Tonka Truck Physics

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The inertial mass of a toy truck was measured by applying a range of measured forces using hanging weights, and measuring the resulting acceleration, resulting in a mass of (2.44 ± 0.04) kg. This does not agree with the gravitational mass, derived from the measured weight, of 2.166 kg. The discrepancy is probably due to an increase in frictional and air resistance forces as the applied force was increased.

Introduction

Perhaps the first true physics experiments were conducted by Galileo when he rolled balls down inclined planes, and found that their acceleration was independent of their mass. A related experiment, which he proposed but probably never carried out, involved dropping balls of different masses off the tower of Pisa. Had he actually done this with a 1-pound iron ball and a 100-pound iron ball, they would indeed have arrived at almost the same time; due to air resistance the 1 pound ball would be 1.3 m off the ground at the instant the 100-pound ball hit.[1] Our modern interpretation for why the gravitational acceleration is independent of mass holds that the "weight" of an object (the gravitational force exerted on it by the earth) is proportional to its mass, while its acceleration in response to any force is inversely proportional to the mass. More quantitatively, we say that the uniform gravitational acceleration comes from the equivalence of the "gravitational mass" m that appears in the law of universal gravitation, $F = -\frac{GMm}{r^2}$ and the "inertial mass" that appears in Newton's second law, $F = ma$.

Einstein's fundamental assumption in deriving general relativity was that the uniform acceleration produced by gravity was not merely experimentally indistinguishable from the uniform acceleration of all objects that would be seen by an observer in an accelerated reference frame, but that in fact these two effects *are the same*, in other words that the way the Earth causes an apple to fall is by curving spacetime.[2]

Physicists continue to explore concepts relating to mass in current research. For example, one of the prime goals of the Large Hadron Collider is to find the Higgs boson, which is thought to impart mass to particles.[3]

In this experiment, we directly tested the equivalence of the gravitational and inertial mass of a Tonka truck.

Experimental Methods

We began by measuring the inertial mass of a toy dump truck (Tonka), using the apparatus shown in figure 1. We applied a measured force using several different hanging weights, and measured the resulting accelerations.

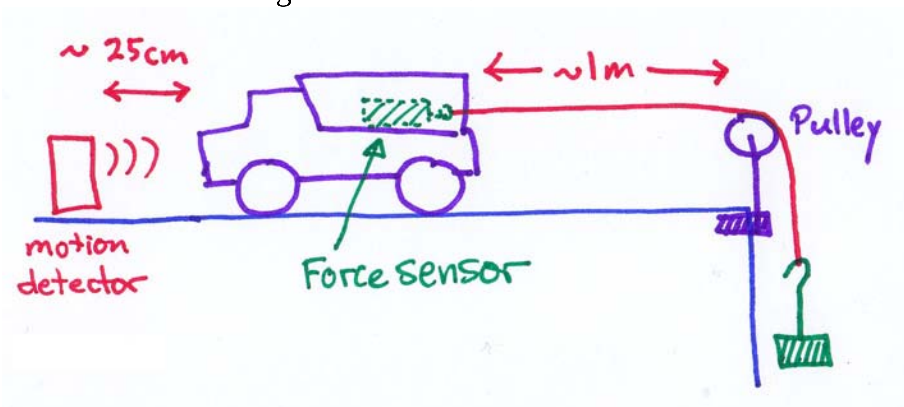

Fig. 1. Apparatus used to measure inertial mass.

We made measurements using a Vernier LabPro interface connected to a "Dual-Range Force Sensor" and an ultrasonic "Motion Detector 2". We taped the force sensor into the bed of the truck, with the force-sensing loop extending horizontally toward the rear. We tied a light string to this loop, and attached the other end to a hanging mass, with a pulley to redirect the force, as shown. We applied WD40 lubricant to the bearings of the pulley and to the bearings of the truck wheels in order to minimize friction. We aligned the pulley by eye to make the string horizontal between the pulley and the force sensor, and also adjusted the angle of the pulley to align the groove of the pulley with the natural direction of the string.

Prior to taking any measurements, we zeroed the force sensor (in the horizontal orientation used for the measurements), and calibrated it using two different weights. We measured the masses of these calibration weights (105.05 g and 204.80 g) using an Ohaus triple beam balance, and converted these to Newtons by assuming a local gravitational acceleration of 9.81 m/s^2. We checked the zero and the 105.05 g calibration immediately after completing our measurements; the zero was correct to within 0.05 N, and the calibration point was correct to within 1%.

We positioned the ultrasonic motion detector in front of the truck; this produced measurements of the truck's position, which were converted to accelerations by the Vernier LoggerPro data collection software. We acquired samples of force and position 30 times per second, the maximum rate allowed by the motion detector.

We made measurements using hanging weights with masses ranging from 55 g to 330 g. For each of these trials, we insured that the hanging weight was stationary (not swinging), and that the string was aligned with the axis of the truck, before initiating the data taking and releasing the truck. We were careful to catch the truck before it collided with the pulley.

We used the LoggerPro software to compute the average acceleration and average force over the time interval for which the acceleration was the most constant. These time intervals were chosen by eye for each trial, and were about 1-1.5 seconds long.

We measured the gravitational mass of the combination of the truck and the force sensor taped to it, using an Ohaus Scout Pro digital balance. We checked the calibration of this balance using standard masses, and found it accurate to within 0.2%.

Results and Analysis

A typical set of raw data is shown in figure 2; the gray area shows the time interval used to compute average force and acceleration

The plot of measured force vs. acceleration is shown in fig. 3. The point at approximately 1 N was taken three times to check for consistency, once at the beginning, once during the sequence from small applied force up to large applied force, and once at the end. The measured forces were consistent within 0.7%, and the measured accelerations within 5%. Judging by eye, the scatter in the acceleration for these three points is consistent with the overall scatter for the data, suggesting that there was little change in the performance of the apparatus between the start and end of the experiment.

If we assume that the frictional force in the truck bearings and in the pulley bearing is independent of speed, then the data should be described by

$$F_{\text{applied}} + F_{\text{friction}} = ma \Leftrightarrow F_{\text{applied}} = ma - F_{\text{friction}} \qquad (1)$$

Therefore, the slope of the graph should be the inertial mass *m*, and the *y*-intercept should give the magnitude of the frictional force. The slope of the best fit line (shown in red) is (2.44 ± 0.04) kg. The intercept is 0.28 N.

The measured gravitational mass was 2.166 kg. (The uncertainty of this measurement is much smaller than the uncertainty for the inertial mass.)

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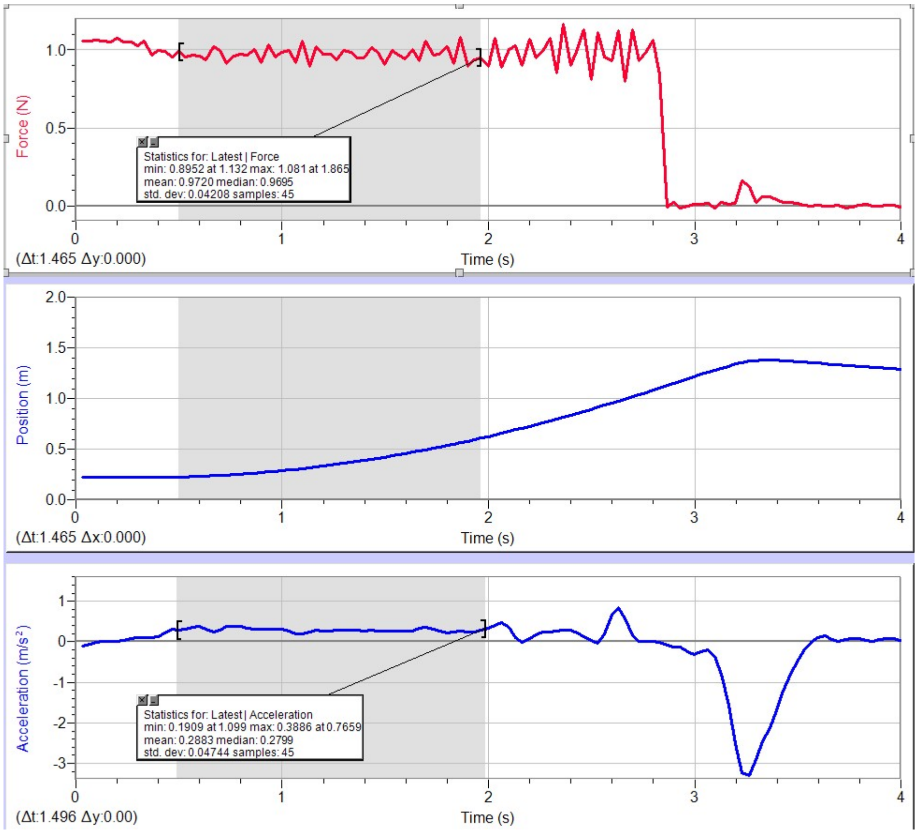

Fig. 2 Typical set of raw data; the shaded region was used to determine average force and acceleration.

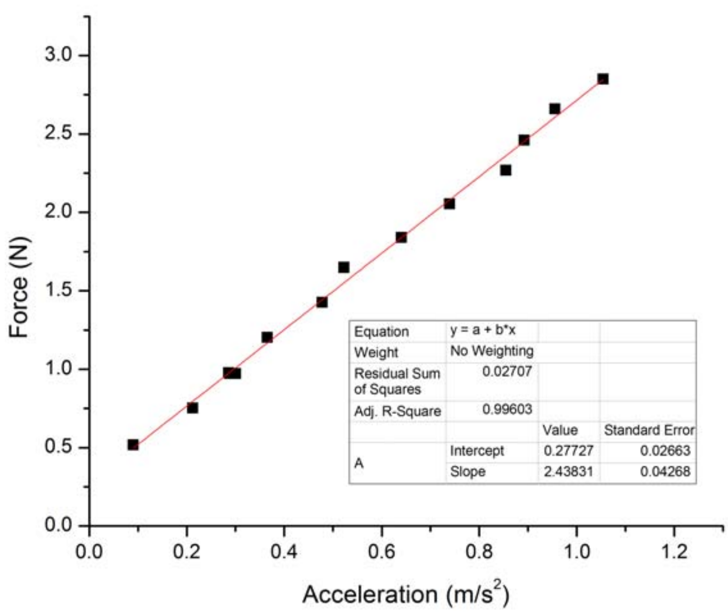

Fig. 3 Measured force vs. measured acceleration.

Discussion and Conclusions

The measured inertial mass is more than 6σ greater than the measured gravitational mass, clearly indicating that there is either a systematic error in the experiment or a problem with the theory.

There are three possible sources of systematic error in the experiment. Although we checked the calibration of the force sensor immediately before and after the measurements, it is possible that friction in the pulley caused the force applied by the hanging mass to be different from the weight of the mass. However, the pulley turned very easily, so we estimate that at the very most the frictional force of the pulley would have been equal to half the weight of the 5 g hanger used to hang the masses. This could introduce an error of about 2-3% into the calibration of the force sensor, which is much smaller than the discrepancy of 13% between the inertial and gravitational masses. Furthermore, we attempted to minimize this potential problem by wiggling the pulley back and forth to ease out any residual tension before doing the calibrations.

The second possible source of systematic error is the value assumed for the local acceleration of gravity. We used the value of 9.81 m/s^2 to compute the forces applied to calibrate the force meter. In fact, the gravitational acceleration varies from place to place on the Earth[4], from a minimum of 9.779 m/s^2 to a maximum of 9.819 m/s^2. However, this variation is only 0.4%, far less than our discrepancy.

The final possible source of systematic error comes from our assumption that the frictional force was independent of speed and of force applied. In fact, as the force applied was increased (by increasing the hanging mass), the downward force on the pulley would increase, thus increasing the friction in the pulley. Furthermore, for greater applied forces, the truck moved faster, leading to a greater force air resistance. Both these effects would cause an upward curvature of the graph in fig. 3, since the effective frictional force increases with acceleration. There is no obvious curvature apparent in our data. However, the size of the added frictional force needed to account for our discrepancy is small; fig. 4 shows the same data as fig. 3, but with a black line added having slope equal to the measured gravitational mass. The vertical offset at the maximum acceleration between the red (best fit inertial mass) and black (gravitational mass) lines is 0.25 N, corresponding to the weight of about 25 g. This seems like a reasonable magnitude for the combination of higher pulley friction and air resistance.

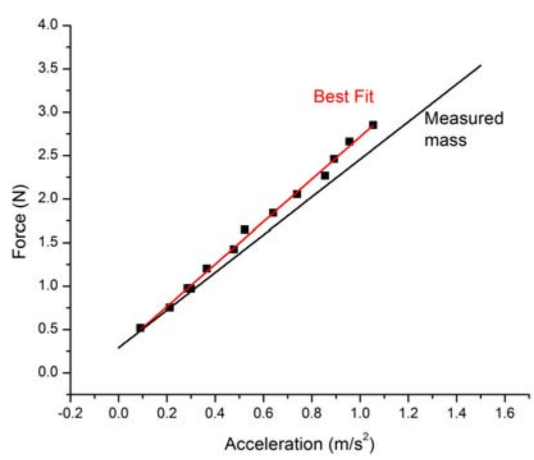

Fig. 4. The slope of the red line is the inertial mass, while that of the black line is the measured gravitational mass.

In a future version of this experiment, the friction of the pulley could be measured as a function of the hanging weight by pulling the weight up at constant speed; the difference between the measured force pulling on the string and the weight of the hanging mass would be the frictional force of the pulley. We have been unable to think of a reasonable method for measuring air resistance in this experiment, but it could be modeled theoretically, given the size and speed of the truck.

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[1] C. G. Adler and B. L. Coulter, *Am. J. Phys.* **46**, 199-201 (1978).
[2] R. Wolfson and J. M Pasachoff, "Physics with Modern Physics for Scientists and Engineers, 3rd Ed.", Addison-Wesley, Reading MA, 1999, p. 1037.
[3] http://www.exploratorium.edu/origins/cern/ideas/higgs.html, retrieved 3-8-11.
[4] http://en.wikipedia.org/wiki/Gravity_of_Earth, retrieved 3-8-11.