ST. LOUIS

PHYSICS DAY

TEACHER MANUAL

Six Flags St. Louis

4900 Six Flags Road

Eureka, Missouri 63025

(636) 938-5300

https://www.sixflags.com/stlouis

Compiled by Nathan A. Unterman

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

Six Flags ST. LOUIS

Why Take a Field Trip to an Amusement Park?

If physics teachers could design the ultimate teaching laboratory, what would it be like? The laboratory would certainly contain devices for illustrating Newton's Laws of motion, energy transfers, momentum conservation, and the dynamics of rotation. It would consist of large-scale apparatus so the phenomena could be easily observed and analyzed. Oh, and of course, the dream laboratory would allow the students an opportunity not only to witness the laws of physics in operation, but also *feel* them!

Well, this dream laboratory does exist and is as close as Six Flags St. Louis! At Six Flags St. Louis, virtually all the topics included in the study of mechanics can be observed operating on a grand scale. Furthermore, phenomena, such as weightlessness, which can only be talked about in the classroom, may be experienced by anyone with sufficient courage.

Students must quantify what they see and feel when doing amusement park physics. Unlike textbook problems, no data is given. Therefore, students must start from scratch. Heights of rides, periods of rotation, and lengths of roller coaster trains must be obtained before substituting data into equations learned in the classroom. Fortunately, only simple equipment is required to obtain data that will allow the calculation of such diverse quantities as a person's potential energy at the top of The Boss . . . the centripetal acceleration of Shazam! . . . or the speed of a passenger on Batman. Diagrammatic representations are more meaningful when you feel the forces in a system.

The Next Generation Science Standards (NGSS) has shifted the emphasis of science education from only pure sciences to pure and applied sciences. This poses new challenges for incorporating appropriate learning tasks in outdoor education, and specifically, physics of the amusement park. We present both old and new standards in this manual during this transition period in science education.

Over the years, many schools have become involved with amusement park physics. In the past (pre-pandemic), "Physics Days" at Six Flags St. Louis attracted thousands of physics students from several states. These students would agree that Six Flags St. Louis provides the ultimate vehicles for learning physics!

Learning Goals and Objectives[1]

Cognitive Goals

Upon the completion of the activities, the student will have an enhanced understanding of the following laws and concepts of physics on the macroscopic scale:

- Kinematics
- Force
- Newton's Laws of Motion
- Friction
- Momentum
- Circular motion
- Rotational motion
- Work
- Power
- Conservation of Laws of Energy and Momentum

The student will:

1. Apply the method of triangulation to determine heights of and distances to various structures.

2. Apply Newton's Laws of Motion to explain the effect of forces on passengers on various rides.

3. Apply the principles of conservation of energy and kinematics to determine the velocity and acceleration of an object after falling through a given vertical distance in a gravitational field.

4. Measure the linear displacement of a chair on the swings as it moves through a complete revolution.

5. Calculate the work done by friction on roller coasters.

6. Estimate the power required to haul a roller coaster and its contents up the high rise.

7. Determine the forces acting on a passenger in circular motion rides.

8. Use an accelerometer to measure centripetal acceleration.

9. Calculate the momentum of objects and qualitatively determine conservation of momentum (particularly on bumper cars).

10. Measure and record their personal physiological responses to their experiences during amusement park activities.

---

[1] AAAS Project 2061, http://www.project2061.org/publications/bsl/online or *Benchmarks for Science Literacy*, ISBN-13: 9780195089868.

Attitude Goal

Through completion of the activities, the student will develop a positive attitude toward the physical sciences and engineering by being challenged with a meaningful task that allows them to accurately predict personal experience.

Appreciation Goals

Through completion of the activities, the student will bridge the gap between schoolwork and life education by seeing them as not isolated from one another.

The student will gain an appreciation of:

1. The safety measures of equipment and design built into the rides and controls.
2. The applicability of physical principles studied in the classroom to large scale phenomena.
3. The value of working in teams to accomplish measuring and analysis tasks.
4. The physics involved in the design and engineering of the rides.

Curricular Design Considerations Using NGSS[2]

Primary Cultural Tenets in Science

Safety.

Science is practiced by a community that engages in collaboration and peer review.

Science is an ever-changing process in which questions are answered by interpreting repeated measurements in a systematic investigation.

The scientific community extends to resources and contacts in the digital realm.

Science is the search for the fundamental properties of nature; engineering is the application of these properties to structure, processing, and performance.

Research and applications of knowledge have ethical implications.

Technology Skills

The student will use:

Computational devices such as calculators and computers.

Spreadsheets to manipulate data and graph relationships.

Appropriate data acquisition equipment for collection and analysis of measurements.

Internet search engines to locate valid course information.

Locate, interact with, and participate with course information utilizing various Internet-Based applications.

Technology for observation and measurement to increase the range and types of questions that can be investigated.

[2] http://www.nextgenscience.org/next-generation-science-standards

Thinking Skills[3]

Critical thinking and skepticism – puzzling away at something and taking account of all possible objections to find an explanation that works.

Deep understanding – looking for deeper and deeper explanations, not being satisfied with a superficial description, looking for the most fundamental answer that has predictive power across many domains.

Seeking consistency – testing that answers are consistent with experience and all other areas of the discipline.

Using experiments to test ideas – refining models through the iterative sequence of:
experiment → model → prediction → test.

Models – developing representations to create models (often mathematical) of systems to make predictions of their behavior in a variety of circumstances.

Correspondence Principle – If a new model is valid, it must account for the verified results of the old model in the region where both models apply.

Reason and logic – striving for logical consistency within arguments.

Quantitative understanding – realizing that quantitative analysis is necessary for proper understanding.

Simplification – simplifying physical situations (components or aspects) to their core elements to enable the use of quantitative models to explain or predict phenomena.

Isolating – isolating physical phenomena to test ideas experimentally.

Approximation and other techniques – making back-of-the-envelope calculations to test the plausibility of ideas, using techniques that consider limiting or extreme cases.

Excising prejudice – being able to step outside immediate experience and accept explanations.

Correlation does not require causation.

Risk Assessment – to make a decision about a particular risk, we need to consider both its risks and benefits, to all constituencies involved.

---

[3] Adapted from: *Science Community Representing Education (SCORE)*, Guidelines for the Content of Key Stage 4 Qualifications, 17. June.2013.
Hunt, Andrew, *Ideas and Evidence in Science: Lessons from Assessment*, SCORE, 2010.

Primary Tenets in Science[4]

Reductionism – Science describes natural phenomena in terms of a small number of laws, which allow predictions to be made on whether and how things will happen.

Universality – The laws of science are universal – they work everywhere.

Unification –There is a drive to reduce the number of laws to as small a number as possible, each one expressed in as economical a way as possible.

Synoptic nature – Physics is an interlinked totality of ideas that must be consistent with each other. Problems can be approached from many different directions.

Cause and effect – Events can be discussed and understood in terms of causes and effects: what makes things happen the way they do.

Mathematical techniques – Physical laws can be expressed in a mathematical form. Scientists develop mathematical representations to describe and predict behavior.

Conservation – Some quantities (charge, mass-energy, matter, and momentum) are conserved. These conservation laws lead to powerful restrictions on behavior.

Equilibrium – Equilibrium occurs when two or more external influences are in balance – balanced forces, balanced moments, balanced pressures, and equal flows in and out.

Differences cause change – For example, temperature difference, pressure difference, potential difference, differences in concentration and unbalanced forces.

Inertia – Things will tend to stay as they are unless something causes them to change.

Dissipation – Many processes have an element that is resistive and dissipative. Dissipation is a result of the tendency of a system to become more disordered.

Irreversibility – Dissipative processes are irreversible. For example, they limit the usefulness and the lifetime of a resource and determine the arrow of time.

Fields – Action at a distance is explained using the construct of fields.

Energy – There is a useful accounting tool – energy – that allows us to do calculations to find out, for example, how long sources will last, or whether some events can happen.

Multiple Representations of Models – Scientific models have multiple representations, including graphs, diagrams, equations, various charts (histograms, pie, etc.), and narrative descriptions.

[4] Main, Peter, *Thinking Like a Physicist: Design Criteria for a Physics Curriculum*, School Science Review, Number 352, pp 46-52, March 2014.

Amusement Park Physics and NGSS[5] Standards

The traditional outdoor education activities involved in a trip to the amusement park have centered on making measurements, reporting results, and making some interpretations. Those activities remain part of the educational materials provided by Six Flags. As an extension, new pedagogical resources are included to address the new science education standards. The NGSS has three dimensions: disciplinary core ideas (content), science and engineering practices, and cross cutting concepts, integrating content with application. This is more reflective of how science and engineering are currently practiced.

The specific Performance Expectations being addressed are:

- HS-PS3-1 Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.
- HS-PS3-2 Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motion of particles (objects) and energy associated with the relative positions of particles.
- HS-ETS1-2 Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.
- HS-ESTS 1-3 When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts.

Two NGSS-aligned activities are presented here. These activities can be scaled up or down to meet the appropriate capability of your students. For an advanced group, mathematical representations with error analysis coupled with a design proposal might be required. For a novice group, basic measurement and a possible solution to the ill-structured problem may be more appropriate.

[5] Next Generation Science Standards, Volume 1: The Standards – Arranged by Disciplinary Core Ideas and by Topics; The National Academies Press, Washington, D.C., ©2013. ISBN-13: 978030927227-8

Ride Groupings

NOTE: The rides that are data collection-friendly are footnoted.

- Roller Coasters
    - Non-inverting[6]
    - Inverting[7]
    - Shuttle[8]
    - Water[9]

- Spinning Rides
    - Single axis[10]
    - Dual axis[11]
    - Complex multiple axes[12]

- Pendulum Rides
    - Single axis[13]
    - Dual axis[14]

---

[6] American Thunder, River King Mine Train, Screamin' Eagle, and The Boss
[7] Batman The Ride, Boomerang, and Ninja the Black Belt of Rollercoasters
[8] Mr. Freeze: Reverse Blast
[9] Log Flume
[10] Colossus, Grand Ole' Carousel, (uniform circular motion); Fire Ball, and SkyScreamer (non-uniform circular motion)
[11] Shazam!, Supergirl Sky Flyer
[12] XCalibur
[13] The Joker Inc.
[14] Spinsanity

I. Amusement Park Ride Design Activities

This activity (I) is an open-ended activity. For a more convergent activity, please see (II) *Site-Visit Prediction and Measurement of Amusement Park Rides (*page 14). The general idea of this activity is to select a grouping of ride (you may need to restrict it to a subset of the grouping) and ask the students to design a ride that would fit into the given grouping. This new ride may fill a range of forces or accelerations that are not currently represented at the park. This may be between the current ranges of forces and accelerations, or outside the existing ride design. For novice students, making measurements, comparisons, and a reasoned proposal for a new ride is appropriate. For a more advanced class, the proposal should embrace a design comprising appropriate heights, radii, etc., and a justification for the new ride. A partial exemplar of the problem statement follows.

Amusement Park Ride Design Task (Novice students)

Six Flags St. Louis has decided to build a new circular ride near the SkyScreamer area of the park. Determine the placement, kind of ride, age appeal (young, teenage, adult, etc.), theme, capacity, and other considerations important for this ride. The ride may be a duplicate of another in the park, if there are long lines at those rides, or it may be a new ride for the park. Compare the forces and accelerations of existing rides in the same grouping of ride to support the specifications for your proposed ride. Be sure to show multiple representations of your work. These might include pictures, diagrams, graphs, narrative and other portrayals of your work.

Amusement Park Ride Design Challenge (Advanced students)

Six Flags St. Louis has decided to build a new circular ride near the SkyScreamer area of the park. Determine the placement, footprint, cost, category of ride, stress levels, age appeal (young, teenage, adult, etc.), theme, capacity, energy transfers, and other considerations deemed important for this ride. 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 a new ride for the park. 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.

Design Challenge Guidelines

Guidelines for this activity might include the following:

- Predictions, hypotheses, and testable crazy ideas for this design task.
- Pre-trip data tables to be completed at the park.
- Equations or other information that might be needed.
- Needed equipment (stop watches, string, calculators, protractors, cameras, accelerometers, etc.).
- Specific responsibilities for each member.
- Criteria for new ride.
- Final report requirements (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, physiological and psychological considerations, safety requirements, . . .).

This is a suggested beginning. Add or change these ideas to match the characteristics of your class. The *Student Manual* question bank may be a useful resource for students.

Here is an example of how a group might analyze turning rides.

This group compares measured accelerations in a column graph.

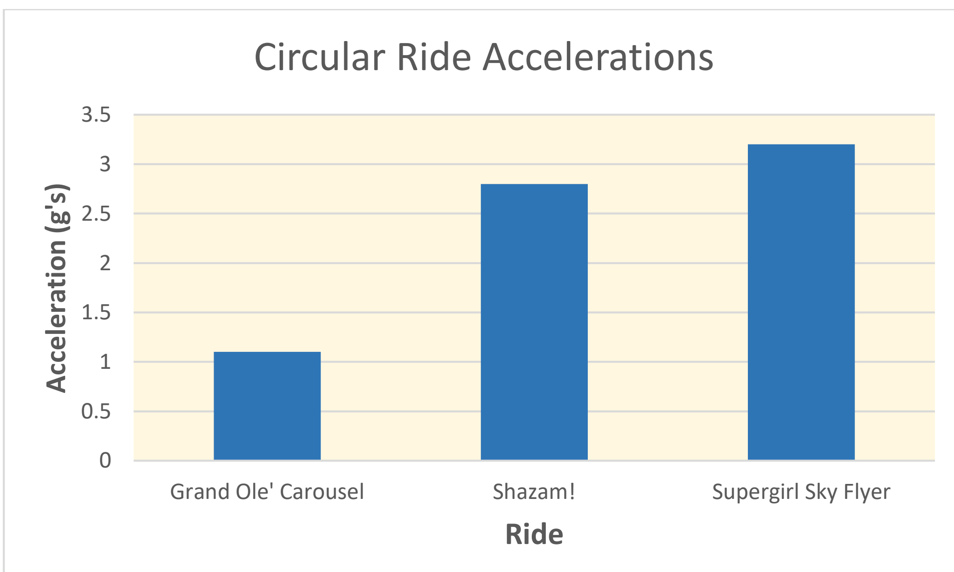


Figure 1 Comparisons of centripetal accelerations for selected rides.

Two comments about these findings: One is that the students did not remain within a single class of rides (single versus dual axis turning rides). This *may* be within the realm of the assignment, depending on your curriculum-based specifications. Two, the graph indicates that there is a gap in accelerations between 1.1 g’s and 2.8 g’s. This would be a prime region for the students to propose a new ride. Similar analysis can be done for other classes or groupings of rides.

Diagrammatic representations for these rides would include force diagrams. Samples are shown here.

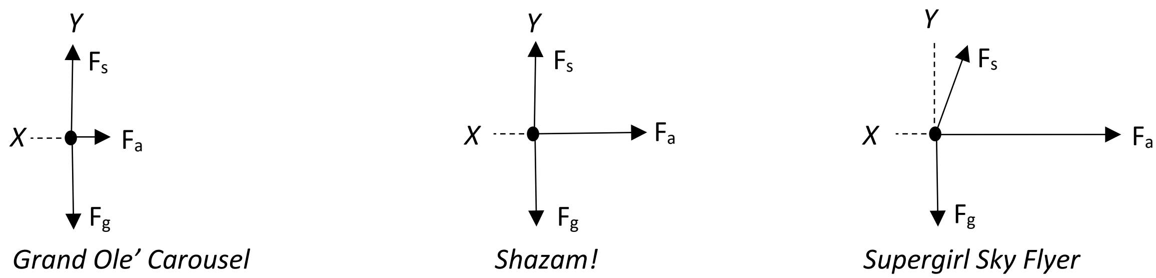


Figure 2 Force diagrams for selected circular motion rides.

Acceleration measurements and force calculations need to be indicated. Finally, a narrative of what was measured, what it means, and a reasoned proposal for the new ride would follow. The ultimate product, be it a presentation, poster, paper, or some other submission should be stipulated at the outset. The degree of difficulty of this activity can be scaled to the needs of the group. Multiple correct solutions for this problem are valued.

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.

II. Site-Visit Predictions and Measurements of Amusement Park Rides

Teacher Notes

This activity is more convergent than the *I. Amusement Park Ride Design* activities (page 9). In this activity, students are asked to make hypotheses and predictions of various aspects of the science and engineering of a selected ride. A variety of ride groupings can be selected or assigned across the class. Categories include, but are not limited to:

- height
- radius
- velocity
- acceleration
- force
- energy
- momentum
- electrical needs
- engineering, capacity, and queue length.
- physiology

Hypotheses and predictions are made pre-trip, measurements are executed during the trip, and analysis to support or refute the hypotheses and predictions are completed post-trip. The final product might be a class presentation, paper, or poster. Typically, three to five categories would be selected. There can be interactions among the categories, such as velocity and momentum, or acceleration and net force.

The degree of difficulty can be tailored to the ability level of the students. Simple predictions comparing the heights of the first and second hills of two roller coasters can be made. (Lift hill heights are generally available on the Internet, but the second and later hill heights are less commonly found.) A more robust set of predictions might be predicting the energy losses of a roller coaster due to friction at the bottom of the initial drop, the top of the second hill, and at the second valley. If students express anxiety about their predictions being correct, stress that they are making an educated guess. The analysis from their data will support or refute the guesses. Stress that scientists and engineers do not know the outcomes of their experiments in advance.

The pre-trip activity requires the students to plan and structure their trip experience. Not only do they need to make one or two hypotheses/predictions per grouping, but also plan the method of measurement, equipment needs, specific equations, data tables, and number of trials. You may require two different ways of making the measurements: electronic accelerometers and hand-held mechanical accelerometers. This student-produced document should be evaluated and returned to the students before the trip. Major omissions, inconsistencies, misconceptions, and other issues can be caught before the trip to make the excursion to the park more meaningful and productive.

The required student product might include a computer presentation of their findings, a paper submission, a poster, a video presentation, or a combination of these. The elements of the final product should be determined at the beginning of the unit.

Site-Visit Predictions and Measurements of Amusement Park Rides

Please complete the Pre-Lab assignment according to the directions below. This must be turned in for approval **before** *you go to the amusement park and attached to your final laboratory report.*

1. Complete the cover sheet information (page 16). Your teacher may assign categories and give other requirements.

2. Select a category and make one well-reasoned prediction. The prediction should be **numeric** and something that will be measured or calculated from measurements made at the park. Predicting that the roller coaster is going the fastest at the bottom of the first hill or that the outer horse on the merry-go-round will be the fastest, are not good predictions since they are not quantitative. A good prediction might be that the roller coaster will be traveling 20 m/s at the bottom of the first hill and 18 m/s at the bottom of the second hill. Please note that these are predictions. Your predictions should be thoughtful, but do not need to match the final measured values.

3. How will you collect data? Will you use mechanical or electronic equipment, or both? Will you need a timing device? How will lengths or radii be measured? Is a protractor needed? Please be specific.

4. List the equations necessary for validating your predictions. Identify all variables. Determine which variables need to be directly measured and which will be calculated based on your measurements. These measurements must be quantities measured at the park. Simply listing concepts is not acceptable.

5. Create data tables for the measured and calculated quantities needed in your investigation. Be sure to leave space for multiple trials. If you are relying on electronic data acquisition, indicate which graphs you will need for your data analysis. Leave room for sketches and diagrams.

6. Refer to the grading rubric to make sure you have met all requirements.

7. Repeat for each category.

Site-Visit Predictions and Measurements of Amusement Park Rides
Pre-Site Visit Plan

COVER SHEET

NAMES OF GROUP MEMBERS:

___________________________________ ___________________________________

___________________________________ ___________________________________

CLASS BLOCK/MODULE/PERIOD: _______________

RIDE GROUPING: ____

RIDE NAME: ____

CATEGORIES OF INVESTIGATION (select all that apply)

- ◻ Height, Radii
- ◻ Velocity
- ◻ Acceleration
- ◻ Force
- ◻ Energy
- ◻ Momentum
- ◻ Engineering
- ◻ Electrical needs
- ◻ Vector analysis
- ◻ Physiology
- ◻ Other (specify) _______________________________________

CATEGORY of INVESTIGATION: ________________________________

PREDICTION(S):

METHOD(S) FOR DATA COLLECTION:

NECESSARY EQUATIONS AND LIST OF VARIABLES:

DATA TABLES:

NAMES: ____ RIDE: __________________

AMUSEMENT PARK REPORT RUBRIC

The data analysis for each prediction should conform to the following format in your class presentation. Each category should include the following:

1. State your prediction.
2. For each method, present the data used to analyze this prediction and how the data were obtained.
3. Show the data analysis. Please include the calculations, units, graphs, diagrams, motion maps, and charts associated with the prediction. Include error analysis and a statement of the confidence your group has for the results.
4. Conclude by supporting or refuting the prediction and providing a valid justification.

Your approved Pre-Lab documents, completed data tables, and other documents required by your teacher must be turned in at the time of your presentation.

CATEGORY:				
Prediction				
Data				
Proper data tables				
Units present and correct				
Multiple trials				
Accuracy				
Explanation of how data were obtained				
Analysis				
Calculations clearly completed				
Graphs				
Diagrams (Force, motion maps, energy charts, etc.)				
Error Analysis				
Confidence based on multiple trials or methods used				
Conclusion				
Supports or refutes hypothesis				
Valid justification				
TOTAL				
			GRAND TOTAL	

AMUSEMENT PARK REPORT RUBRIC (continued)

PART OF PROJECT	SCORE
Pre-Lab	
Class presentation	
Written report	
Other	
Total	

EXEMPLAR:

Site-Visit Predictions and Measurements of Amusement Park Rides

Pre-Site Visit Plan

COVER SHEET

NAMES OF GROUP MEMBERS:

___Maggie___________________________ ________Justin_____________________

____Ines___________________________ ________Cedrick__________________

CLASS BLOCK/MODULE/PERIOD: ____A45_______

RIDE GROUPING: ____single axis spinning ride_____________________

RIDE NAME: _______Grand Ole' Carousel___________________________

CATEGORIES OF INVESTIGATION (select all that apply)

- □ Height, Radii
- □ Velocity
- □ Acceleration
- □ Force
- □ Energy
- □ Momentum
- □ Engineering
- □ Electrical needs
- □ Vector analysis
- □ Physiology
- □ Other (specify) ___Motion ________________________

EXEMPLAR:

Site-Visit Predictions and Measurements of Amusement Park Rides

CATEGORY of INVESTIGATION: ____Engineering___________________

PREDICTION(S):

The capacity of the ride is 600 guests per hour.

METHOD(S) FOR DATA COLLECTION:

Count the number of available seats and measure the cycle time start to the next start.

NECESSARY EQUATIONS AND LIST OF VARIABLES:

Time of one cycle, start to start.

Divide the cycle time by 60 minutes to get the number of cycles per hour.

Count the number of total seats.

Multiply the number of seats by the number of cycles per hour to get the capacity.

DATA TABLES:

Trial	1	2	3	Average
Cycle Time (minutes)				
Seats				

$$\frac{\boldsymbol{cycles}}{\boldsymbol{hour}} = \frac{\boldsymbol{single\ cycle}}{\boldsymbol{60minutes}} = \underline{\hspace{6cm}}$$

$$capacity = seats * \frac{cycles}{hour} = \underline{\hspace{7cm}}$$

EXEMPLAR:

Site-Visit Predictions and Measurements of Amusement Park Rides

CATEGORY of INVESTIGATION: ___Motion______________________

PREDICTION(S):

The outermost horse will have twice the tangential velocity, acceleration, and force as the innermost horse.

METHOD(S) FOR DATA COLLECTION:

1. *Hand-held horizontal accelerometer and stopwatch.*
2. *Electronic accelerometer.*

NECESSARY EQUATIONS AND LIST OF VARIABLES:

$C = 2\pi r$ *Outer horse to horse distance* ___________ *Number of horses in circle* ________

Inner horse to horse distance ___________ *Number of horses in circle* ________

Outer circumference ______________ *Inner circumference* _________________

$v = \frac{2\pi r}{T}$ *T = period of revolution =* ______________

$a = \frac{v^2}{r}$

$F_{net} = ma$ *Mass of rider:* ______________

$a = g \sin \theta$ *Angle of protractor accelerometer deflection:* __________

DATA TABLES:

Horse to horse distance _____ *Number of horses in circle* _____ *T = period =* ______________

Mass of rider: ______________

Trial	1	2	3	Average
Cycle Time (minutes)				
Angle of deflection				

From electronic vest, the acceleration-time graphs will be needed.

Pre-Trip Class Activities

1. Review kinematics and dynamics. It is helpful to present the students with whiteboard problems for preview in class. You can provide students with typical data and graphs for them to perform calculations, draw diagrams, and the like.

2. To demonstrate a ride, set up a model of a rotating swing ride or a Hot Wheels™ track with a vertical loop. Students can take measurements of the angle of the swing chains as a function of the speed of rotation, or of the mass of the passengers. They can practice measuring the time needed for a car to pass through a point on the track by taping two cars together to make a measurable train. Ask from what minimum height the car must fall to stay on the track of the vertical loop. These experiments are good for both demonstration and laboratory purposes. It leads naturally to the role of friction in transferring energy to heat that would otherwise be available for speed. Students are prepared for the fact that their calculation, using ideal conditions, will differ from the actual velocities that they will measure in the park.

3. Construct accelerometers. If you will be constructing mechanical accelerometers, cut the plastic tubing ahead of time. Both horizontal and vertical devices in the Pasco Scientific kit can be constructed easily in a single class period. Calibrating the horizontal device takes some explanation and is a good homework assignment. Accelerometer kits come in class sets of 15 (15 vertical and 15 horizontal devices). The cost can be folded into the overall charge for the field trip.

   Order using catalog number ME-9426, from http://www.pasco.com/

4. Select a triangulation activity, such as finding the height of a nearby tall object, as a laboratory exercise. The flagpole in front of the school is a favorite object for measuring heights. Remember that the equations assume that the pole is perpendicular to the baseline. If your pole is on a mound, the activity will not give accurate results. This affords an excellent opportunity to discuss error analysis.

5. Practice measuring by pacing. Triangulating a horizontal distance can lead into a discussion of how we know the distances to stars and across rivers without bridges.

6. If you will be using data acquisition hardware and software, create activities for the students to have familiarity with the equipment and to practice understanding how to analyze the output.

7. Show a video, website, etc. of actual rides to give students some concept of the size and speed of certain rides.

8. Emphasize that students are not required to ride the rides. Only the accelerometer readings are taken on the rides. All other measurements are taken by an observer on the ground.

9. Post a map of the park. Encourage students to ride the most popular attractions *before* the park becomes crowded. Locate the First Aid station and discuss how students can reach you if necessary. Establish a rendezvous place in the park where you will be stationed at during designated times.

10. Create laboratory groups and activities for the park. Students should stay in groups for educational and safety reasons. Announce requirements and options, when the work is due, and how it will be graded. Students must know that line-cutting, inappropriate language, and unsafe behavior are grounds for expulsion from the park by Six Flags St. Louis Security. Students who cut lines and are made to leave the park must wait outside park gates until the rest of their school group leaves for the day. There may be additional consequences from the school.

11. Six Flags uses an electronic detection system at the front gate. Purses, knapsacks, bags, etc. are subject to search. Glass containers are prohibited. All school and municipal rules apply to the visit, including consumption of controlled substances. Proper attire (shirts, no bikini tops, shoes, etc.) are to be worn always.

12. Electronic data collection instruments are helpful but not necessary. Two suppliers that have been long time supporters for Physics Day are:

    Pasco Scientific
    http://www.pasco.com

    Vernier Software and Technology
    http://www.vernier.com

13. There are several different smart phone apps that may help in data collection and analysis. Suggested apps are *Physics Toolbox* by Vieyra Software, and another is *phyphox* by RWTH Aachen University. *Physics Toolbox* has a rollercoaster mode built in, and *phyphox* can create an experiment by combining the altitude and accelerometer sensors. This will only work for phones that have a barometer. Some phones do not have this sensor. If using a smart phone, a water-resistant wrist or arm pocket protective case with secure straps or Velcro is strongly recommended and required in some cases.

Tips to the Teacher

1. Equipment needed in the park:
    - Timing device, at least one per group. Stopwatch, phone, etc. will work
    - Accelerometers; mechanical, electronic, or both
    - Measuring string, shoe length, and knowledge of their pace
    - Calculator, writing device, and paper
    - Ziploc™ bag for student documents and equipment
    - Dry clothes, as needed

2. Distribute tickets as they exit the bus to speed entry into the park.

3. Remind students to double-check the restraints on each ride. *Emphasize that safety is a serious matter and must be observed at all times.*

4. When ordering tickets, check with the park sales office for meal deals. If there is an all-you can-eat catered meal option that affordably provides everyone with lunch, you may want to consider this option. Be sure that students are aware that no outside food is allowed in the park unless there is some medical or religious requirement.

5. Announce the lateness penalty for either boarding the bus at school or leaving the park.

6. If the student work is due as the bus arrives back at school, you will get it on time, but the product will be less refined compared to submission on the following day.

7. Be sure students know how to identify your bus. Place a large sign in the front window or some other insignia. This may involve some advance preparation.

8. Sufficient adult chaperones are needed on each bus, in case you need someone to stay with an ill student.

9. Be sure to explain to students that timing devices should be used for timing rides while watching and *not* while riding the ride.

10. Permission slips must indicate any special medical conditions including directions for treatment and a way of contacting parents.

11. Instruct students to wear secure shoes or sneakers and bring appropriate clothing and sun block. This can mean a windbreaker for a borderline weather day or a change of clothing if they intend to go on water rides.

How to Use the Historical Question Bank

This question bank in the *Student Manual* has been designed to include questions that are frequently found in pre-NGSS Amusement Park Physics packets. We have designed the packet this way to give ideas of ranges and kinds of questions that would support appropriate learning. The questions vary across grade and ability levels. If you choose a more traditional activity, only one or two rides should be assigned per group. This affords them the time to run multiple trials and to delve deeply into the science and engineering of the thrill-inducing machine.

We encourage students to keep a journal or laboratory report. This 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 more complete story.

Student Mass

When calculating forces, momenta, energy, and other quantities requiring mass, we recommend establishing the *standard mass* of a typical rider to be 60 or 70 kilograms. This will produce more meaningful numbers for the introductory-level student who will relate it to their sensations, versus trying to relate it to the loads the roller coaster or other equipment sustains. By employing a standard mass, students do not need to divulge personal information, facilitating easier ride comparisons in the post-trip discussions. The Student Manual recommends 65 kilograms.

Roller Coaster Mass

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

Instrumentation

Mechanical Accelerometers

As with any technology, there are advantages and disadvantages in data collection methodology. With the protractor and spring accelerometers, the slower reaction rate and characteristic noise filtering of the body holding the devices yield clean readings. The measurements with these devices are single points that need to be remembered by the student as they ride. It can be challenging to recall both values and locations on the ride for more than two or three points. It is easiest to collect maximum and minimum values of the accelerations, however precision may be affected.

Many teachers use the building and calibration of the mechanical devices as lessons in instrumentation. Calibration of these devices often leads to discussions on how to set zero.

Electronic Accelerometers

Electronic accelerometers yield a large data set that often confuses students. Since the sensors are extremely sensitive, most data sets have significant noise. Smoothing the data often reduces the noise in the measurement. Three-point averaging is usually sufficient, but depending on the sampling rate, five- or seven-point averaging may be more appropriate. Unless the students have had some experience with these statistical techniques, they may have difficulty interpreting the results. Meaningful graphical analysis requires a variety of spreadsheet skills. Details of this are in the *Vertical Circular Ride* section, below.

Under certain circumstances, the altimeter (based on the barometer sensor) may yield erroneous readings. This is discussed in detail in the *Electronic Data Collection* section below.

If the rider does not wear the sensor orthonormal to the motion, corrections are needed. Orthonormal is where the axis of motion is forward, the vertical axis is perpendicular to the track, and right-left is mutually perpendicular to the other two axes. In most horizontal motion, it is a reasonable approximation to calculate the scalar acceleration:

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

The directional components are lost but can be inferred from the track layout and position of the roller coaster on the ride. If the acceleration at a point is needed, this method does not work well for vertical loops, particularly barrel rolls. 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. In some cases, translational and rotational analytical geometry methods need to be employed.

Another difficulty with vertical loops is that most are not circular, and the motion is not uniform. Many students apply equations for uniform circular motion and find large errors. Fireball is a circular ride with non-uniform motion and is discussed on page 36.

Electronic Data Collection

Students need experience using the sensors before going to the amusement park. An activity at school might be ascending and descending stairs, an elevator, or playground slide at school to better understand the instrumentation, data collection, and interpretation.

Data may be collected with mechanical devices or electronic devices. A discussion of mechanical devices is found on pages 41– 46. Three-axis accelerometers with altimeters are available for Pasco Scientific and Vernier Software and Technology. Many classrooms employ these sensors, and we assume familiarity with their use. A number of smartphone apps exist as well. There are other apps that may do the same things. 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.

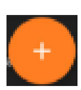
Figure 3 Sample carriers for smartphones and sensors.

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 are phone apps, like *Physics Toolbox* by Vieyra Software, and *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 causing a back-pressure upon entry. This is due to the membrane on the internal electronic sensor deforming or bulging, giving an erroneous reading. Two examples of problematic data are shown here.

Strong Accelerations

The following graph was collected on The Joker Inc.:

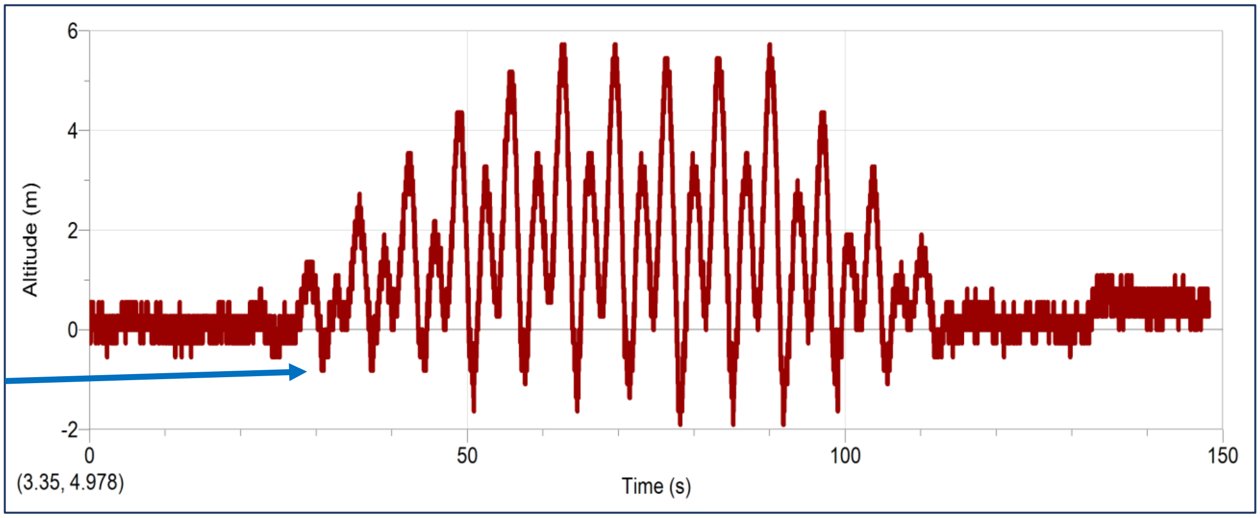


Figure 4 Altitude versus Time graph for The Joker Inc. Note that during the ride erroneous negative altitude readings are recorded (arrow).

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 (sister park, Great America). The back-pressure 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 roller coaster are below the platform level.

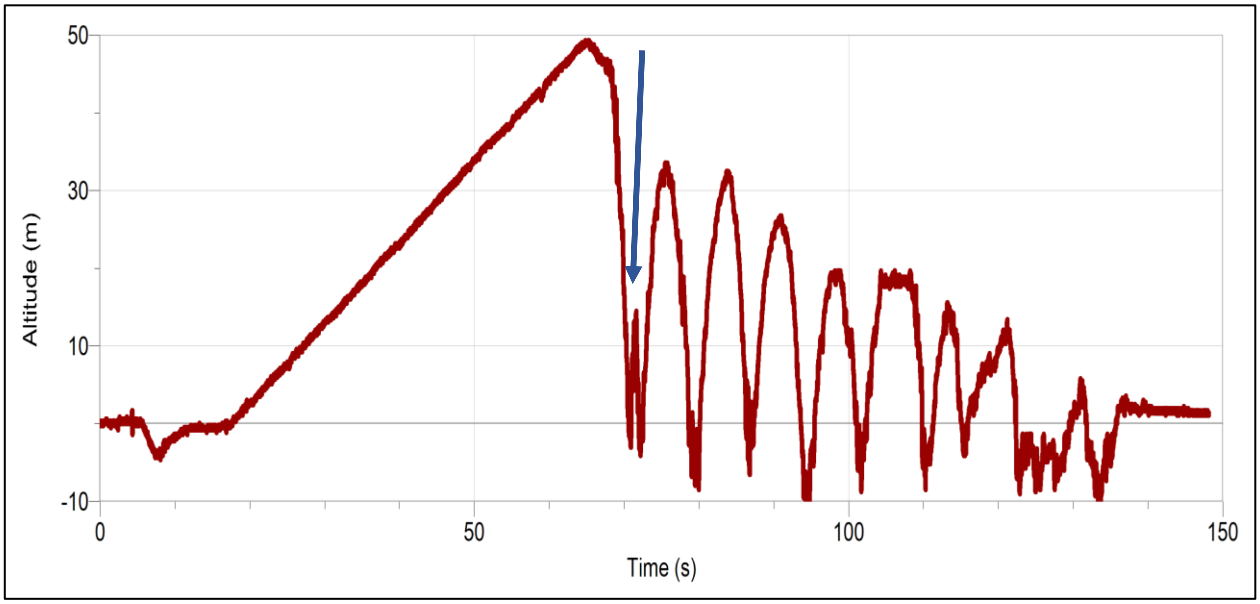


Figure 5 Altitude versus Time graph for Raging Bull. Note that during the ride an erroneous positive altitude reading is recorded (arrow).

The anomaly occurs at about 72 seconds as shown in Figure 5 (arrow). A motion of 15 meters up and then down in 3 seconds is not part or the ride design.

Roller Coasters

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 6 shows the a_x, a_y, and the a_z acceleration plots from American Thunder, an out and back, non-looping wooden roller coaster.

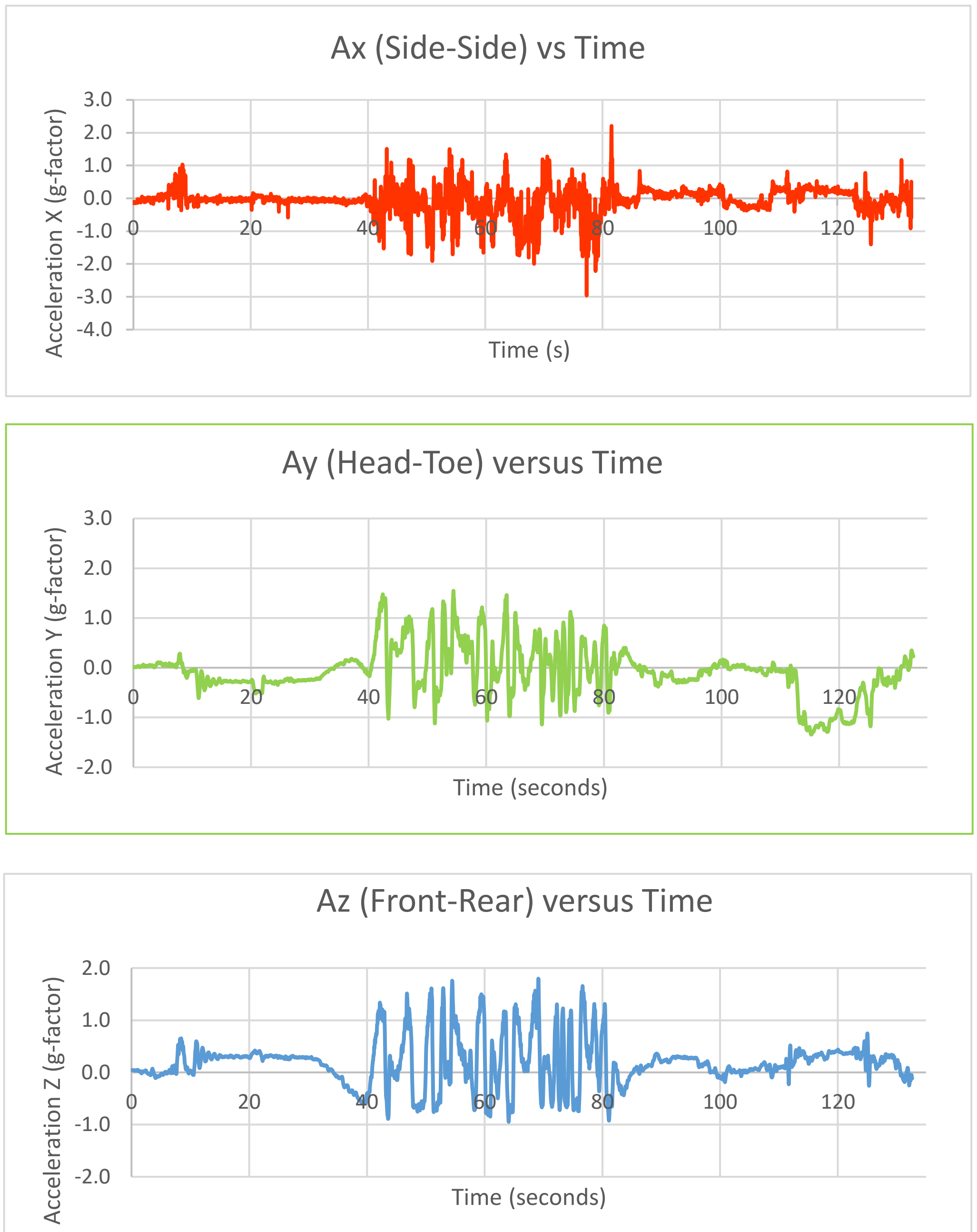


Figure 6 Component accelerations for a non-looping roller coaster.

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 roller coaster on the ride. For American Thunder, see the track layout on page 47. If the acceleration at a specific point is needed, this method does not work well for vertical loops, particularly barrel rolls. 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. The scalar plot is shown in Figure 7.

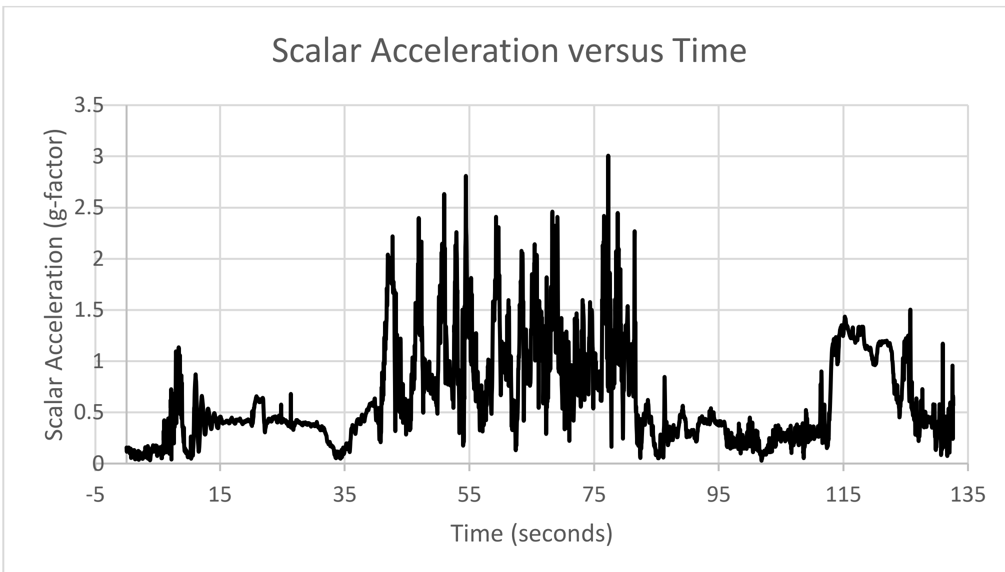


Figure 7 Scalar acceleration, combining component accelerations in Figure 5.

There are mathematical techniques for reducing noise by employing 3-point averaging. This is discussed in the Fireball section (page 36)

Roller Coasters (Advanced)

On many rides, the seat position matters. This is more obvious in close inspection of the electronic data. There are differences between inner and outer seat positions (particularly in circular motion rides), front and rear positions (roller coasters and vertical arc rides), and position of seat on pendulum rides. This may be an interesting investigation as a separate study. One such example is shown in Figure 8 of differences in timing for vertical acceleration on a compressed air launch (horizontal) looping roller coaster. The difference in arriving at a particular elevation at a different time changes the intensity of the acceleration. This study and may be appropriate for a more advanced class. Since most instruction in Introductory Physics idealizes the objects of interest as a single point. When presented with an extended object, new and sometimes novel interpretations are made. The position closest to the center of mass resembles curricular examples. In the front seat of a roller coaster, events happen later than expected (the onset of positive acceleration occurs after going over a crest); in the rear seat, events happen sooner than expected (onset of positive acceleration occurs before reaching the crest, yielding enhanced airtime). Similar differences happen for negative acceleration in valleys.

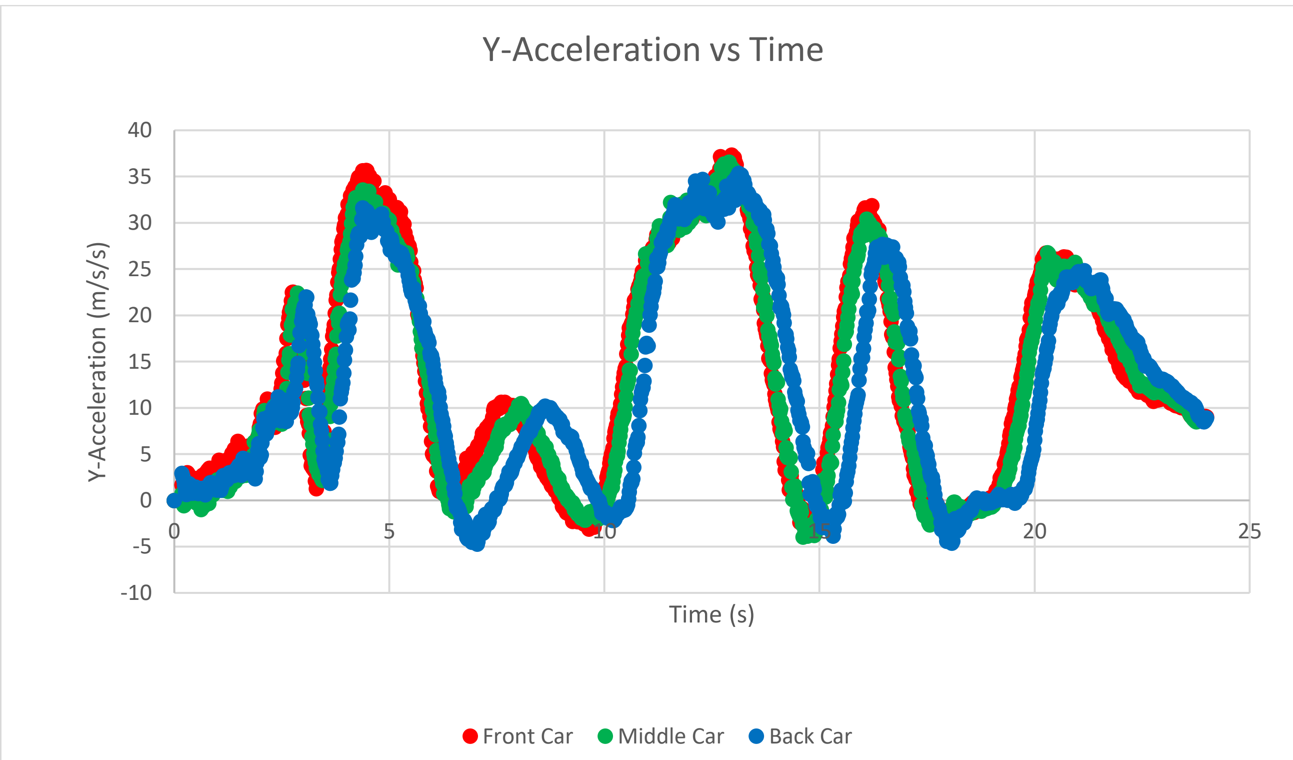


Figure 8 Roller coaster vertical acceleration versus time in front, middle, and rear seats.

Because of noise and some of the complexity involved in electronic data (sensor tilted or bumped during the ride), many teachers opt for just the spring and horizontal accelerometer data collection for their classes. Moving averages and other statistical techniques to smooth the electronic data are beyond the preparation of most high school students. Some teachers ask for a comparison of the mechanical data with unfiltered electronic data. Select the method that best suits your students.

Dual Axis Turning Ride

Shazam! (Page 60) has an interesting set of graphs. The right-left and the forward-back plots are phase shifted. You can see this when they are plotted together in Figure 12. What is unusual is that there is a small vertical acceleration for a seemingly planar ride. This is due to the flexing of the arm due to the large loading. In advanced classes, Fourrier Transform analysis can be applied to find the frequencies.

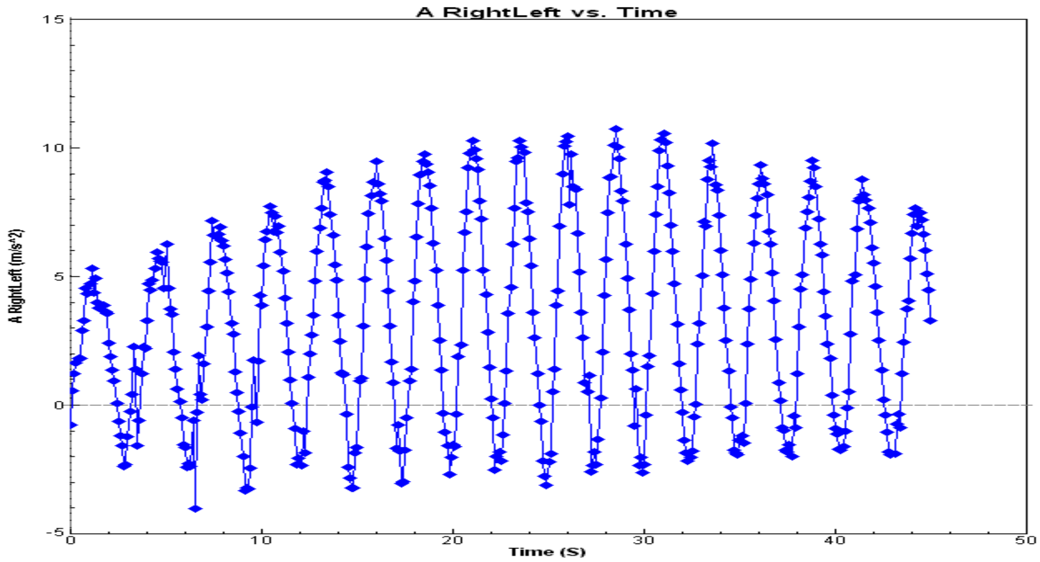


Figure 9 Plot of right - left motion versus time. Since this is a dual axis turning ride, there are moments of retrograde motion. For a more detailed discussion, see N. Unterman, Amusement Park Physics: A Teacher's Guide, Second Edition*, Walch Publishing 2001. pp. 77-79 and J. Walker, "The Amateur Scientist" Scientific American Vol. 249 No. 4 pp 162-169 Oct. 1983*

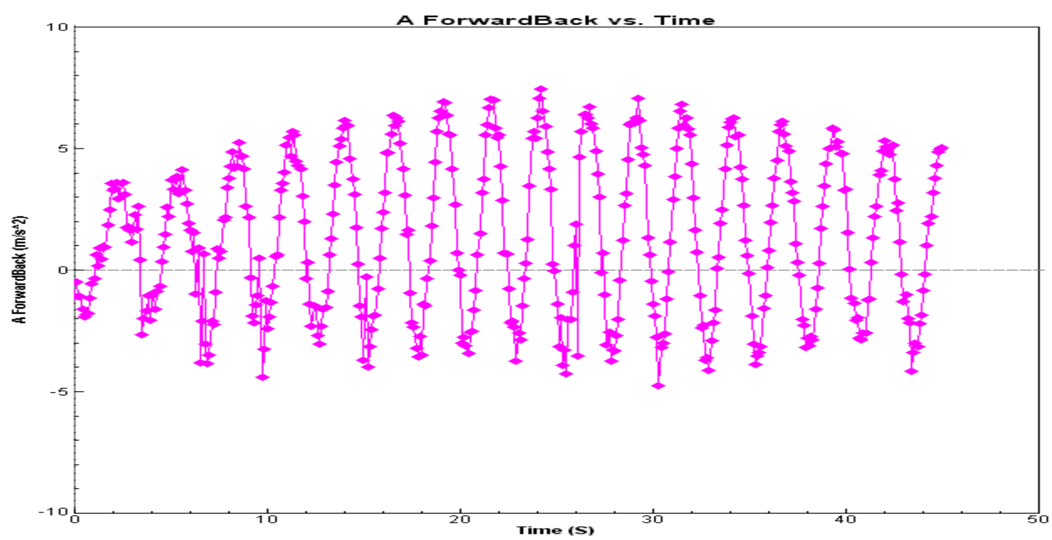


Figure 10 Plot of forward - back motion versus time. Since this is a dual axis turning ride in counter-clockwise -- counterclockwise mode, some retrograde motion is shown in the region below the axis.

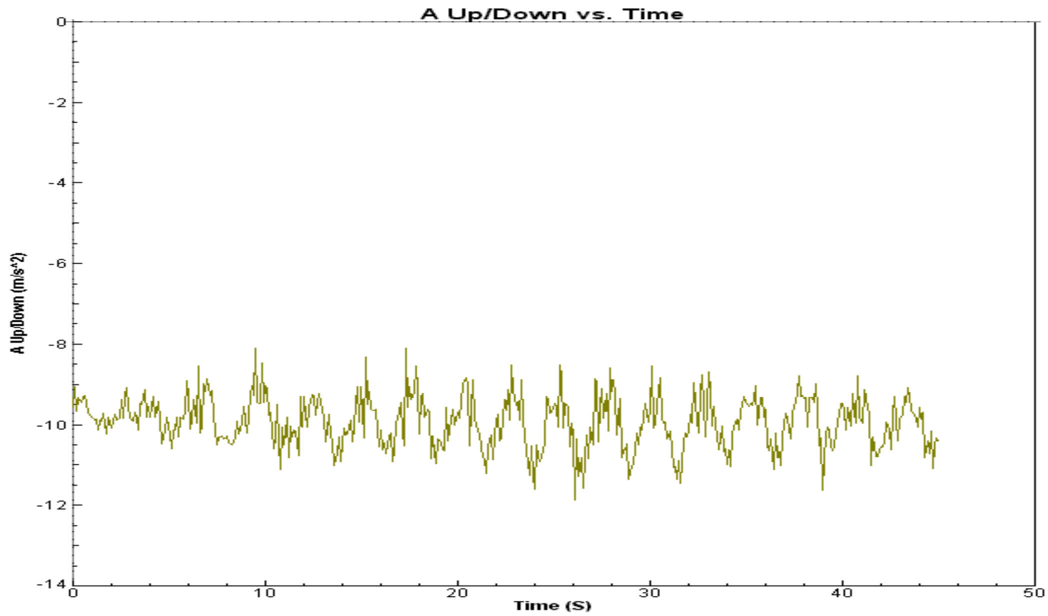


Figure 11 Plot of vertical motion versus time. Although a constant background of -9.8 N/kg is expected, there is some vertical variation during high acceleration stress moments.

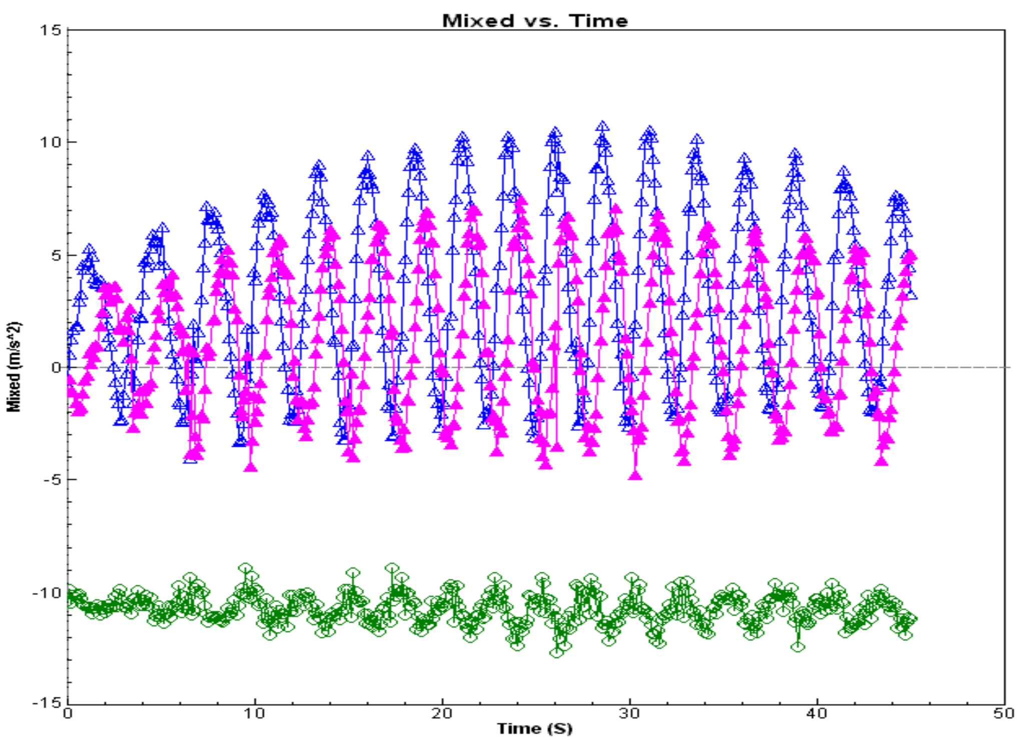


Figure 12 An overlay of right-left (blue), forward-back (magenta), and vertical (green) motions.

Electronic Data Analysis – Vertical Circular Rides

Many students and teachers have some confusion about using the electronic data for vertical loop analysis on driven rides like Fireball, unlike uniform circular motion rides such as Colossus. 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 several non-uniform motion tutorials found online. We recommend a review of such material. What is presented here is, in part, repeated in the student manual. We will use the ride Fireball as the 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 13 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 15). 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 13. The first few rows of data from an electronic sensor program.

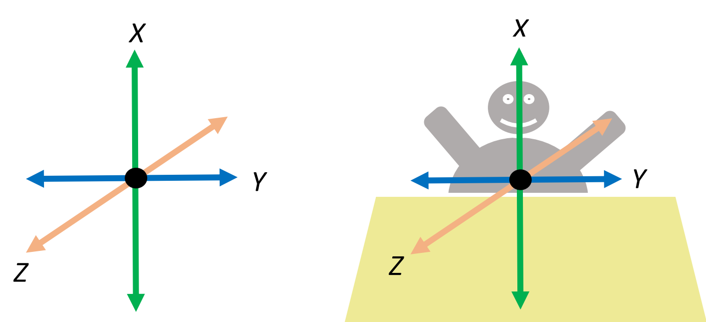


Figure 14 Since there is no requirement on the orientation of the accelerometer-sensor on the wearer, it is important to explicitly state the frame of reference in which the data were collected. For this Fireball example, the frame is shown.

	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 Acceleration (m/s^2) Exponential 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 15. 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 13) is found in columns A, C, G, H, and I (Figure 15). 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/(C3/2))))*

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

$\omega = {}^{\theta}/_{t}$ = *F466 = ((E466+E465+E464)-(E465+E464+E463))/(3*C2)*

Column J: Centripetal acceleration: $a_{centripetal} = \omega^2 r$ = *J466 = (F466^2)*(C3*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 is different 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 16) The combination of these gives the net acceleration. Consider carefully how the tangential acceleration may be extracted from the data.

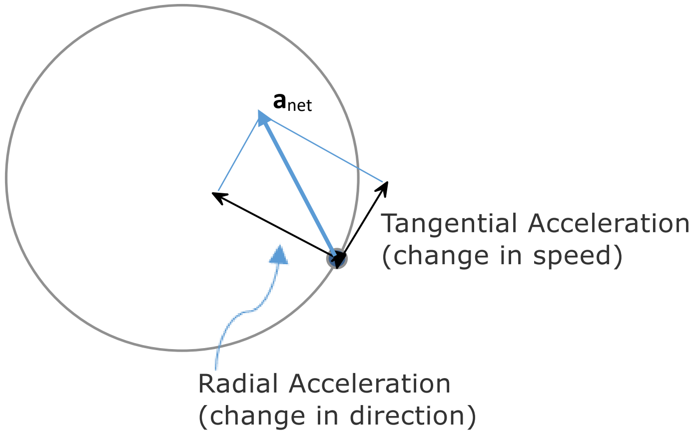


Figure 16 Vector diagram of the radial and tangential acceleration, and the net acceleration (blue).

Below is a sampling of graphs from Hangover applying the data from Figures 13 and 15. There are many more 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?

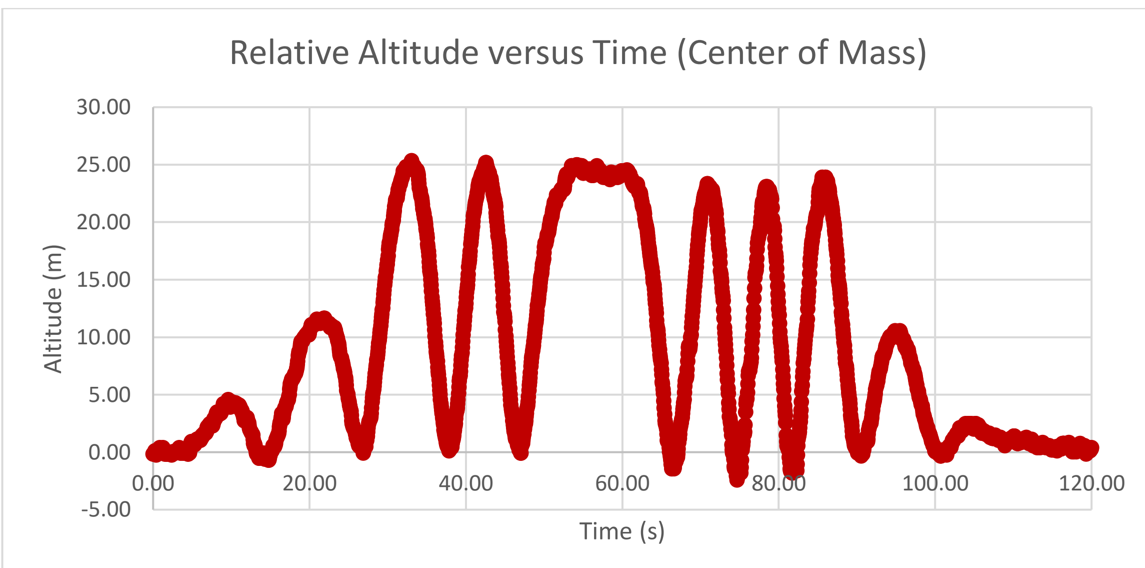


Figure 17 Some values of altitude are less than zero due to the downward shift of the accelerometer on the wearer and compression of the seat during the ride.

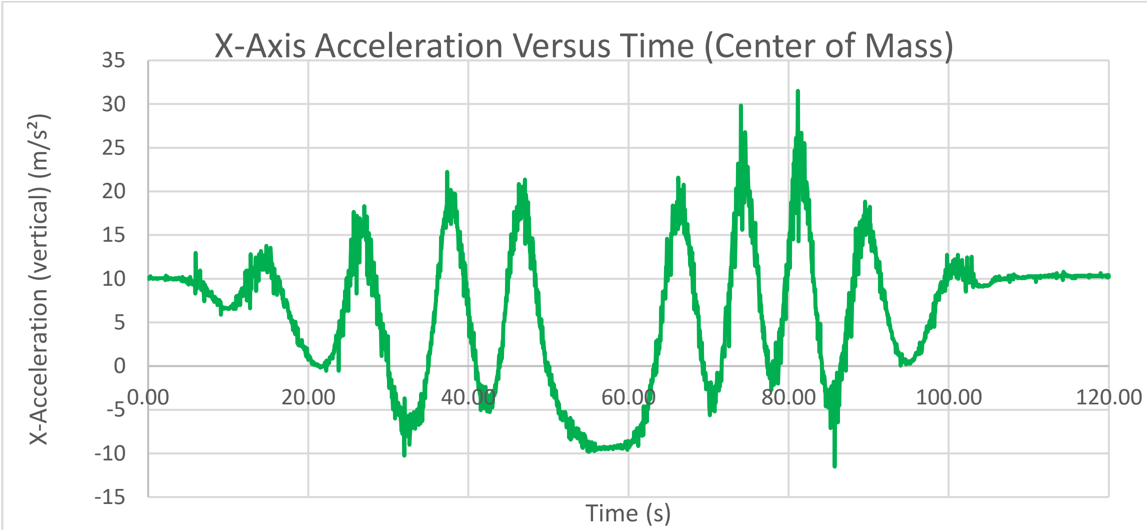


Figure 18 These data have the background gravitational field intensity included. It is important to understand that these numbers are derived from forces. Read the manufacturer's information on how the data in the vertical direction is collected, processed, and reported. For example, at 9 o'clock, about 22 seconds, the vertical (X) acceleration channel is really directed horizontally, and is zero. Note that the forward z-acceleration (Figure 20) at the same point shows the gravitational field intensity.

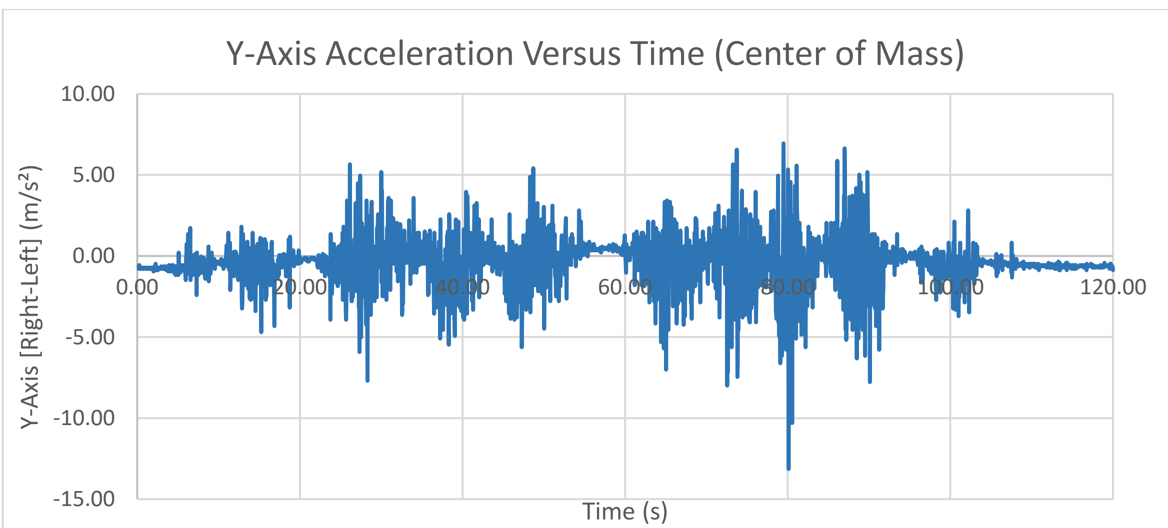


Figure 19 There is no significant right-left acceleration. The reason for this is small lateral motion of the sensor and passenger during the ride. The starting and ending non-zero values are due to a slight tilt in how the accelerometer was placed and worn in the vest.

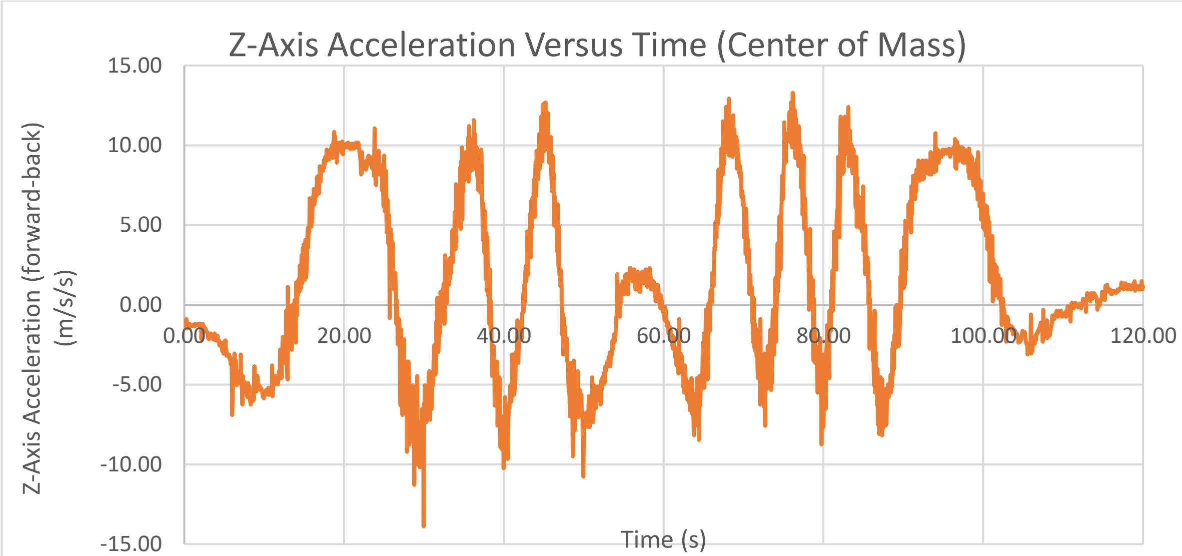


Figure 20 The forward-back data are not perfectly zeroed since the seat for the passenger is leaning back slightly. Please see the note on the X-axis acceleration and match this with the Relative Altitude and narrative about this ride at the beginning of this section.

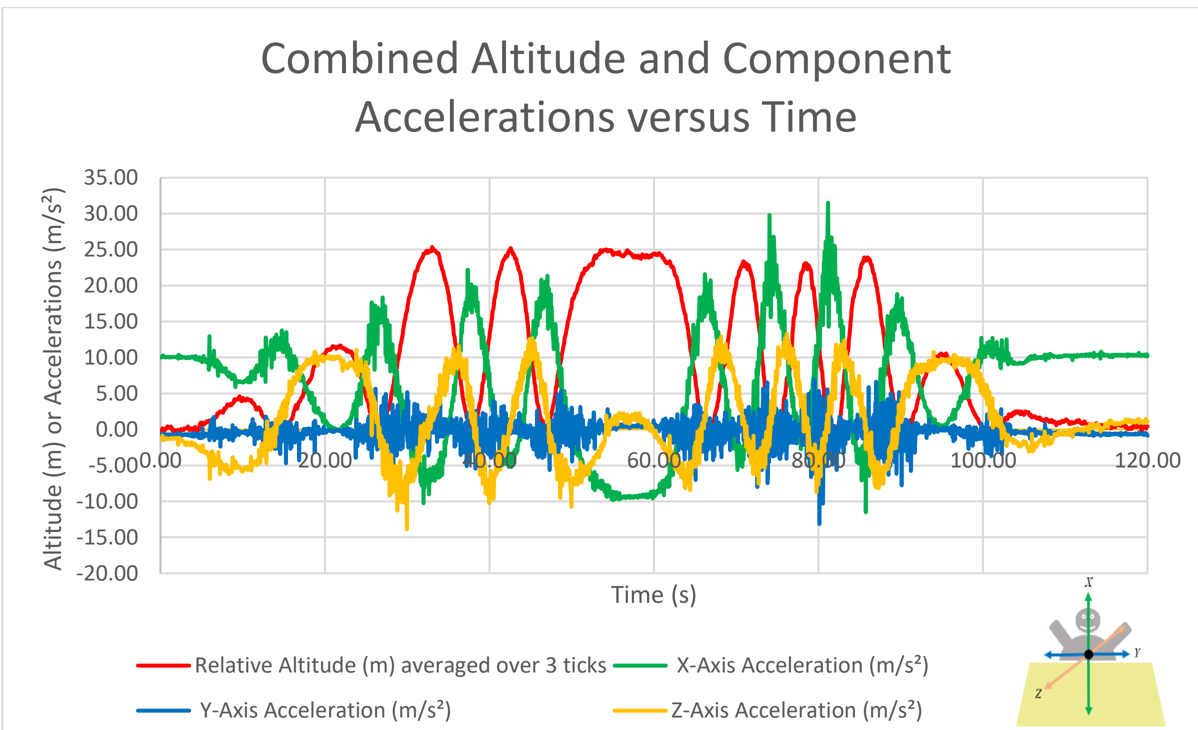


Figure 21 Although busy, the combined graph can help visualize some of the motion. Recall that these data are from the passenger's frame of reference.

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

Suggestions for Taking Measurement

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 22. 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.

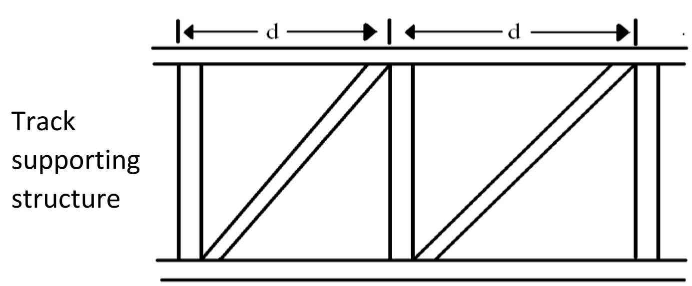


Figure 22 Detail of cross-members of a roller coaster structure.

Triangulation: For measuring height by triangulation, a sextant (Figure 23) can be constructed. Practice this with the school flagpole before you come to Six Flags St. Louis.

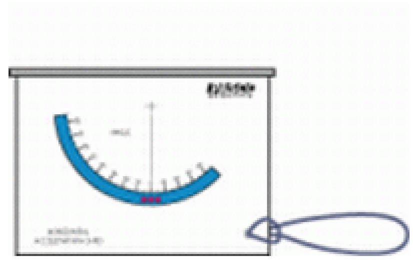


Figure 23 Protractor accelerometer and sextant.

Suppose the height *h* of the SkyScreamer® must be determined. *Notice that this shows the height of the final ride ascent, not the height of the tower*. Since you cannot measure the distance of baseline all the way to the tower structure, you need a local baseline, *b*. You will need to employ the Law of Sines as in Figure 24.

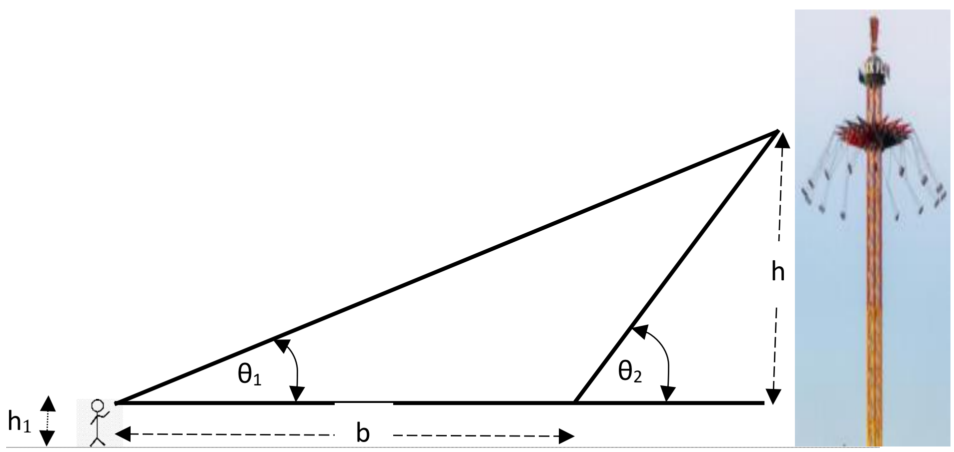


Figure 24 Drawing of geometry for finding height.

Knowing θ_1, θ_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:

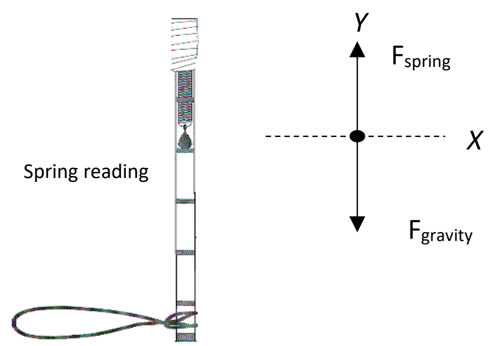


Figure 25 Vertical accelerometer and accompanying force diagram.

Using Newton's second law, $F_{net} = F_{spring} - F_{gravity} = ma_{net}$, 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 (Figure 26). 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

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

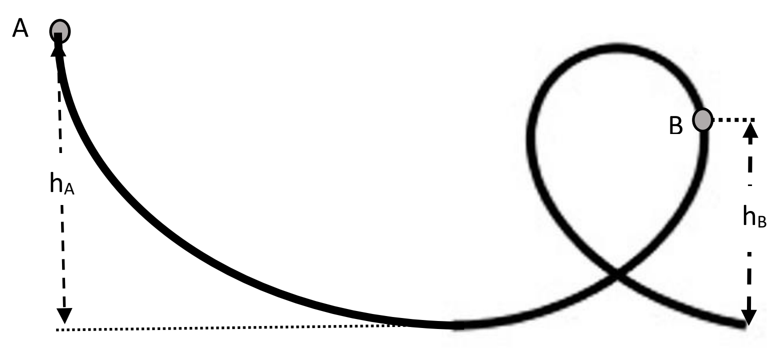


Figure 26 Velocity calculation at a point in a clothoid loop.

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 27).

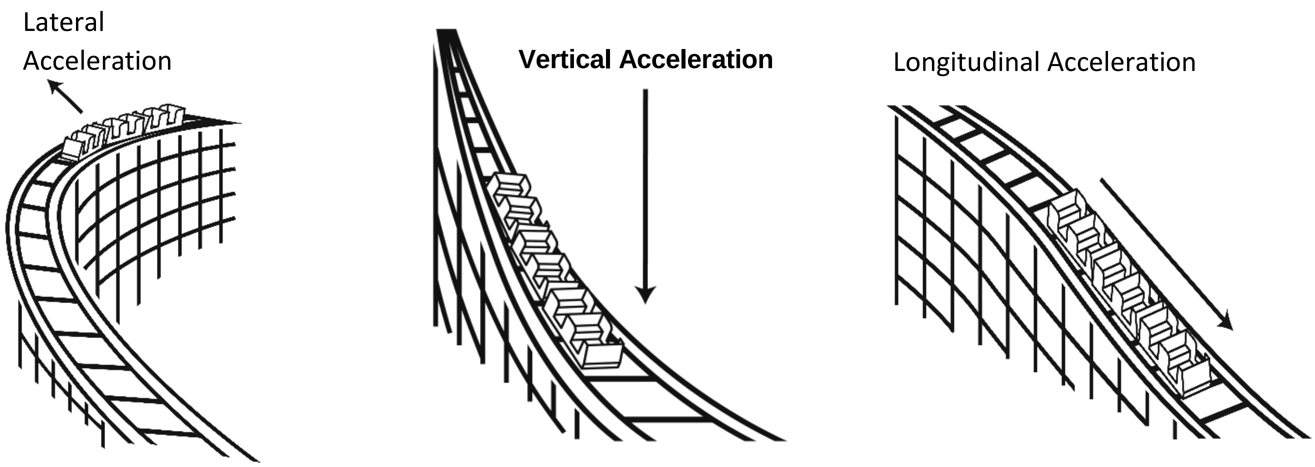


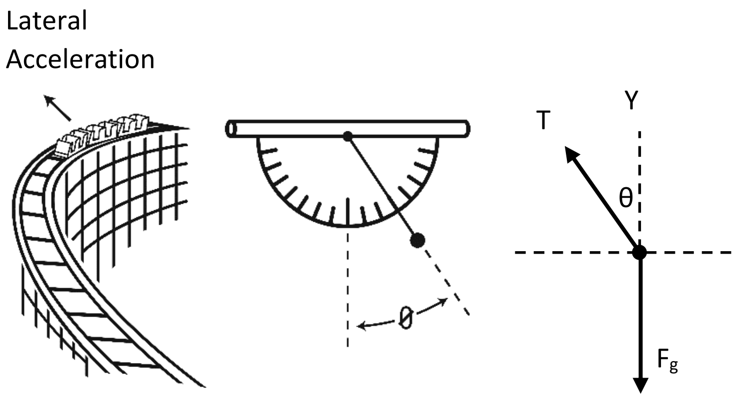
Figure 27 Acceleration terms.

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 (maximum *g*'s pulled 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 28).



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

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

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

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

Figure 28 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:

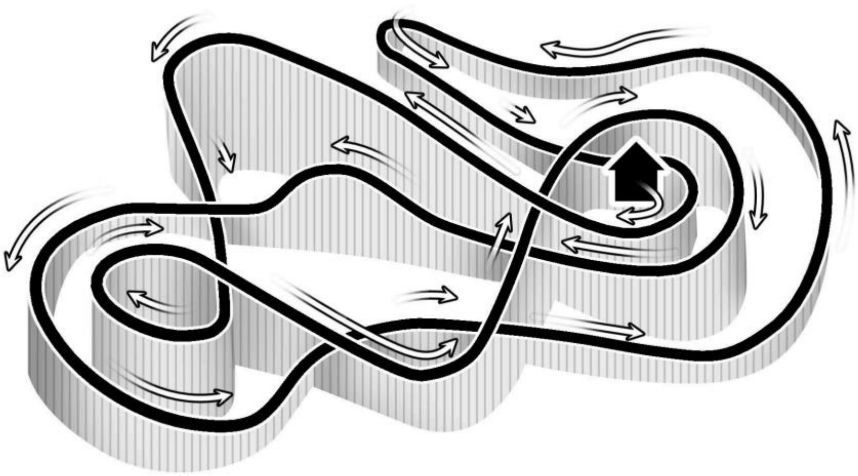
$$\boldsymbol{a_c = \frac{v^2}{r}}$$

Ride Information

The information in this section is general background information for each ride. Many times, a student might ask about manufacturer, track layout, a picture (also available in the student manual) and other information. This section is intended to be a general reference and not an answer key. Please note that all stated values are *approximate*, and vary due to factors including loading, viscosity of lubricants, temperature, wind, humidity, barometric pressure, strength of sunlight (heating effects), materials being used that day, etc.

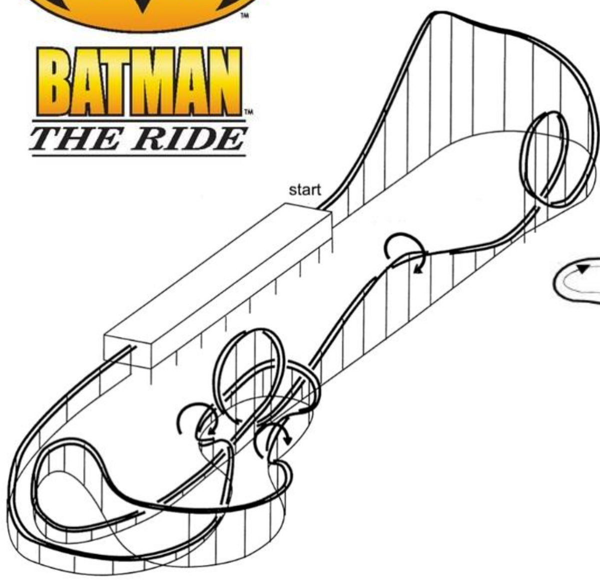
For a discussion of mass values, please go to page 26.

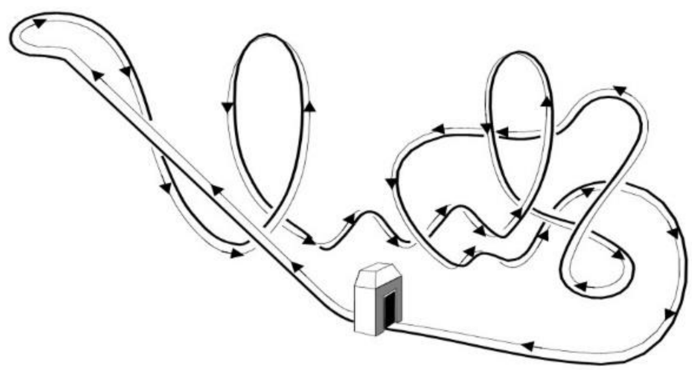
Amusement Park Mind Bogglers and a Scavenger Hunt are included at the end of the end of the Student Manual question bank.



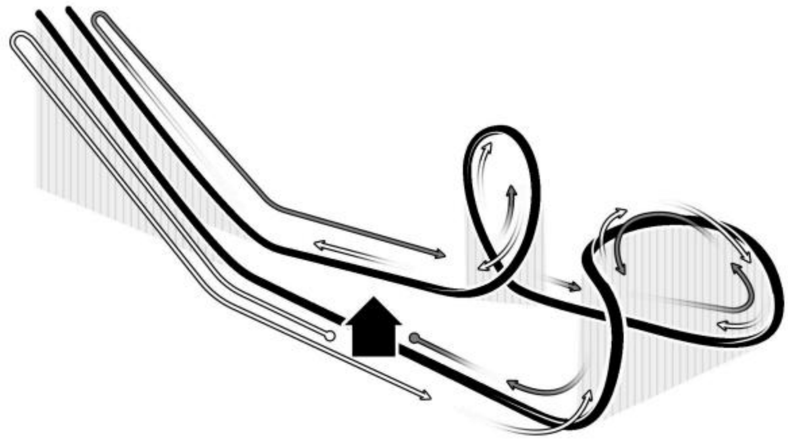
WHAT:	Wooden roller coaster, single chain lift
WHEN:	20.June.2008
DESIGNED and CONSTRUCTED BY:	Great Coasters International
TRACK LENGTH:	827 meters
NUMBER OF TRAINS AND CARS:	2 trains, 12 two-person cars each
NUMBER OF PASSENGERS:	24 per train
NUMBER OF GUESTS PER HOUR:	850
GREATEST HEIGHT:	25 meters, 16 hills total
HEIGHT OF FIRST DROP:	24 meters
ANGLE OF LIFT HILL:	20º
LENGTH OF FIRST LIFT:	73 m
CHAIN LIFT SPEED:	2.5 meters per second
MOTOR:	92 Kilowatts
MAXIMUM SPEED:	21.4 meters/second
DURATION OF RIDE:	2.5 minutes

BATMAN THE RIDE





WHAT:	Inverting suspended steel coaster, “heart-line spin”
WHEN:	22.April.1995
DESIGNED and CONSTRUCTED BY:	Bolliger and Mabillard; Monthey, Switzerland
TRACK LENGTH:	821 meters
NUMBER OF TRAINS AND CARS:	2 trains, 8 cars per train
NUMBER OF PASSENGERS:	32 passengers per train
NUMBER OF GUESTS PER HOUR:	1280 - 1400
GREATEST HEIGHT:	32 meters
HEIGHT OF FIRST DROP:	25.7 meters
ANGLE OF LIFT HILL:	30^{o}
LENGTH OF FIRST LIFT:	51.4 meters
CHAIN SPEED OF LIFT HILL:	2.5 meters/second
MOTOR:	147 kilowatts
INVERSIONS:	5; 2 vertical loops, 1 inline twist, and 2 corkscrews
MAXIMUM SPEED:	22.4 meters/second
LOOPS:	5 inversions
DURATION OF RIDE:	2.0 minutes
SPECIAL FEATURES:	Outside looping, suspended high-speed chairlift-type vehicles, "heart-line spin."



WHAT:	Steel inverting (shuttle) coaster; chain lift
WHEN:	8. June.2013
DESIGNED and CONSTRUCTED BY:	Vekoma (Peter Clerx, Arrow Dynamics)
TRACK LENGTH:	285 meters
NUMBER OF TRAINS AND CARS:	One train, 7 cars
NUMBER OF PASSENGERS:	28 per train
NUMBER OF GUESTS PER HOUR:	760
GREATEST HEIGHT:	35.5 meters
HEIGHT OF FIRST DROP:	33 meters
ANGLE OF LIFT HILL:	65^{O}
CABLE SPEED OF FIRST LIFT HILL:	1.6 meters/second
CHAIN SPEED ON SECOND LIFT HILL:	matches train speed, therefore variable
EACH MOTOR:	147 Kilowatts
AVERAGE ANGLE OF DROP:	65°
MAXIMUM SPEED:	21 meters/second
LOOPS:	3 inversions, including Cobra roll
DURATION OF RIDE:	1.8 minutes

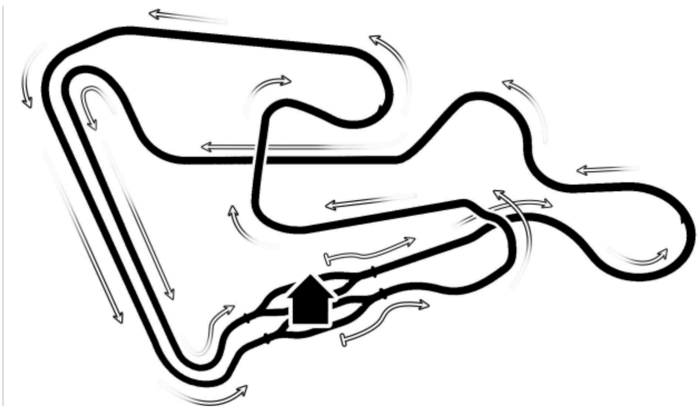
THE GIANT WHEEL

COLOSSUS

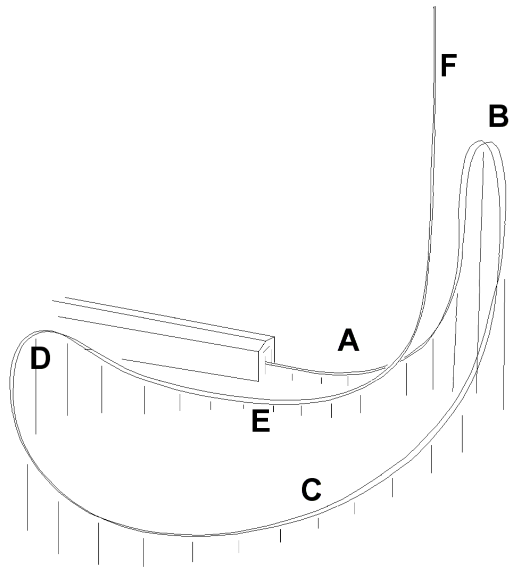
WHAT:	Ferris Wheel, uniform circular motion
WHEN:	18.April.1986
DESIGNED and CONSTRUCTED BY:	Huss
PASSENGERS PER CABIN:	6
NUMBER OF CABINS:	32
NUMBER OF GUESTS PER HOUR:	1280
GREATEST HEIGHT:	55 meters
TANGENTIAL SPEED:	0.23 meters/second (Constant)
DURATION OF RIDE:	12.5 minutes (one trip around)

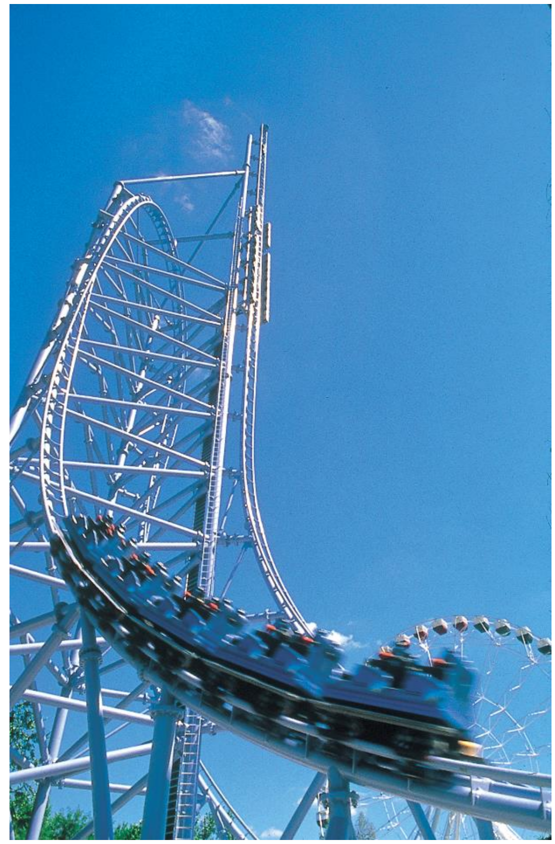
WHAT:	Giant vertical circular thrill ride, **non**-uniform circular motion
WHEN:	7.May.2016
DESIGNED and CONSTRUCTED BY:	Larson International
RIDE SEATING:	2 per row, 12 rows
NUMBER OF GUESTS PER HOUR:	420
DIAMETER:	22 meters
INVERSIONS:	6 per cycle, typically (3 in each direction)
VELOCITY:	Variable, with a maximum of 13.4 meters per second
SPECIAL NOTE:	Software and operator choice can change the sequencing of motion. Ride experience may not be repeatable.
DURATION OF RIDE:	1.5 minutes

WHAT:	Single axis flat ride carousel
WHEN:	1972
DESIGNED and CONSTRUCTED BY:	Philadelphia Toboggan Company, 1915, Model 35
RIDE SEATING:	68 animals (58 jumpers), two chariots (12 passengers), 4 rings, some outermost do not undulate.
NUMBER OF GUESTS PER HOUR:	750
RADII:	Outer: 7.10 m; 3rd ring: 6.00 m; 2nd ring: 5.05 m; inner: 4.25 m
MAXIMUM ROTATIONAL VELOCITY:	2 revolutions/minute
MAXIMUM TANGENTIAL VELOCITY:	1.5 meters/second
DURATION OF RIDE:	2.0 minutes
OTHER INTERESTING FACTS:	Unusual Roman Chariot

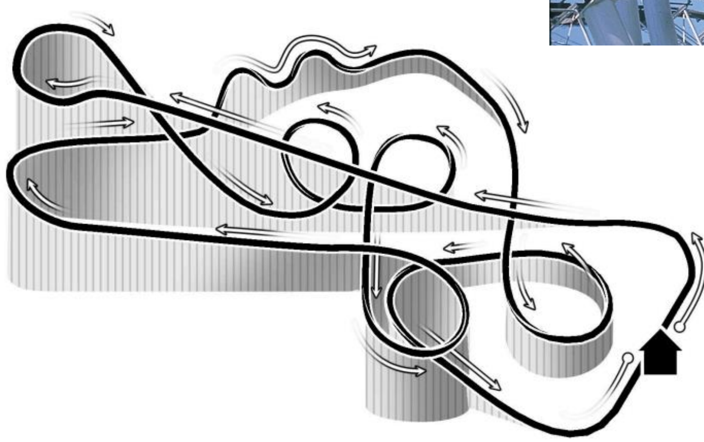


WHAT:	Flume Water Ride (hydroflume)
WHEN:	5. June.1971
DESIGNED and CONSTRUCTED BY:	Arrow Dynamics
FLUME LENGTH:	380 meters
NUMBER OF BOATS/SEATS:	32 boats (both flumes), 4 guests per boat
MASS OF BOAT:	227 kilograms
NUMBER OF GUESTS PER HOUR:	2000
GREATEST HEIGHT:	17 meters
ANGLE OF LAST DROP:	40º
ANGLE OF LAST LIFT HILL:	25º
LENGTH OF LIFT HILL:	40.2 meters
DURATION OF RIDE:	3.0 minutes
SPECIAL NOTE:	There are two lift hills. The information above is for the second hill.





WHAT:	Inverting steel coaster, shuttle, linear induction
WHEN:	11.April.1998; revised 5.May.2012
DESIGNED and CONSTRUCTED BY:	Premier Rides, Werner Stengel and Jim Seay, designers
TRACK LENGTH:	421 meters
NUMBER OF TRAINS AND CARS:	2 trains, 5 cars per train
NUMBER OF PASSENGERS:	20 passengers per train
NUMBER OF GUESTS PER HOUR:	750
GREATEST HEIGHT:	66 meters
HEIGHT OF DROP:	59 meters
MAXIMUM SPEED:	31 meters/second
LOOPS:	1 inversion, traversed twice
DURATION OF RIDE:	1.5 minutes
PROPULSION:	Linear induction motor

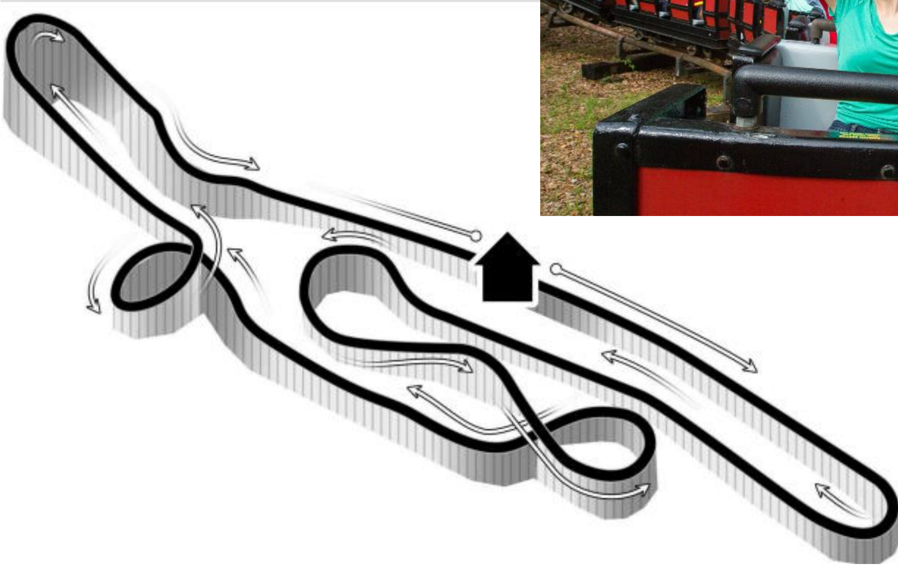


WHAT:	Inverting steel coaster
WHEN:	8.April.1989
DESIGNED and CONSTRUCTED BY:	Arrow Dynamics/Vekoma
TRACK LENGTH:	740 meters
NUMBER OF TRAINS AND CARS:	3 trains, 7 cars per train
NUMBER OF PASSENGERS:	28 passengers per train
NUMBER OF GUESTS PER HOUR:	1600
GREATEST HEIGHT:	33 meters
HEIGHT OF FIRST DROP:	24 meters
ANGLE OF LIFT HILL:	30º
LENGTH OF FIRST LIFT:	48 meters
CABLE SPEED OF LIFT HILL:	2.5 meters/second
MAXIMUM SPEED:	25 meters/second
LOOPS:	4 inversions
DURATION OF RIDE:	2.0 minutes

PANDEMONIUM

This is a chaotic ride that exceeds easy analysis within the high school curricula. A chaotic ride is where (1) small differences in initial conditions yield big changes in motion (like paper airplanes or smoke streams) and (2) all points in the constrained region are eventually encountered (like a rubber duck in a bathtub). All points are deterministic (not random).

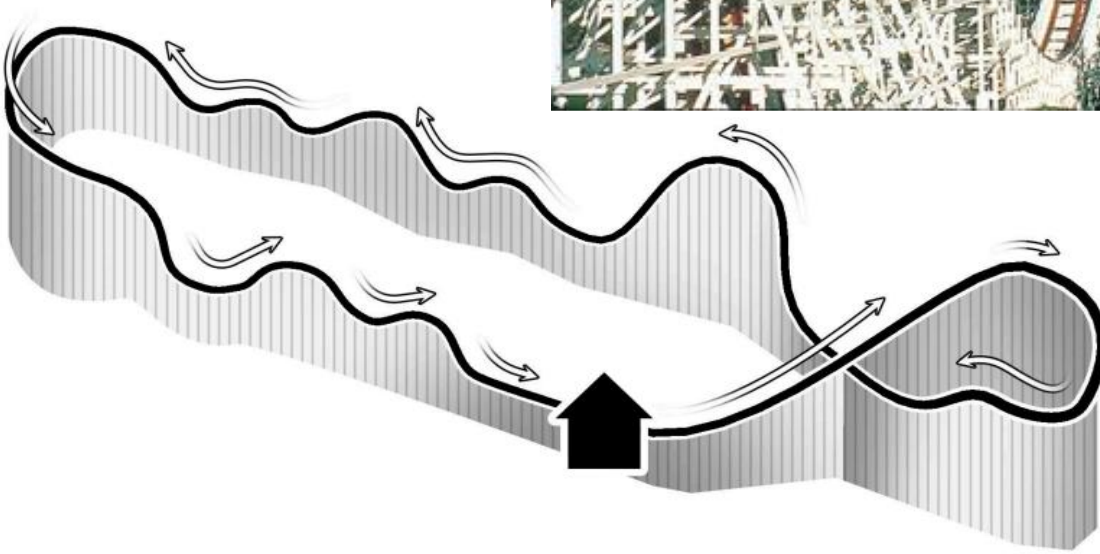
WHAT:	Steel, spinning car, chain lift. Model 420
WHEN:	21.April.2007
DESIGNED and CONSTRUCTED BY:	Werner Stengel/Gerstlauer
TRACK LENGTH:	412 meters
NUMBER OF TRAINS AND CARS:	7
CAR LENGTH:	2.1 meters
RADIUS OF ROTATION OF GUEST:	0.8 meters
NUMBER OF PASSENGERS:	4 per car
NUMBER OF GUESTS PER HOUR:	700
GREATEST HEIGHT:	16 meters
HEIGHT OF FIRST DROP:	15 meters
ANGLE OF LIFT HILL:	40^{o}
LENGTH OF FIRST LIFT:	23.3 meters
MAXIMUM SPEED:	18 meters/second
DURATION OF RIDE:	1.9 minutes



Since this roller coaster is not easily visible from the public areas of the park, we recommend electronic data collection only.

WHAT:	Steel out and back coaster; three lifts
WHEN:	5.June.1971
DESIGNED and CONSTRUCTED BY:	Arrow Dynamics
TRACK LENGTH:	723 meters
NUMBER OF TRAINS AND CARS:	3 trains, 5 cars each
NUMBER OF PASSENGERS:	6 per car
NUMBER OF GUESTS PER HOUR:	1800
GREATEST HEIGHT:	19 meters
HEIGHT OF FIRST DROP:	12 meters
MAXIMUM SPEED:	16.5 meters/second
DURATION OF RIDE:	3.0 minutes
LIFT HILLS:	3

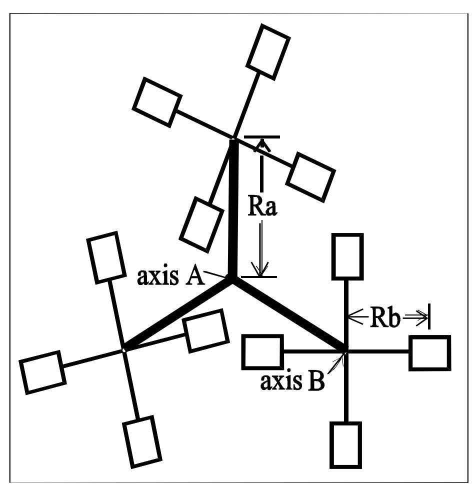
SCREAMIN' EAGLE



WHAT:	Wooden roller coaster, single chain lift
WHEN:	10.April.1976
DESIGNED and CONSTRUCTED BY:	Philadelphia Toboggan Company/ John C. Allen
TRACK LENGTH:	1180 meters
NUMBER OF TRAINS AND CARS:	2 trains, 6 four-person cars each
NUMBER OF PASSENGERS:	24 per train
NUMBER OF GUESTS PER HOUR:	1100
GREATEST HEIGHT:	34 meters
HEIGHT OF FIRST DROP:	28 meters
ANGLE OF LIFT HILL:	20°
LENGTH OF FIRST LIFT:	99.4 meters
CHAIN SPEED OF LIFT HILL:	2.5 meters/second
MOTOR:	74 Kilowatts
AVERAGE ANGLE OF FIRST DROP:	40°
MAXIMUM SPEED:	28 meters/second
DURATION OF RIDE:	2.5 minutes

INDUSTRY NAME OF RIDE:	Scrambler®
WHAT:	Dual axis turning ride
WHEN:	1972
DESIGNED and MANUFACTURER BY:	Eli Bridge Company
RIDE SEATING:	12 cars, 2 or 3 seats per car, 4 cars per pod
NUMBER OF GUESTS PER HOUR:	750
PRIMARY RADIUS (R_A):	4.4 meters
POD RADIUS (R_B):	3.4 meters
PRIMARY ARM RATE:	11 revolutions/minute
SECONDARY ARM RATE:	6 revolutions/minute
DURATION OF RIDE:	1.5 minutes

A series of high-speed accelerations are the rule (not the exception) in this exciting ride. This thrill ride consists of three arms of four cars, each capable of holding three guests. Seated guests ride through a star-shaped pattern at speeds up to 11 meters per second. The bench-like seats the riders sit on accelerate as they pass the center spot of the star and stop when they reach the star's perimeter.

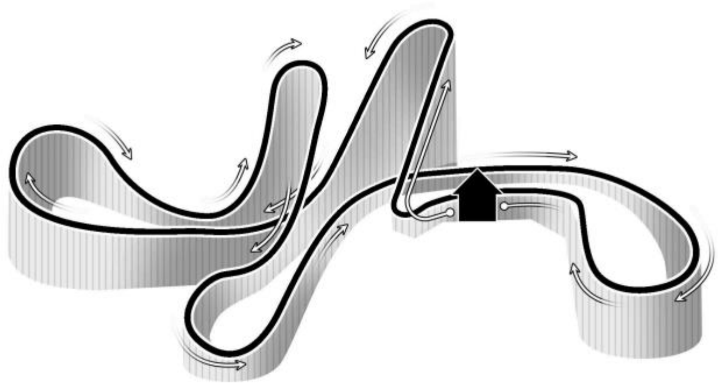


WHAT:	Spinning swing ride with elevator; can work in reverse
WHEN:	14.May.2011
DESIGNED and CONSTRUCTED BY:	Funtime
RIDE SEATING:	16 swings, 2 seats each
NUMBER OF GUESTS PER HOUR:	480
MAXIMUM DIAMETER OF SWING PATH:	30 meters
MINIMUM DIAMETER OF SWING PATH:	16 meters
TOWER HEIGHT:	72 meters (This is not ride ascent height.)
MAXIMUM TANGENTIAL SPEED:	19 meters/second
ROTATIONAL VELOCITY:	5.5 revolutions/minute in slow phase; up to 8 RPM
DURATION OF RIDE:	2.5 minutes

WHAT:	Swinging, spinning half-pipe ride (mega-disc)
WHEN:	26.May.2017
DESIGNED and CONSTRUCTED BY:	Zamperla (Disk'O)
RIDE SEATING:	40
NUMBER OF GUESTS PER HOUR:	435
HALF PIPE RADIUS:	about 15 meters
TRACK HEIGHT:	15.5 meters
PLATFORM ROTATIONAL SPEED:	14 revolutions/minute counterclockwise
PLATFORM DIAMETER:	8.5 meters
DURATION OF RIDE:	2.0 minutes

SUPERGIRL SKY FLYER

WHAT:	Dual axis tilting turning ride
WHEN:	25.May.2019
DESIGNED and CONSTRUCTED BY:	Zamperla Endeavor
RIDE SEATING:	24 single seat swings
NUMBER OF GUESTS PER HOUR:	240
MAXIMUM DIAMETER:	15.0 meters
MAXIMUM HUB HEIGHT:	20.5 meters
ANGLE OF TILT FROM HORIZONTAL:	75^{O}
ROTATIONAL SPEED:	14 revolutions/minute
MAXIMUM TANGENTIAL SPEED:	11.2 meters/second
MOTOR:	140 kilowatts
DURATION OF RIDE:	3 minutes



WHAT:	Wooden roller coaster, single chain lift
WHEN:	29.April.2000
DESIGNED and CONSTRUCTED BY:	Custom Coasters International; Dennis McNulty and Larry Bill
TRACK LENGTH:	1412 meters
NUMBER OF TRAINS AND CARS:	3 trains, 6 four-person cars each
NUMBER OF PASSENGERS:	24 per train
NUMBER OF GUESTS PER HOUR:	1500
GREATEST HEIGHT:	37.2 meters
HEIGHT OF FIRST DROP:	45.7 meters
ANGLE OF LIFT HILL:	30º
LENGTH OF FIRST LIFT:	74.4 meters
CHAIN SPEED OF LIFT HILL:	0.45 meters/second idling, 2.7 m/s when coupled
AVERAGE ANGLE OF FIRST DROP:	50º
MAXIMUM SPEED:	30 meters/second
DURATION OF RIDE:	2.9 minutes

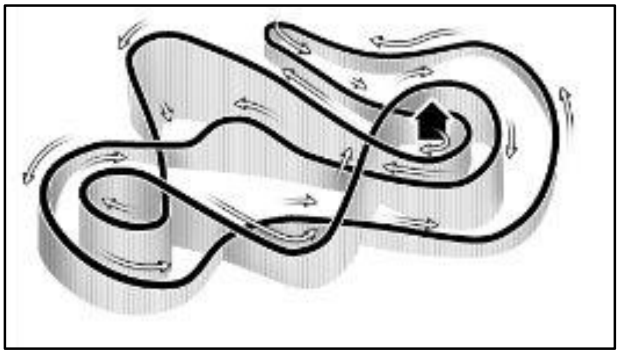
WHAT:	Pendulum ride (Driven, not free pendulum)
WHEN:	4.April.1980
DESIGNED and CONSTRUCTED BY:	Intamin (Pirate Ship, Bounty)
MAXIMUM SWING ANGLE:	170 degrees
LENGTH OF BOAT:	14 meters
NUMBER OF SEATS:	10 rows; 5 per row
NUMBER OF GUESTS PER HOUR:	700
MINIMUM ACCELERATION:	0.4 g
MAXIMUM ACCELERATION:	1.4 g
POWER OF SWING MOTOR:	52200 watt reversing DC drive
MAXIMUM TANGENTIAL SPEED:	12.5 meters per second
PENDULUM RADIUS:	13.9 meters
DURATION OF RIDE:	2.0 minutes

XCALIBUR

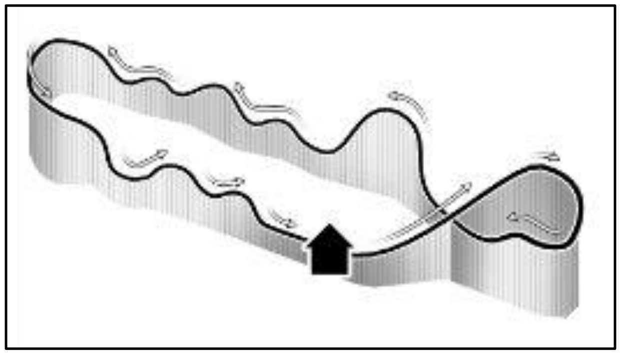
WHAT:	Dual axis vertical spinning ride
WHEN:	2003
DESIGNED and CONSTRUCTED BY:	Nauta Bussnik Baily
RIDE SEATING:	16 cars; 4 passengers per car
NUMBER OF PASSENGERS PER HOUR:	1100
HEIGHT ABOVE GROUND OF FULL SWING:	about 33 meters
MAX SWING ANGLE:	360^{o} degrees
PENDULUM LENGTH:	about 16 meters
PLATFORM DIAMETER:	14.2 meters
DURATION OF RIDE:	2.0 minutes

Selected Roller Coaster Track Layouts

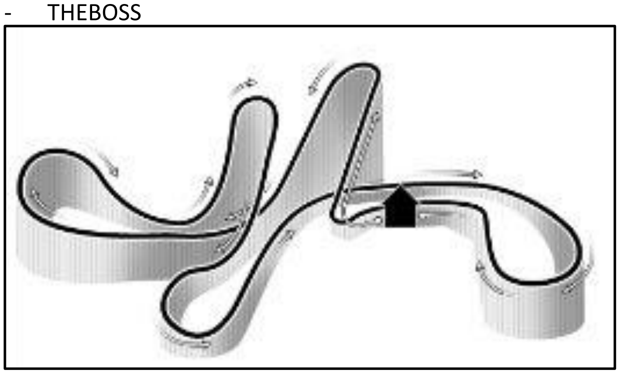
AMERICANTHUNDER



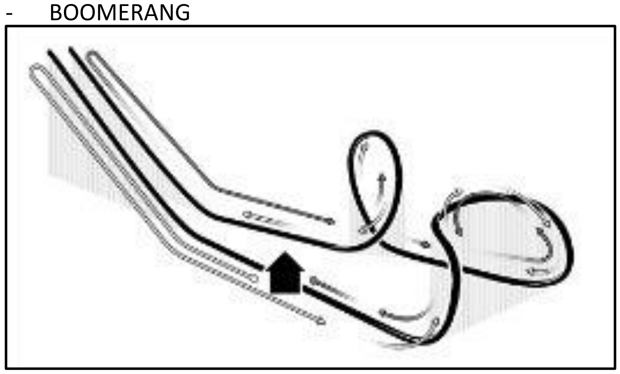
SCREAMIN'EAGLE



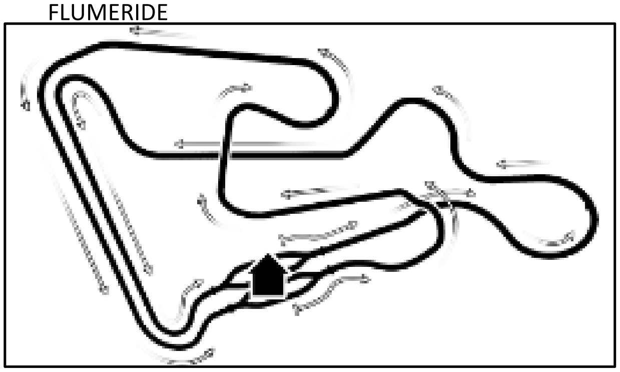
- THEBOSS



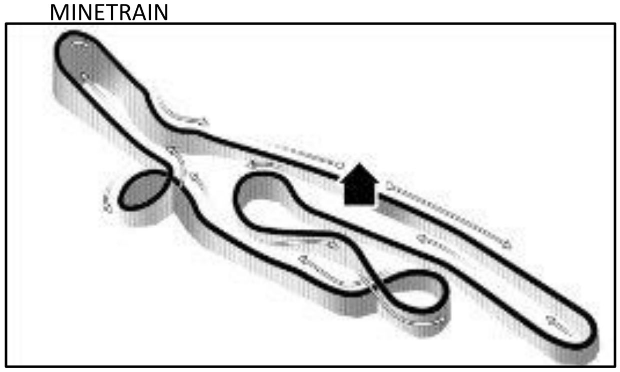
- BOOMERANG



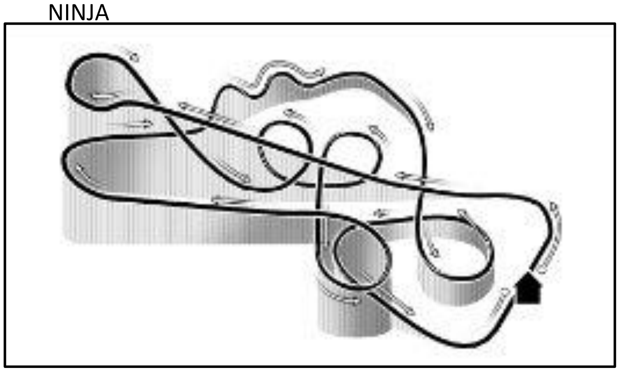
FLUMERIDE



MINETRAIN



NINJA



Amusement Park Physics Resource List

Articles from Periodicals

Bartlett, Albert A., "Which Way is ‘UP’ or the ‘Force of Gravity’ in Some Simple Accelerated Systems." *The Physics Teacher,* Volume 10, Number 8, pp. 429-437. November 1972.
Article on defining frames of reference.

Escobar, Carole, "Amusement Park Physics," *The Physics Teacher,* Volume 28 pp. 446-453. October 1990.
Excellent background source for teachers.

Exploratorium Quarterly, Volume 11, Issue 2. Summer 1987 (entire issue).
This has a broad review of the science and talks of illusions in the carnival area.

Jones, Christopher, "What a Blast," *Compressed Air,* Volume 103, Number 6, pp. 22-29. September 1998.
The only review to date of a new kind of thrill ride that runs on compressed air.

Monteiro, Martin and Arturo Marti, “Resource Letter MDS-1: Mobile devices and sensors for physics teaching,” *American Journal of Physics,* Volume 90, Number 5 pp 328-343, May 2022.
Excellent review of phone apps, how they work, and related articles for classroom use.

McGehee, John, "Physics Students’ Day at Six Flags/Magic Mountain," *The Physics Teacher,* Volume 26, Number 1, pp. 12-17, January 1988.
Description of Physics Day at Six Flags/Magic Mountain.

Natale, Kim "Final Exam in an Amusement Park" *The Physics Teacher* 23, no. 4 (1985): 228

Roeder, John L., "Physics and the Amusement Park," *The Physics Teacher,* Volume 13, Number 6, pp. 327-332. September 1975.
Discussion of field trip and some science of the amusement park.

Summers, Carolyn, and Howard Jones "Roller Coaster Science" *Science and Children* 21, no. 2 (Oct. 1983): 2-14

Taylor, George, Joseph Page, Murray Bentley, and Diana Lossner "A Physics Laboratory at Six Flags Over Georgia" *The Physics Teacher* 22, no. 6 (September 1984): 361-367.

Walker, Jearl, "The Amateur Scientist," *Scientific American,* Volume 249, Number 4, pp. 162-169. October 1983.
An excellent non-mathematical article detailing the physics of numerous rides.

Bound Materials

Anderson, Norman, *Ferris Wheels: An Illustrated History*, Bowling Green State University Popular Press, 1992. ISBN 978-0879725327.

An outstanding scholarly work on the history and construction of Ferris Wheels. Includes numerous references, patent drawings, etc.

Bakken, Clarence, *Amusement Park Physics, 2nd* Edition, Amusement Park Physics Handbook Committee, American Association of Physics Teachers, College Park, MD. 2011.

This is an excellent update to Carole Escobar's book (below). It has an excellent section on electronic accelerometers. ISBN 978-1931024129

Cartmell, Robert, *The Incredible Scream Machine: A History of the Roller Coaster,* Amusement Park Books, Inc., Fairview Park, OH 44126. 1987. ISBN 978-0879723415.

History and construction of roller coasters. Some engineering notes.

Escobar, Carole, editor, *Amusement Park Physics Handbook,* Amusement Park Physics Handbook Committee, American Association of Physics Teachers, College Park, MD. 1989. ISBN 978-0917853539.

Major resource for teachers. Includes activities and The Physics Teacher article reprints.

Gryczan, Matthew, *Carnival Secrets. How to Win at Carnival Games, Which Games to Avoid, How to Make Your Own Games*, Piccadilly Books, Colorado Springs, CO, 1993. ISBN 978-0941599248.

Outstanding paperback that discusses the science, probability, and construction of carnival games. Some can be easily made into physics labs.

Mangels, William F., *The Outdoor Amusement Industry: From Earliest Times to the Present, 1952.* Library of Congress Catalog Card Number: 52-13299.

History of amusement parks and carnivals.

Martensson-Pendrill, Ann-Marie, *Physics for the Whole Body in Playgrounds and Amusement Parks,* American Institute of Physics Publishing, 2022. ISBN (Print): 978-0-7354-2351-0.

Exceptional text and resource. Very detailed and extensive.

Munch, Richard, *Harry G. Traver: Legends of Terror*, Amusement Park Books, Mentor, OH. 1982. ISBN 0-935408-02-9

Biographical information about a roller coaster designer. Contains track layouts.

Unterman, Nathan A., *Amusement Park Physics: A Teacher's Guide, Second Edition;* J. Weston Walch, Publisher, Portland, ME. ©2001. ISBM 978-0825142644.

Major resource for teachers. Includes question bank, activities, and background.

Weisenberger, Nick, *Coasters 101: An Engineer's Guide to Roller Coaster Design*, self-published, ©2015. ISBN 978-1468013559.

Good engineering background. Some formula and conceptual errors.

Phone Apps

phyphox Physical Phone Experiments
https://phyphox.org/

Vieyra Software
Physics Toolbox
https://www.vieyrasoftware.net/physics-toolbox-sensor-suite

Web Materials

St. Louis Area Physics Teachers
http://www.slapt.org/resources/sixflags/index.html

The Physics Classroom
https://www.physicsclassroom.com/

Physics World
https://physicsworld.com/a/twists-turns-thrills-and-spills-the-physics-of-rollercoasters/

Lund University
https://tivoli.fysik.org/english/

Videos

Scientific American Frontiers – The World of Science with Woody Flowers, PBS, 8:00 p.m., October 10, 1990

America Screams, Hosted by Vincent Price. Rhino Home Video, RNVD 1419, 1987

NOVA: Roller Coaster! NOVA Season 21, PBS WGW706, November 1993

**Video analysis software is available from many sources. Search, *video analysis software*.

**There are many videos on YouTube and other places on the Internet. Care should be taken in selecting these, as many do not treat the science and engineering accurately.

Suppliers

Pasco Scientific
800-772-8700
http://www.pasco.com/

Vernier Software & Technology
888-837-6437
http://www.vernier.com/

Physics Toolbox
http://www.vieyrasoftware.net

phyphox Physical Phone Experiments
https://phyphox.org