EN4: Dynamics and Vibrations
Laboratory 2: Tipping Resistance of a Baby Walker

1. Introduction

In this lab, you will investigate the tip resistance of one design of baby walker. In particular, you will: (a) perform the ASTM safety standard F977-03 stability test (section 7.3), and (b) test the simple theoretical model developed in the HW #7: Babywalker Analysis (in Appendix B), by measuring the critical speed at which the walker will overturn when hitting obstacle. Part (b) will require you to make measurements to enable you to characterize the rolling resistance of the walker as well; we leave it to you and your lab-mates to decide on a means of doing this.

2. General Instructions

- Before you perform the experimental part of the laboratory, you should read the ASTM standard carefully. Pay particular attention to Section 7.3 *Stability Test*, and Section 7.6, *Step Test.* Note that you will not be carrying out the step test directly, but using the mass/pulley system described in that section to accelerate your walkers.
- The experimental measurements will be done by groups of 5 or fewer students. Three groups may do the experiment at one time.
- Final reports are due Friday, April 6, 5:00 pm, to Mrs. Stephanie Gesualdi on the 7th floor.

3. Tests to be performed:

(i) The ASTM stability test (section 7.3 of the standard). This will determine the walker's Stability Index and ensure the walkers ability to resist tips due to leaning over.

(ii) A test that will eventually allow a determination of the critical speed required to overturn the walker.

(iii) A test to determine the rolling resistance of the walker.

4.1 Preliminary Measurements

(i) Record the model of baby walker that you are using. Weigh the walker (without a crash dummy) using the spring balance provided.

(ii) The walker you will test has an adjustable height. Put the seat at its highest setting and place a ~17lb baby model in the walker; use the bungee chord to strap it in place. Weigh the baby model by the spring balance. Locate the position of the center of mass of the system above the base of the walker. Do this by suspending the walker from a single point. Note that the COM must lie vertically below the point of suspension and must also lie in the symmetry plane of the walker.

(iii) Measure the wheelbase dimension b for the front and rear contact points on the bumper. Note that b may be smaller for a rear collision than a frontal impact. Record any other dimensions that you think might be helpful in predicting the stability.

4.2 Obstacle Tests

Perform the ASTM stability test on the walker, following the instructions in Section 7.3 of the ASTM safety standard. Use the wooden frame as an obstacle, and use a ~17lb crash dummy. Instead of attaching the pull rope to the crash dummy, attach it to a sensible point on the walker. In practice, a baby's armpits are generally level with the top of the tray.

4.3 Dynamic Stability Test

(i) Place a ~17lb crash dummy in the walker and set the walker to its maximum height. Make sure the dummy is firmly bungee-chorded to the walker.

(ii) Connect the cable to the front of the walker and place the front edge of the bumper a distance of 12 inches from the obstacle. Align the walker so that it will hit the obstacle head-on. Run the cable over the pulley and attach a ~17lb weight (for some cases, you may need more weights to tip the walker over) to the cable end. Release the walker and observe what happens once the obstacle is encountered.

(iii) Assuming the walker did not tip over, repeat the test in part (ii) starting the walker farther back from the obstacle, thereby increasing its collision speed. Each time, record the starting distance and continue the repetition until you have determined the critical distance necessary to overturn the walker. At this critical distance, the walker’s center of mass will just barely make it to the point vertically above the obstacle.

(iv) Repeat the tests for reverse impacts. Keep the walker set to its maximum height for all the tests.

4.4 The rolling resistance

In order to relate the walker speed on impact and the starting distance in the dynamic, you must have an expression for the rolling resistance of the walker. In this part of the lab, you are asked to decide as a group, how you would like to measure this. Any or all of the materials you have used in the previous parts of the lab may be used. Some additional materials are also provided such as angle measures and scales. It is suggested that you measure the resistance several times using at least two different methods. This way will enable you to give a reasonable average measure of the resistance and an estimate of the accuracy of this average.

5. Report Format

(i) **Cover sheet** should show a title, your name, the names of the other members of your lab group, and the date the experiment was performed.

(ii) **Introduction: S**ummarize the objective of the report and give any background information that you think is relevant. Outline the results that will be presented in the report and summarize the conclusions. It should be as short as possible (300 words).

(iii) **Theory:** Present briefly the model that you developed to predict the conditions necessary for a walker to overturn. Outline the idealization; describe the steps in the calculation and give the result. Show the graph of b-v-h from your previous homework and compare it with the ASTM safety index. Comment on the comparison.

(iv) **Experiment:** Describe the experiments and the results. A subsection should be devoted to a description and discussion of your rolling resistance experiment and its result and your assessment of its accuracy. Give the final experimental result for the tipping speed of the walker, and discuss its accuracy. Compare the predictions of the theory for the dynamic test.

(v) **Conclusions**: Evaluate the ASTM safety test and suggest changes if you think they are appropriate. In particular, think about whether there are any circumstances in which a walker could pass the ASTM test, but be unsafe. Note that the objective of the ASTM code is to provide manufacturers with the simplest possible test that will determine whether a walker is resistant to overturning. Is the dynamic test that you performed here a better test of stability? Can you devise a better dynamic test? In addition, think about changes to baby walker design that would improve their safety.

General instructions on report: Presentation is important. If possible, your report should be prepared using a word processor and printed using a good quality printer. All graphs should be clearly labeled; axes should be labeled with the variables and their units. Make sure your report is well organized; and present topics in a systematic way. Written style is important too: make sure your sentences are well structured; don't switch between tenses in a paragraph; avoid using the same word too many times in successive sentences. It is considered bad form to use the words `I' and `We' in technical reports. Try reading your report aloud: if it doesn't sound good, it's badly written. Above all, be brief. Your reports will be judged by the quality and number of ideas in it, not by their length. A significant proportion of the grade for your report will also be awarded for presentation and written English. If you find writing difficult, you are welcome to ask the graduate TAs and professors for help.

APPENDIX A: Pre-report and a lab note to perform the experiment

EN 4: Dynamics and Vibrations

Brown University, Division of Engineering

LABORATORY 2: Tipping Resistance of a Baby Walker

Date and Time ____

Team Name: ____

Your Name: ____

Other Members 1)____

2)____

3)____

4)____

Teaching Assistant Initials ____

* Every student must bring in this two-page pre-report before the experiment is carried out and the pre-report signed by a TA must be attached to the final report to get full credit.

Page 1

Objectives and Preliminary Introduction (less than half page with font 12)

Brief Description of Experimental Procedure (less than half page with font 12)

* This page must be filled in before you come to the lab to carried out the experiment.

Page 2.

Laboratory Note

Team Name: ____________________ Date: ____________________

TA signature ____________________

Record on-site observations and calculations on this page

* Each team must bring in one set of this three-page Laboratory Note printed, and the note filled in during the experiment must be signed by a TA when the experiment is completed. Copies of the filled-in note must be distributed among the team members, to be used for individual data processing. The copies must be attached to the final report.

Table 1: Stability Index Test

Weight of Walker (lb)			Weight of baby dummy (lb)
Forward tipping	*d* (inch)	Tipping force *F* (lbf)	Stability Index I
Rear tipping	*d* (inch)	Tipping force *F* (lbf)	Stability Index I

Table 2A: Dynamic Stability Test

Weight of the accelerating block (lb):		
Forward tipping		
Test #	Acceleration Distance (inch)	Tipping (Y/N)
1		
2		
3		
4		
5		
6		
7		
8		
9		
Rear tipping		
Test #	Acceleration Distance (inch)	Tipping (Y/N)
1		
2		
3		
4		
5		
6		
7		
8		
9		

Table 2B: Rolling Resistance Test (prepared by yourself)

Appendix B: Predicting the Safety of a Baby Walker Guidelines for theoretical analysis

1. Introduction

Baby walkers are designed to give infants a means of mobility before they are old enough to crawl or walk. All baby walkers sold in the USA must conform to the ASTM safety standard F977-03. (A full copy of the ASTM standard was distributed in class. Copyright restrictions do not allow us to make the standard available online). Organizations such as the Juvenile Products Manufacturers Association certify products that conform to the standard. The standard is intended to guarantee that baby walkers are safe. For example, it requires that holes or slots in the walker are large enough that a baby's fingers don't get trapped, that any springs attached to the walker be covered, and that no part of the walker will pinch or cut a child during normal use or reasonably foreseeable misuse. In addition, the standard requires that all baby walkers be subjected to a series of tests, which were devised to ensure that (i) a baby walker will not break under the forces acting on it during normal use, (ii) the walker will not easily tip over when hitting an obstacle, a ledge, or when a child leans over.

Despite these rigorous safety standards, walkers are dangerous pieces of equipment. According to a study by the Harborview Injury Prevention & Research Center, there are approximately 29,000 children treated in hospital emergency rooms for baby walker-related injuries. Many more are injured but go to physicians' offices and clinics. The number of injuries has more than doubled in the past 12 years. There is at least one death per year.

The United Kingdom's Child Accident and Prevention Trust asserts that 30% of all children using baby walkers experience an injury. Pediatricians have recommended banning baby walkers due to the large number of walker related injuries. Nevertheless, walkers remain popular: babies seem to enjoy using them, and parents are usually desperate to keep their young children entertained (and quiet!) Although a few alternatives to the standard walker design have been developed, they are not likely to replace the conventional baby walker in the foreseeable future. Here is one design that looks as if the baby could safely go over Niagra Falls!

The Harborview Injury Prevention & Research Center states that approximately 60% of baby walker related injuries are due to falls down stairs. The bulk of the remainder are due to burns occurring when the child touches a heater, stove, or hot liquid such as coffee. A smaller, but significant percentage occurred because the walker tipped over when it hit an obstacle, such as a threshold or the edge of a carpet. The aspects of the walker safety you will be testing are those pertaining to the walker's ability to hinder stairway and obstactle induced falls. This computer assignment concerns the obstacle-tip aspects.

2. Calculation

Here, you will develop a simple theoretical model which predicts whether the walker will overturn when it hits an obstacle, and you will use your theoretical results to evaluate the ASTM standard which regulates the tipping resistance of a walker design. In Lab #2, you will test the predictions of your theory experimentally.

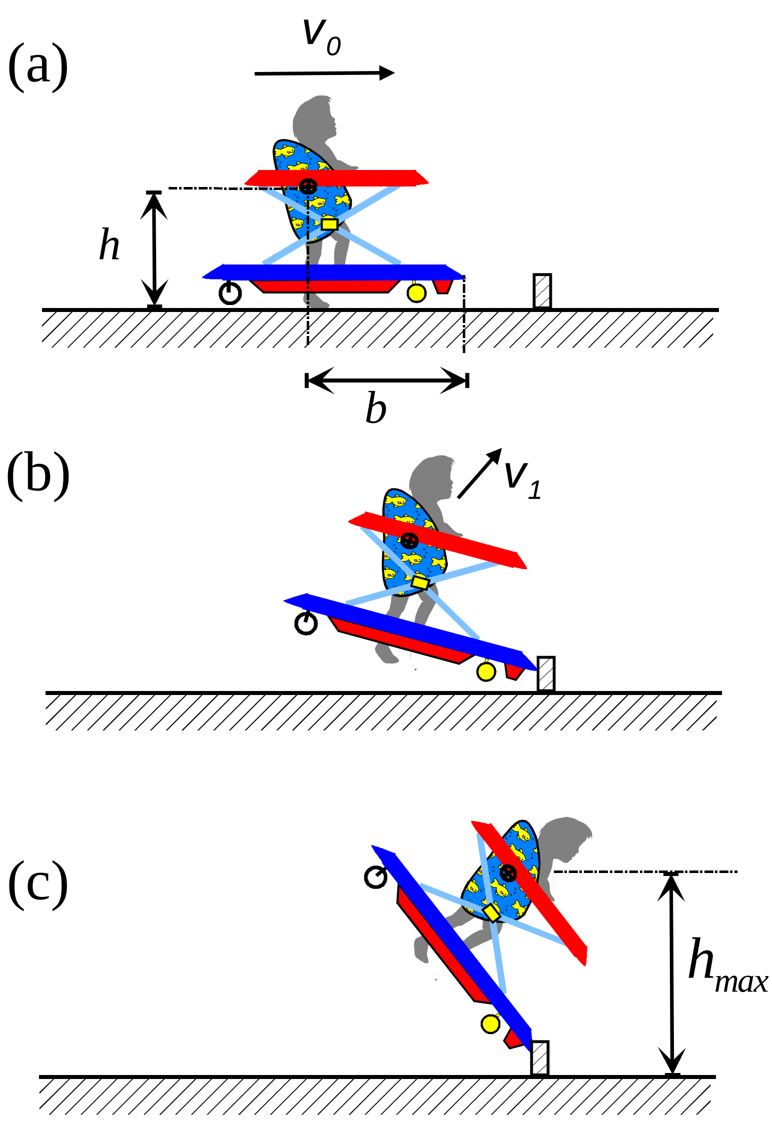

Fig. 1: A walker hitting an obstacle

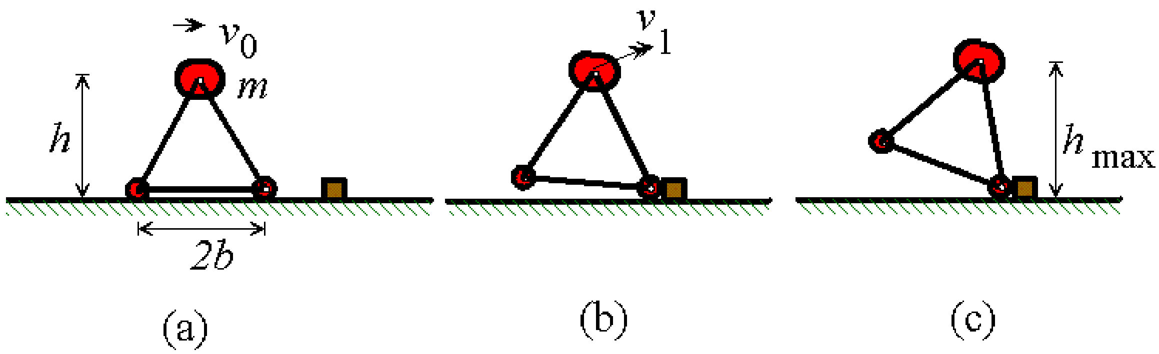

Fig. 2: An idealized walker hitting an obstacle

Idealize a baby walker as shown in Fig. 2: assume that the baby and walker is represented by a particle of mass m, which is supported by a rigid massless triangular frame. Let b denote the horizontal distance from the center of mass to the leading edge of the walker, and use h to denote the height the center of mass above the ground. Suppose that the leading edge the walker hits a stationary obstacle. Our objective is to find the critical speed required to overturn the walker, in terms of m, g, b and h. Let v_o denote the speed of the walker just before it hits the obstacle, Fig. 2a. Assume that the collision with the obstacle is perfectly inelastic, so that the front wheel remains in contact with the obstacle after the impact. You can use conservation of angular momentum to find the speed of the center of mass of the baby v_1 just after impact (Fig. 2b.)

Assume that the walker continues to rotate about its front wheel as it overturns. Energy conservation will lead you to an expression for the height reached by the baby's center of mass when it just stops moving, Fig. 2c. Show that the critical speed required to overturn the walker is given by

$$v_0 = \left\{ 2gh\left(1+b^2/h^2\right)\left(\sqrt{1+b^2/h^2}-1\right)\right\}^{1/2} \tag{1}$$

Next, we will predict the conditions that must be satisfied for our idealized baby walker to satisfy the ASTM safety standard. The ASTM test procedure is illustrated in Fig. 3. A crash dummy representative of a 6 month old baby is placed in the walker. The front wheel of the walker is immobilized, and a horizontal force is applied just under the crash dummy's armpit until the walker tips over. The maximum force F required to overturn the walker is recorded, together with the horizontal distance d moved by the force before loss of stability. ASTM define a `stability index' I for the walker as follows

$$I = \alpha F + d \tag{2}$$

where the coefficient α has a value of one inch per pound. The ASTM code states that I must exceed 18 inches. Show that for the idealized baby walker shown in Fig. 2,

$$F = mgb/h, \quad d = b \tag{3}$$

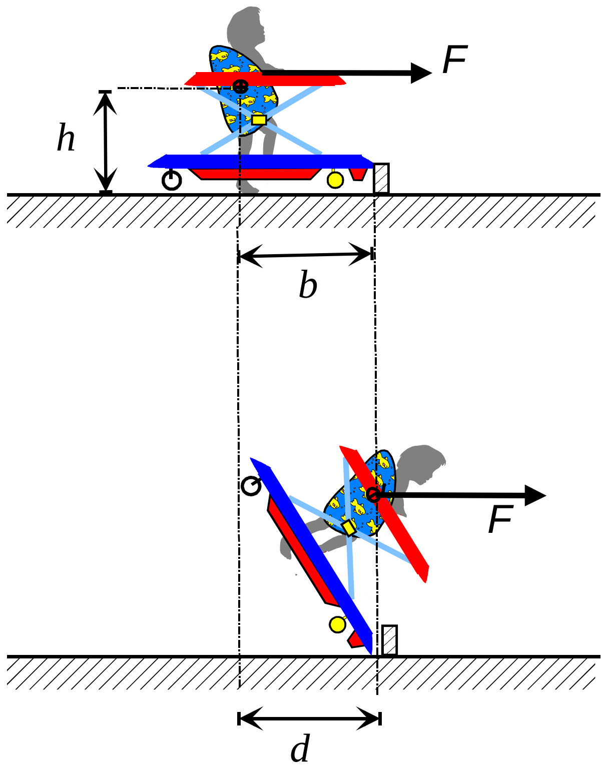

Fig. 3: The ASTM stability test

3. Computational Problem

Finally, we consider the implications of these results. ASTM's standard states that children reach a top speed of just over 4 feet per second. Other agencies, such as the United Kingdom's Child Accident and Prevention Trust, give much higher estimates: 2 meters per second. In any case, an infant whose walker is pushed or pulled by an older sibling or is moving down a ramp might go even faster. At minimum, the wheelbase of a walker should be wide enough so that a baby moving at 5 feet per second will not tip over when encountering an obstacle.

Homework#7(1)

Suppose that the baby+walker weight is mg = 17 lbs+8 lbs=25 lbs. Using Excel or MAPLE, plot a graph of the wheelbase of the walker b (in inches) as a function of the height h (also in inches) required to

- satisfy the ASTM safety standard;
- ensure that the tipping speed will not exceed V0=5ft/sec;
- ensure that the tipping speed will not exceed V0=4ft/sec;
- ensure that the tipping speed will not exceed V0=3ft/sec;

All your results should be shown on the same graph. Be careful with dimensions: everything should be in inches, inches per second, etc! Be sure to label your graph carefully and mark on it `safe' and `unsafe' regions. If you are using MAPLE, you need not solve eq. (1) for b. The desired plots b -v- h. can be made using implicitplot. This command is contained in the MAPLE package of procedures called plots. To access implicitplot and other useful plotting procedures, load the package using the command with(plots). Consult the on-line Maple help for instructions in the use of this command.

4. More calculations:

Homework#7(2)

In the ASTM standard *Step Test* (Section 7.6), the walkers are accelerated so that they are moving at a prescribed speed when they meet the edge of a stairway. The method is described in detail in the standard and discussed in the ASTM appendix X1.1. The walker is placed on a horizontal surface a distance *d* from the obstacle; a counter weight of mass *M* is attached using the pulleys as shown in Figure 4a. The mass *M* is released with the system initially at rest, causing both the walker and the counterweight to accelerate. A free-body diagram (Figure 4b) showing the horizontal forces that act on the walker including force *P* due to rolling resistance (see Figure 4b). Show that the speed v_0 of the walker upon impact is given by

$$v_0 = \sqrt{\frac{2d(Mg - P)}{m + M}} . \tag{4}$$

Homework#7(3)

Look at table 1 at the top of page 8 in the ASTM standard, and refer to the note X1.3 in the ASTM appendix. In each of the six cases, use equation (4) to calculate the value of the rolling resistance that are implicit in the step tests. Does it appear from these values of *P* that ASTM assumes the linear relation (5) appearing in Appendix C of this instruction to characterize rolling resistance? If so, what is the coefficient μ_r? (Note: M=8 lbs, weight of the walker is assumed to be 8 lbs as well for Table 1 in the ASTM standard)

End of Homework#7

When you test a walker in the lab to evaluate its performance upon encountering an obstacle, you will use the weight and pulley system in figure (4) to accelerate the walker to a desired speed. As such, you will have to have a decent estimate of the rolling resistance *P*. You will have to decide with your group on a way measure *P* for the walker with its ~17lb dummy in the lab using relatively simple tools: a spring scale, ruler, ramp, weights or other easily obtained devices. In the report you will describe the tests, explain the assumptions made (e.g. the static rolling resistance is approximately equal to the kinetic resistance), and give an error estimate for your measurements.

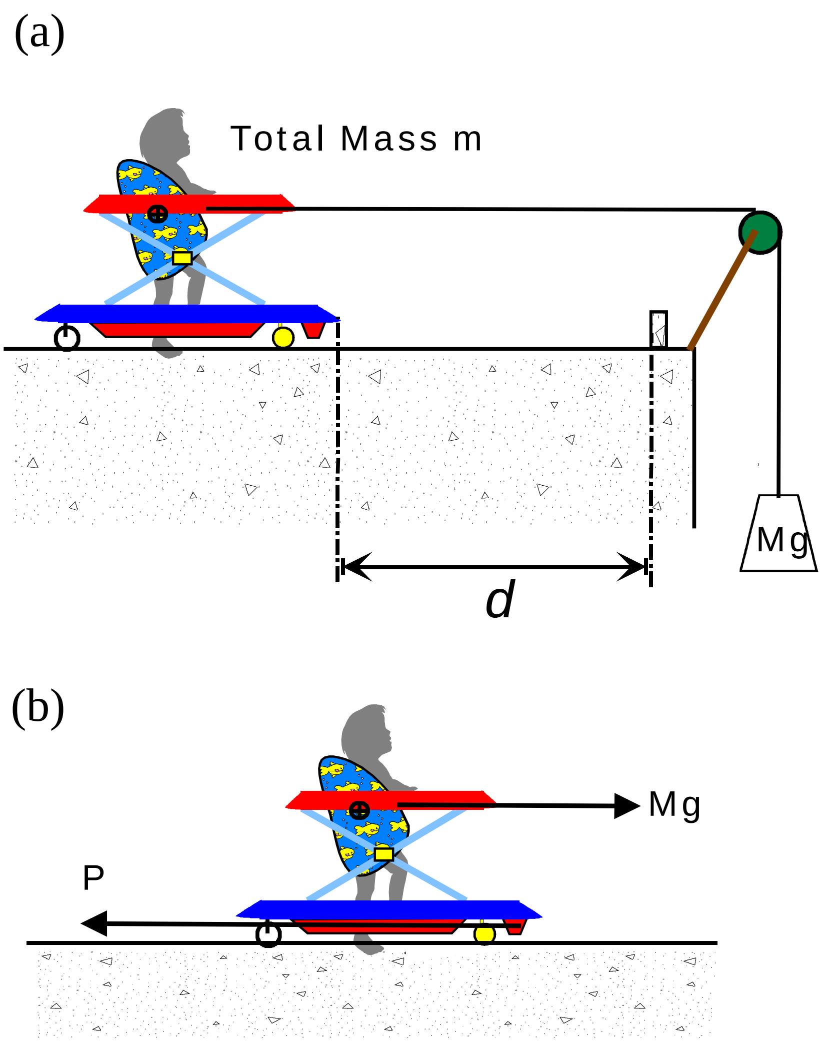

Figure 4: Acceleration of the walker using the mass and pulley

5. What you should hand in as an appendix in your lab report:

- Your derivation of equations (1), (3) and (4);
- Your graphs;
- A table showing the values of the rolling resistance in each of the 6 cases listed in Table 1, and a brief discussion of these values.

Maple worksheets or lists of Maple commands are not required.

Appendix C: Rolling Resistance

Rolling resistance is a force that tends to slow a wheel rolling along a surface. There are two main sources of rolling resistance. One source is the action of kinetic friction at the axle, where the axle and wheel make contact, as shown in figure 5a. The second source is a result of the deformation of both the wheel and the surface over which it rolls. The wheel may flatten and depress the surface. As such, rather than having a *point* or *line* of contact between the wheel and the ground, contact occurs over an area, and in a sense, the wheel is always rolling slightly uphill. This is illustrated in figure 5b. On the walkers, axle friction most likely dominates in the front caster wheels, while deformation friction plays a large role for the rubber rear wheels.

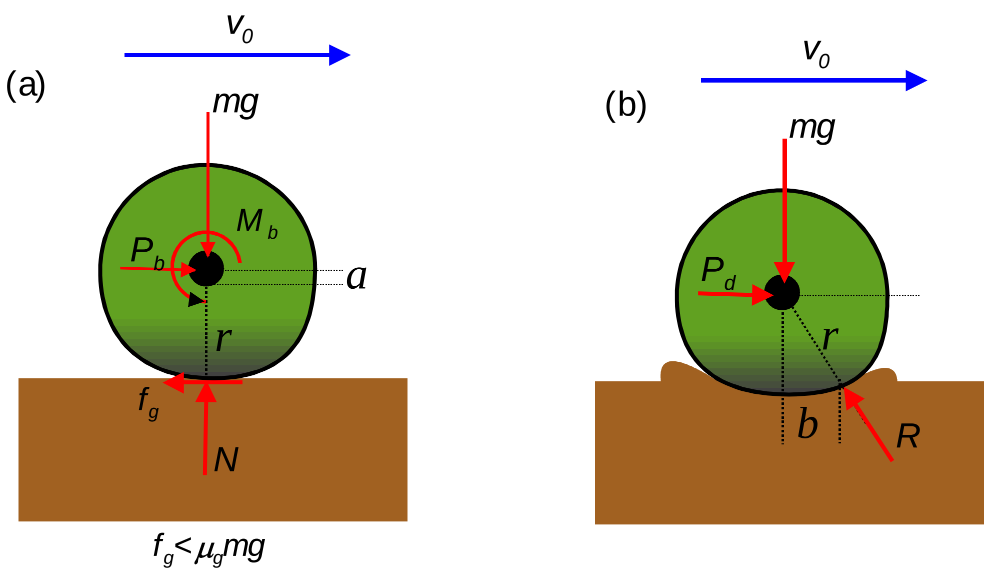

Figure 5: Sources of Rolling resistance. (a) Axle friction (b) Wheel/surface deformation.

For practical purposes, rolling resistance generally must be experimentally determined for a given system, although in some (not all) applications a reasonable means is provided by the definition of a wheel-and-surface dependent coefficient of rolling friction μ_r . Then the rolling resistance force is

$$P=\mu_r mg. \tag{5}$$

In many cases, however, this relation is not a good representation of the situation and measurements must be made to give find a dependence of P on mg.

To get a sense of the mechanisms behind rolling resistance, consider first the roll of bearing friction. As a result of this friction, there is a moment M_b acting on the wheel due to the sliding contact of the wheel and axle. The force f_g is the force of static friction on the exerted on the tire by the ground. To overcome the bearing friction, a horizontal force $\boldsymbol{P}_b$ must be applied. Summing forces and moments for the system leads to the result for the force P_b:

$$P_b = M_b / r\,. \tag{6}$$

The moment itself depends on many factors, but a simple estimate is given by assuming that a kinetic friction force is distributed around the hub edge, which leads to

$$M_b = \mu_k mga \,. \tag{7}$$

that μ_k is the coefficient of kinetic friction between the axel and wheel, and *a* is the axle radius.

The rolling resistance due to deformation of the wheel and ground is depicted in figure 5b. The resultant reaction force ***R*** exerted by the ground on the wheel over the contact area acts at a point *B* along the contact area a small distance *b* in front of the wheel center. In order to counteract the effects of the offset *b* and prevent the wheel from slowing, a horizontal force $\boldsymbol{P}_d$ must be applied. Summing forces and moments for the system leads to the result

$$P_d = mgb / r \,. \tag{8}$$

How is the distance *b* determined? Intuitively, one would think that the value of *b* depends on the weight *mg*, radius *r* of the wheel, and the elastic properties of both the wheel and ground. These are all indeed factors in a characterization of the rolling resistance. The sum of the two types of rolling resistance gives the net force:

$$P = P_b + P_d = mg\left(\mu_k a + b\right)/ r, \quad b = b(r, mg). \tag{9}$$

Replacing the above with a linear relation $P=\mu_r mg$ relies on an assumption that *b* is independent of *r* and *mg.*

In addition to the two sources of rolling resistance mentioned above, the surface roughness can play a role. No material surface is perfectly plane; even when very smooth, there are numerous microscopic irregularities called "asperities". Inelastic collisions may occur as the asperities are struck resulting in a loss of energy.

For more on rolling resistance, see page 129 of Schuam's Outline: *Engineering Mechanics: Statics and Dynamics*, 5^{th} edition, McGraw Hill.