Experiments for *INTRODUCTORY PHYSICS* and *ASPC*

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The Student Lab Report Handbook
A Guide to Content, Style and Formatting for Effective Science Lab Reports

Contents

Experiment 1 The Pendulum Lab

Learning Objectives

Features in this experiment support the following learning objectives:

1. General objectives for laboratory experiments (see page 4).
2. Collect data in an organized fashion.
3. Control variables in an experiment.
4. Present data in tables.
5. Develop a complete lab report from scratch.

The real purpose of the fun little Pendulum Lab is to introduce students to experimental methods, including data collection, using a lab journal, manipulating variables one at a time, setting up tables, and report writing. The physics of the pendulum is incidental. For this reason, this is an excellent experiment to perform within the first two weeks of the school year, independent of the topic under study in the curriculum.

Materials for this experiment cost only a few dollars. The experiment is simple to perform and can be conducted in 45 minutes. Students are fascinated by the apparent simplicity of the problem, and the answer to it, which they invariably fail to guess correctly in advance. They are intrigued that such a simple set up can return such a non-intuitive result.

Materials Required (per lab team, four students max per team)

1. nylon string, 1 meter
2. large paper clip
3. large steel washers (3)
4. meter stick, broom handle, yardstick, or similar item
5. duct tape or masking tape
6. clock with sweep second hand (the classroom wall clock works fine) or stop watch

Experimental Purpose

Determine the explanatory variables that affect the period of a pendulum.

Overview

Using simple materials, each student team makes a pendulum and tests it to see how many periods (full swings over and back) the pendulum will complete in a 10-second time interval. Students adjust the variables (the starting angle, the weight, and the length of the string) independently, conducting three separate trials for each configuration. Students record the data in their lab journals.[1] When all trials have been completed, students analyze their data to determine which variables affected the period in their trials. When trials are conducted carefully the data should clearly show that only the length of the string affects the period.

The pendulum is made by unfolding a large paper clip to use as a hook. The paper clip is attached to the end of a string. The other end of the string is tied to the end of a meter stick (or similar item) and the meter stick is placed on a table top so the pendulum hangs over the edge and swings freely. The meter stick is held in place on the table top by masking tape or duct tape. Large washers are hooked onto the paper clip and serve as the weights.

Pre-Lab Discussion

Cover the following items with the entire class the day before the lab exercise.

1. Define the period of an oscillating system and its unit of measure. In any oscillating system the period is the length of time required for the system to complete one full cycle of the oscillation. Commonly the lower-case Greek letter tau, τ, is used to denote the period. The period is measured in seconds (s).
2. Ask students to suggest the possibilities for explanatory variables that could affect the period of a pendulum. In terms of the "scientific method," this discussion corresponds to the "state the problem" step. There are three mechanical possibilities inherent in the pendulum itself: the weight, the length of the string, and the starting angle from which the pendulum is released. Guide the discussion until these three possible explanatory variables are identified. Confirm that there are other marginal factors that may affect the period such as the air or the rotation of the earth, but that these variables will not be considered in this experiment.
3. Give the teams a few minutes to discuss the three possible explanatory variables as a team. Ask them to consider their own experience and practical mechanical knowledge and form a team hypothesis about which one(s) will affect the period. The teams' discussions will constitute the "research" step of the scientific method. Instruct the students to document their team's hypothesis in their lab journals.
4. Explain the fact that since a single period of a pendulum would be too short to measure accurately, we will instead allow the pendulum to swing freely for 10 seconds while the number of complete swings is counted. (One "swing" is all the way over and all the way back to the starting position.) This is much easier to measure and gives us the same information as the period itself. (In fact, we could compute the period from the 10-second swing data by dividing 10 seconds by the number of swings counted.) The team member counting the swings should closely observe the position of the pendulum and estimate the total number of swings in one 10-second interval to the nearest 1/4 swing. So the data collected for each trial

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1 In addition to data there are many other items that students need to record in their lab journals. For complete details on the use of lab journals, please see *The Student Lab Report Handbook*, available from Novare Science and Math at novarescienceandmath.com.

during the experiment consists of the number of complete swings, plus any partial swing rounded to the nearest 1/4 swing, completed by the pendulum in ten seconds.

5. Review the need to test each explanatory variable independently, and present how this can be managed for the three variables being tested here. Since this is probably the first time students have conducted an experiment with three variables to test, the teacher needs to show students how to do this and how to set up appropriate tables for collecting data. These matters can be presented as follows:
   a. Of the three variables under test, the angle is easiest to change. So it makes sense to set up each configuration of the pendulum and test it at two different starting angles.
   b. Students will first construct the pendulum with the longest possible string (full length) and the heaviest weight (all three washers). For this configuration the string needs to be 75 to 100 cm long. Students will test this pendulum at each of two different angles. The small angle will be when the pendulum is pulled back about 10 degrees from vertical to be released. The angle can be estimated by one of the team members. Three trials will be conducted at this angle to assure that the data are consistent.
   c. The large angle will be about 40 degrees from vertical. As before, three trials must be conducted.
   d. Students must record all the data for these trials in their lab journals in a table like the one below. In each cell in the table students record the number of swings the pendulum completed in the ten second timing interval.

Number of swings completed by long string, heavy weight pendulum		
trial	small starting angle	large starting angle
1		
2		
3		

   e. Since changing the weight on the pendulum can be done quickly, it makes sense to change this variable next. So after completing the six long string, heavy weight trials, students will take off two of the washers, keep every thing else the same, make another table for "long string, light weight" data and conduct the trials, using small and large angles (three trials each) as before.
   f. After completing the two tables of long string trials, students will shorten the string down to about 25 cm long. Then they conduct trials to fill up two more tables (one for heavy weight, one for light weight) as before. Students will have four tables of data in all, and must conduct 24 separate trials.

6. To assure the best accuracy, encourage students to check that the meter stick is steady while the pendulum is swinging. Tell them also to make sure that the large angle is 3-4 times as large as the small angle, without going over 45 degrees or so from vertical, and that the long string is 3-4 times as long as the short string. The general rule is that for each of the three variables under test, the large value of the

variable should be at least three times the small value. This degree of variation will assure that if the variable does affect the period the data will clearly show it.

7. Teams should divide up the tasks for conducting the trials. One team member watches the clock and gives the signals to start and stop the trials. Another team member pulls back and releases the pendulum at the correct angle on the signal, making sure to start the pendulum from a reliably consistent position. A third team member carefully counts the swings until the stop signal is given, calling the number of swings to the nearest quarter swing. A fourth team member can record the data in his or her lab journal and share it with the other team members after the data collection is complete.

Scoring the Student Lab Reports

At the school where I developed this experiment we introduce students to the full requirements of report writing in ninth grade. During the rest of the fall term and on into the spring term students are expected to improve the quality of their reports with each new attempt. Our goal is that by the time they finish their freshman year the students are very familiar with standard report content, style and formatting, and have developed solid descriptive and analytical skills. Thus prepared, they enter their tenth grade science courses equipped to engage their science studies at an even deeper level, being able to focus more on the science and less on learning how to write lab reports.

This being the case, this is the students' first report, the first in a series of reports designed to train them in the art of writing good technical papers. The goal for the first one is that they are able to get the major building blocks in place. There is a lot to learn, and writing good reports entails many details, including a lot of specific formatting requirements. My policy for this first report is that any student who reads through the basic chapters of *The Student Lab Report Handbook*[2] and makes a good faith effort to put together a good report that includes the essential ingredients with serviceable English writing will receive at least a B. I expect on this first report that the students will miss many of the formatting requirements described in *The Handbook*. This is not a problem. Writing good reports takes practice, so I gradually raise the grading standard with each new report throughout the year.[3]

Student Instructions

A set of instructions you may reproduce and give to students begins after the illustrations. This set of instructions is taken from my freshman science texts *Introductory Physics* and *Accelerated Studies in Physics and Chemistry*.

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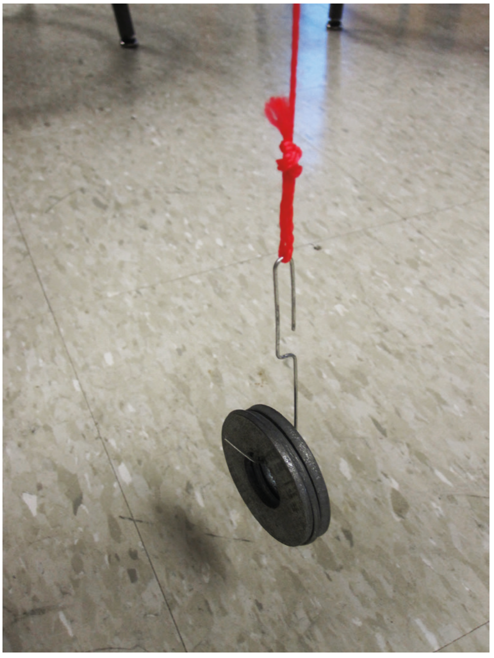
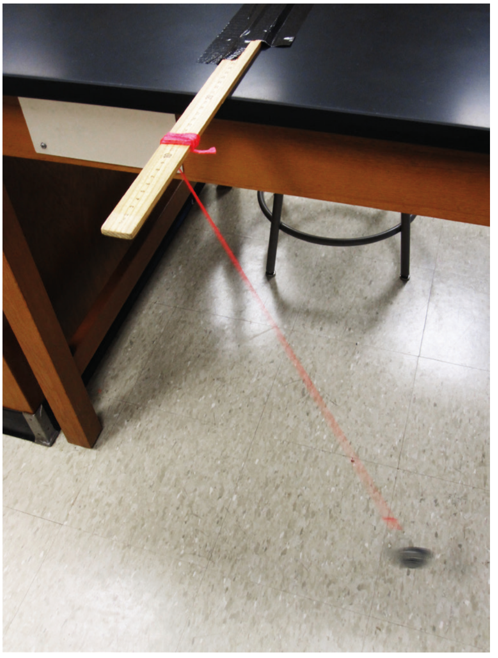
2 See the Introduction for details.

3 I presented a grading rubric for high school lab reports in my 2010 book, *Teaching Science so that Students Learn Science*.



String, hook and weights ready to go.



The pendulum in action.

Student Instructions

The Pendulum Lab

Variables and Experimental Methods

We are going to conduct an investigation involving a simple pendulum. This experiment is an opportunity for you to learn about conducting an effective experiment. In this investigation you will learn about controlling variables, collecting careful data, and organizing data in tables in your lab journal.

To make your pendulum, your team will bend a large paper clip into a hook. Then you can connect the hook to a string, and connect the string to the end of a meter stick. Then lay the meter stick on a table with the pendulum hanging over the edge and tape the meter stick down. Now you can hang one or more large metal washers on the hook for the weight.

In this fun experiment your goal is to identify the explanatory variables that influence the period of a simple pendulum. A pendulum is an example of a mechanical system that is *oscillating*, that is, repeatedly "going back and forth" in some regular fashion. In the study of any oscillating system an important parameter is the *period* of the oscillation. The period is the length of time (in seconds) required for the system to complete one full cycle of its oscillation. In this experiment the period of the pendulum is the response variable you will be monitoring. (Actually, for convenience you will be monitoring a slightly different variable, closely related to the period.) After thinking about the possibilities and forming your team hypothesis, you will construct your own simple pendulum from string and some weights and conduct tests on it to determine which variables actually do affect its period and which ones do not.

In class you will explore the possibilities for variables that may affect the pendulum's period. Within the pendulum system itself there are three candidates, and your instructor will lead the discussion until the class has identified them. (We will ignore factors such as air friction and the earth's rotation in this experiment. Just stick to the obvious variables that clearly apply to the problem at hand.)

Then as a team you will continue the work by discussing the problem for a few minutes with your teammates. In this team discussion you will form your own team hypothesis stating which variables you think will affect the period. To form this hypothesis you will not actually do any new research or tests. Just use what you know from your own experience to make your best guess.

The central challenge for this experiment will be to devise an experimental method that tests only one explanatory variable at a time. Your instructor will help you work this out, but the basic idea is to set up the pendulum so that two variables are held constant while you test the system with large and small values of the third variable to see if this change affects the period. You will have to test all combinations of holding two variables constant while manipulating the third one. All experimental results must be entered in tables in your lab journal. Recording the data for the different trials will require several separate tables. For each experimental setup you should time the pendulum three times and record the result in your lab journal. Repeating the trials this way will enable you to verify that you have good, consistent data. To make sure you can tell definitively that a given variable is affecting the period, you should *make the large value of the variable at least three times the small value in your trials*.

Here is bit of advice about how to measure the period of your pendulum. The period of your pendulum is likely to be quite short, only one or two seconds, so measuring it directly with accuracy would be difficult. Here is an easy solution: Assign one team member to hold the pendulum and release it on a signal. Assign another team member to count the number of swings the pendulum has completed, and another member as a timer to watch the second hand on a clock. When the timer announces "GO" the person holding the pendulum releases it, and the swing counter starts counting. After exactly 10.0 seconds the timer announces "STOP" and the swing counter states the number of swings that have been completed. Record this value in a table in your lab journal. If you have four team members, the fourth person can be responsible for recording the data during the experiment. After the experiment the data writer can read off the data to the other team members so they can enter the data in their journals.

This method of counting the number of swings in 10 seconds does not give a direct measurement of the period, but you can see that your swing count will work just as well for solving the problem posed by this experiment, and is a lot easier to measure than the period itself.

One more thing on measuring your swing count: Your swing counter should state the number of swings completed to the nearest 1/4 swing. When the pendulum is straight down, it has either completed 1/4 swing or 3/4 swing. When it stops to reverse course on the side opposite from where it was released, it has completed 1/2 swing.

When you have finished taking data, review the data together as a team. If you did the experiment carefully your data should clearly indicate which potential explanatory variables affected the period of the pendulum and which ones did not. If your swing counts for different trials of the same setup are not consistent, then something was wrong with your method. Your team should repeat the experiment with greater care so that your swing counts for each different experimental setup are consistent.

Discuss your results with your team members and reach a consensus about the meaning of your data. You should expect to spend at least four hours writing, editing and formatting your report. Lab reports will count a significant percentage of your science course grades throughout high school, so you should invest the time now to learn how to prepare a quality report.

Your goal for this report is to begin learning how to write lab reports that meet all of the requirements outlined in *The Student Lab Report Handbook*. One of our major goals for this year is to learn what these requirements are and become proficient at generating solid reports. Nearly all scientific reports involve reporting data, and a key part of this first report is your data tables, which should all be properly labeled and titled.

After completing the experiment all of the information you will need to write the report should be in your lab journal. If you properly journaled the lab exercise you will have all of the data, your hypothesis, the materials list, your team members' names, the procedural details, and everything else you need to write the report. Your report must be typed, and will probably be around two or three pages long. You should format the report as shown in the examples in *The Student Lab Report Handbook*, including major section headings and section content.

Here are a few guidelines to help you get started with your report:

1. There is only a small bit of theory to cover in the Background section, namely, to describe what a pendulum and its period are. You should also explain why we are using the number of swings completed in 10 seconds in our work in place of the actual period. As stated in *The Student Lab Report Handbook*, the Background section must include a brief overview of your experimental method and your team's hypothesis.
2. Begin your Discussion section by describing your data and considering how they relate to your hypothesis. In this experiment we are not making quantitative predictions, so there will be no calculations to perform for the discussion. We are simply seeking to discover which variables affect the period of a pendulum, and which do not. Your goal in the Discussion section is to identify what your data say and relate that to your reader.
    a. What variables did you manipulate to determine whether they had any effect on the period of the pendulum?
    b. What did you find? Which ones did affect the period? How do the data show this?
    c. Were you surprised by what you found?
3. If you would like to produce a really outstanding report, consider exploring the following questions in your discussion:
    a. Many clocks use pendulums to regulate their speed. What is it about pendulums that makes them good for this?
    b. How would this work in an actual clock?

Experiment 2 The Soul of Motion Lab

Learning Objectives

Features in this experiment support the following learning objectives:

1. General objectives for laboratory experiments (see page 4).
2. Present theoretical predictions and experimental results on the same set of axes in a graph.
3. Use theory to make quantitative predictions of experimental results.
4. Use proper formatting and presentation for graphs in reports.
5. Explore and learn how to use unfamiliar scientific equipment.

For over a decade my freshman students called this investigation of Newton's Second Law of Motion the Pick-up Truck Lab. For many of them, especially the boys who love exhibiting their strength while pushing my Ford F-150 pick-up truck around in the school parking lot, it is probably the most enjoyable experiment in the entire year. For getting the students out of the classroom and allowing them to be physically active, this is about as good as it gets in a physics class!

I got the idea for this experiment from a journal article I read by another physics teacher over 20 years ago.[1] In this experiment students have their first chance to use theory to predict the outcome of an experiment and compare their experimental results to their predictions. If done well the difference between the predictions and the results can turn out surprisingly low, significantly less than 5%. The subsequent report entails learning how to prepare graphs showing both predicted and experimental values.

As I write this I have just replaced my old truck with a new KIA Soul and have modified the apparatus to make it work with this new vehicle. I am including photos of both vehicles to suggest different ways to make the experiment work. I have also done the experiment with a Dodge 4-door sedan (Intrepid). I suppose many different vehicles could be made to work. The main requirements are that the rear of the vehicle is vertical or nearly so for proper placement of the force-reading scales, and that the vehicle is not too large, so that reasonable amounts of force result in reasonable amounts of acceleration. If you (the teacher) do not own a suitable vehicle for this experiment try getting one of the parents involved with his or her own vehicle. They will have a great time with the students.

Achieving results within 5% of the predictions was only possible because while doing this experiment over and over I chased lurking variables like a bloodhound for over a dozen years. I learned a great many details that can make this experiment a resounding success. Naturally, I am going to present all these here in this chapter, but the downside of doing so is that the chapter will be somewhat long. Believe me, this experiment is so much fun that it is all worth it.

1 Unfortunately, I have been unable to locate this article in order to cite it appropriately.

Even though the lengthy instructions may make this experiment appear daunting, in its basic form it is actually easy to do and requires no special equipment. Students simply push a car using inexpensive bathrooms scales to measure and monitor the force, while other students time the vehicle in order to establish an experimental value for the acceleration. The forces the pushers apply are used to work up theoretical values for the acceleration. I suggest that when you perform this experiment for the first time you go with this simple approach. Then whenever the budget permits, you can look into acquiring the equipment and building the apparatus for the more sophisticated approach.

Setup and data collection for this experiment can be completed in approximately 50 minutes.

Materials Required (for the class)

Note: If bathroom scales are used for the experiment, you will need two of them. If the PASCO equipment is used for the experiment and is fastened to a support rack as described below, then you will still need one bathroom scale for weighing the driver and the support rack.

1. bathroom scales (2); (Stay away from digital scales. Humans cannot respond as fast to changing numerals as they can to a swinging pointer. Use inexpensive, old-fashioned scales that read with a dial or needle.)
2. pick-up truck, KIA Soul, or other vehicle for the purpose
3. measuring tape, such as the 30 meter, wind-up metric tape AP6323 available from Flinn Scientific (flinnsci.com)
4. stop watch
5. duct tape

Additional optional equipment if digital readers are used:

6. PASPORT 2-Axis Force Platform, PS-2142 (2); (available from PASCO, pasco.com)
7. Xplorer GLX (2); (available from PASCO, pasco.com)
8. Force platform handle set, PS-2548 (2); (available from PASCO, pasco.com)
9. Force platform support rack (see the illustrations below for construction suggestions)

Experimental Purpose

Use Newton's Second Law of Motion to predict the acceleration of the vehicle under different applied forces and compare the predicted accelerations to experimental values.

Overview

The entire class conducts this experiment as a group, sharing the data recorded. The idea is to push a vehicle with known, constant forces over a known distance (10.00 m) starting from rest while timing it with a stop watch. The resulting acceleration may be computed as

$$a = \frac{2d}{t^2}$$

Two students push the vehicle simultaneously, pressing on the rear of the vehicle with bathroom scales or other devices so they can monitor the forces they are applying. Four different values of force are applied, resulting in four different values of acceleration. Three trials are conducted for each force. A set of trials is judged valid if the three time measurements are within a one-second range from highest to lowest. For a given force value, the times from all three trials are averaged to determine the experimental value of acceleration.

The predicted values of acceleration for the four different applied forces are determined from Newton's Second Law,

$$a = \frac{F}{m}$$

Before the day of the experiment the teacher must drive the experimental vehicle to a weighing station to be weighed (full tank of gas, no driver). I use a local landscaping supply company that has a truck scale for weighing trucks hauling stone, and when I tell them I am a science teacher they are always happy to weigh my car. You can report the weight in pounds to the students and let them determine the vehicle mass for themselves. Values of acceleration are computed from the total applied forces and the vehicle mass. (The mass must include the mass of the experimental driver and the force measurement equipment, as described below.)

The acceleration predictions are much more accurate if friction forces are deducted from the values of force applied by the students. A good approximation for the total friction force is found by having one student push the car as slowly as possible while barely keeping it in motion at a constant speed. (This must be done in the location where the experiment is to be performed, because the slope of the pavement makes a huge difference in how much force is required to overcome the kinetic friction of the brake pads and wheel bearings.) The value of the force required to do this is deducted from each applied force to obtain the net force values used in Newton's Second Law for the predictions.

As recommended in the original article on this idea, I conducted this experiment for many years using two inexpensive bathroom scales purchased from a discount store for under $10 each. The students simply hold the scales against the back of the car or truck and watch the dial on the scale, adjusting the strength of their pushing to hold the force as steadily as possible on the desired value. The scales remain in place by friction while the forces are applied. The results are surprisingly good, especially considering that the forces are impossible for the pushers to hold steady. The forces bounce up and down above and below the desired value. But with two people pushing they average out well to give an average value close to the desired value.

Over the years as funds became available I looked into higher-tech ways of monitoring the forces. PASCO makes a nice tool for measuring the forces, the PASPORT 2-Axis Force Platform, that connects to a portable data collection tool called the Xplorer GLX. (Both of these are expensive, and you need two sets for this experiment. But the Xplorer GLX is a versatile tool that can be used for many other types of data collection, including several other experiments and demonstrations described in this book.) The force platforms are too bulky and heavy for the pushers to use them without support, so I built a wooden rack to mount on the back of the pick-up truck to hold the two force platforms. Now that I am doing the experiment with a KIA Soul, I modified the rack so it would work with this different vehicle. Both versions of the support rack are shown in the illustrations beginning on page 31.

The PASCO equipment allows one to collect data into a digital file and display the data graphically in a computer application for analysis. The display on the Xplorer GLX can also be set to show a simulation of an analog dial, which is much easier for the pushers to read and respond to than a digital display. One can also calibrate the maximum reading of the display of the Xplorer GLX for maximum resolution. I now conduct this experiment every year using the PASCO equipment. The students get a kick out of the digital equipment, and the whole set up is less finicky than doing the experiment with bathroom scales (which are hard to zero or tare, and tend to slip around). In summary, go high-tech if you can. But if you can't, this lab is still a ton of fun. The students love it and the data collection and analysis are very effective ways of learning about Newton's Second Law of Motion.

Experimental Conditions

The optimum conditions for doing this experiment would be inside a large, air-conditioned building, on a clean, smooth, level surface. If you have access to such ideal conditions take advantage of them. Here's why such conditions matter.

First, wind can make a significant difference in the acceleration of the vehicle. This problem is significantly worse when using a hatch-back vehicle with the hatch open, as with my KIA Soul. The open hatch catches the wind, affecting the net force on the car and causing large errors. So select a location for the experiment where the wind is blocked by a nearby building.

Second, in a parking lot all surfaces are intentionally designed to slope for proper drainage. This means that the best you can do is minimize the slope of the pavement, but you can't eliminate it. Select a location with as little slope as possible.

Third, the slope of the pavement may not be uniform, and different amounts of slope will produce different net forces on the car. Even over the 10-meter course of the car timing zone the slope can change enough to cause significant error. Select a location where the slope of the pavement is as uniform as possible.

The air conditioning is not really necessary. But in Texas, doing this experiment in September, the students pushing the car tend to get hot and sweaty (and stinky). Naturally, we gung-ho scientists never let little things like this get in our way, but I always wondered if I should try to persuade the Athletic Director to let us perform this experiment in the gym! If you have an outdoor basketball court on level concrete, that would be close to ideal. If the court is sheltered from wind then it would have everything you need except cool weather.

If you have to make do out in a parking lot somewhere, you must at least choose a location horizontal enough that the vehicle will not begin to roll by itself anywhere in the timing zone after given a little push.

Pre-Lab Discussion

Students should read the Student Instructions handout for basic information about the purpose of the experiment and procedures. Additionally, review the following items with students the day before the experiment:

1. One of the major ways theories are tested is by forming testable hypotheses and devising tests to try to confirm them. In this experiment that is what we are doing. Our theoretical framework is Newton's Laws of Motion. Our hypothesis is that we can accurately predict the acceleration of the vehicle using the Second Law. Our experimental plan is to predict the acceleration of a vehicle as a function of force applied at the back, measure the actual acceleration for the same forces, and compare the results to the predictions by computing the percent difference.[2]

2. Newton's Second Law may be written as

$$a = \frac{F}{m}$$

Written this way the equation indicates that the acceleration is the dependent variable and depends on the force, the independent variable. This is the equation we will use to make our predictions. All we need to know to predict the acceleration for a given force is the mass of the car. The teacher is going to provide the class with the weight of the car which students can use to determine the mass of the car. We also need to include the masses of the driver and of the force measurement equipment, if significant (see below).

Newton's Second Law is a linear equation. Acceleration varies in direct proportion to force, with constant of proportionality equal to 1/m. A graph of this equation should be a straight line with slope 1/m.

3. There is a lot of friction in the brake pads of a car, because the pads touch the disk rotors all the time, not just when the brakes are applied. This means that not all of the force applied by the pushers is going to contribute to the acceleration. Some of it is simply overcoming the friction of the brake pads (and wheel bearings). Thus, we are going to strive for maximum accuracy by measuring the friction force at the beginning of the experiment. Then we will subtract it from the forces applied by the pushers and use this net value of force in our calculations of the predicted values. Thus our equation for the predicted values will be

$$a = \frac{1}{m} \cdot \left(\text{Force applied by pushers} - \text{estimated friction force}\right)$$

(Many students, unknowledgeable about cars, will spell brakes as "breaks." This friction discussion is a good time to have them make note of the correct spelling.)

4. To determine our experimental values of acceleration we will use the equation

$$a = \frac{2d}{t^2}$$

2 See Appendix.

We will make a timing zone on the ground with start and finish lines indicated by duct tape. The timing zone will be 10.00 meters long and we will time the vehicle during each trial with a stop watch. (Alas, many students, ignorant of the world of hardware, think duct tape is spelled "duck" tape, so you may as well inform them now of the correct spelling of this word, too. The fact that there is a brand of duct tape called Duck Tape just confuses the matter.)

5. Discuss the four different force values to be used during the experiment. Quote the force values in pounds if you are using bathroom scales, and show the students how to convert the values into newtons for their analysis. If you are using the PASCO force sensors you can work directly with forces in newtons. Values I have used in the past are as follows:

   F-150 Pick-up truck:

      110 N each (220 N total), 130 N each, 170 N each, and 200 N each.

   KIA Soul:

      100 N each (200 N total), 125 N each, 150 N each, and 175 N each

   Note: The values above are based on the weights of the vehicles (the Soul weighs a lot less than the F-150) and the friction forces that had been measured previously for the specific vehicle involved, which were 110 N for the pick-up truck and 140 N for the Soul. The first time you conduct this lab you will want to measure the friction before making final decisions about the specific forces to use. However, experience has shown that forces above 200 N each, which is over 40 pounds, are not reasonable, since students cannot reliably push harder than this on an accelerating vehicle and keep the force up for the duration of the 10-meter trials.

6. We will conduct at least three separate trials for each force value. We will judge our data to be valid when we get three time measurements that are within one second of each other. That is, the spread between the highest and lowest times is 1.00 s or less, with a third time in between. This will require our pushers to really focus on applying constant forces. It is impossible to make them perfectly constant, but constancy is the goal.
7. One of the main elements in the report for this experiment will be a graph of acceleration vs. force showing the four predicted acceleration values and the four experimental acceleration values on the same graph. After the experiment we will go over in detail how to construct such a graph using Microsoft Excel.[3] We expect the four predicted values to make a perfect line. The experimental values of acceleration will correspond to the same values of force as the net force values used for the predictions, so we should see the experimental values lying close to the predicted values, either directly above or directly below. If our data are accurate, the experimental values should follow a nice, linear trend.

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3 This procedure is described step-by-step, with color screen captures for reference, in *The Student Lab Report Handbook*. See the Introduction for details.

8. We need to select a student to be the driver. The vehicle will not be running during the experiment, but someone has to hold the steering wheel steady. In electing this student we will give precedence to anyone who has a driver's permit already. There is one caveat: The driver must consent to being weighed and having his or her weight published to the class.
9. In addition to the driver, we need a timer to operate the stop watch, and a data recorder to log the data reported by the timer into his or her lab journal. We will use two students as pushers for a given force, and they will push the vehicle as many times as they have to until we get three valid time measurements. Then we will get two fresh pushers for the next force value. Students not involved in any of these tasks will be needed on the return pusher crew to return the vehicle to the starting line for the next trial.
10. For a large vehicle like a pick-up truck, the work of pushing is quite physically demanding. Without adequate strength the force a student applies will inevitably decrease as the vehicle picks up speed. This means that with young students like freshmen, most girls and the smaller boys can't really handle it (despite their burning enthusiasm for experimental science!). Thus, the larger boys will be needed for the pushing. (That's just the way it is. Life isn't fair.) With a smaller vehicle like the Soul, lower forces can be used because the vehicle mass is significantly lower. This allows a more democratic selection process for the coveted position of pusher!
11. Students who will be assigned as pushers need to wear appropriate shoes. They will need to lean over and push hard without their shoes slipping on the pavement. Sport shoes are best. Cowboy boots or other smooth-soled shoes are worst.

Detailed Experimental Protocols

1. Select the location for the experiment based on considerations discussed in Experimental Conditions above.
2. Using duct tape, the students mark off two parallel lines 10.00 meters apart for the timing zone. Position the student timer with the stop watch at the finish line. The stop watch should be started on the audible signal, and stopped when the front bumper of the vehicle crosses the finish line.
3. Make the following measurements and record the data. (It is best to do this before beginning the trials with the vehicle, otherwise one tends to forget about them.)
    a. Weigh the driver, reporting the weight to the data recorder.
    b. Weigh the force platforms and mounting bracket, and report the weight. (If bathroom scales are being used the weight is insignificant and this step can be neglected.)
    c. Determine the friction in the brakes by having one student push the vehicle as slowly as possible, but at a steady, constant speed. Estimate the average force the student has to apply to accomplish this. Record this force value, to be used later as the friction force. Note: All modern brake pads have metal particles in them that oxidize (rust) from the moisture in the air whenever the vehicle is at rest. This rust is rubbed off when the brake pads are in use. To make sure

the friction force is consistent during the experiment, drive the car around the parking lot a couple of times while holding the brake on slightly with your left foot. This will polish the rust off the brake pads and make the friction both low and constant during the experiment.

4. Place the vehicle transmission in neutral and leave it there for the duration of the experiment.
5. Tare the force scales. Dial-type bathroom scales have zeroing knob. The PASCO force platforms have a button for setting the zero. Mounted vertically, the readers never read quite zero, but they are close (within 10 or 15 N of zero, which is only 1/4 lb or so).
6. For each new trial the vehicle is positioned with its front bumper at the starting line. The vehicle is at rest with the student driver in the driver's seat holding the brake on.
7. The two pushers apply the appropriate force to their scales or force platforms and hold it there. They need to pre-load this force before the starting signal and hold it steady in a ready position.
8. If you are using the PASCO force platforms with the Xplorer GLX data collectors, you will also need to assign two students to hold the data collectors, which serve as the force indicators, in front of the pushers' faces, walking along with them so the pushers can monitor the forces they are applying. Of course, if you are using bathroom scales this is not necessary.
9. Tell the pushers to keep their hands and fingers completely on the scales. No fingers should hang off the edges and push on the vehicle directly. (This is more of a problem with the bathroom scales because the pushers have to hold them up, tempting them to wrap their fingers around the sides.)
10. To start the trial someone with a loud, projecting voice does the count-off: READY—SET—GO! (I always reserve this esteemed position for myself, the leader of the class, and the guy with the loudest and most projecting voice around.) On "GO," the timer starts the stop watch and the driver releases the brake. Be sure to emphasize to the pushers that at the GO signal they are to do ABSOLUTELY NOTHING. They are already at the ready, holding the correct value of force on the scale, and they just need to hold it there. Analysis of data files collected with the Xplorer GLX shows that the pushers tend to feel the joy of the moment and push harder when the GO signal is given. May heaven bless them for their enthusiasm, but this obviously introduces error. So tell them to hold rock steady on the force value, and not to give any joyful nudges when the GO signal occurs.
11. Another important thing to warn the pushers about is that as the vehicle picks up speed it becomes increasingly difficult to maintain the force value. Analysis of Xplorer GLX data files also shows that forces tend to decrease toward the end of the run. This is because it is hard for the pushers to maintain the force while keeping up with the vehicle and maintaining traction on the ground. Warn the pushers about this, and admonish them constantly during each run to "Hold it steady, pushers! Don't fade out!" This problem is all the more significant at the high force values, so encourage those pushers accordingly.

12. When the front bumper of the vehicle crosses the finish line, which the timer is watching carefully from her or his assigned position, the timer stops the stop watch and reports the time value to the data recorder who is standing by. The leader should keep track of the data and continue authorizing new trials until the one-second spread criterion for three trials is achieved.
13. After crossing the finish line the driver can gently apply the brake to help stop the vehicle. It is a good idea to warn the driver not to hit the brake too suddenly or the pushers might get unpleasantly bumped around.
14. After the vehicle is brought to a stop the other students leap into action and push the vehicle back to the starting position, carefully lining up the front bumper with the starting line in preparation for another trial. You may as well warn them right from the first to take it easy when pushing the car back into position. They tend to get enthusiastic, and I am always concerned that if the vehicle gets moving too fast it will run over someone's foot. So tell them to push it back at a nice calm, reasonable speed, and to stay on duty until the car is lined up at the starting line and the driver has the brake on, ready for the next trial.
15. After the experiment is complete and your class is back in the classroom, have the data recorder share the official time data with the other students so everyone can get the data into their lab journals.

Alternate Experimental Method

If you have the funds to procure the PASCO equipment then you might be interested in an experimental method that can improve the accuracy of this experiment even further. The downside to this method is that you will have to spend a lot of time fooling with the data files during and after the experiment.

The major source of error in this experiment is the difference between the force value target and the actual forces applied to the vehicle by the pushers. My procedures try to minimize this source of error by calling for a maximum spread of one second in the time data for the trials at a given force. However, this does not eliminate the error. It is quite possible that the pushers undershoot or overshoot their targets very consistently. This would make the times consistent, but there would be an undetected bias in the data. This alternate method takes care of this problem.

The alternate method works like this. Select 10 or 12 force values ranging from forces that will barely make the car accelerate (about 100 N each) up to the maximum the students can deliver (around 200 N each). Then assign all students other than the driver and the timer to pushing duty (smaller kids to lower force values, big beefy athletes to higher values). Then perform a single trial at each chosen force and use the Xplorer GLX not only as a reader but also as a data recorder. With actual force data for the trial you can use the mean value of the force data to construct your predictions.

As an example, with the primary method you might have a target force for a set of trials at 150 N. Your pushers would do the best they can, and you would use 150 N (times two for two pushers) in your prediction of the acceleration for that force. Using the alternate method you just tell the pushers to push at 150 N but you record the force data file while it is happening. The actual values of the forces the pushers produce do not matter, because you will take the mean values from the two data files for the two pushers and use these actual mean values to calculate your acceleration prediction.

This method requires that during each trial the students holding the Xplorer GLX data readers for the pushers to see must also be responsible for starting and stopping the data recording during the trial. They should accurately start the recording on the GO signal, and stop the recording on a STOP signal called out by the stop watch operator.

Since accuracy of maintaining a specific force is not an issue with this method, there will be much more flexibility in assigning students to push the vehicle. When accurate force maintenance is required, strong students capable of holding the force values all the way through the trial must do all the pushing. By using the mean force from the data file all students can be involved in the pushing without fear that those with modest strength will fade at the end of the trial.

Student Instructions

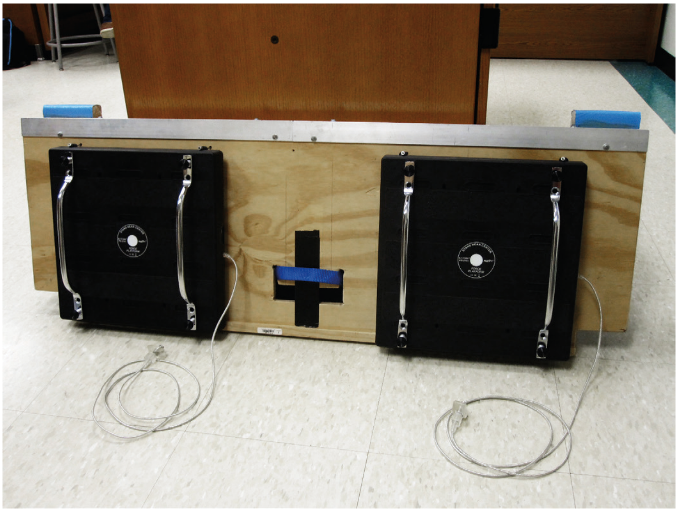
A set of instructions you may reproduce and give to students begins after the following illustrations. This set of instructions is taken from my freshman science texts *Introductory Physics* and *Accelerated Studies in Physics and Chemistry*.

Force platform mounting bracket as originally built for a pick-up truck consists of a 1x6 across the top fastened with screws to a panel of 3/4-inch plywood with a piece of aluminum angle. The wooden lip across the bottom supported the weight of the force platforms.

Close-up of the bracket. Visible on the edge of the plywood is an eyescrew used for a cable that held the force platforms in place. Also visible is one of the two sections of dowel rod that fit into the stake holes of the pick-up bed. (Alas, new trucks don't have stake holes! How will future generations of physics teachers cope?)

Two boys pushing the force platforms on the back of the truck while two girls carry the Xplorer GLX readers, holding them where the boys can see them while they push.

Mounting bracket modified to fit the Soul. The padding is a swimmer's flotation device I cut up and glued to the bracket with contact cement. Tie-down straps connect to rear seat headrests as shown in the other photos. The small steel cables (barely visible near the top) hold the force platforms onto the bracket on the other side.



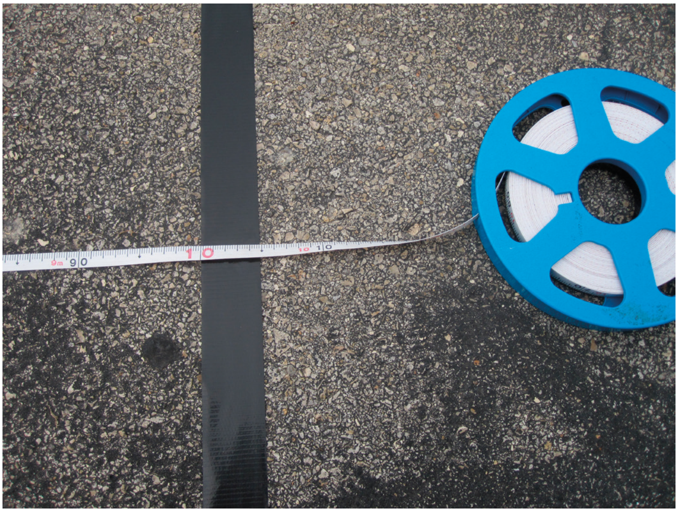
The force platforms on the modified bracket. The handles visible in this photo are sold separately by PASCO and were a later addition to our setup. The handles make it a lot easier on the pushers' wrists.

The modified setup mounted on the Soul and ready to go. The cords hanging from the force platforms are connected to the Xplorer GLX readers.

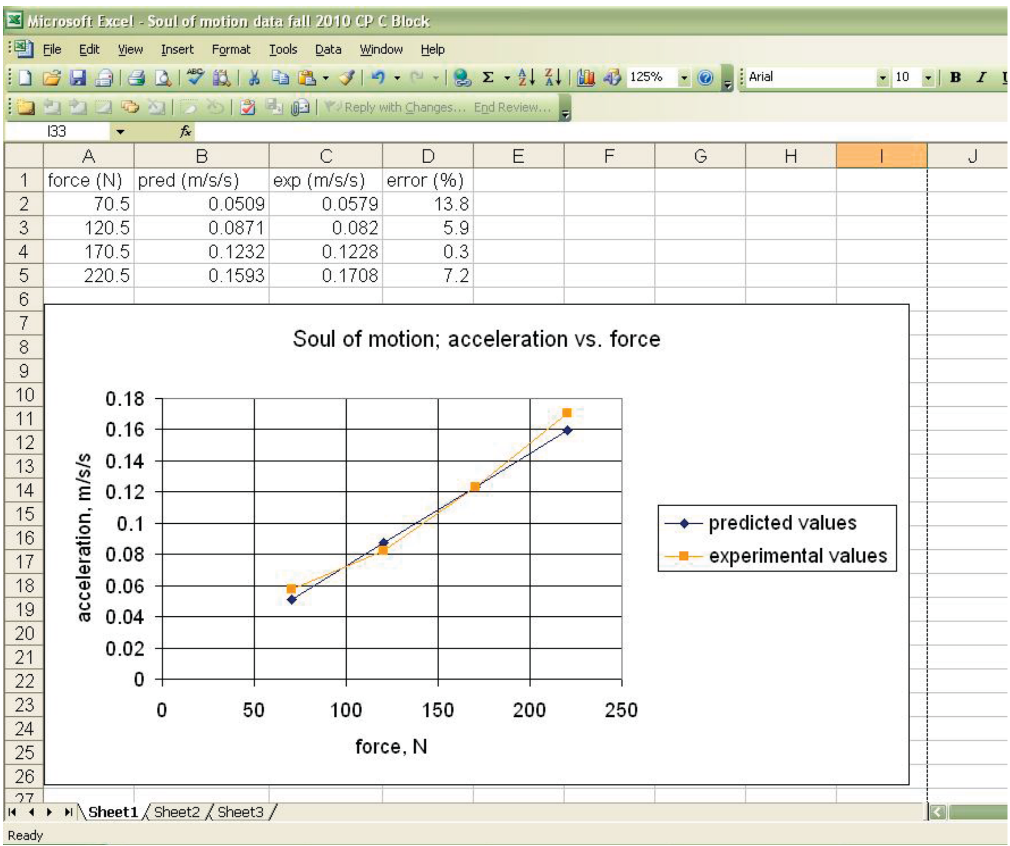
Close-up of installed bracket with mounted force platforms. The feet of the force platforms are resting on the wooden lip running along the bottom of the bracket. Barely visible at the top of the force platforms are the steel cables coming through the plywood and looping through some mounting holes that are molded into the plastic force platform housing.

View from inside the car showing the tie-downs holding the bracket to the back of the car. The tie-downs loop around the support rods of the head rests in the back seat.

Another inside shot of the straps.

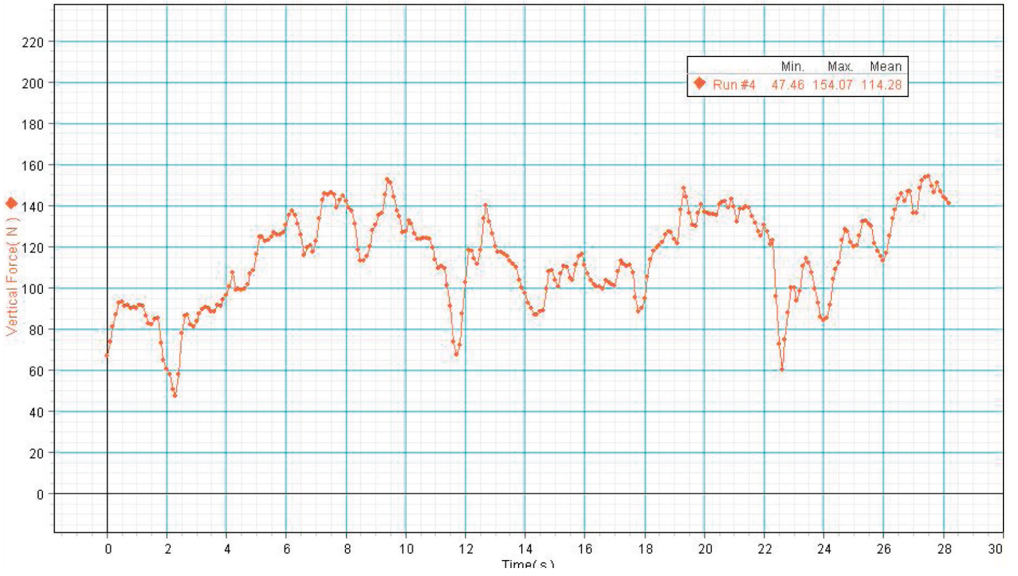


Laying out the timing zone on the pavement with a wind-up meter tape.



force (N)	pred (m/s/s)	exp (m/s/s)	error (%)
70.5	0.0509	0.0579	13.8
120.5	0.0871	0.082	5.9
170.5	0.1232	0.1228	0.3
220.5	0.1593	0.1708	7.2

Decide for yourself whether or not you want to show this graph to your students ahead of time, but if this experiment is performed with care, you can get excellent results like these (actual 2010 data). Note that the column labeled "error" from this old data file would now be labeled something like "P-R diff ratio," in accordance with my comments in the Appendix on the use of the term "experimental error."



This is a sample data file from the Xplorer GLX during a friction measurement. A single pusher is instructed to push the car as slowly as possible at a constant speed. We took the friction data in the actual timing zone for nearly 30 seconds. In the upper right you can see that the mean force value is 114.28 N. This data file gave us the best possible estimate for the net force necessary to keep the car in motion, which is a combination of the forces from friction and the slope of the pavement.

The gang in action!

Student Instructions

The Soul of Motion Lab
Newton's Second Law of Motion

Note: The report for this experiment requires you to set up a graph showing predicted and experimental curves on the same set of axes. Procedures for creating such a graph in two different versions of Microsoft Excel (one for PCs and one for Macs) are described in detail in *The Student Lab Report Handbook*. Procedures for creating graphs in other applications, such as on a Mac using Pages, are available as free downloads from novarescienceandmath.com.

You will have a great time with this experiment. We will meet out in the parking lot as a class. We are going to push a vehicle from the rear using scales that measure the force the pushers are applying to the vehicle. We will time the vehicle as it accelerates from rest through a ten-meter timing zone and use the time data to calculate the experimental values of the vehicle's acceleration. Using the mass of the vehicle and Newton's Second Law, we will predict what the acceleration should be for each amount of pushing force used. Our goal will be to compare our predicted accelerations to the experimental values for four different force values. We will graph the results and calculate the percent difference to help us see how they compare.

This experiment is an excellent example of how experiments in physics actually work. The scientists have a theory that enables them to predict, in quantitative terms, what the outcome of an experiment should be. Then the scientists carefully design the experiment to measure the values of these variables and compare them to the predictions, seeking to account for all factors that could affect the results. If the theory is sound and the experiment is well done, the results should agree well with the theoretical predictions and the percent difference should be low.

In our case, when a force is applied to a vehicle at rest, it should accelerate in accordance with Newton's Second Law of Motion, $a = \frac{F}{m}$, which predicts that the acceleration depends on the force applied. So Newton's Second Law is our theoretical model for the motion of an accelerating object. Now, we know that a motor vehicle has a fair amount of friction in the brakes and wheel bearings, which means that not all of the force applied by our pushers will serve to accelerate the car. Some of it will simply overcome the friction. Also, the ground will probably not be perfectly level, and this will affect the acceleration as well. So to make our model as useful as possible we will want to use the actual *net* force on the vehicle in our predictions so that they will be as accurate as possible. More on this below.

For our data collection we need a way to measure what the vehicle's acceleration actually is, so that we can compare it to our predictions. You already know an equation that gives the acceleration based on velocities and time. However, we have no convenient way of measuring the vehicle's velocity. (The vehicle will be moving too slowly for the speedometer to be of any use.) Fortunately, there is another equation we can use if we time the vehicle with a stop watch as it starts from rest and moves through a known distance. If we know the distance and the time, and the acceleration is uniform, we can calculate the vehicle's acceleration with the equation $a = \frac{2d}{t^2}$. This is the equation we will use to determine the experimental acceleration value for each force, using the average time for each set of trials.

Here are some crucial details to make our experiment as successful as possible:

1. We will always have two students pushing on the vehicle, so for each force value our pushers use the total applied force will be twice that amount. We will use four different force values in the experiment.
2. We need to measure friction so we can subtract it from the force the pushers are applying to get the net force applied for our predictions. To measure the friction we will simply get one pusher and estimate the absolute minimum amount of force needed to keep the vehicle barely moving at a constant speed. As you know from our studies of the Laws of Motion, vehicles move at a constant speed when there is no net force. So if the vehicle is moving at a constant speed it means that the friction and the applied force are exactly balanced. This allows us to infer what the friction force is.
3. We will use four different values of pushing force. For each force value, we need to time the vehicle over the ten-meter timing zone at least three times. The forces the pushers apply to the vehicle will vary quite a bit, so if we get three valid trials at each force we will have three good data points for the time. You can then calculate the average of these times and use it to calculate the experimental value of the acceleration of the vehicle for that force.
4. The major factor introducing error into this experiment is the forces applied by our pushers. Pushing at a constant force while the vehicle is accelerating is basically impossible. (The dial on the force scale will be jumping all over the place.) But if our pushers are careful they can push with an *average* force that is pretty consistent. We need some kind of standard to judge whether or not we have had a successful run with good, consistent pushing. Here is the criterion we will use: When we get three trials that have time measurements that are all within a range of one second from highest to lowest, we will accept these values as valid. If our times are not this close together, we will assume that the pushing forces are not consistent enough and we will keep running new trials until we get better data.
5. The instructor will take the vehicle, with a full gas tank, to get it weighed and will report this weight to the class. We need to make sure to measure the weight of the driver and the weight of the scale support rack (if there is one). These weights will need to be added to the weight of the vehicle, and the mass determined for this total weight. (Of course, the instructor will also make sure the gas tank is full on the day of the experiment, since the fuel in the tank could amount to 1–2% of the vehicle weight.)

Considerations for Your Report

In the Background section of your report, be sure to give adequate treatment to the theory we are using for this experiment. In the Newton's Second Law equation, acceleration is directly proportional to force, so a graph of *acceleration* vs. *force* should be linear. In the Background you should use this concept to explain why we expect our experimental acceleration values to vary in direct proportion to the force. Explain the equations we are using to get the predicted and experimental acceleration values. Since we are using two different equations your Background section should include explanations of both of them and what they are needed for. The force we are using to make our predictions takes friction into account. You need to explain how friction is taken into account, why we are doing so, and how this relates to the equations.

In the Procedure section don't forget the important details, such as how we measured the friction force, weighed the driver, and judged the validity of our time data.

In the Results section, all time data should be presented in a single table, along with the average times for the trials at each force value applied by the pushers. All of the predicted values, experimental values and percent differences should be presented in another table or two. Do not forget to state all of the other values used in the experiment, such as the vehicle weight, the weights of the driver and support rack, the distance, the total mass you calculated, and the friction force. (As *The Student Lab Report Handbook* describes, in any report, all of the data collected must be presented, and they all must either be placed in a table or in complete sentences.)

In the Discussion the main feature will be a graph of *acceleration* vs. *force*, showing both the predicted and experimental values on the same graph for all four force values. Carefully study Chapter 7 on graphs in *The Student Lab Report Handbook* and make sure your graph meets all of the requirements listed.

For your predicted values of acceleration, use the total mass of the vehicle, driver and support rack. The instructor will tell you the weight of the vehicle, which you should record in your lab journal. The weights of the driver and support rack determined during the experiment should also be recorded in your journal. Convert the total weight from pounds to newtons, then determine the mass in kilograms by using the weight equation, $F_w = mg$.

For the force values in your predictions, use the nominal amount of force applied (the two pushers' forces combined) less the amount of force necessary to overcome the friction (which will be determined during the experiment).

Table 2-1 summarizes the calculations you need to perform for each set of trials.

The heart of your discussion will be a comparison of the two curves representing acceleration vs. force (displayed on the same graph), and a discussion of how well the actual values of acceleration match up with the predicted values. In addition to this graphical comparison you must compare the four predictions to the four experimental acceleration values by calculating the percent difference for each one, presenting these values in a table and discussing them.

To compare the curves, think about the questions below. Do not write your discussion section by simply going down this list and answering each question. (Please spare your instructor the pain of reading such a report!) Instead, use the questions as a guide to the kinds of things you should discuss and then write your own discussion section in your own language.

Variable	Equation	Comments
force	net force = (2 x force for each pusher) – (friction force estimate)	There are four values of net force, one for each set of trials.
predicted acceleration	predicted accel = (net force)/(total mass)	Net force is as calculated above. Mass is determined from the total weight. There is a predicted acceleration for each value of net force.
experimental acceleration	experimental accel = (2 x distance)/(avg time)^2	Distance is the length of the timing zone. Average time is the average of the three valid times for a given trial. There is an experimental acceleration for each value of net force.

Table 2-1. Summary of equations for the calculations.

Thought Questions and Considerations for Discussion

1. Are both of the curves linear? What does that mean?
2. Do they both look like direct proportions? What does that imply?
3. Do the curves have similar slopes? What does that imply?
4. How good are the results? A percent difference of less than 5% for an experiment as crude as this would be remarkably good. If the ratio is greater than 5%, you must identify and discuss the factors that could have contributed to the difference between prediction and result. In this experiment there are several, including wind that may have been blowing on the vehicle.
5. Do not make the mistake of merely assuming that the fluctuations in the pushers' forces explains everything, without taking into account the precautions we took to eliminate this factor from being a problem (our time data validity requirement).
6. Also do not make the mistake of assuming that friction explains the difference between prediction and result. Friction can only affect the data one way (slowing the vehicle down). So if friction was a factor, the data have to make sense in light of what friction would do. But further, since measuring friction and taking it into account in our predictions was part of our procedure, a generic appeal to friction will not do.
7. Finally, do not make the mistake of asserting that errors in the timing or the timing zone distance measurement explain the difference between prediction and result. You should consider just what kind of percentage of error could realistically be in these measurements, and whether that kind of percentage helps at all in explaining the difference you have between prediction and result. For example, the timing zone was 10.00 meters long. If it was carefully laid out

on the pavement, it is unlikely that the distance was in error by more than a centimeter or so. Even including the slight misalignments of the vehicle that cropped up, the distance could probably not have been off by more than, say, 10 or 20 cm. But this is only 1 – 2% of 10 m, and if you are trying to explain a percent difference of 5 or 10% or more this won't do it. Similar considerations apply to the time values. Given the slow speed the vehicle was moving, how far off could the timing have been? What kind of percentage error would this produce?

Alternate Experimental Method

If your class is using digital devices such as the PASCO Xplorer GLX to read forces, you can use a slightly different experimental method that will improve results and lower the difference between prediction and result. One of the major sources of error in this experiment is the difficulty the pushers have in accurately applying the correct amount of force to the vehicle. If you are using bathroom scales to measure the force, there is nothing that can be done about this problem, and the pushers will simply have to do the best they can.

However, with the digital devices you can eliminate the problem of force accuracy by using the actual average values of the forces applied by the two pushers to calculate the predicted values. The Xplorer GLX can record a data file of the applied force during a given trial, and when reviewing the data file back at your computer you can view the mean value of the force during the trial. This mean value can then be used to calculate the predicted acceleration from Newton's Second Law. Using this method to form your predictions will eliminate much of the uncertainty surrounding the forces that are being applied to the car.

Here are a few details to consider if you will be using this alternative approach to collecting data:

1. You will not need to select four different force values in advance and push the vehicle repeatedly at each force value. Instead, only a single trial is needed for each force.
2. Select 10 or 12 different target force values and run a single trial with each. The force targets should range from low values that will barely get the vehicle to accelerate, all the way up to the highest values the pushers can deliver. For each trial tell the pushers the target force, and tell them to do their best to stay on it during the trial. But it won't matter nearly as much how accurate the pushers are because you will be using the average of the actual data from the digital file to make the predictions, rather than relying on the pushers to maintain the target force accurately.
3. The method for determining values of net force for the predictions will be similar to that shown in Table 2-1. The difference is that instead of doubling the target force for each pusher, you will add together the actual mean forces obtained from the data files for each pusher and subtract out the friction force.

4. The time of each trial will be used to determine the experimental value of the acceleration.
5. Calculate the percent difference for each trial and report these values in the report. Also calculate the average of the percent difference values and use this figure in your discussion of the results.