The Static Stability Factor –
A Dynamic Introduction to Engineering

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Abstract

Most students want to become engineers so they can design and build things. An introductory course in engineering should pique those interests and provide information and activities which show the breadth of the field of engineering. This paper presents a series of laboratory activities based on the Static Stability Factor (SSF), used in vehicle design to determine under what conditions a vehicle will spinout or rollover.

The student interest is natural. Many students have been involved in spinouts and even rollovers during their driving experiences which lead them to be curious about the factors that are significant. They can usually guess that the trackwidth and the weight (more correctly, the center of gravity) of the vehicle are significant. The SSF is equal to one-half the trackwidth of the vehicle divided by the height of the center of gravity. Hence, it is easy to understand and manipulate. This leads to a simple series of experiments using five similar vehicles with varying trackwidths. These are:

1) Determination of rollover angle and calculation of the center of gravity.
2) Measurement of sliding friction leading to rollover.
3) Stability measurement on a rotating table.
4) Demonstration of superelevation using a ramp on the rotating table.

Topics which can be discussed are broad and represent some of the spectrum of engineering, including friction and interfaces, vehicle design, experimental measurements and errors, experimental safety, graphical presentation, data acquisition instrumentation and control, road and traffic safety, effects of tires and suspension systems and vehicle stability alarms. This is also related to the design and construction of the Mars Rover Vehicles through an excellent NOVA video entitled "Mars: Dead or Alive" on the interaction between engineers and scientists.

Introduction

The University of Wyoming College of Engineering has had a required 1 hour introductory freshman course for over 12 years. Entitled ES1000 – Orientation to Engineering, it was originally developed under a University Studies Program which was created to insure that all university graduates have a general core curriculum. The course as it was initially implemented had some very broad requirements with little flexibility in regard to specific college needs.

However, as the course matured, many of the original requirements were relaxed or dropped so that the courses could be better adapted by the individual colleges.

One consequence of this relaxation of requirements allowed the engineering course to implement a "Design Challenge" for the freshman students to construct and test models under extreme conditions.[1] Four challenges have been developed, including designing and constructing:

- Foamcore vehicles which will protect an egg from a sledgehammer blow on the rear and side,
- Balsa wood aircraft which had to be launched from a spring loaded launcher,
- Mousetrap cars that have to complete a slalom course, and
- Motorized vehicles which must traverse a course made of sand and clay and crossing a bridge.

The students have eight weeks to develop their device and are limited to a cost of $15.00 to $20.00 or less. The students have indicated that the Design Challenge has been the most interesting aspect of the course.

A second consequence of the university requirement relaxation has been to give more time for professors to present topics which they believe the students would find useful and interesting in engineering. Currently there are about five 30 minute blocks of time available throughout the semester during which topics such as design process, team building, creativity and the design challenge are discussed. This paper is focused on a project which relates to several areas of engineering, deals with experimental design and errors and provides an opportunity to discuss the nature of decision making in design.

SUV's, Rovers and the Static Stability Factor

Most students want to become engineers so they can design and build things. An introductory course in engineering should pique those interests and provide information and activities which show the breadth of the field of engineering. In order to give some insight into engineering design, a topic should show how the design process implements the principles of physics and modeling so engineers can make intelligent decisions about the design, its construction and its safety. An example involves vehicular safety in regards to stability and rollover resistance in extreme or emergency situations.

The student interest is natural. Based on an informal survey in two ES1000 classes in the fall of 2004, as many as 50% of the students have been involved as drivers or passengers in spinouts and almost 25% involved in rollovers during their driving experience. When presented with information that 12,000 people have died in rollover accidents over the previous ten years[2], they become curious about the factors that are significant in rollovers and spinouts. They can guess that trackwidth, tires, weight, speed and road conditions are significant factors in automobile accidents.

These factors are significant in off-road vehicles as well, including the two most off-road vehicles in the solar system, the Mars Rovers *Spirit* and *Opportunity*. This becomes the lead-in for presenting a video from the NOVA series from PBS titled "Mars-Dead or Alive."[3] The video (and the accompanying website, http://www.pbs.org/wgbh/nova/mars/) shows in graphic detail how scientists and engineers work together to solve one of the greatest problems in space research, how to successful land a vehicle to work autonomously on another planet. This work was described by Tau Beta Pi as one of three "amazing American engineering teams [which] stunned the world with their record-smashing achievements in flight and on the surface of Mars in 2004."[4] The video is also excellent in describing the nature of engineering design, consisting of repeated hypothesis, testing, evaluation, analysis and new hypothesis until the problem is solved.

The problem of vehicle stability is then described based on the Static Stability Factor (SSF), the ratio of the one-half the trackwidth T divided by the height of the center of gravity H of the vehicle. Penny[5,6] has derived expressions for the SSF based on

- The angle of tilt of the vehicle prior to rollover, $SSF = \frac{T}{2H} = \tan(\phi)$,
- The velocity v of the vehicle around a turn of radius r, $SSF = \frac{T}{2H} = \frac{v^2}{rg}$,
- The effect of surface slope ϕ around a turn, as in superelevation on a road surface,
  $$SSF = \frac{\frac{T}{2H} - \tan(\phi)}{\frac{T}{2H}\tan(\phi) + 1} = \frac{v^2}{rg}$$, and
- The effect of road surface friction μ_k on rollover and sliding, $SSF = \left.\frac{T}{2H}\right|_{critcal} = \mu_k$.

Together, these suggest three experiments and a demonstration that were used this past semester.

The Experiments

Two sets of five model vehicles were constructed using Baltic birch plywood, #10 all-thread and wooden wheels as shown in Fig 1. Baltic birch was selected for its consistency and lack of voids so when all ten vehicles were completed, their masses were within 5 grams of average. Adjustments with washers and nuts produced two groups, one with an average mass of 332.5±0.4 grams and the other with an average mass of 330±0.2 grams.

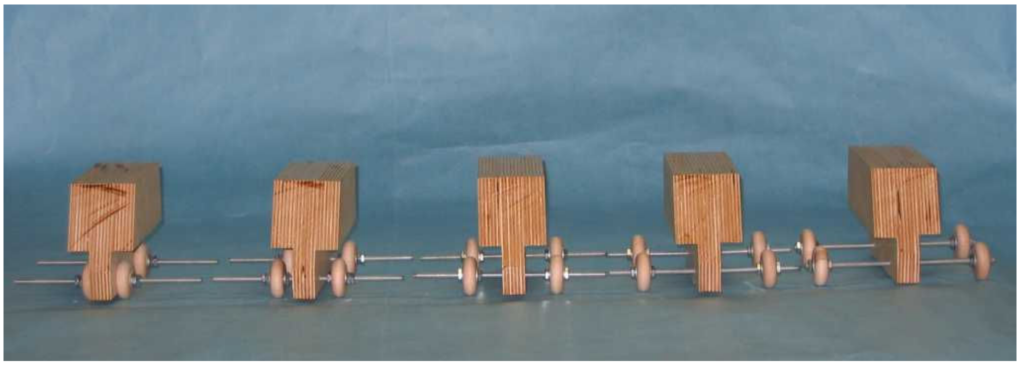

Figure 1 - Five Wooden Vehicles with Differing Track Widths

Each set has vehicles with differing trackwidths of 30 mm, 50 mm, 70 mm, 100 mm and 130 mm, respectively. Two sets were made of all items because two ES1000 classes are taught concurrently so each class can have its own set.

Two sets of ramps were constructed. The simple ramps are just 250 mm boards with a lip on them that act like curb stops. As the ramp is lifted, the lip forces the vehicle to tip over. The second set of ramps have differing surfaces on them

Experiment 1 – Determination of Rollover Angle and Calculation of Center of Gravity

This is a simple experiment. The class is divided into five groups of four. Each group gets one of the vehicles. The vehicle is placed on the ramp with the wheels next to the curb. The ramp is slowly lifted until the car tilts. The students measure the height of the edge of the ramp and determine the tangent of the tilt angle ϕ. This is repeated five times and then the vehicles are exchanged until each group has determined the tilt angle for each trackwidth.

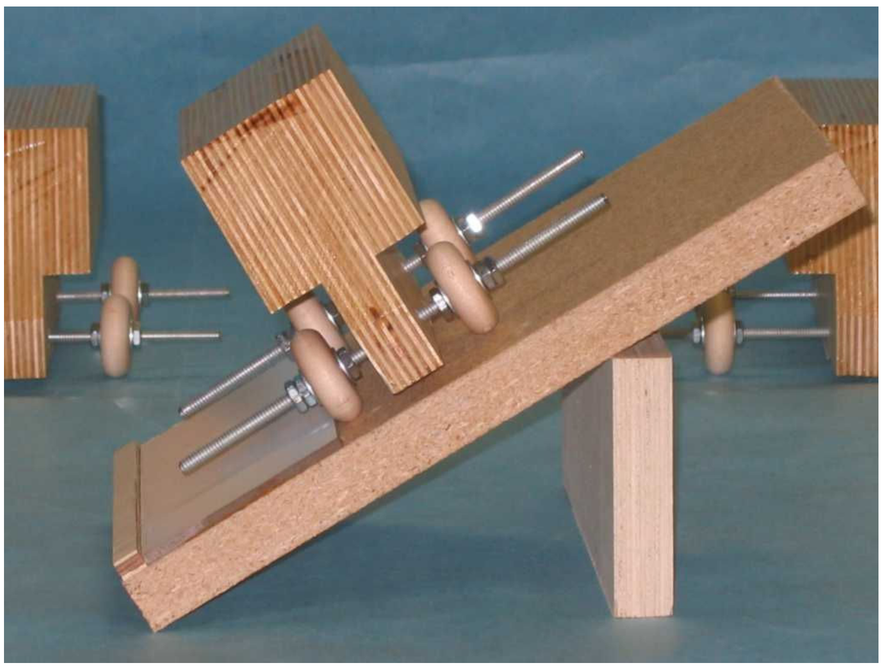

Figure 2 – Rollover Test to Determine SSF

Figure 3 shows a set of results from one group. The trend shows a straight line between the rollover angle and the trackwidth, as would be expected because of the uniformity in vehicle size and weight. The center of gravity is calculated by dividing the trackwidth by two times the tangent of the rollover angle. The height of the center of gravity is 41.1±1.2 mm.

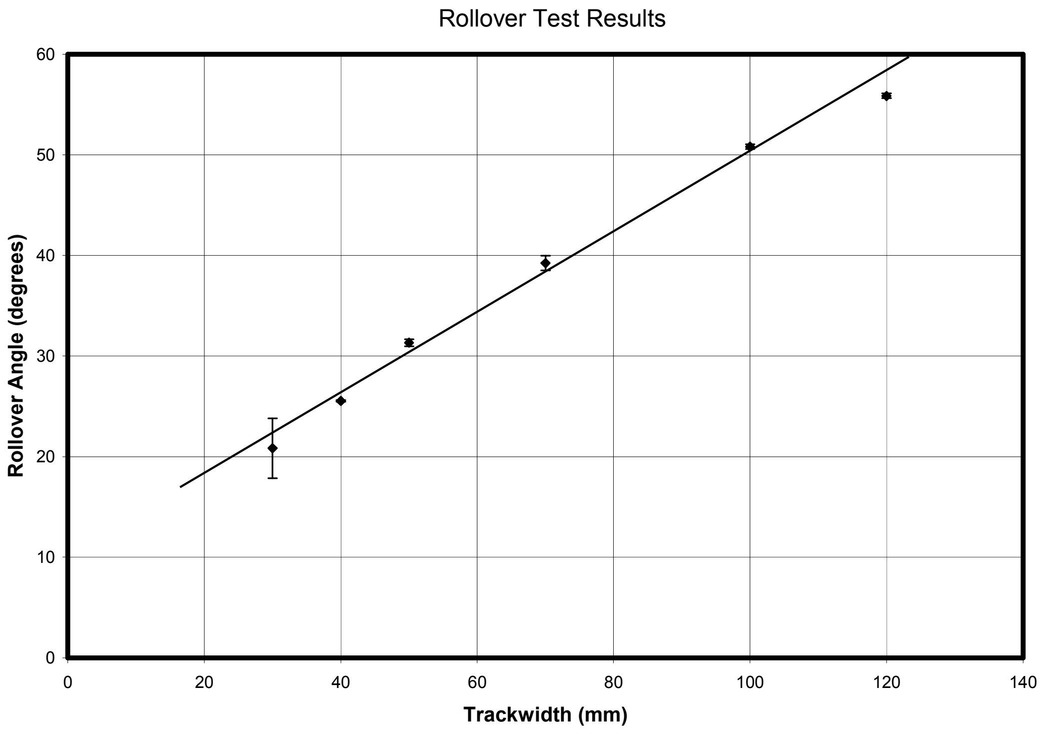

Figure 3 - Rollover Angle as a Function of Trackwidth

The point at 30 mm trackwidth shows the standard deviation error bars (as do the other points as well). Other data sets often show more error. This is a good time to discuss the nature of the errors. There are a number of error sources even in this simple test. The students describe the difficulty in maintaining the angle while the measurement is being made, determining the exact point where the vehicle tilts, and others. The errors can be described and calculated. The errors can be summed and shown to equal zero, providing no new information. The errors can then be squared and summed. Finally, the standard deviation of the measurements can be calculated for each point. Finally, the nature of the trend line can be discussed. This simple experiment provides a number of good examples for experimental analysis at an unambiguous level.

Experiment 2 – Sliding Friction Leading to Rollover

This experiment uses the second set of ramps. Each ramp has a different surface on it including a smooth bath paneling, an aluminum panel, a natural wood surface, a 120 grit sandpaper and a 40 grit sandpaper. Each group has a ramp and is asked to repeat the previous experiment. In this case, some vehicles will tilt over like before and others will slide on the surface. The students are then asked to measure the angle at which the vehicle tilts or slips. Figure 4 shows two vehicles on a ramp with a 140 grit sandpaper surface. The lower vehicle with a narrow 50 mm trackwidth is tilting at this angle. The higher vehicle with a trackwidth of 100 mm is still stable and may tilt or slide at a greater angle.

Figure 4 - Friction Tilt Ramp with 140 Grit Sandpaper Surface

The results of this test are shown in Figure 5. In all cases, the vehicles slipped on the bath panel, the aluminum and the wood. The vehicles rolled on the sandpaper surfaces except for the two widest trackwidths where they slipped. Slippage is defined by the coefficient of friction, i.e., the tangent of the slip angle. In general, the students are able to state that when the coefficient of friction is less than the Static Stability Factor, the vehicle will slip in a turn. When the

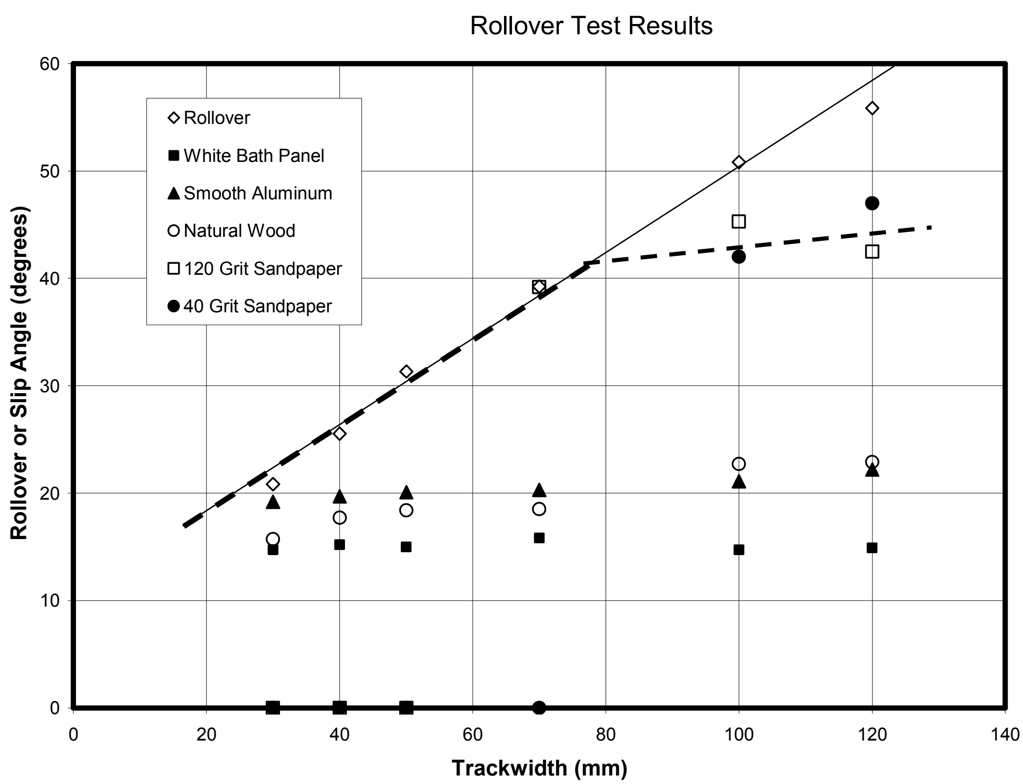

Figure 5 - Sliding Friction Results

coefficient of friction is greater than the SSF, the vehicle will rollover in a turn. A critical SSF can be defined as one which equals the coefficient of friction of the road surface. Therefore, it can be hypothesized that the heavy dashed line represents the stability curve for the sandpaper and that the break in the curve is the critical slip angle.

In addition, this data set shows that the bath panel is so smooth relative to the wooden wheel on the vehicle that the coefficient remains constant. The two other materials appear to increase in friction coefficient as a function of trackwidth, indicating that there may be some interaction between the surface and the wooden wheel that was not present on the bath panel.

Experiment 3 – SSF Measurement on a Rotating Table

The third experiment measures the vehicle's SSF on a rotating table, shown in Figure 6. The table has two hinged segments which are covered with 40 grit sandpaper. In addition, there are fixed walls at the ends of the sections and Velcro loops to loosely constrain the vehicles.

Figure 6 - Rotating Table with a Flat Surface on the Right and a Superelevation on the Left

The Static Stability Factor can be determined using the relationship $SSF = \frac{T}{2H} = \frac{v^2}{rg}$ where v is the linear velocity of the vehicle spinning at a radius r from the center. The velocity is obtained by determining the speed of rotation of the table when either the vehicle slides to the outside or when it rolls over. While the process is simple, the tachometers available were not sensitive enough to give an accurate rotation rate at failure. Rates were estimated and the calculations indicated that the process produced appropriate results.

The significance of experimental safety can be discussed in this experiment. When the table was first constructed, one of the wide trackwidth vehicles was placed on the sandpaper before the Velcro was put on. When the vehicle reached the critical speed, the vehicle flipped over and caught on the vertical plate by the two inside wheels. Had those wheels not caught, the vehicle would have been thrown complete off the table.

Experiment 4 – Demonstration of Superelevation

The left section in Figure 6 shows the section tilted up to produce a superelevation for the vehicle. While a relationship is available to calculate the SSF, it was just shown as a demonstration that greater tilts allow the table to rotate faster, which translates into a faster velocity around a turn when compared to the flat surface.

An interesting result is indicated in the figure. The vehicle is at a tilt that is close to its SSF, i.e., it is close to tipping over at this slope. Had the surface been the bath panel with the low value of friction, the vehicle would have slipped down the slope. The practical consideration is if the road is icy, it is possible for the superelevation to be great enough to cause the vehicle to slide into the center if it is traveling at a low rate of speed.

Additional Considerations

This set of seeming simple experiments provides a wealth of information to discuss about the engineering design process. These topics include:

- Vehicle Design,
- Experimental Design,
- Source of Errors,
- Defining Mean and Standard Deviation,
- Interpretation of Results and Trends including Graphical Presentation
- Data Acquisition instrumentation and control,
- Friction and interfaces,
- Experimental Safety, and
- Orientation to the Engineering Disciplines

In fact, there is so much that could be discussed that the time is not sufficient for the work. Much of this work can be done independently of class. The experiments could be described during the normal class time and the students could do the work for the next class.

It was easy to add a component of this design to the Design Challenge. I required my classes to have a minimum SSF of 1.12 for their Martian Dune Buggies. This was sufficient to cause several of my groups to be disqualified. However, since the additional criterion was not required for everyone, I didn't disqualify them from any of the general awards.

The models would be easy to transport to junior and senior high schools and could be used as a simple demonstration in the Physics courses or to math and science students in general.

Conclusions

The experimental study of the Static Stability Factor is an excellent component for the freshman Orientation to Engineering course. Its concept is easy to understand, it is easy to model and it produces data which permits a straight forward analysis of the data. In addition, a simple error analysis can be performed to define the mean and standard deviation about a point and provide an understanding of the nature of the trend. Students are naturally interested in the topic and the analysis because it correlates with their own experience. The components are easy to produce and are rugged enough to be able to use in high school and middle school presentations.

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Biographies

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