Model 19
Inclined plane with small force gauge

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DESIGN TASK

First construct the model according to the building instructions, without the force gauge and the two setup aids.

- Ensure that the car can roll smoothly. Its four wheels must run easily. The two horizontal wheels should keep it on track.
- You can slightly raise the inclined plane and see how fast a car placed at the end accelerates. The car is caught by the slightly springy strut.

THEMATIC TASK

1. Leave the track on the table. If the table is level, it will now be exactly horizontal. For the following considerations, we will refer to this position as an angle of 0° to the horizontal.

   a) Push the car to the end of the track (away from the articulated suspension on the base plate). Slowly lift the track with your hand. Why doesn't the car start moving at the slightest deflection?

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b. Observe how the car accelerates faster when you release it on a more elevated track. (The static strut at the bottom cushions the impact, but don't overdo it—otherwise, the model or components may be damaged.)

2. Now add the force gauge and the two setup aids to the model. This will allow us to measure and evaluate the forces that occur. Make sure that the force gauge reads "0" on its scale when the spring inside it is completely relaxed.

At fischertechnik, I-struts are attached lengthwise to components such as static beams. Their dimensions are based on a 15 mm grid – this is the distance between two holes in the beams. I-struts are always an integer multiple of this dimension.

X-struts, on the other hand, are designed for mounting at a 45° angle. Their length follows the rules of Pythagoras' theorem: they correspond to integer multiples of 15 mm multiplied by √2.

a. Try to deduce why the "45° erection aid" with X-brace lengths of 84.8 mm and static straps of 21.2 mm results in an erection angle of exactly 45° when aligned vertically.

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b. Why does the "30° setup aid" with I-struts 60 and static brackets 15 in a vertical alignment result in a 30° setup angle?

3. Let's measure the force in newtons (N) that the trolley exerts on the force gauge at different installation angles:
    - When the track is horizontal, the force will be 0 N.
    - When the track is positioned vertically, it is the total weight of the car (to prevent it from falling off the track, you have to hold it lightly – if possible without exerting any force upwards or downwards).
    - However, we are also interested in angles between 0° and 90°.

There are various ways to determine the angle of inclination:

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- The two 7.5 building blocks on the bottom of the building plate are designed to hold a set square in place against the track. The zero point of the set square should be exactly in the middle of the hole in the joint blocks. You can then easily read the current angle of inclination from the thin slot in connector 45, which is inserted into the bottom of the track. You may want to do this in teams of two – one person holds the track while the other reads the angle.
- The two setup aids, 30° (the shorter one) and 45° (the longer one), are clipped into the strut adapters (which look like spring cams but have a round pin) located at about 2/3 of the track length. The specified installation angle is achieved when the struts point exactly vertically downwards and the building blocks 15 at the lower end stand firmly and straight on the base plate.
  Important: The building blocks are *not* positioned in such a way that they should be inserted into the grooves of the building plate – if they were, the struts *would not be* exactly vertical. The building blocks simply lie flat on the base plate. The struts run down exactly vertically from their suspension point on the track.

a. Enter the measured force in a table like the following:

Angle of installation	Measured force (in N)	Percentage of the measured force relative to the weight force (at 90° angle of installation)
0°	0.0 N	0%
15°		
30°		
45°		
60°		
75°		
90		100%

b) At what angle is the force exerted exactly half (50%) as great as the weight force?

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EXPERIMENTAL TASK

We can also think of our inclined plane as a scale for the cart, which we operate at different angles. If we measure the total weight (in N) at an angle of 90°, we can calculate the mass (in kg) of the cart using the acceleration due to gravity g (the acceleration that a freely falling body experiences on the Earth's surface due to gravity). The following applies:

$$F = m * a$$

The force F is equal to the mass m of the body multiplied by the acceleration a.
It follows that:

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

In our case, the acceleration a is the acceleration due to gravity. The average acceleration due to gravity (it is not exactly the same everywhere on Earth due to uneven mass distribution) is g_N = 9.80665 m/s^2 . If we read the force F in N (Newtons) on the force gauge, we can calculate its mass as

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

. We have g_N accurate to five decimal places – great! So can we also calculate the mass m of our car in kg accurate to five decimal places? To a tenth or even a hundredth of a gram?

That depends on how accurately we can measure the force in the first place!

The measurement with the track positioned vertically (90° angle of installation) shows, for example, a weight force of 0.8 N. Fundamental different types of errors come into play here:

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- Systematic errors arise because we are doing something fundamentally wrong. That sounds worse than it is: we cannot avoid many systematic errors.

  - For example, we have friction in the rollers of the carriage and in the bearing of the axle with the spring, the extent of which we do not know.
  - We may not have attached the scale correctly—e.g., slightly offset from the correct position—and thus misread all force measurements by a certain amount.
  - The scale may not have been printed correctly.
  - We do not know the exact acceleration due to gravity at the location where we are taking the measurements (although it will be approximately 9.81 m/s^2 everywhere).
  - We could be looking at the scale at an angle, causing a false reading.
  - And so on and so forth... It is good to be aware of systematic errors, but quantifying them is usually difficult.

- Reading errors and statistical errors:

We can "quantify" these, i.e., express them in numbers that we can calculate with. We have to estimate how accurately we can read the scale. One division of the scale corresponds to 0.1 N. We can look at it carefully, adjust everything properly, and yet, even with a trained eye, we can only reliably and reproducibly read 1/10 of a scale division at best. That would be 1/10 of 0.2 N = 0.02 N. So we cannot read the force any more accurately than to 0.02 N!

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Now we can calculate how accurate our measurement of force is in percentage terms: 0.02 N reading error for a weight of 0.8 N is therefore

$$\frac{0{,}02N}{0{,}8N} = 0{,}025 = 2{,}5\%$$

Our measurement error is therefore 2.5% (systematic errors not taken into account!).

With a value of this accuracy, we can now enter our formula:

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

Since m is proportional to F (g_N , which is a constant), the calculated mass m will also have an inaccuracy of 2.5%.

1. Using *F=0.8 N*, a reading error of *0.02 N*, and g_N , calculate the mass of the car in kg or g and also indicate the expected error in kg.

Repeat the measurement at the angle of inclination at which the force on the dynamometer is only half the weight force. Calculate, again with a reading error of 0.02 N and using g_N , the mass and the accuracy of the calculation (again, both in kg and g, respectively).

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APPENDICES

Further information

[1] Wikipedia: Inclined plane.

[2] Dennis Rudolph: Measurement errors and error analysis. At gut-erklaert.de.

[3] Ulf Konrad: Error calculation. At ulfkonrad.de.

[4] Ulf Konrad: Error propagation. At ulfkonrad.de.

[5] Wikipedia: Error propagation. Note: The mathematics used goes beyond secondary school level.

[6] Dr. Alexey Chizhik: Measurement errors. Georg August University of Göttingen. Note: This link is for those who are interested in seeing how far error calculation can go. The level is that of a physics degree. By scrolling forward with the link