bottom. Find the percent of difference.

14. Draw force diagrams to scale for a 65-kilogram rider, where $0^o$ is at the bottom, at 0, 90, 180, and 270 degrees.

15. Calculate the net force of a typical rider at the top and bottom of the ride. What is the direction of each of these forces?

16. Compare the normal forces at the bottom and top of the ride. Compare the net force at each of these points. Explain why the normal forces vary, but the net force does not.

17. Measure the cabin height. At the top of the ride, the cabin lies inside the supporting wheel, closer to the center hub than at the bottom. Calculate the centripetal acceleration at the top and bottom and find the percent difference.

18. How fast would Colossus need to rotate to have a centripetal acceleration of 0.2 *g*?

## Friction

19. What role does friction play on the seat at the $90^o$ and $270^o$ positions of the ride? ($0^o$ is at the bottom)

## Energy

20. Calculate the change in gravitational potential energy for a rider at the bottom and top of the ride.

21. On Colossus, the rotational velocity is constant, and therefore the kinetic energy is constant. The gravitational potential energy changes. Where does this energy transfer from and to? Draw energy bar charts showing the flow of energy.

# NON-UNIFORM CIRCULAR MOTION RIDES


- *An electronic vest or phone app to record data for this activity is required.*
- *Record your seat position.*

Many students have some confusion about using the electronic data for vertical loop analysis on driven rides like Fireball, unlike uniform circular motion rides such as a Ferris Wheel. This often arises from the motion of the ride not being uniform speed, and not understanding the frame of reference of the rider. There are a number of non-uniform motion tutorials found online. We recommend a review of such material. What is presented here is, in part, repeated in the Teacher's Manual. The ride Fireball is used as an example.

The operational software for Fireball can be programmed for different experiences, and some installations allow the operator to change ride characteristics. Most times, once parameters are set, they are not changed, and repeatable measurements can be made. Commonly, the experience is similar to the data captured in Figure 24, but may differ. A word description of this motion: For the center of mass (middle car), starting at the bottom of the ride, the passenger goes clockwise (CW) to 8 o'clock, counterclockwise (CCW) to 3 o'clock, CW twice over the top and then dwells at the top, CCW three times over the top stopping at 3 o'clock, CW to 7 o'clock, and then back to the starting position.

From the accelerometer-Altitude sensors, a data table is generated (Figure 26). You may either work with that table within the software used to collect the data, or export the data to a spreadsheet program.

| | Remote Data | | | | |
|---|---|---|---|---|---|
| | Time (s) | Altitude (m) | Y Acc ($m/s^2$) | X Acc ($m/s^2$) | Z Acc ($m/s^2$) |
| 1 | 0.00 | 0.0 | -0.34 | 3.51 | 10.32 |
| 2 | 0.05 | 0.0 | -0.49 | 2.93 | 10.99 |
| 3 | 0.10 | -0.3 | -0.57 | 3.15 | 10.25 |
| 4 | 0.15 | 0.0 | -0.03 | 3.29 | 10.39 |
| 5 | 0.20 | 0.0 | -0.80 | 3.15 | 10.25 |
| 6 | 0.25 | 0.0 | -0.03 | 3.59 | 10.25 |

*Figure 23. The first few rows of data from an electronic sensor program.*

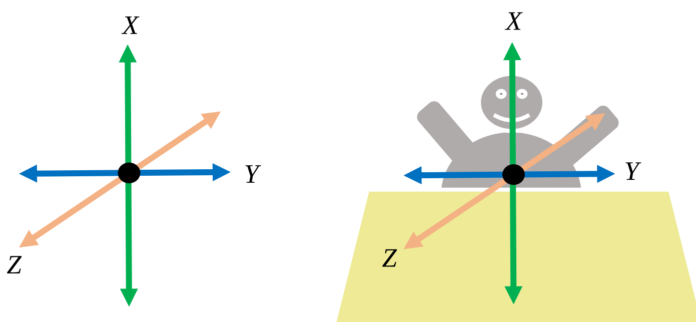



*Figure 24 Since there is no requirement on the orientation the accelerometer wearer affixes the accelerometer sensor, it is important to explicitly state the frame of reference in which the data were collected. For this Fireball example, the frame is shown.*

| | A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | **Remote Data: Fireball - Center of Mass** | | | | | | | |
| 2 | | Δt (s) | 0.05 | | | | | | | | |
| 3 | | Diameter (m) | 25.44 | | | | | | | | |
| 4 | | | | | | | | | | | |
| 5 | Time (s) | Relative Time (s) | Altitude (m) | Relative Altitude (m) averaged over 3 ticks | Theta θ (radians) [down is zero] | Omega ω (radians/s) Averaged over 3 ticks | Y-Axis (Right-Left) Acceleration ($m/s^2$) | X-Axis (Up-Down) Acceleration ($m/s^2$) | Z-Axis (Forward-Back) Acceleration ($m/s^2$) | Centripetal Acceleration ($m/s^2$) | Centripetal Acceleratior ($m/s^2$) Exponentia smoothing |
| 462 | 92.80 | 22.80 | 10.35 | 11.10 | 1.44 | 0.10 | 0.12 | 1.01 | 8.98 | 0.12 | 0.06 |
| 463 | 92.85 | 22.85 | 10.08 | 10.92 | 1.43 | -0.10 | -0.57 | 1.08 | 8.91 | 0.12 | 0.10 |
| 464 | 92.90 | 22.90 | 10.08 | 10.92 | 1.43 | -0.10 | -0.18 | 1.01 | 8.69 | 0.12 | 0.11 |
| 465 | 92.95 | 22.95 | 10.35 | 10.92 | 1.43 | -0.10 | -0.41 | 1.30 | 9.21 | 0.12 | 0.12 |
| 466 | 93.00 | 23.00 | 9.80 | 10.83 | 1.42 | -0.05 | -0.57 | 1.38 | 8.98 | 0.03 | 0.12 |
| 467 | 93.05 | 23.05 | 10.35 | 10.92 | 1.43 | 0.00 | 0.05 | 0.86 | 9.35 | 0.00 | 0.06 |
| 468 | 93.10 | 23.10 | 10.08 | 10.83 | 1.42 | -0.05 | -1.26 | 1.45 | 8.98 | 0.03 | 0.02 |

*Figure 25. Selected rows of data exported into a spreadsheet and expanded for analysis. At the time shown, the position of the train was at about 8 o'clock, making the z-axis pointing nearly up, and x-axis toward the center of the circle.*

The original sensor data (Figure 24) is found in columns A, C, G, H, and I (Figure 26). Cell C2 has the time interval, and Cell C3 has the diameter of the ride. Zero degrees is down. The highlighted data are from the first forward movement, leaving 8 o'clock returning downward.

Column B: Relative time is the elapsed time from starting the ride motion minus the elapsed time from starting the accelerometer.

Column D: We added a scaling factor (in this case, 0.75 m) so that the lowest point is closest to zero meters, and then did *3-point averaging. D466 = ((C466+C465+C464)/3) + 0.75*

Column E: Angle Theta (θ) is calculated in radians by:

$\theta = cos^{-1}(1 - (^{h}/_{r}))$ *= E466 = IF (D466<0,0,ACOS(1-(D466/($C$3/2))))*

Column F: Omega (ω), radians per second, 3-point averaged:

$\omega = {}^{\theta}/_{t}$ *= F466 = ((E466+E465+E464)-(E465+E464+E463))/(3*$C$2)*

Column J: Centripetal Acceleration: $a_{centripetal} = \omega^2 r$ *= J466 = (F466^2)*($C$3*0.5)*

In some sources, there are suggestions for using $a_{net} = \sqrt{a_x^2 + a_y^2 + a_z^2}$ to find the net acceleration. Since the accelerometer is really a force meter, parsing the force due to gravity at different angles is difficult. Without compensating for the force due to gravity, this equation will not give meaningful results.

Since the train moving in a powered vertical circle is not uniform circular motion, the net acceleration differs from the centripetal acceleration. From circular motion, we can find the centripetal acceleration, as described above. This is the acceleration due to the change in direction. The acceleration due to change in speed is the tangential acceleration. (Figure 26) The combination of these gives the net acceleration. Consider carefully how the tangential acceleration may be extracted from the data.

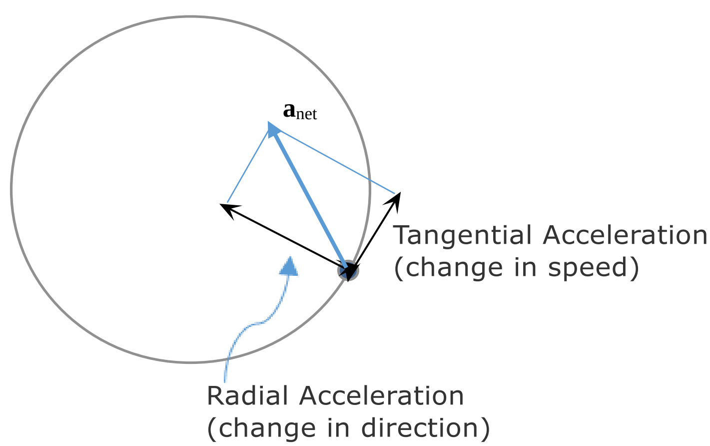



*Figure 26 Vector diagram of the radial and tangential acceleration, and the net acceleration (blue).*

Below is a sampling of graphs from Fireball applying the data from Figure 25. There are many more possible comparisons. All these examples are with data collected at the center row position of the train, left seat. How will the graphs differ if data were collected at the far end of the train, or facing in the reversed direction?

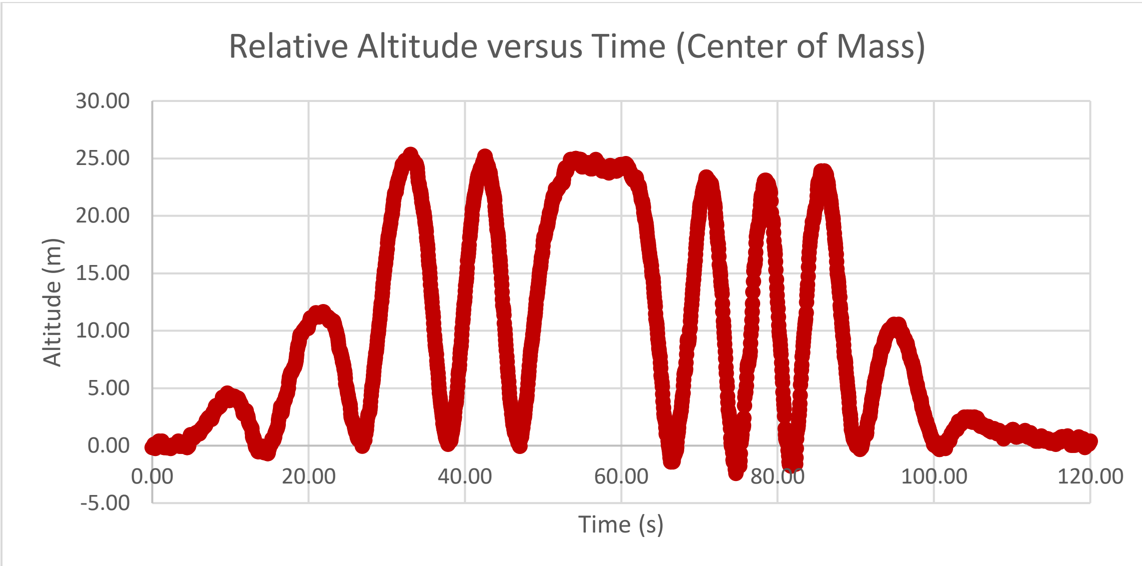



*Figure 27 Some values of altitude are less than zero due to the downward shift of the accelerometer on the wearer and compression of the seat during the ride.*

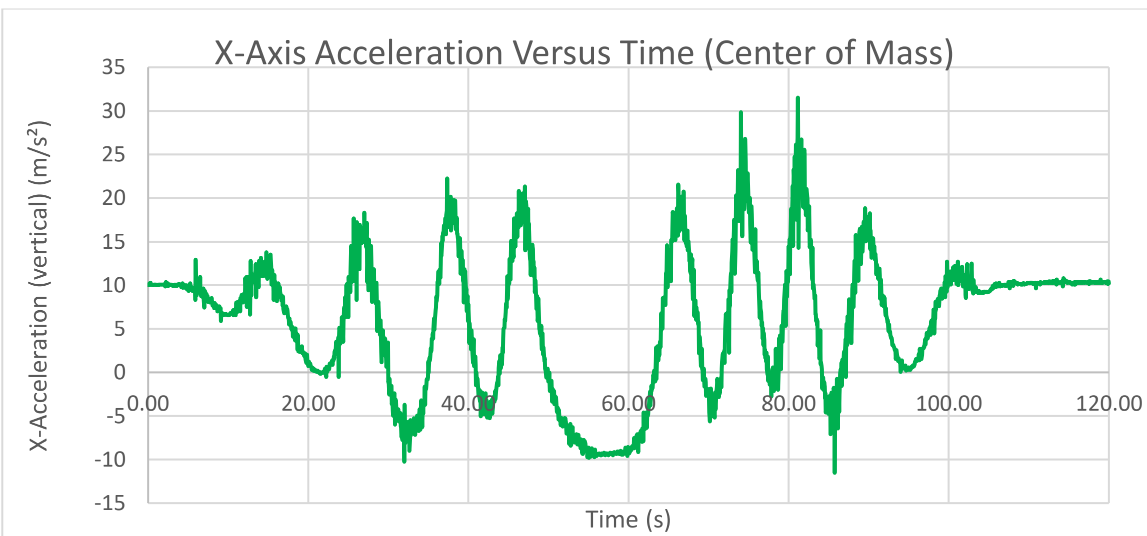



*Figure 28 These data have the background gravitational field intensity included. It is important to understand that these numbers are derived from forces. Read the manufacturer's information on how the data in the vertical direction is collected, processed, and reported. For example, at 270º (9 o'clock), about 22 seconds, the vertical (X) acceleration channel is really directed horizontally, and is zero. Note that the forward z-acceleration (Figure 31) at the same point shows the gravitational field intensity.*

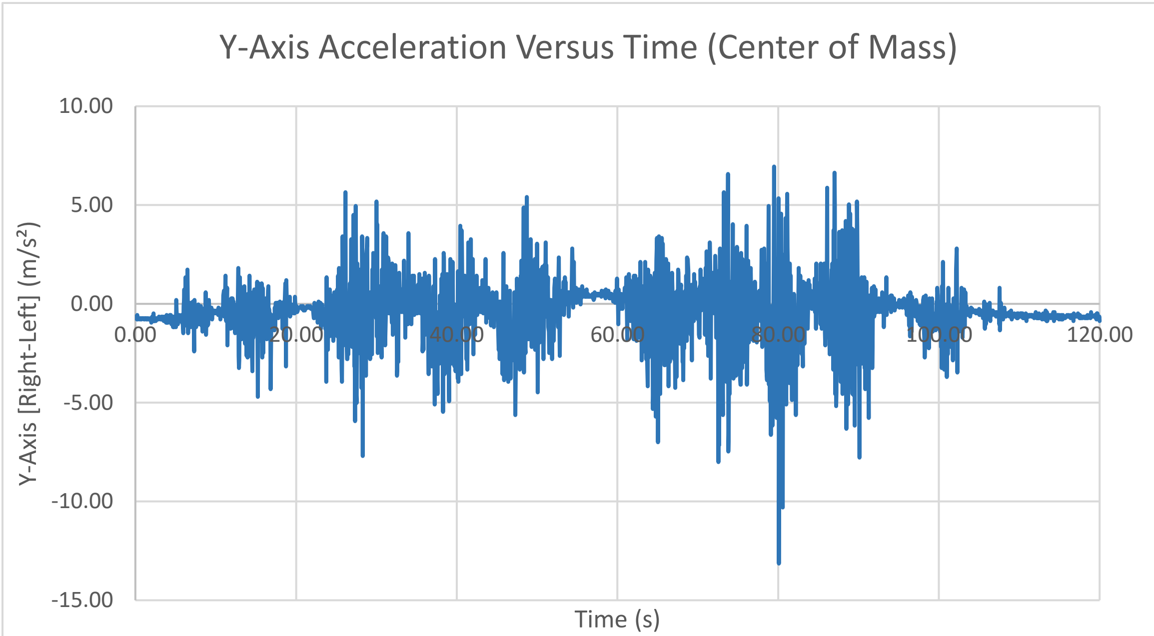



*Figure 29   There is no significant right-left acceleration. The reason for this is small lateral motion of the sensor and passenger during the ride. The starting and ending non-zero values are due to a slight tilt in how the accelerometer was placed and worn in the vest.*

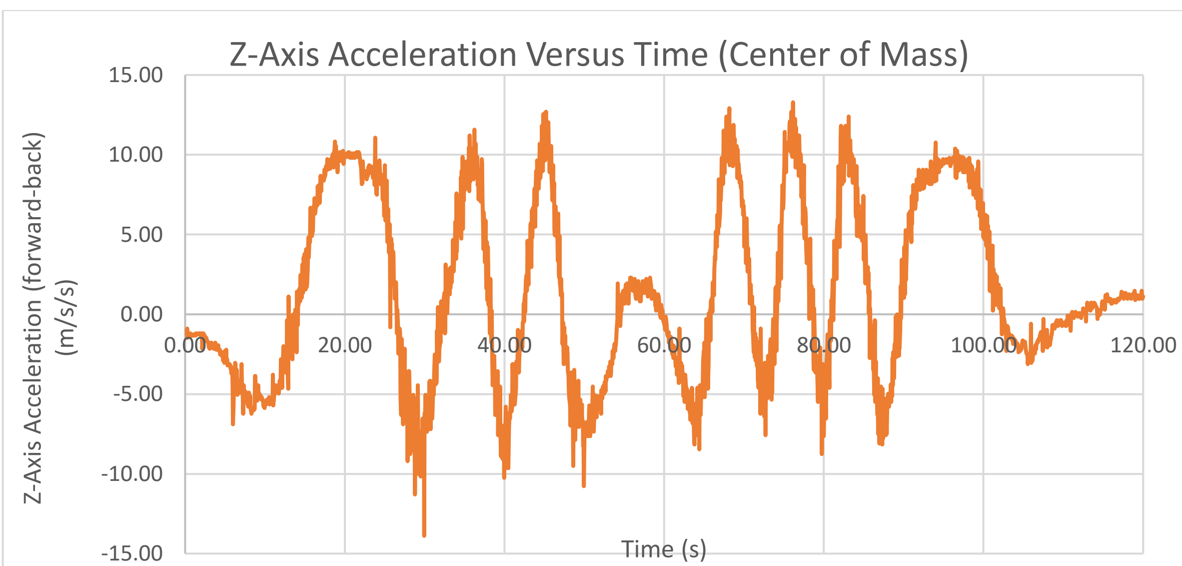



*Figure 30   The forward-back data are not perfectly zeroed since the seat for the passenger is leaning back slightly. Please see the note on the X-axis acceleration and match this with the Relative Altitude and narrative about this ride at the beginning of this section.*

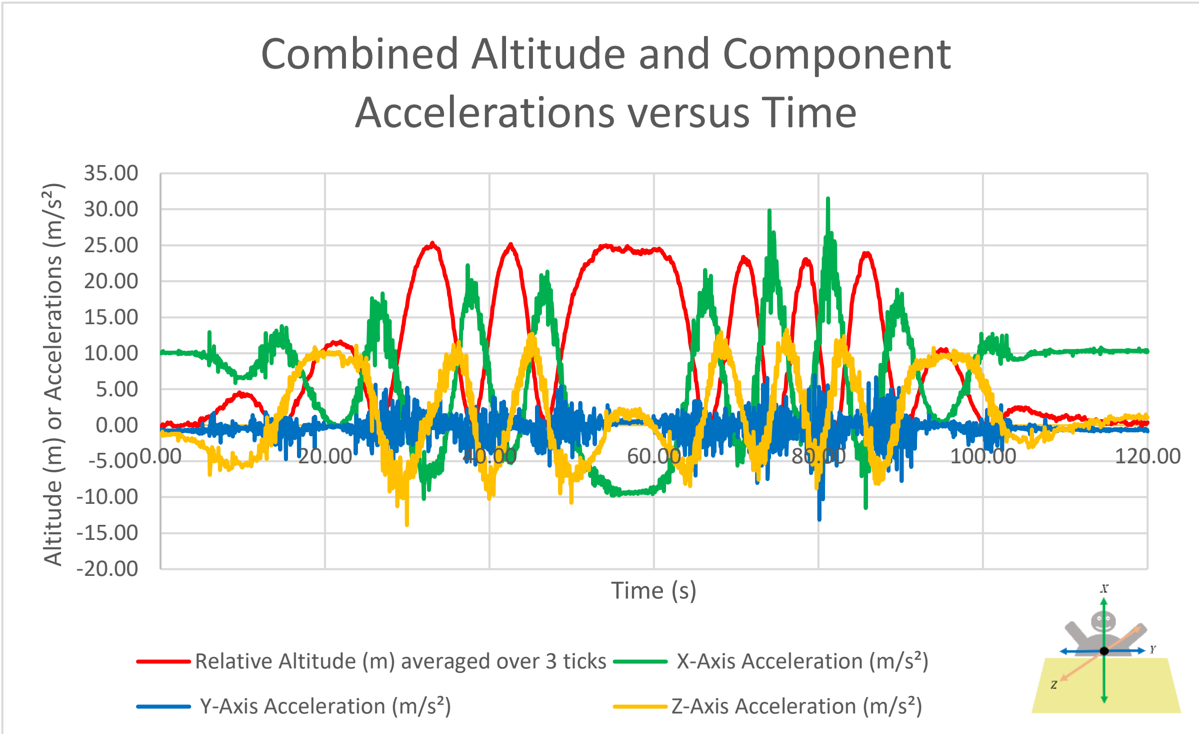



*Figure 31 Although busy, the combined graph can help visualize the motion. Recall that these data are from the passenger's frame of reference.*

Thanks to Tony Valsamis, Bob Froehlich, and Allen Sears for their assistance on this section.

## Narrative

1. The advertising for this ride claims that it is the largest loop coaster. Citing data collected from a looping rollercoaster in the park and Fireball data, support or refute the claim.

2. Since this is circular motion, explain why the centripetal acceleration graph in the direction of the center of the circle versus time varies. Cite specific evidence for your claim.

3. Why is the Y-axis acceleration (left-right) versus time not always zero?

## Engineering

4. What is the capacity per hour for this ride?

## Height

5. Determine the height and radius of the ride using two different methods. Calculate the percent difference between these measures.

## Velocity

6. Knowing the length of the train, measure the velocity of the train as it passes through (not pauses) the top, the sides, and the bottom. Show that your results support the claim that this is non-uniform circular motion?

## Centripetal Forces and Accelerations

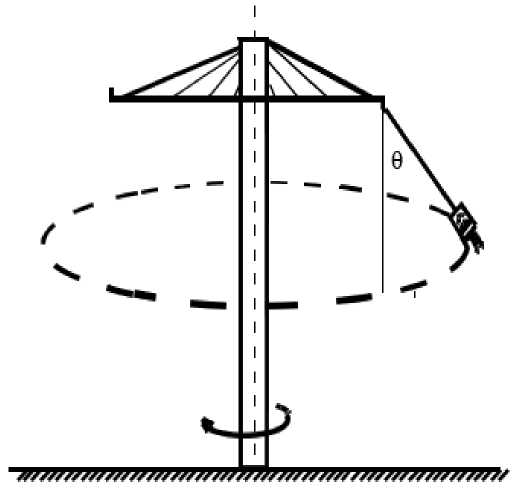
7. The centripetal acceleration indicates the change in direction of the velocity, the tangential acceleration indicates the change in speed. Draw the vector diagram for the centripetal, tangential, and net accelerations (net acceleration is the sum of the other two) at eight equally spaced points around the ride when making a complete revolution. Indicate on the Altitude versus Time graph and on a pictorial representation where or when each of the vector diagrams are located.

8. How will the graphical results differ if the passenger is located at:
   A. one end of the train versus at the center of mass?
   B. facing in the reversed direction?
   C. Sketch supporting graphs for each claim.

9. Since the force due to gravity or some component is part of the accelerometer measurements, explain why it is not correct to claim that:

$$a_{net} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

10. Draw force diagrams when at rest, passing through the top and bottom of the ride. Calculate the normal force of a person passing through the bottom and passing through the top (not at rest) of the ride. What is the percent of difference passing through the top and bottom from when it is at rest?




## Narrative

1. What causes the swings to move out as the ride accelerates? Be sure to include Newton's First and Second Laws in the answer.

2. Can the rate of rotation be great enough that the supporting chain is parallel to the ground? Support the answer using diagrams and words.

3. Consider this thought experiment. DO NOT ACTUALLY DO THIS EXPERIMENT. If you were to drop a shoe during maximum rotation, what path would the shoe take from an observer on the ground? From an observer above the ride? Explain why the shoe would not hit the center tower of the ride.

4. Which way does down appear from the rider's frame of reference when orbiting at the maximum rate? Why would this be?

## Engineering

5. List a minimum of 5 safety devices on this ride. Include the purpose of each.

6. Determine the hourly capacity of the ride.

## Velocity

7. Draw a motion map of a swing revolving at the maximum rate.
8. Measure the radius of the ride at rest and at maximum tangential velocity. What is the ratio of the larger radius to the smaller?
9. What is the rest circumference and the circumference of orbit at maximum tangential velocity?
10. What is the period of rotation?
11. Measure the length of one chain and the angle the chain makes with the vertical when at maximum tangential velocity.
12. At maximum speed, what is the displacement of a swing in 4 complete revolutions? What is the distance the swing traverses during this time?
13. The maximum tangential velocity can be measured using data from the (1) circumference and (2) the accelerometer. Calculate this both ways and find the percent of difference of the answers.
14. Calculate the maximum rotational velocity with the maximum tangential velocity.
15. Draw quantitative graphs of the vertical velocity versus time and height versus time during the ascent, while the ride dwells at the top, and during the descent of the ride.

## Heights

16. Determine the height the swing ascends to. Note that this is *not* the height of the tower.
17. Calculate and compare the velocity of ascent with the velocity of descent.

## Centripetal Forces and Accelerations

18. Draw a force diagram of a swing at rest, and then at the rightmost position when going at maximum rate.
19. Determine the normal force on a rider when the ride is moving at the maximum rotational rate.. How does this compare to the normal force of the rider at rest?
20. Show that the angle of the swing to the vertical is independent of the mass of the rider.

## Friction and Air Resistance

21. How does the air resistance change as the rotational rate increases? Is it linear, quadradic, or some other function? Support your answer.

## Energy

22. What is the change in gravitational potential energy of the rider between getting on the swing and the place of maximum ascent? Where is this energy stored?

# DUAL-AXIS TURNING RIDES

Shazam!

## Narrative

1. Sketch the path of a rider during one full revolution of the log arm of the ride as viewed from a stationary position above Shazam!

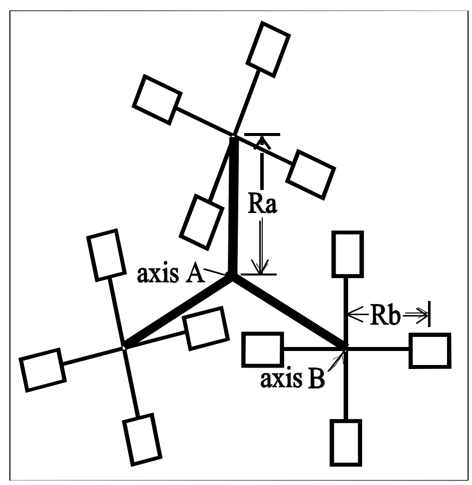



*Figure 32 Line diagram of Shazam!*

2. Where along the path is the speed relative to the ground:
   A. maximum?
   B. minimum?

3. What is the direction of the velocity when the speed is:
   A. at maximum?
   B. at minimum?

4. Where along the path is the acceleration:
   A. maximum?
   B. minimum?

5. If someone were watching from a stationary position above the Shazam!, how would they describe the different forces acting on a rider? What would the direction of these forces be? What is the direction of the net force?

6. What is the position of a passenger along the path when:
   A. There is the greatest force?
   B. There is the least force?
   C. What are the directions of the forces in Parts A and B?
   D. What is the apparent force called?

## Engineering

7. What is the capacity per hour for this ride?

8. In multi-axis rides like this one, the large and small arms may both go clockwise, both counterclockwise, or one clockwise and one counterclockwise. How is Shazam! designed? How would the ride be different if it were the other design?

## Velocity

9. Make the following measurements (refer to Figure 33):
    A. The time (period) and frequency of $T_b$ it takes a rider to make one full rotation about Axis B.
    B. The time (period) and frequency of $T_a$ it takes Axis B to make one full rotation about Axis A.
    C. Radius '$R_a$' and radius '$R_b$'.

10. Calculate the tangential velocity for
    A. the long arm.
    B. the pod of seats.

11. Determine the minimum and maximum tangential velocities for a rider.

12. In Question 9, was the synodic or sidereal period measured? How does the difference of these two periods change the velocity, acceleration, and force computations?

13. Using trigonometry functions, write the equations of motion for this ride. Include position, velocity, and acceleration equations.

14. Is there any retrograde motion of a rider? If so, where?

## Forces and Accelerations

15. Calculate the magnitude of
    A. the acceleration of the long arm.
    B. the acceleration of the pod of seats.
    C. the maximum and minimum accelerations.
    D. Compare the calculated accelerations with values measured using an accelerometer.

16. Knowing the mass of a passenger and maximum and minimum accelerations, calculate the maximum and minimum forces acting a rider during one revolution.

17. For the most comfortable ride with a partner, the passenger with more mass should sit on the outer side of the pod. Please explain this in terms of Newton's Laws.

18. Calculate the minimum coefficient of static friction between the seat and a rider during maximum lateral acceleration.

19. Apply fast Fourier transform analysis (FFT) to the acceleration data to find the primary frequencies of the ride. Are the forward-back and right-left frequencies different?

*Many of the questions asked on SkyScreamer may be applied to this ride. Specific questions to tilting chain flyers are in this section.*

## Narrative

1. Look at two different points on the Supergirl Sky Flyer. Is the tangential speed the same for each point? If the answer is no, under what conditions will the tangential speed be the same for each point? If the answer is yes, what does each point have in common?
2. At full extension, explain how this is not an example of uniform circular motion.

## Engineering

3. List a minimum of 5 safety devices on this ride, and what is the purpose of each.
4. Determine the hourly capacity of the ride.

## Velocity

5. Measure the period of rotation. Calculate the frequency.
6. How much does the radius of a rider change from the axis of rotation at different points of the orbit? (This is subtle. The angle the seat hangs from the plane of the rotating structure is different at various points of the orbit.)
7. Calculate the average tangential velocity of a passenger. How much does this vary from the minimum and maximum tangential velocity? With Question 6.

## Heights

8. Measure the change in height between the lowest and highest positions of a rider.

## Forces and Accelerations

9. Draw a force diagram for a guest on Supergirl Sky Flyer at the following positions, where $0^o$ is at the bottom: 0, 90, 180, and 270 degrees. During the time of tilt.

## Centripetal Forces and Accelerations

10. Using a force meter, determine the range of normal forces for a passenger on this ride. At what point is the force greatest? Least? Please explain.

11. Under what conditions would the normal force (force due to the seat) become zero for the $180^o$ (top) vertical position? Calculate the speed of the car necessary to cause the force due to the seat to be zero.

12. While the Supergirl Sky Flyer is moving in a horizontal circle, derive a relationship between angle each seat cabins out from the vertical and the linear speed.

## Energy

13. The motor for Supergirl Sky Flyer 44.4 kilowatts. Knowing the time of ride and the number of cycles per hour, estimate the electric cost at 7.51 cents per kilowatt-hour.

# PENDULUM RIDES

## The Buccaneer


### Narrative

1. Does the position of your seat affect the way you feel on this ride? Please explain.
2. Describe the sensation of weight:
    A. at rest
    B. moving through the lowest point
    C. at the highest point
    D. halfway up, going up
    E. halfway up, going down
3. Do you feel the same as the ride swings forward as when it swings backward?
4. To feel the lightest, should you sit closer to or farther from the center of the boat?
5. Is The Buccaneer a free swing or a driven pendulum? Support your claim.
6. Does the number of people on the ride alter the tangential velocity of the ride operation?
7. When you are the highest above the ground
    A. Are you traveling slowest or fastest?
    B. Are you lightest or heaviest?
    C. Compare the answers to parts A and B with the experience on a swing in a local playground.
8. Explain why conservation of gravitational potential energy and kinetic energy (strictly) does not apply to this ride. Where else is energy coming from or going to?

### Engineering

9. List a minimum of 4 safety devices on this ride. Include the purpose of each.
10. Determine the hourly capacity of the ride.
11. What design considerations must there be for the driving tires of the boat?
12. Carefully observe the driving tires. Note that they are not rotating at a constant rate. What is the reason for this design? How is the electronic sensor in the hub telling the motor direction and rate of rotation?

## Velocity

13. Determine the period and frequency using one ride cycle:

    A. For small oscillations
    B. For large oscillations
    C. Is the period significantly affected by the amplitude (size) of the oscillations? If so, find the percent difference.

14. Determine the tangential velocity when the boat is:

    A. at rest
    B. moving through the lowest point with small and large oscillations
    C. at the highest point with small and large oscillations
    D. halfway, going up with small and large oscillations
    E. halfway, going down with small and large oscillations

## Heights

15. Measure the radius of the swing of the ride.

16. Determine the minimum and maximum height a center seat reaches.

17. Determine the minimum and maximum height an end seat reaches.

## Forces and Accelerations

18. Record the vertical accelerometer readings when the boat is:

    A. at rest.
    B. moving through the lowest point.
    C. at the highest point.
    D. halfway up, going up.
    E. halfway up, going down.

19. Where did the maximum acceleration occur? Is this point the same for every seat?

20. Draw and label a force diagram of all of the different forces acting on a passenger during the ride.

21. Calculate the centripetal acceleration when:

    A. at rest
    B. moving through the lowest point
    C. at the highest point
    D. halfway up, going up
    E. halfway up, going down

## Energy

22. Using the information from Question 13 and Question 14, calculate the change in gravitational potential energy for each of the two rider positions.

23. How do the points of greatest gravitational potential energy compare to the following?
    A. Points of lowest accelerometer readings
    B. Points of maximum accelerometer readings
    C. Points of minimum velocity
    D. Points of maximum velocity

24. How do the points of greatest kinetic energy compare to the following?
    A. Points of lowest accelerometer readings
    B. Points of maximum accelerometer readings
    C. Points of minimum velocity
    D. Points of maximum velocity

# AMUSEMENT PARK PHYSICS MIND BOGGLERS

1. List the rides that undergo uniform circular motion.

2. List the rides that undergo vertical circular motion, whether or not it is uniform circular motion.

3. Why can't the formula $a = 4\pi^2 r / T^2$ be used for non-uniform vertical circular motion?

4. Please list any velocity-dependent forces. Is gravity a velocity-dependent force? Please support your answer.

5. Why do amusement park operators first run the rides empty?

6. Define a conservative force. Is the force of gravity a conservative force? Is the force of friction a conservative force?

7. In your opinion, should amusement park rides be designed for speed or acceleration?

8. Fill out the following chart. Please indicate whether the listed quantity is a vector (V) or scaler (S). Also, give the correct SI unit for the listed quantity. Please draw the correct symbol for each quantity.

| QUANTITY | TYPE | UNIT | SYMBOL |
|---|---|---|---|
| Work | | | |
| Power | | | |
| Acceleration | | | |
| Force of Friction | | | |
| Potential Energy | | | |
| Kinetic Energy | | | |
| Speed | | | |
| Mass | | | |
| Height | | | |
| Time | | | |
| Angular Velocity | | | |
| Total Mechanical Energy | | | |
| Revolutions | | | |
| Angle Theta | | | |

9. Why is a simple pendulum like a rollercoaster ride?

10. Please design your own rollercoaster. Label regions of maximum and minimum kinetic energy. Also, label regions of maximum and minimum gravitational potential energy.

11. Define in your own words kinetic and gravitational potential energy. Can an object have gravitational potential energy but not kinetic energy? Give an example at Six Flags St. Louis. Can an object have kinetic energy but not gravitational potential energy? Give an example at Six Flags St. Louis. Can an object have zero gravitational potential energy and zero kinetic energy? Give an example at Six Flags St. Louis today.

12. Can a rollercoaster have an eastward velocity and a westward acceleration? Can rollercoaster have an eastward velocity and a downward acceleration? Give an example of each.

13. What rides at Six Flags St. Louis start with nearly all gravitational potential energy and very little kinetic energy? What rides at Six Flags St. Louis start with kinetic energy and very little gravitational potential energy?

14. Give an example of a ride at Six Flags St. Louis where the speed is constant, but the acceleration is not zero.

15. Do your sense organs feel velocity or acceleration? Is the human body an accelerometer? Please explain. Include an example of when and how your body “feels” this type of motion.

16. Cite four situations at Six Flags St. Louis in which all of Newton's three laws are illustrated.

17. Where is the center of mass of Six Flags St. Louis?

18. Cite a situation at Six Flags St. Louis in which the following cases are true: The angle between a velocity vector and the acceleration vector is (1) 180 degrees; (2) between 180 and 90 degrees; (3) 90 degrees; and (4) zero degrees.

19. Does the phrase, 3 "*g*'s," refer to a force or to an acceleration? Please Explain.

# SIX FLAGS ST. LOUIS PHYSICS SCAVENGER HUNT

Find an example of each of the following quantities, entities, or concepts in the park?

| QUANTITIES, ENTITIES, CONCEPTS | EXAMPLE |
|---|---|
| Constant Speed | |
| Constant Velocity | |
| Acceleration | |
| Circular Motion | |
| Centripetal Force | |
| Centripetal Acceleration | |
| Inertia | |
| Net Force | |
| Equilibrium | |
| Frictional Force | |
| Fictitious Force | |
| Inertia Frame of Reference | |
| Non-inertial Frame of Reference | |
| Action-Reaction forces | |
| Newton's First Law | |
| Kinetic Energy | |
| Potential Energy | |
| Work | |
| Conservative Force | |
| Non-Conservative Force | |
| Sensation of Weightlessness | |
| Doppler Effect | |
| Plane Mirror | |
| Concave Mirror | |
| Convex Mirror | |
| Refraction | |
| Standing Wave | |
| Polarization | |
| Strobe Light | |
| Free Fall | |