Kitchen-Top Science – Eddy Current Braking

Real science does not necessarily need a fully equipped laboratory and/or extreme budgets. An intelligent experimental design can reduce costs dramatically.

Where I have bought something specifically for this experimental work I have said how much it cost and exactly what it was. This is for the sake of reproducibility and definiteness, but should not be taken as an endorsement of the item or vendor chosen.[1]

Kitchen-Top Setup

Note the 45° child's school set square used to set the slope of the Perspex sheet to a definite angle.

[1] It is also important to note that I have not been paid for any product placement or indeed for anything else related to this work.

Materials Testing

In order to test different materials you have to have different materials! Also, cutting sheet metal whilst keeping it flat is not easy by hand. I therefore ordered some 100mm x 100mm squares from a supplier off the internet for whom this is a standard size.[2]

Aluminium 1050 (1.2mm)
Brass CZ108 (1.2mm)
Copper C106 (1.2mm)
Stainless Steel 316 (0.9mm)

The material grades are just what the supplier offered and were not chosen specifically. The stainless steel was an after thought, costing me extra shipping fees ☹. Three grades of stainless were chosen, but the only common size was 0.9mm. As it turns out only the 316 sample was suitable and that *was* available in 1.2mm. The best comparison would have been with identical thicknesses, but science has taken a back seat to economics in this case.

It is worth mentioning why the stainless steel samples of 430 and 304 were not used. Firstly 430 is a magnetic grade of stainless steel. 430 is unsuitable for these tests because the magnet just sticks to it, even when upside down. The 304 sample is another matter. 304, also known as A2, should be non-magnetic and yet at the edges the magnet could just manage to stick to the material enough to prevent sliding. This was not roughness on the edges, but could be a change of magnetic properties due to the cutting of the sheet. This in itself is interesting from an engineering viewpoint.

Measurement Process

It turns out that my camera [3] has a “super-slow motion” mode so this was chosen as the measurement method. The camera specification *claims* 240 frames per second at QVGA (320×240). It would be at best incautious to take such a specification at face value. With image compression running in real time it is possible that the frame rate depends on the amount of data changing between frames.[4] As a precaution, all movies were taken with a stopwatch [5] running in the scene for comparison. This technique eliminates ambiguities of which slow-motion speed the camera was set to, as well as taking into account any unspecified (undocumented) “features” of the recording process.

The camera was facing directly down onto the sliding surface, as set by eye. Since we don’t want to get variations between the frictional resistances of the surfaces, all tests were done using the same sheet of paper as the sliding surface. Additionally this paper was printed with a series of parallel lines, 5mm apart (created in MS Word), to provide accurate distance measurements.

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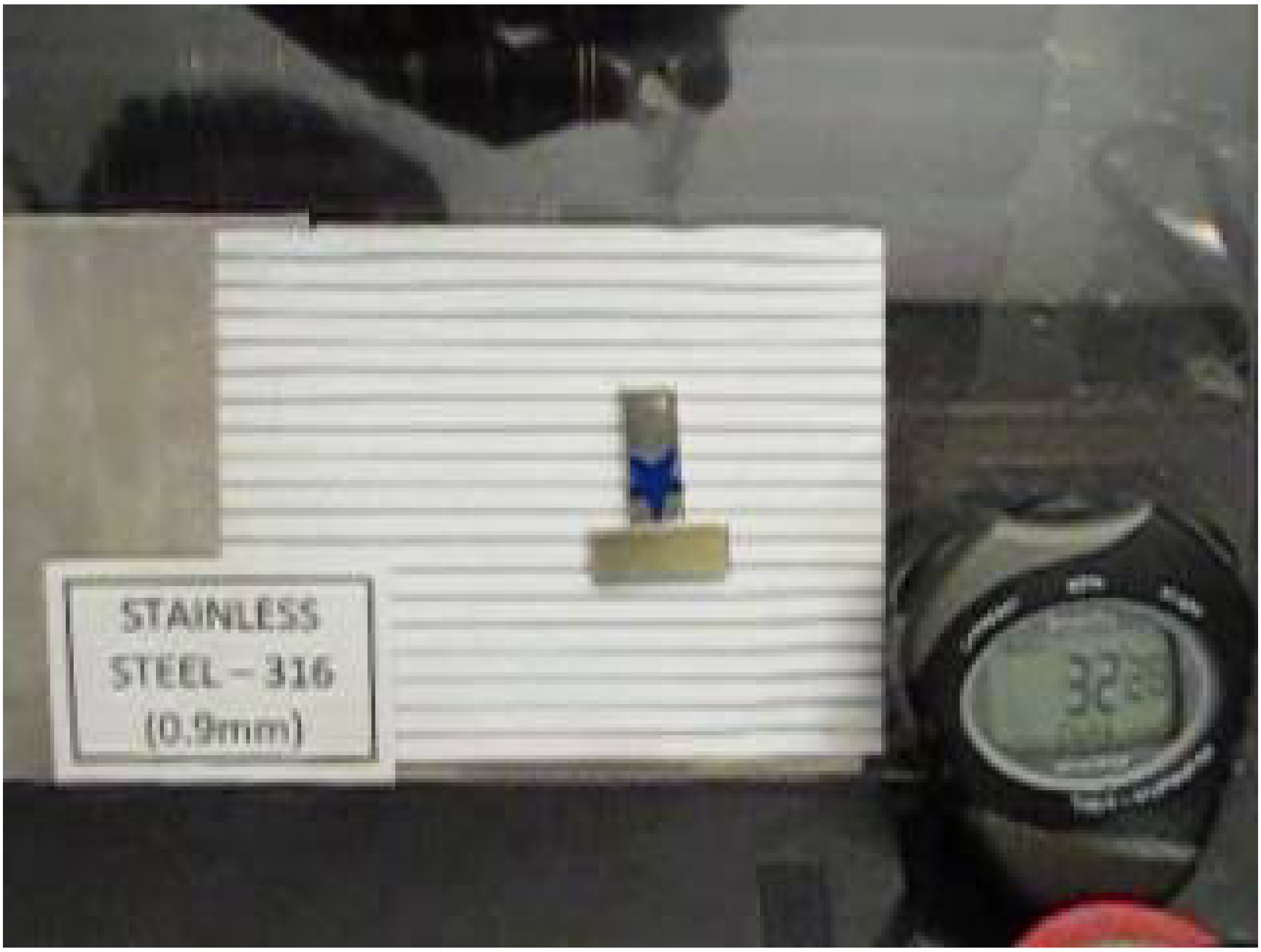
[2] These were all supplied by www.metaloffcuts.co.uk. The first order was for copper, aluminium, mild steel and brass (£21.35 inc shipping and tax). The second order was for stainless steel grades 304, 316 and 430 (£16.42 inc shipping and tax).

[3] Canon PowerShot SX510HS

[4] Technical support for the supplier have stated that the frame speed is constant.

[5] This seems to be an own-brand item by Argos, labelled ARG010 and 11763.

The ambient lighting level was not adequate for high quality images so a portable 500W worklight [6] was projected onto the ceiling to give a strong but diffused light.



This snapshot was taken from one of the recorded .MOV movie files, played on VLC media player 2.1.5, and saved using the built-in snapshot facility.[7]

The magnet is actually two Neodymium super-magnets [8] stuck together using their own magnetic attraction (no adhesive needed). This T-shaped arrangement is more stable than a single rectangular magnet on its own. Some experimenters use circular magnets rather than rectangular magnets, thereby avoiding the stability issue, but they miss out on some important science by doing so. For now we will stick with the T-shape to do the material comparison and come back to the shape aspect later on.

This T-shape raises another interesting point. The experiments presented here are not the first version of the experiments. The results of the earlier experiments increased understanding of the phenomena so that better experiments could be devised.

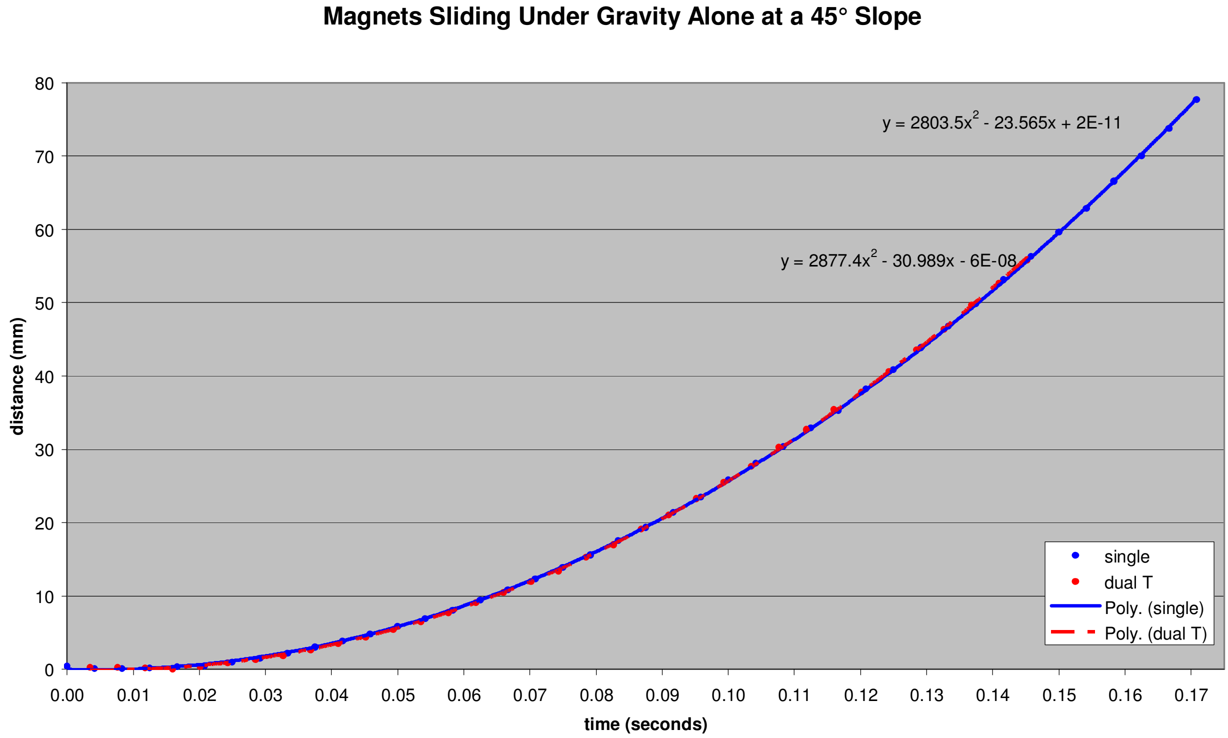
[6] Robert Dyas own brand, £19.99

[7] Note that using the standard Windows screenshot method does not work unless you disable hardware acceleration.

[8] These were described as 24 x 9 x 2mm Neodymium super magnets when bought from Choice DIY via amazon.co.uk in June 2013. 4 magnets cost £10.42 including shipping and tax.

The self-adhesive blue star [9] on the upper magnet was used to give the auto-tracking analysis software [10] something to lock on to.

The first experimental data presented is for magnets sliding down the lined paper with no metal behind. This is the no eddy current control experiment. The track data was exported from the Tracker software to MS Excel 2003 for plotting. The Tracker software produced both ***x*** and ***y*** data for the position track. Whilst the position was dominantly ***y*** values, the ***x*** values were not discarded. Instead a position value was created as $p = \sqrt{x^2 + y^2}$ to give the true (Pythagorean) distance from the origin.



The data points fit a smooth curve with much lower noise than was expected. Both the single magnet and the dual T-shaped magnet slide at remarkably consistent rates.

There are two ways to get a velocity plot from the data. The first way gives a very smooth plot because we take the equation for the regression curve and differentiate it.

Using ***s*** for distance and ***t*** for time, the regression curve for the single magnet is:

$$s = 2803.5 \cdot t^2 - 23.565 \cdot t$$

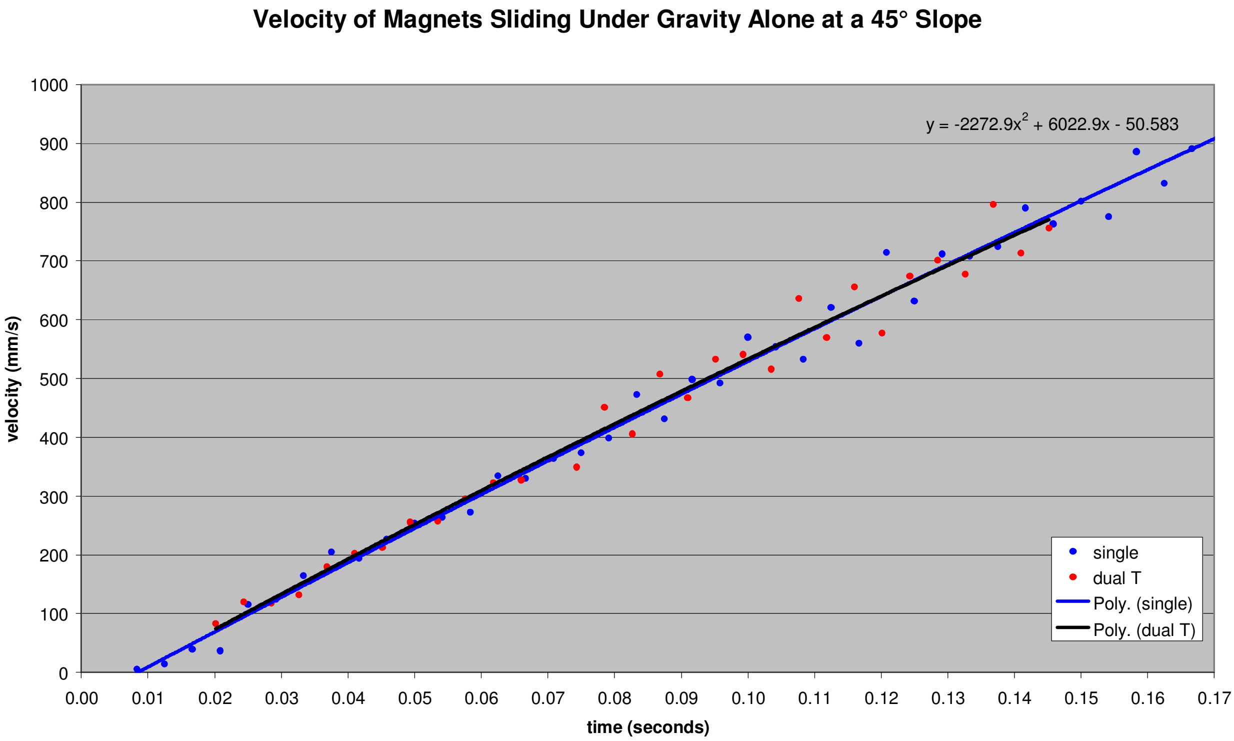
Read from the excel graph but neglecting the 2E-11 offset.

$$v = \frac{ds}{dt} = 5607 \cdot t - 23.6$$

This says that the velocity is increasing linearly with time (constant acceleration) and that the velocity at time t=0.17 is roughly 930mm/s.

[9] IVY range from Platignum Ltd
[10] Tracker v4.87 by Douglas Brown, https://www.cabrillo.edu/~dbrown/tracker/

The second method of plotting the velocity is more direct. We take $v = \frac{ds}{dt} \cong \frac{\Delta s}{\Delta t}$. In words we simply take the change in distance between two adjacent measurement intervals and divide by the change in time for this interval. This definition is essentially no different to the elementary definition, $\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$ and is easily calculated in Excel.



This time the regression curve is $v = -2272.9 \cdot t^2 + 6022.9 \cdot t - 50.6$, which at t=0.17 gives v=908 mm/s.

Which of these two velocity results is more likely to be correct? They are only different by a couple of percent so they tend to confirm each other, but should you present the apparently noisy time-difference version or the more theoretical calculus version? The answer might come from whoever is paying/funding the experiment. Maybe the higher velocity supports your product better. Maybe your salary is up for review and you need a "good result" from this experiment!

The obvious next question is: what is the acceleration? Using the position data directly we get

$$a = \frac{dv}{dt} = \frac{d^2 s}{dt^2} = 5607 \text{mm/s/s}$$

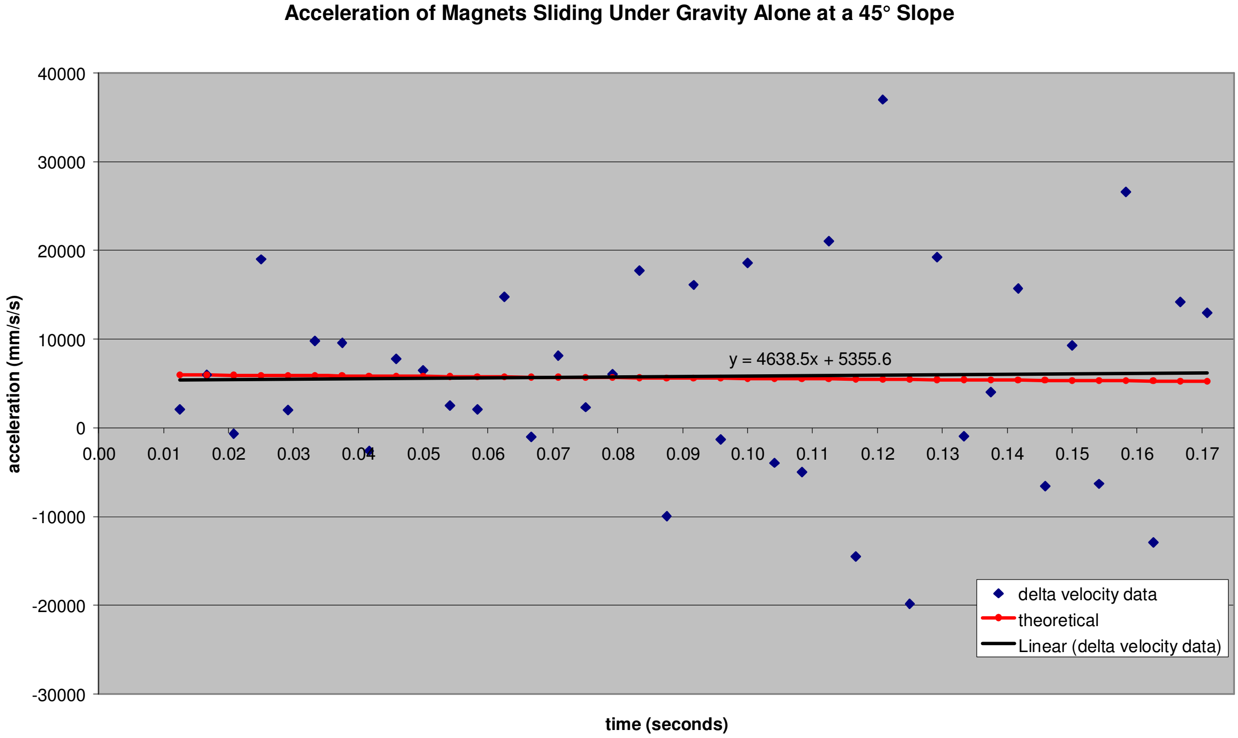
Alternatively we could use the velocity curve

$$a = \frac{dv}{dt} = -4545.8 \cdot t + 6022.9$$

This seems more reasonable because the acceleration is slowing as the magnet speeds up. The acceleration is a maximum initially of 6023mm/s/s and falls to 5250mm/s/s at t=0.17s.

Notice that we must not use the regression curve to predict (extrapolate) too far into the future because the regression equation says that with increasing time the acceleration will stop and then reverse!

Of course we could use the difference between the adjacent velocity values in our Excel spreadsheet to directly plot the acceleration.

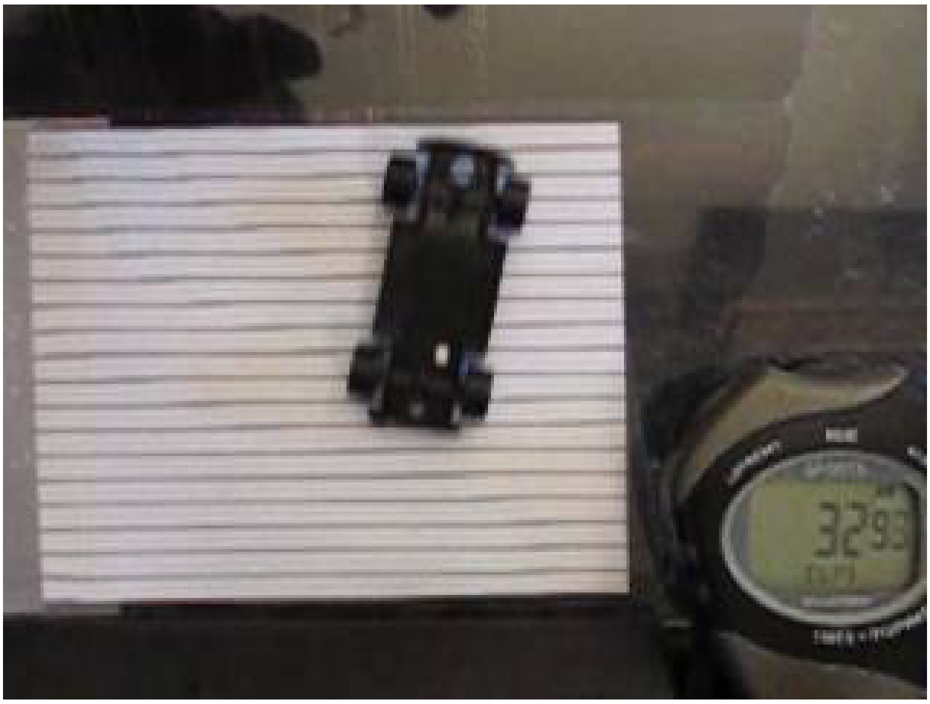


Wow! What a mess. Notice that we basically have one set of data, but that by choosing different ways of analysing the data we can unconsciously (or deliberately) bias the results.

Now there is a danger here of getting too interested in what is going on with this measurement process. We already know that the eddy current tests run at a much slower speed than the non-eddy current tests, so any timing uncertainties become less relevant for the real work. However we do have time for one last experiment.

This time we will be using a toy car from the Hot Wheels collection.[11] The body was held onto the chassis by riveting. Drilling off the two rivetted heads allowed the wheel assembly to be used separately. The idea is that this wheeled arrangement should give lower friction than the sliding magnets as an ultimate acceleration test.

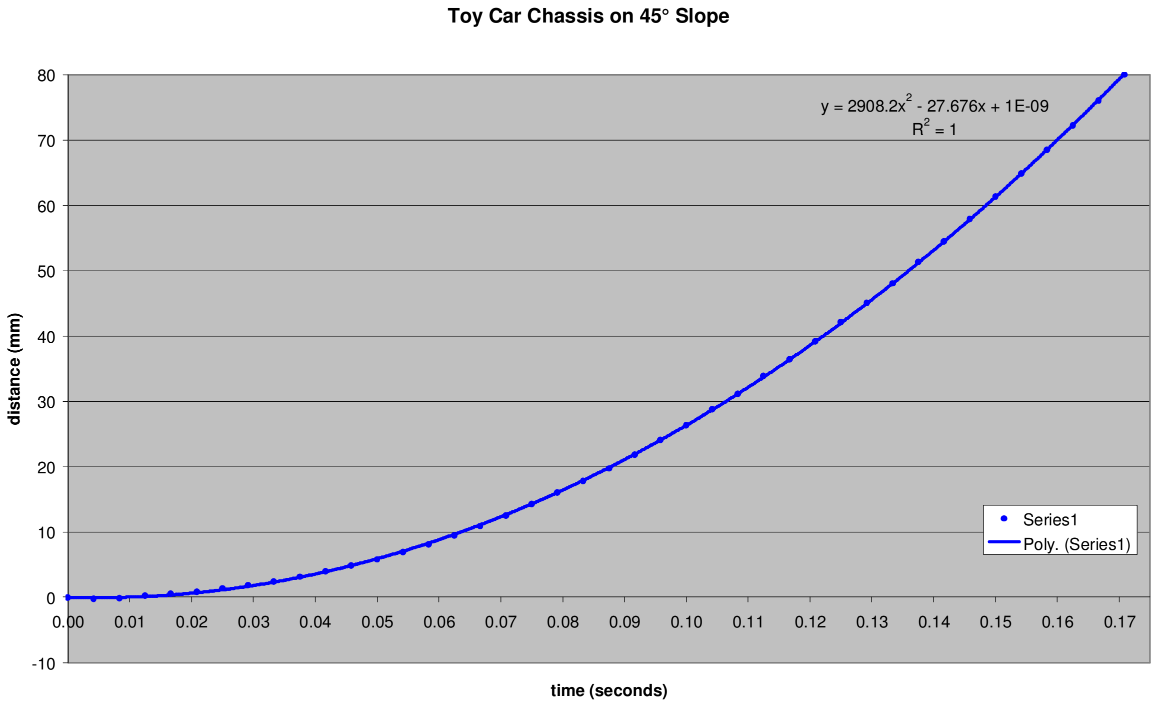
Whilst it is obvious from the video clip that the car was not running straight down the track, this was not so obvious whilst doing the experiment!



The white dot is Pentel Micro Correct [12] applied like quick-drying paint as a marker for the auto-tracking software.

[11] £1.49 from Argos.

[12] A brand of correction fluid, of which there are many commercial variants such as Tipp-Ex, Wite-Out & Liquid Paper.

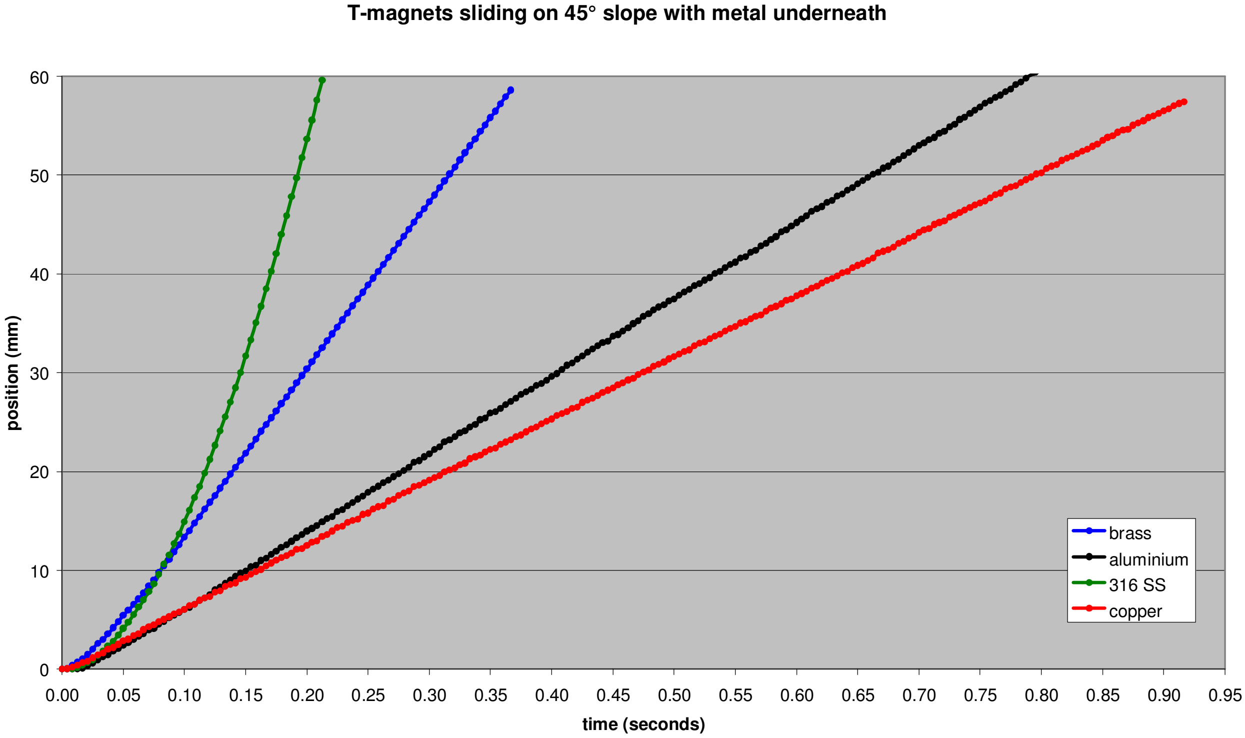


We can now immediately read the acceleration from the regression curve as double the 2908 multiplier of the squared term.

$$s = 2908.2 \cdot t^2 - 27.676 \cdot t$$

The acceleration is 5816 mm/s/s. The standard gravitation constant is 9807 mm/s/s, but we could expect no more than 6934 mm/s/s due to the 45° ramp angle, and in fact a bit less than that due to the car running at an angle to the ramp.

Eddy Current Braking Test Results

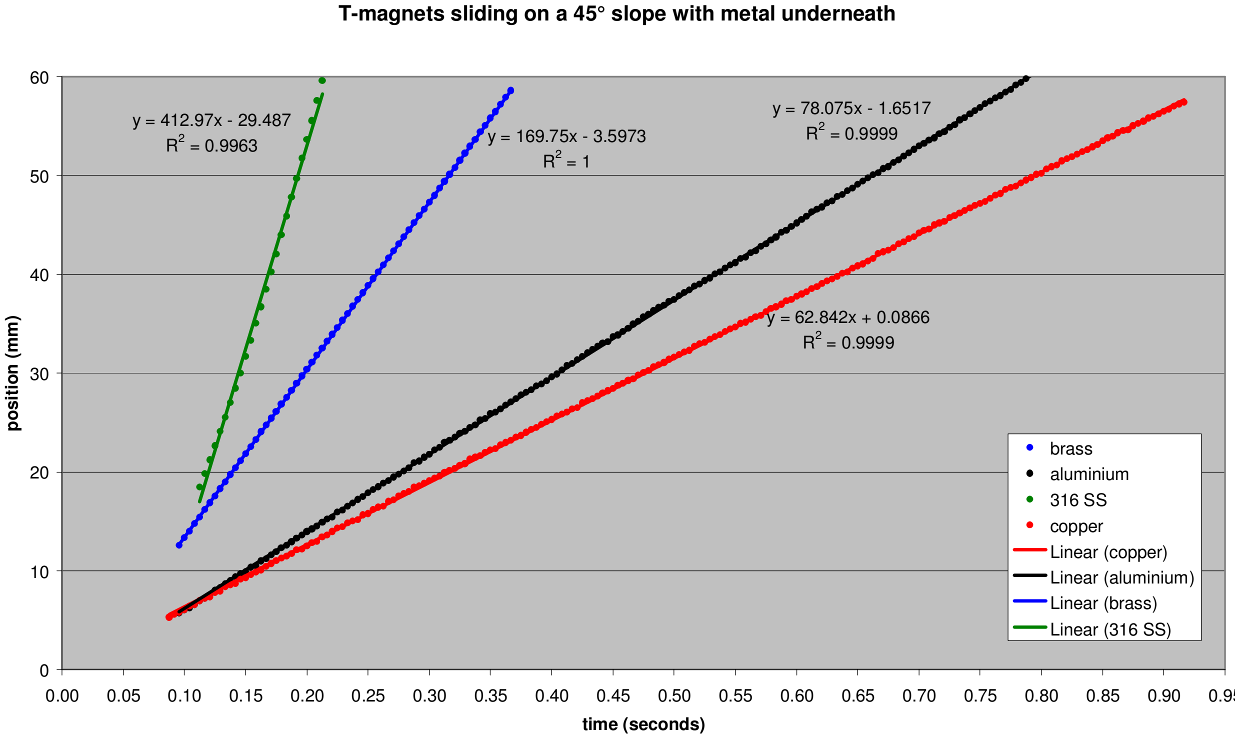


There is clearly a significant difference between the metals, and the plots seem to give constant velocity after an initial acceleration period. In order to get some quantitative information about the velocity we want to fit a linear regression line to the data, but not including the initial acceleration region. For everything other than the 316 SS it seems we can start from t=0.10 whereas for the 316 we should start at around t=0.12. All we have done here is to change the range of the data used for the graph and then apply Excel's built-in linear regression calculation to the curves.

Now we can read the steady-state (terminal) velocities directly from the regression lines.

Metal	Terminal Velocity (mm/s)	Resistivity (nΩ·m)
316 SS	413	749
Brass	170	80
Aluminium	78	28
Copper	63	17

One has to be cautious with the resistivity data since alloys can have very variable resistivity figures quoted. Directly measuring the resistance of the sheets is not practical without specialist (expensive) equipment.

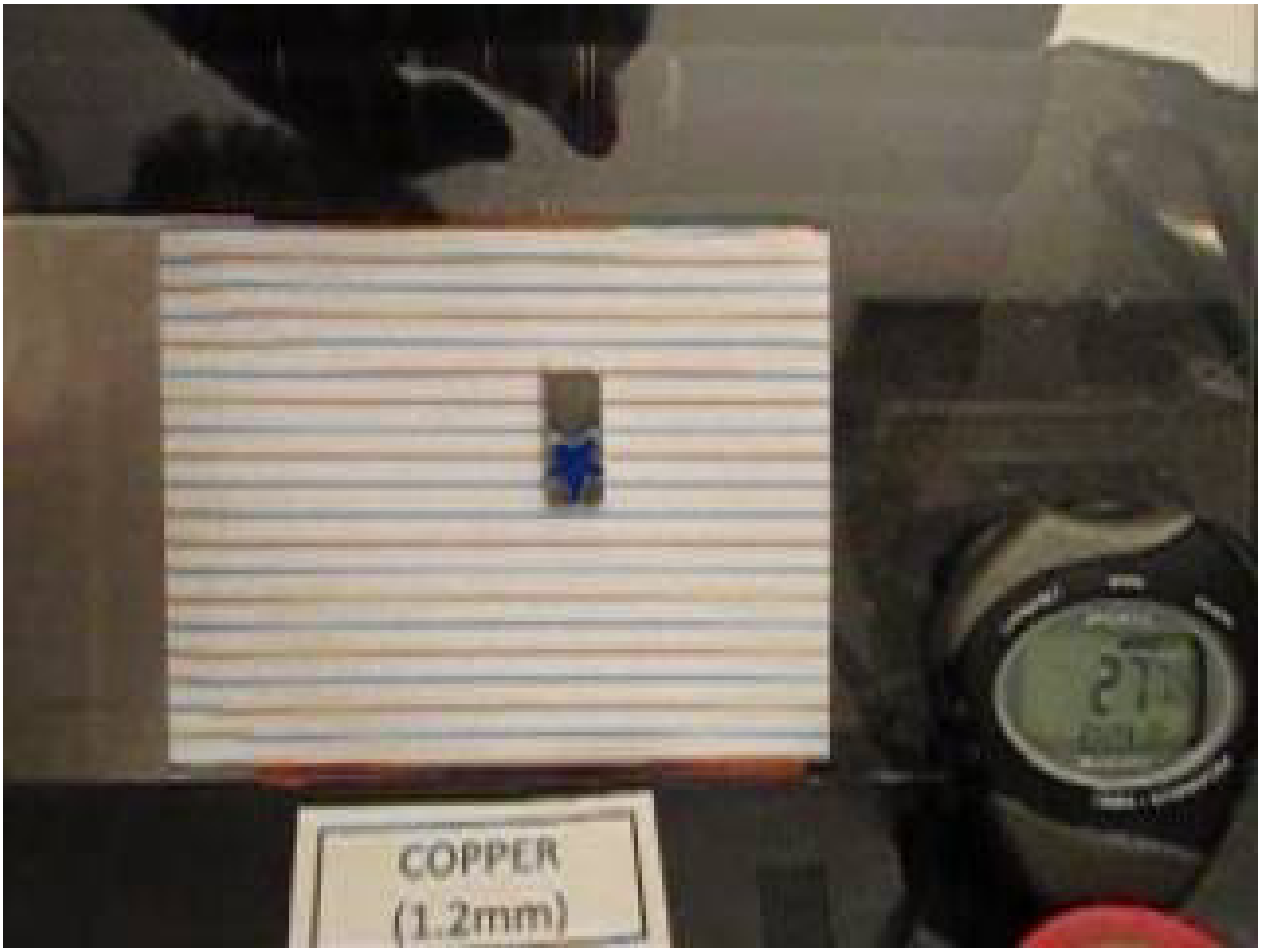


We can't reasonably fit the resistivity data to the terminal velocity data. There is no obvious proportionality of the velocity to the resistivity, or to the square root of the resistivity, and using more complex functions is unreasonable with only 4 data points, especially since the 316 SS data point has the additional complexity of being measured with a different thickness of material.

We are expecting a retarding force (eddy current drag) to be created which is a function of the resistivity, but also of velocity. We are also expecting that the retarding force is an increasing function of velocity, but not necessarily a linear function. We would want a lot more points, and a lot more reliable resistivity data, before deciding what law the velocity was following with respect to the resistivity.

Magnet Orientation

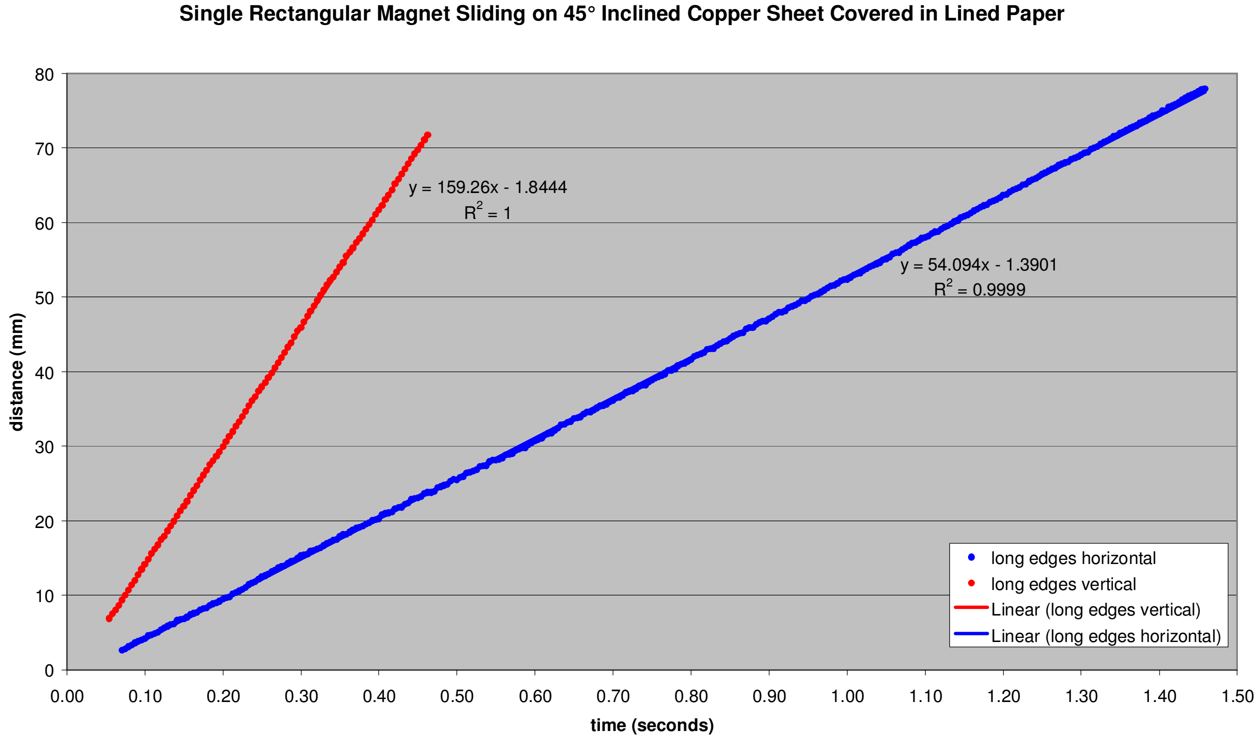
I am going to call the orientation of the magnet shown below as “long side vertical”.



When you first start out learning about magnets it is very helpful to plot field lines and see how when a wire cuts a field line there is electromagnetic induction. So in this setup if we think of the copper plane as horizontal strips of conducting material then as the field passes through the strips there will be lots of cutting of field lines. The amount of cut field lines might then be taken as being some function of the area of the magnet and the strength of the magnetic field. Easy to understand. So if the magnet is rotated 90°, such that the long side is now horizontal, presumably since the area and the field strength are unchanged, the eddy current drag will be the same and the magnet will slide at the same speed.

Think about it BEFORE you read on. Once you know the experimental answer it is too late to claim that you have (or could have) predicted the result.

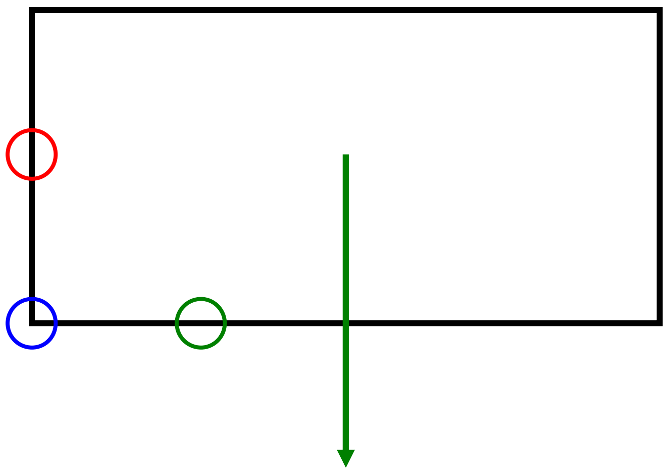
And then we do the experiment …



This time I have just stopped the early plotting of data to get straight to a valid linear regression plot. The velocity can then be read directly from the regression lines, namely 54 mm/s when the long edge is horizontal and 159 mm/s when the long edge is vertical. That's three times faster! This is outrageous, impossible – shocking! You should be shocked, intrigued or at least interested. This is interesting science which you would miss using circular magnets, or an experimental setup with a fixed rotating disc and a controllable electromagnet.

The result of this experiment might be termed "retrospectively obvious" (or "wise after the event"). The idea was to ***predict*** what would happen. If you tell some Professor of Physics about this and get them to explain it, that is backwards. Get them to predict what happens ***before*** knowing the result! The thing to take away from the surprise is that it is easy to get "caught out" when doing something new. Don't be so arrogant that you build a whole large machine before trying out a small model.

When doing the experiment with the long side horizontal, the magnet is unstable. It "likes" to rotate so that the long side goes more vertical; there is less resistance to that motion. It feels as though each small element of the edge of the magnet is having a retarding force acting on it, but this force is less when there is another element above or below that element (in the direction of motion).



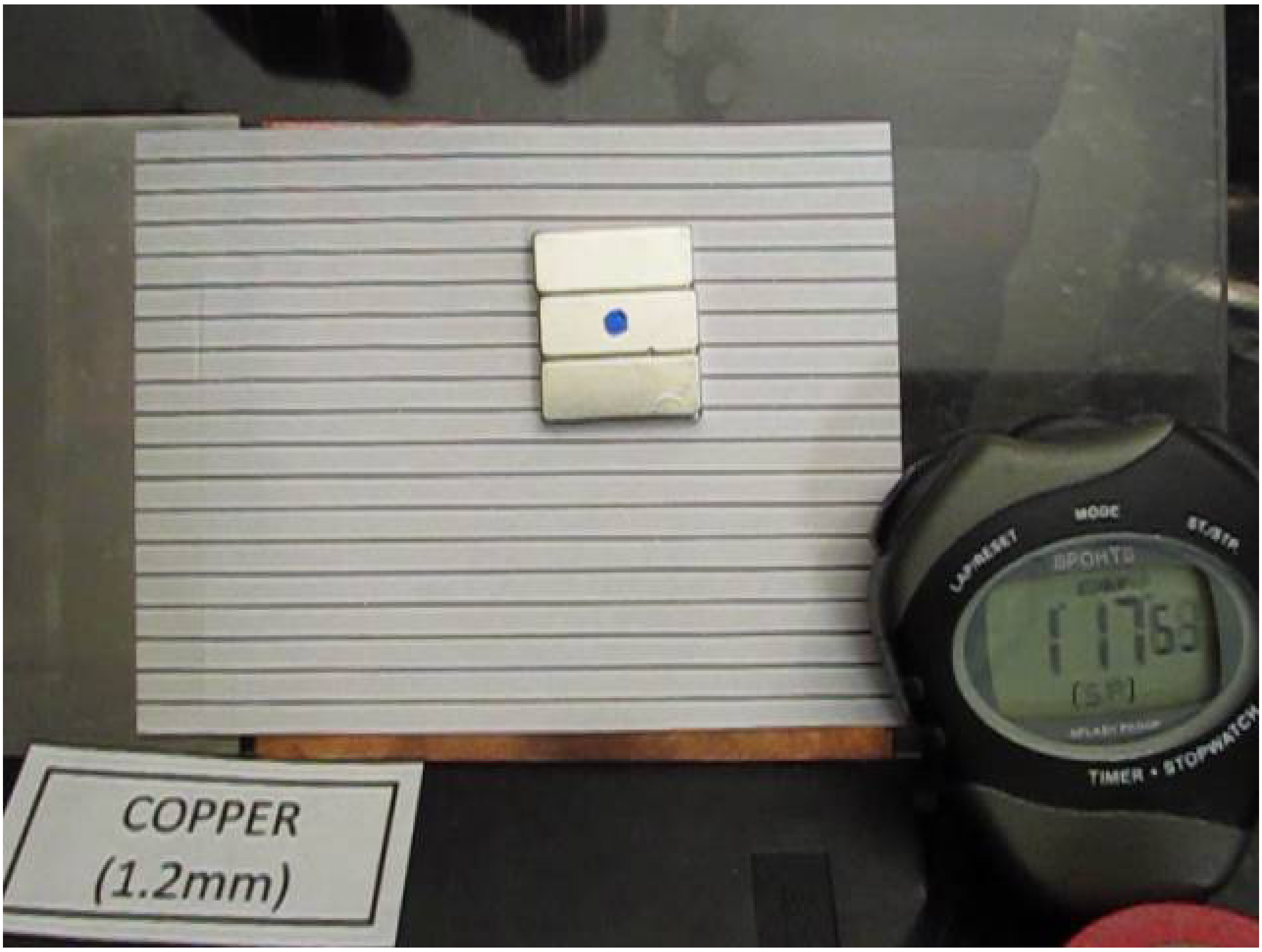
Consider the black outline as the shape of the magnet. The green arrow shows the direction of motion of the magnet over a copper plate. The circles are notional regions on the copper plate that we are going to talk about, but the copper plate itself is uniform.

Imagine the magnet crossing the green circle. As the magnet approaches the circle the field strength increases, but once the bulk of the magnet is over the circle the field is relatively constant until the back edge of the magnet crosses the green circle and the field decreases again. As the magnet crosses the blue circle there is a changing field, but along that short vertical edge, at say the red circle, there is little extra change.

The eddy current force is stronger with a greater rate of change of flux. Because the magnet is specified as 24mm × 9mm, the long edge is about 2.7× longer than the short edge. The resultant 2.9× reduction in speed now doesn't seem so unreasonable.

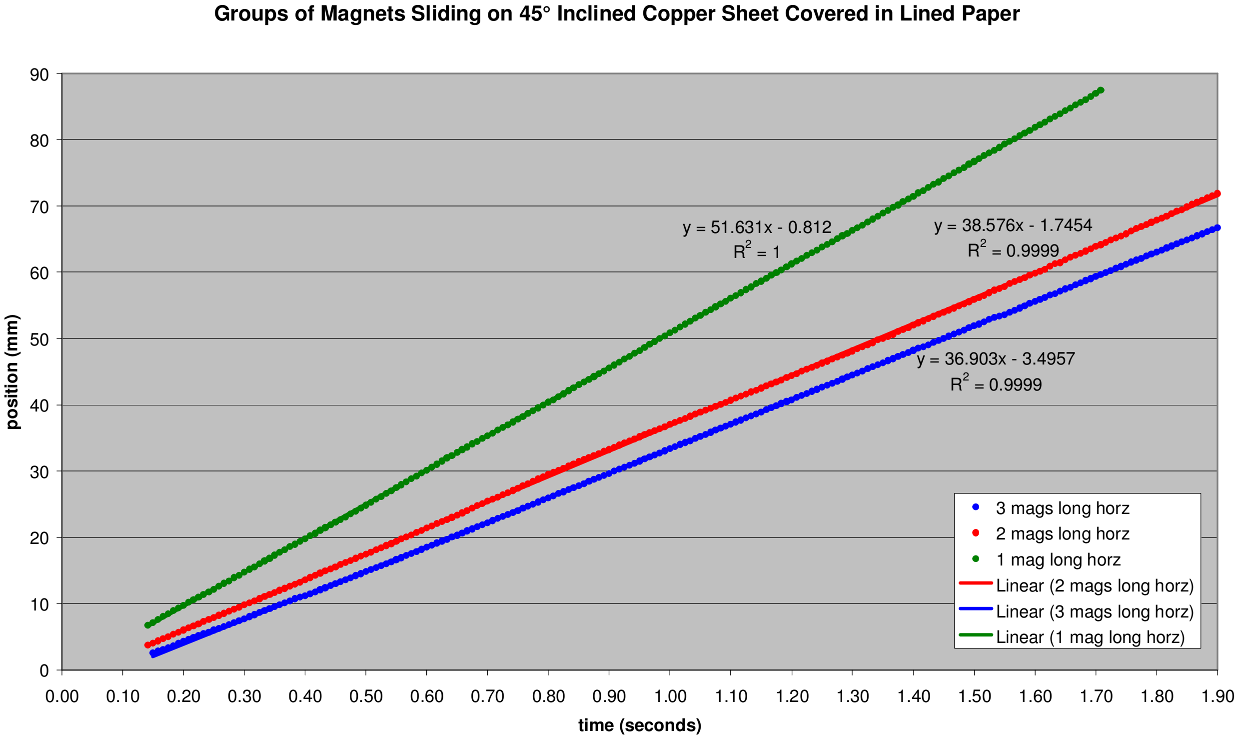
Just to round off the collection of experiments I present the results of sticking one, two or three magnets together (using their own magnetic pull), with their long edges horizontal. Notice that the image quality is considerably better because I changed the camera speed to 120 fps (640×480 – VGA). I also tried a round tracking target, as the star target is non-ideal when the magnet starts to rotate as it travels.

It should be noted that the stop-watch was too blurry at 240 fps to say anything useful about the 1/100th second intervals. Even with full VGA resolution and 120 fps the stop watch did not read well on the camera image. Basically the stop-watch is designed to be stopped – and then give an accurate time reading. It is not expected that people with super-human vision would be looking at the display in real time! All results presented have therefore largely relied on the camera manufacturer's speed claims. On the other hand, if the camera was producing frames at a fairly random rate, the velocity plots would not be as good as they are. Therefore the experiment itself tends to confirm the quality of the camera timing.



So, which goes faster: one, two or three magnets, and how much faster?

No cheating!



One magnet:	52mm/s
Two magnets:	39mm/s
Three magnets:	37mm/s

I am happy with the one to two magnet change. Putting on the second magnet reverses the field on the second long edge making a much greater rate of change of flux. I would have thought the third magnet, adding another strong reversal, would have had a bigger impact.

Notice that the single magnet is now reading 51.6mm/s whereas the previous graph had it as 54.1mm/s. Given that the magnet can rotate and therefore speed up, the reproducibility on a different day, possibly with a different magnet, on a freshly setup slope, seems quite reasonable.

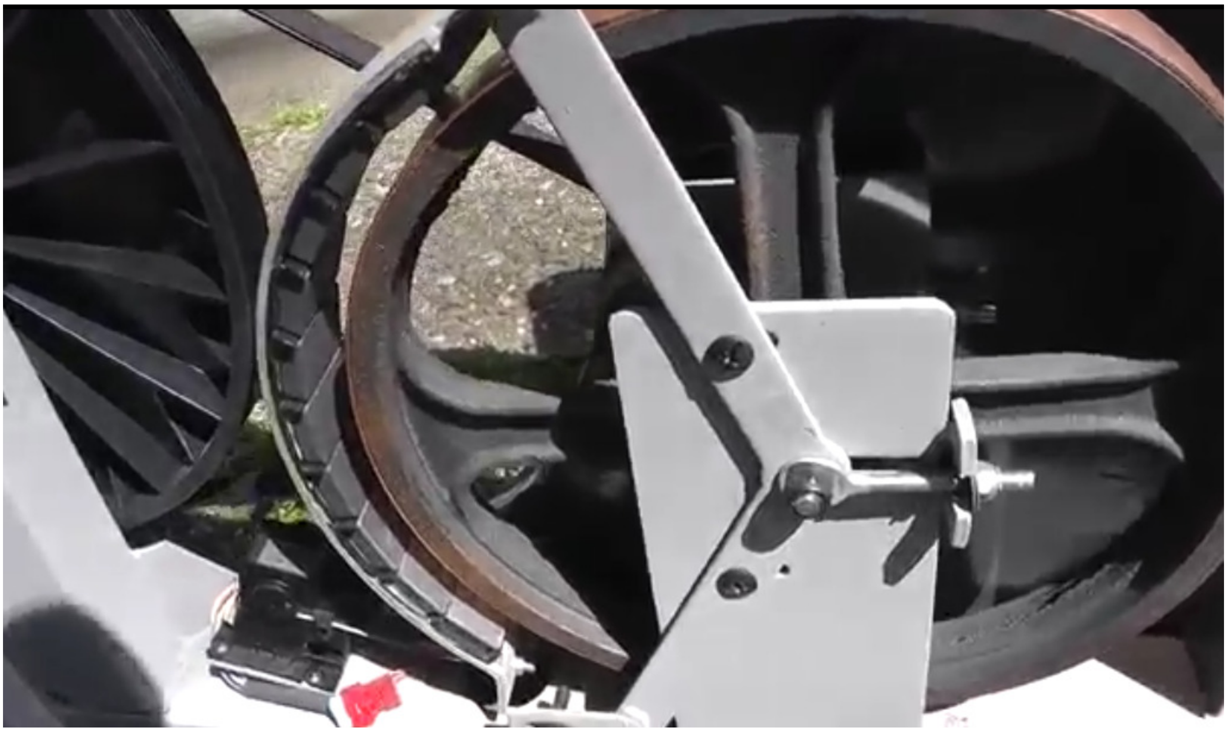
One could repeat the experiments multiple times and reduce the uncertainty, but that starts to become boring and unproductive. The whole point is to get a feeling for how these things work, not to re-write text books with supremely accurate experimental data.

Acknowledgement

I had originally intended to use the 5mm ruled lines to read off distances as I stepped through the high-speed frames. I am indebted to Douglas Brown's free Tracker software, without which the analysis of the data would have been epically boring.

Appendix 1: Commercial Use of an Eddy Current Brake

The following image was snipped from a video by user rwg42985 on YouTube.[13] It shows part of an exercise machine (elliptical cross-trainer) labelled Image 8.0.



The big wheel is described in the video as being cast iron with a copper rim (easily seen at the top right of the above image). To the left of this iron wheel is an arc of magnets with alternating poles (N-S-N-S…) as you go around the rim. The outermost arc to which the magnets are attached is presumably iron/steel.

There is a small motorised actuator at the bottom which controllably pushes the magnets closer to the spinning wheel, thereby increasing the eddy current braking effect. You can just see part of the drive belt at the top-centre of the image. The cast iron wheel is running faster than the treadle-driven wheel to the left by virtue of the gearing effect of the drive belt on different sized pulley wheels.

How do you produce such a design? I can only speculate that it was done by trial and error. You have to make something but you don't get too many goes at it. That's a cast iron wheel with significant tooling costs. You can machine one from solid, but that is still expensive. Note that you have to have the wheel, rim and magnet arc as a set with appropriate curvatures. Just changing the thickness of the copper rim, for example means changing at least one other part as well. Changing the iron wheel requires all three parts to change. Probably you would make models until it works well enough. Then if you sell enough you can get more money from management/investors to get it better.

Finite analysis software for magnetics does exist, but whether or not it works correctly for eddy current simulation is unknown (to me). It is likely to cost £10,000+ per user however.

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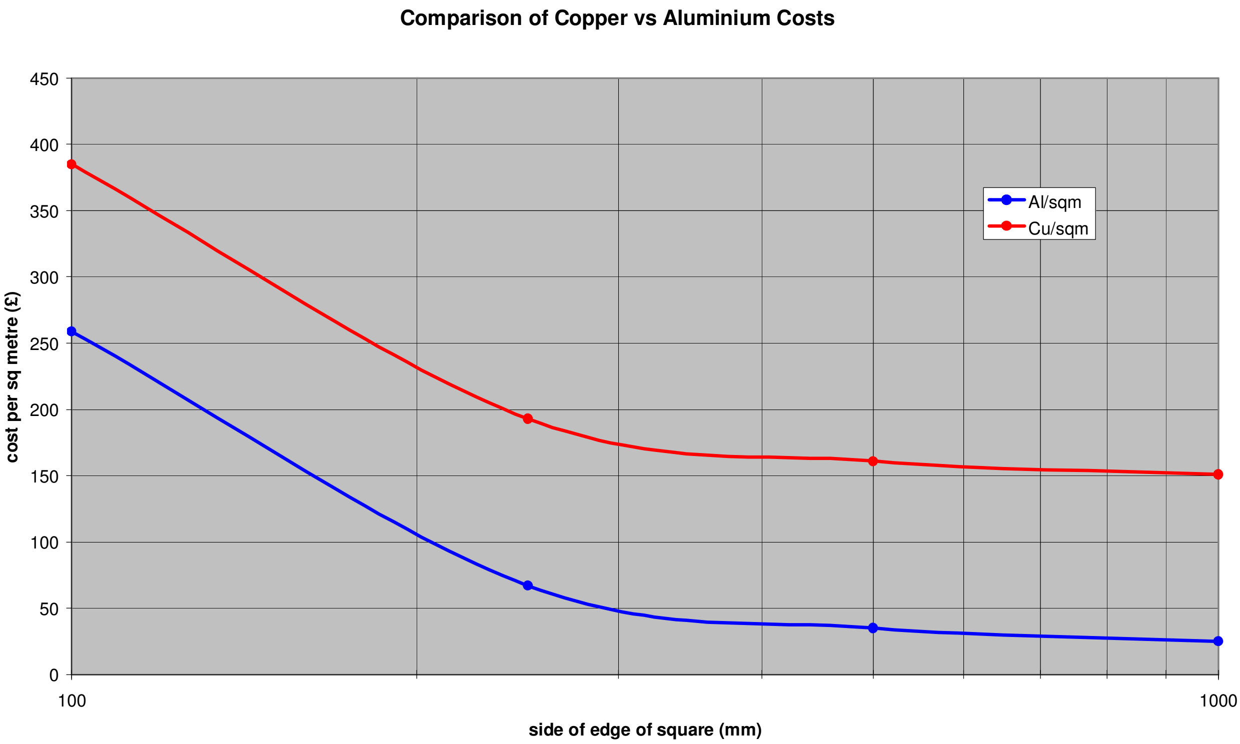
[13] It is again important to stress that we are not endorsing or recommending published material by user rwg42985. We are simply acknowledging his effort in freely providing the video of this stripped down exercise machine.

Appendix 2: Costs of Materials

Copper is evidently a better material for eddy current brakes, or is it?



This is the cost of 1.2mm thick sheets of aluminium and copper from the internet supplier mentioned previously. Copper sheet is remarkably expensive!

As it turns, out Aluminium wire has uses for overhead power lines and moving coil systems, but Aluminium wire for coil winding is not nearly as easy to get hold of as copper wire. You often can't just pick whatever material you like based only on technical requirements; cost, availability and lead time can affect design decisions too.