Physics IA draft- **“drag force created by eddy currents” or “magnetic braking due to eddy currents” or “harnessing the power of eddy currents”**

Introduction

I always wondered how brakes work and why do we need them. I know that they use friction to slow down the rotation of the wheels, but this just means that they can wear out leading to a potential safety hazard. This made me ponder if we could make contactless brakes, so that we would never have to replace components again. The first idea that I had was using magnetic repulsion since it is contactless, but I was not quite sure how.

I initially tried slowing down a normal ceiling fan with the use of repulsion. I did this by attaching magnets on each of the three wings. Then by holding a larger stronger magnet near the moving wings I tried to slow them down by ensuring that both the magnet’s poles are pointing each other. I first powered on the fan and then turned it off once it reached a desired speed, then I held the magnet near the moving blades expecting them to slow down. In contrast they did not which made me realize that while the same pole was repelling the blades in the opposite direction the other pole was repelling it in the direction of the motion, indirectly cancelling out the effect of the magnets.

Then I took inspiration from how roller coaster brakes work. They use faraday’s law of electromagnetic induction coupled with Lenz law to smoothly slow down the fast-moving roller coaster. This is how I came up with a topic for my physics IA, I had enough knowledge to design an experiment to understand how increasing the changing magnetic field strength affects the magnitude of the induced magnetic field strength in a conductive metal. A better understanding of this topic will help me comprehend the concept of magnetic braking and help me explore various applications of electromagnetism along with its negative effects.

Background information

According to faraday’s law of induction, a changing magnetic flux will induce EMF in a nearby conductive material. An induced EMF implies that current is also produced in the material. Additionally, Ampere’s law states that a moving charge creates a magnetic field and therefore the induced current also creates a magnetic field. Here the direction of the induced current is governed by Lenz’s law - “the direction of the induced current is such that it creates a magnetic field that opposes the initial change in magnetic flux” so this induced current will create a magnetic field which will oppose the changing magnetic flux inducing the current in the first place. These loops of induced currents are called eddy currents.

Since induced eddy currents create a magnetic field, the source that creates these eddy currents will experience a force in the opposite direction due to repulsion between the two fields. This opposing force is the drag force acting on the source which resists its motion. This drag force can be calculated by the following formula:

$$F_d = \alpha \sigma \delta B_o^2 A v \qquad (1)$$

Here α is the shape factor related to the pole face of the magnet(unitless). σ is the conductivity of the metal, in this case aluminium (S/m). δ is the thickness of the metal (m). B_o is the field strength in the gap between the two magnets (T). “A” is the area of the magnet’s pole face and “v” is the relative velocity between the magnet and the conductor.

“α” is a constant that is dependent on the dimensions of the magnet, it is calculated as following:

$$\alpha = 1 - \frac{1}{2}\left[4\tan^{-1}\left(\frac{l}{w}\right) + \ln\left(1 + \frac{w^2}{l^2}\right) - \frac{w}{l}\ln\left(1 + \frac{l^2}{w^2}\right) \right] \qquad (2)$$

where “l” and “w” are length and width of the pole face of the magnet.

A simple yet efficient way of calculating the drag force acting on a moving source would be to use gravity as the driving force acting on the source, so a free falling source near a conductive material will be fast enough to generate adequate drag force. The source will accelerate towards the ground and we can derive the drag force by calculating the net force acting on it using the following formula:

$F_{net} = F_g - F_d$	(3)

(F_d is subtracted because it is opposing the force of gravity.)

The free falling body can be recorded and the video can be analysed to extract information like displacement and time. By careful observation, the time taken for the body to travel a certain distance can be recorded which is then used to calculate the velocity in that time period.
This velocity is then inputted in the following suvat equation to calculate a_{net} and therefore a_d. Therefore, F_d can be calculate with the use of a_d.

$v = u + at$	(4)

Where v is the final velocity, u is the initial velocity, a is the net acceleration acting on the body and t is the magnitude of the time-period.

Research question

There are many factors affecting the drag force produced by the changing magnetic field such as dimensions of the magnet, thickness of the conductive material and what the material is made of. The most significant variable affecting the drag force is the magnitude of the magnetic field. Therefore, I decided to explore the effects of varying magnetic field strength on the drag force induced. Hence the research question of this investigation is:

"How does varying the magnetic field strength affect the drag force created due to eddy currents when a nonconductive trolley slides through an aluminum bar?"

Hypothesis

In view of the fact that the magnetic field strength directly affects the magnitude of the drag force, I hypothesis that increasing the field strength will increase the drag force experienced by the body. This means that the falling body will accelerate downwards, but not at 9.8 m/s^2, instead the acceleration will be decreased significantly due to the drag force acting on the body. As more magnets are added to the falling body the decent time will be increased. Since velocity will also affect the drag force, it will increase as the body is accelerated towards the ground, after a certain point the drag force will equal the force exerted by gravity and the falling body will reach a terminal velocity. After enough increments to the magnetic field strength the decent time will not increase since the field strength is so strong that the body reaches terminal velocity in the first few seconds of its decent which will result in same decent times for all larger increments of field strength. Since equation (1) depicts a linear relationship between velocity and drag force, it can be predicted that the graph of velocity against drag force will start from the origin and the slope of that graph will increase with increasing magnetic field strength. This means that larger magnetic fields will generate larger drag forces for smaller velocities.

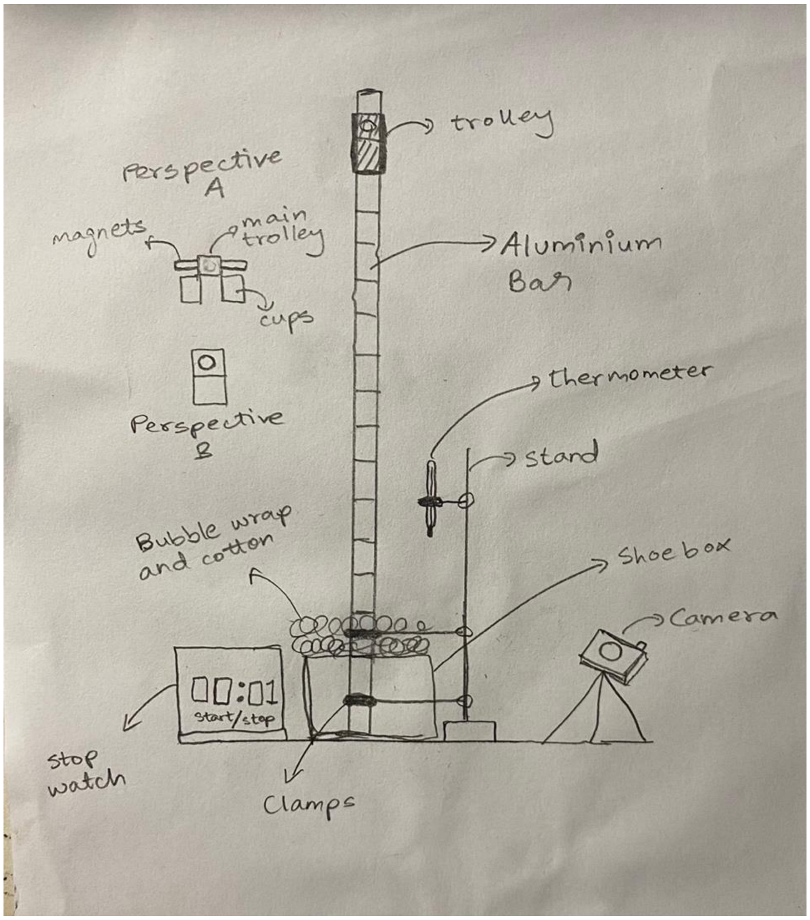
Variables

Type of variable	Variable name	How is it controlled/varied?	Uncertainty
Independent variable	Magnetic field strength (T)	It will be varied by stacking identical magnets on each other.	-

Dependent variable	Drag force (N)	This will be calculated with the help of distance travelled by the trolley against time, then using Suvat equations we can calculate the net force acting on it. The net force will be gravitational force minus the drag force.	
Control variable	Mass of the trolley (kg)	Mass will affect the force acting on the trolley by gravity, it is crucial to keep it constant to get fair results.	$\pm$ 0.0001 kg
	Dimensions of the magnet(m)	Dimensions of the magnet determine the strength and the shape of the field lines; it is necessary to keep them constant throughout the experiment so that the eddy currents are identical. They are also used in equation (1) therefore it is important that we only vary magnetic field.	$\pm$ 0.00001 m
	Drop height (m)	So that the trolley travels the same amount of distance in all trials.	$\pm$ 0.00001 m
	Room temperature(K)	Since resistance of the metal is dependent on temperature, it will also affect the current and therefore the magnetic field induced in the bar, therefore it is important to keep the temperature constant. If significant, temperature changes could expand the aluminum bar since it has a very low melting point.	$\pm$ 0.5 K
	Dimensions of the bar(m)	since the eddy currents are dependent on the dimensions of the material they are created in; they should be kept constant.	$\pm$ 0.00001 m

Experimental setup

A hollow rectangular trolley is made from PVC board such that it can slide perfectly on the aluminum bar which also has a rectangular cross section. To keep the mass of the trolley same throughout the whole experiment, cardboard cups were attached to either side of the trolley to hold sand as weights. It is very important that all the apparatus used are all non-ferromagnetic so that they don’t interfere with the field symmetry of the magnets, that is the reason aluminum, PVC, sand, and cardboard are used. To prevent damage to the trolley from the fall, cotton and bubble wrap are placed at the base of the bar. The aluminum bar is kept perpendicular using a shoe box and two stands, this increases the stability of the bar. The bar is graduated every 5 cm so that displacement can be calculated. A slow-motion camera is set so that the whole setup is visible in the frame of the video. A stopwatch and a thermometer are placed beside the setup so that they can be recorded with the falling body. Two magnets are attached on either side of the trolley so that no additional support is required to attach them on the trolley. As a control, the trolley with no magnets attached to it is also recorded, so that the drag force due to eddy currents can be compared to the free fall of the trolley.
Here is a diagrammatic sketch of the experimental setup.



Apparatus

1. Aluminum bar
2. Stands with clamps
3. Shoe box
4. Cotton and bubble wrap
5. Thermometer
6. Stopwatch
7. Slow motion camera
8. Neodymium Magnets
9. PVC board, Cardboard, and adhesive
10. Sand
11. Thick gloves

Experimental procedure

1. Once the experimental setup is complete place the camera such that it is placed as low as possible, this will ensure that all the graduations are visible, thereby avoiding parallax error since the gap between the trolley and the bar is very minute.
2. Hang a stopwatch beside the setup so that the camera can record it simultaneously.
3. Weigh the trolley with highest number of magnets attached to it, this will be its maximum weight possible.
4. Now add sand to an empty trolley so that it matches the mass of the trolley with the maximum magnets.
5. Start the camera and then the stopwatch.
6. Drop the trolley from top of the bar.
7. Drop the trolley 3 times with the same number of magnets.
8. Turn the camera off.
9. Now add magnets and remove sand in a way that the mass remains constant.
10. Repeat steps 5 to 8 for all magnet increments, make sure to drop it from the same height.

Safety and ethics

- To make the trolley out of PVC board precise cuts were supposed to be made and because the board is very thick a cutter was required. It is important to wear thick gloves when working with sharp tools to avoid getting cut.
- Neodymium magnets were used for this experiment which are extremely strong. They are supposed to be handled with care and always wear gloves to avoid pinching. Also, it is very common for strong magnets to chip and these chipped pieces can be very sharp.
- Keep the magnets at least 20 centimeters away from electronic devices as they could damage the internal memory of the device.

Raw data

Experimental calculations:

Since the data is stored in a video format, careful observation is required to extract important values like displacement and time. I recorded the time every 5 cm travelled by the trolley and created a table of position against time. To calculate the varying velocity of the trolley I used the formula $\frac{\Delta s}{\Delta t}$ where Δs was 0.05 m. Once I derived the velocity of the trolley for every 5 cm, I used equation 4, $v = u + at$ to calculate the net acceleration of the trolley for that same displacement.

Table 1- free fall

position (m)	trial 1	trial 2	trial 3	time(s)	uncertaity (max-min)/2	delta t	v(m/s)
0	0	0	0	0	0	0	0
0.05	0.09	0.1	0.1	0.10	0.005	0.097	0.52
0.1	0.13	0.13	0.13	0.13	0	0.033	1.5
0.15	0.16	0.17	0.16	0.16	0.005	0.033	1.5
0.2	0.19	0.19	0.2	0.19	0.005	0.03	1.67
0.25	0.21	0.22	0.22	0.22	0.005	0.023	2.14
0.3	0.23	0.25	0.24	0.24	0.01	0.023	2.14
0.35	0.26	0.27	0.26	0.26	0.005	0.023	2.14
0.4	0.28	0.29	0.28	0.28	0.005	0.02	2.5
0.45	0.31	0.3	0.3	0.30	0.005	0.02	2.5
0.5	0.33	0.32	0.32	0.32	0.005	0.02	2.5
0.55	0.35	0.34	0.33	0.34	0.01	0.017	3
0.6	0.35	0.36	0.35	0.35	0.005	0.013	3.75
0.65	0.36	0.37	0.37	0.37	0.005	0.013	3.75
0.7	0.38	0.39	0.37	0.38	0.01	0.013	3.75
0.75	0.39	0.4	0.39	0.39	0.005	0.013	3.75
0.8	0.4	0.42	0.4	0.41	0.01	0.013	3.75
0.85	0.41	0.43	0.42	0.42	0.01	0.013	3.76

Table 2- one magnet on each side

position (m)	trial 1	trial 2	trial 3	average t (s)	uncertaity (max-min)/2	delta t	u (m/s)	v (m/s)	anet (m/s^2)	ad (m/s^2)
0	0	0	0	0	0	0	0	0	0	0
0.05	0.1	0.12	0.11	0.11	0.01	0.110	0	0.45	4.13	5.67
0.1	0.15	0.17	0.16	0.16	0.01	0.050	0.45	1	10.91	-1.11
0.15	0.19	0.2	0.19	0.19	0.005	0.033	1	1.5	15	-5.2
0.2	0.22	0.23	0.22	0.22	0.005	0.030	1.5	1.67	5.56	4.24
0.25	0.24	0.26	0.25	0.25	0.01	0.027	1.67	1.875	7.81	1.99
0.3	0.27	0.28	0.27	0.27	0.005	0.023	1.88	2.14	11.48	-1.68
0.35	0.29	0.3	0.3	0.30	0.005	0.023	2.14	2.14	0	9.8
0.4	0.31	0.32	0.33	0.32	0.01	0.023	2.14	2.14	0	9.8
0.45	0.34	0.34	0.34	0.34	0	0.02	2.14	2.5	17.86	-8.06
0.5	0.37	0.36	0.35	0.36	0.01	0.02	2.5	2.5	0	9.8
0.55	0.39	0.38	0.37	0.38	0.01	0.02	2.5	2.5	0	9.8
0.6	0.4	0.39	0.4	0.40	0.005	0.017	2.5	3	30	-20.2
0.65	0.41	0.41	0.41	0.41	0	0.013	3	3.75	56.25	-46.45
0.7	0.41	0.43	0.43	0.42	0.01	0.013	3.75	3.75	0	9.8
0.75	0.42	0.45	0.44	0.44	0.015	0.013	3.75	3.75	0	9.8
0.8	0.44	0.46	0.45	0.45	0.01	0.013	3.75	3.75	0	9.8
0.85	0.45	0.47	0.47	0.46	0.01	0.013	3.75	3.75	0	9.8

Table 3- two magnets on each side

position (m)	trial 1	trial 2	trial 3	average t (s)	uncertaity (max-min)/2	delta t	u (m/s)	v (m/s)	anet (m/s^2)	ad (m/s^2)
0	0	0	0	0.00	0	0	0	0	0	0
0.05	0.1	0.1	0.11	0.10	0.005	0.103	0	0.48	4.68	5.12
0.1	0.15	0.14	0.17	0.15	0.015	0.050	0.48	1	10.32	-0.52
0.15	0.19	0.18	0.2	0.19	0.01	0.037	1	1.36	9.92	-0.12
0.2	0.22	0.21	0.24	0.22	0.015	0.033	1.36	1.5	4.09	5.71
0.25	0.25	0.24	0.27	0.25	0.015	0.030	1.5	1.67	5.56	4.24
0.3	0.28	0.27	0.3	0.28	0.015	0.030	1.67	1.67	0	9.8
0.35	0.31	0.32	0.31	0.31	0.005	0.030	1.67	1.67	0	9.8
0.4	0.35	0.32	0.34	0.34	0.015	0.023	1.67	2.14	20.41	-10.61
0.45	0.36	0.35	0.37	0.36	0.01	0.023	2.14	2.14	0	9.8
0.5	0.38	0.38	0.39	0.38	0.005	0.023	2.14	2.14	0	9.8
0.55	0.4	0.4	0.41	0.40	0.005	0.020	2.14	2.5	17.86	-8.06
0.6	0.42	0.42	0.43	0.42	0.005	0.020	2.5	2.5	0	9.8
0.65	0.44	0.44	0.45	0.44	0.005	0.020	2.5	2.5	0	9.8
0.7	0.47	0.45	0.47	0.46	0.01	0.020	2.5	2.5	0	9.8
0.75	0.49	0.48	0.48	0.48	0.005	0.020	2.5	2.5	0	9.8
0.8	0.5	0.51	0.5	0.50	0.005	0.020	2.5	2.5	0	9.8
0.85	0.52	0.52	0.53	0.52	0.005	0.020	2.5	2.5	0	9.8

Table 4- three magnets on each side

position (m)	trial 1	trial 2	trial 3	average t (s)	uncertaity (max-min)/2	delta t	u (m/s)	v (m/s)	anet (m/s^2)	ad (m/s^2)
0	0	0	0	0	0	0		0	0	0
0.05	0.15	0.14	0.13	0.14	0.01	0.140	0	0.36	2.55	7.25
0.1	0.2	0.2	0.19	0.20	0.005	0.057	0.36	0.88	9.27	0.53
0.15	0.24	0.24	0.23	0.24	0.005	0.040	0.88	1.25	9.19	0.61
0.2	0.28	0.27	0.26	0.27	0.01	0.033	1.25	1.5	7.5	2.3
0.25	0.31	0.3	0.3	0.30	0.005	0.033	1.5	1.5	0	9.8
0.3	0.34	0.33	0.34	0.34	0.005	0.033	1.5	1.5	0	9.8
0.35	0.37	0.37	0.36	0.37	0.005	0.030	1.5	1.67	5.56	4.24
0.4	0.4	0.39	0.4	0.40	0.005	0.030	1.67	1.67	0	9.8
0.45	0.43	0.42	0.42	0.42	0.005	0.027	1.67	1.87	7.81	1.99
0.5	0.44	0.45	0.45	0.45	0.005	0.023	1.87	2.14	11.48	-1.68
0.55	0.47	0.47	0.47	0.47	0	0.023	2.14	2.14	0	9.8
0.6	0.49	0.5	0.49	0.49	0.005	0.023	2.14	2.14	0	9.8
0.65	0.53	0.51	0.51	0.52	0.01	0.023	2.14	2.14	0	9.8
0.7	0.55	0.54	0.53	0.54	0.01	0.023	2.14	2.14	0	9.8
0.75	0.56	0.56	0.57	0.56	0.005	0.023	2.14	2.14	0	9.8
0.8	0.58	0.58	0.6	0.59	0.01	0.023	2.14	2.14	0	9.8
0.85	0.61	0.61	0.61	0.61	0	0.023	2.14	2.14	0	9.8

Uncertainty:

Variable	Uncertainty
Displacement (m)	$\pm$ 0.0005 m
Time (s)	$\pm$ 0.01 s

Using this we can propagate the uncertainty for velocity and acceleration since both the values were calculated using displacement and time. Using the following formula, the uncertainty of Δt, u, v and a was calculated:

$s_0 \pm 0.001$ m and $t_0 \pm \Delta t$ $v = \Delta s/\Delta t = v_0 \pm v\left(\frac{.001}{.05} + \frac{.02}{\Delta t}\right)$ m/s $a = \Delta v/\Delta t = \frac{\frac{\Delta s}{\Delta t_2} - \frac{\Delta s}{\Delta t_1}}{\Delta t_2} \pm a\left(\frac{v\left(\frac{.001}{.05}+\frac{.02}{\Delta t_2}\right)+u\left(\frac{.001}{.05}+\frac{.02}{\Delta t_1}\right)}{\Delta v} + \frac{.02}{\Delta t}\right)$ m/s^2	Since all the data was recorded for every 5 cm, Δs is 0.05 for all uncertainty calculations. Here in the equation for acceleration u is the initial velocity and v is the final velocity in that time frame equal to Δt. so v for one time interval is equal to u for the next time interval.

Table 5- uncertainty table

	one magnet(each side)		two magnet(each side)		three magnets(each side)	
position	v	anet	v	anet	v	anet
0	0	0	0	0	0	0
0.05	0.050	0.83	0.03	0.55	0.03	0.42
0.1	0.082	0.33	0.12	0.40	0.04	0.15
0.15	0.069	0.49	0.10	0.64	0.05	0.25
0.2	0.071	0.48	0.13	0.72	0.09	0.44
0.25	0.113	0.72	0.13	0.91	0.05	0.00
0.3	0.082	0.85	0.12	0.00	0.05	0.00
0.35	0.079	0.00	0.06	0.00	0.06	0.37
0.4	0.110	0.00	0.14	0.94	0.05	0.00
0.45	0.050	0.80	0.10	0.00	0.06	0.44
0.5	0.119	0.00	0.07	0.00	0.07	0.55
0.55	0.116	0.00	0.08	0.78	0.04	0.00
0.6	0.098	0.13	0.08	0.00	0.06	0.00
0.65	0.075	0.13	0.08	0.00	0.08	0.00
0.7	0.164	0.00	0.10	0.00	0.08	0.00
0.75	0.204	0.00	0.08	0.00	0.06	0.00
0.8	0.158	0.00	0.07	0.00	0.08	0.00
0.85	0.156	0.00	0.07	0.00	0.04	0.00

Theoretical calculations

Once all the necessary values are inputted into equation (1), a function of drag force in terms of velocity can be created for different values of magnetic field strength and then those graphs can be compared to investigate the relationship between drag force and magnetic field strength. Cylindrical magnets were used in the experiment and therefore the following formula is used to calculate the magnetic field of the magnets:

$B = \frac{Br}{2}\left(\frac{D+z}{\sqrt{R^2+(D+z)^2}} - \frac{z}{\sqrt{R^2+z^2}}\right)$	(5) Here z is constant since the distance between the magnet and the bar doesn't change; it is equal to half the distance between the magnets attached on either sides.

Where Br is the remanence field dependent on the material of the magnet. I used neodymium magnets which have a remanence field equal to 1.2 T; D and R being the thickness and radius of the magnet respectively and z is the distance from the pole face on the symmetrical axis. To increase the IV- magnetic field strength, I stack identical magnets on top of each other, so in the formula for magnetic field only the thickness of the magnets changes since we consider the stacked magnets as one. To attach the magnet on the trolley the same number of magnets were set on the other side of the trolley so that they magnetically attach themselves on the trolley using attraction. The magnets on the other side have identical magnetic fields and are at the same distance from the center of the bar, therefore equation (1) can be modified to account for this additional magnetic field by multiplying the magnitude of the field by 2, assuming that magnetic fields add together.

$F_d = \alpha\ \sigma\ \delta\ (2B_o)^2\ v$ $F_d = 4*\alpha\ \sigma\ \delta\ B_o^2\ v$	(6) Here α is the shape factor of the pole face and since the magnets used have circular pole shape, the length and width of the pole are identical and therefore α equals to 0.5 for cylindrical magnets.

Some important variables that need to be mentioned before calculating the theoretical data are as follows:

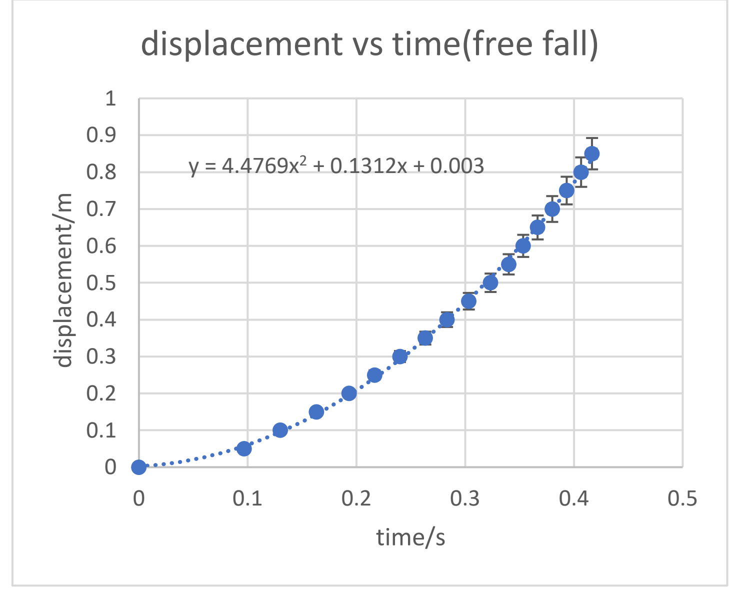
radius of the magnet	0.0075 m
thickness of one magnet	0.0018 m
thickness of the bar	0.005 m
distance between the magnets	0.012 m
conductivity of aluminium	37700000 S/m

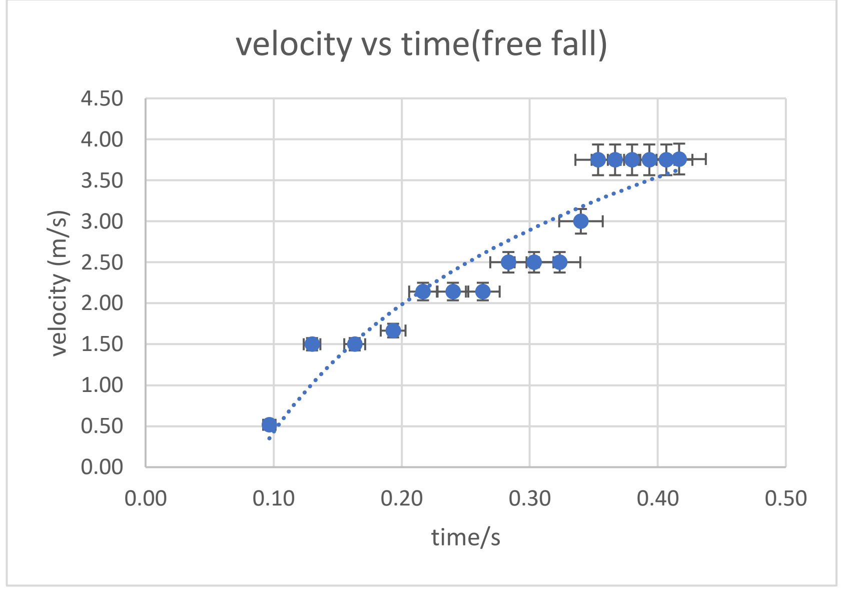
Inputting the dimensions of the magnet in equation (5) and then inputting the respective magnetic field in equation (6), we can calculate theoretical drag force as a function of velocity for varying magnetic field strength. Dividing the drag force function with mass of the trolley we get theoretical acceleration.

magnets stacked on one side	thickness of all the magnets(D)	magnetic field strength (B)	raw function of drag force $F_d = 4*\alpha\ \sigma\ \delta\ B_o^2\ v$	processed function of drag force	acceleration of drag force(F/m)
1	1.8 mm	0.057683 T	$4(0.5)(3.77e7)(0.005)(0.015)^2(0.057683)^2(v)$	0.282241v	3.16413v
2	2.1 mm	0.065439 T	$4(0.5)(3.77e7)(0.005)(0.015)^2(0.065439)^2(v)$	0.363243v	4.07223v
3	2.4 mm	0.072746 T	$4(0.5)(3.77e7)(0.005)(0.015)^2(0.072746)^2(v)$	0.448892v	5.03242v

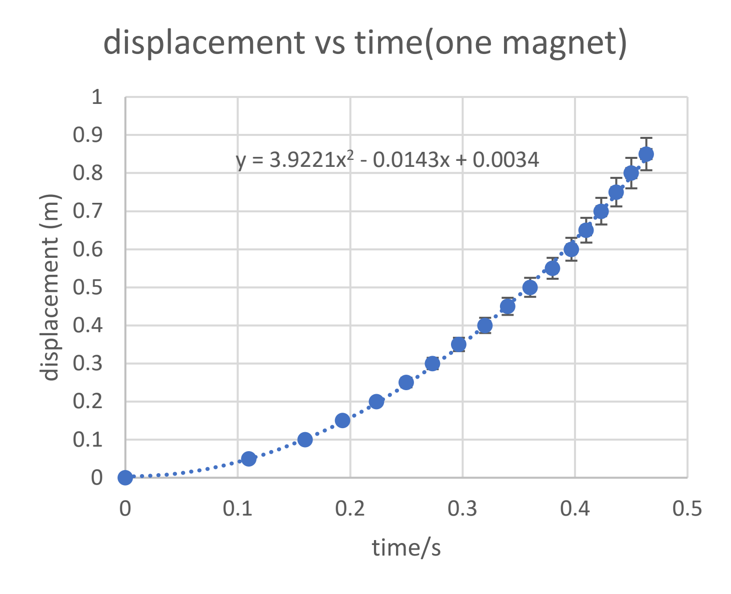
Graphical representation

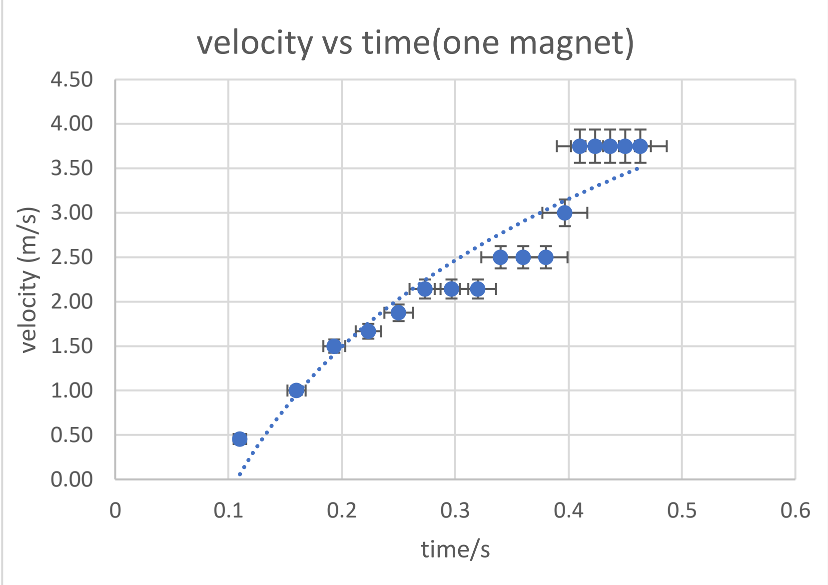
Graphs 1 and 2



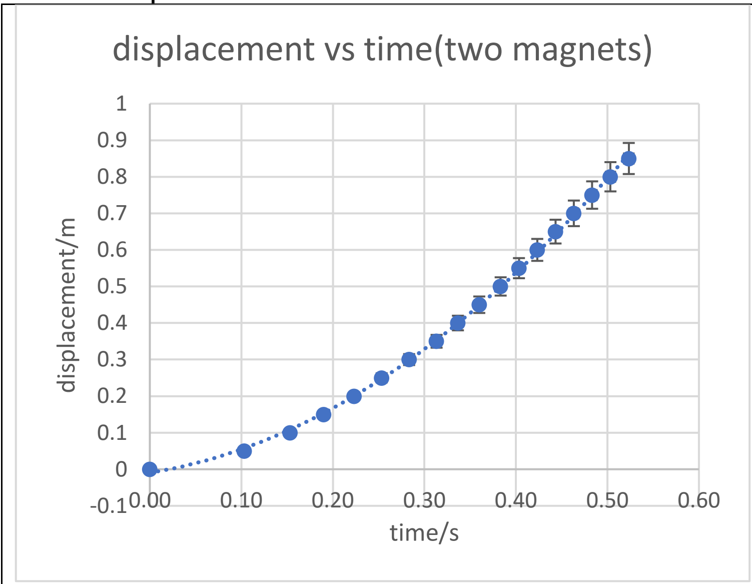


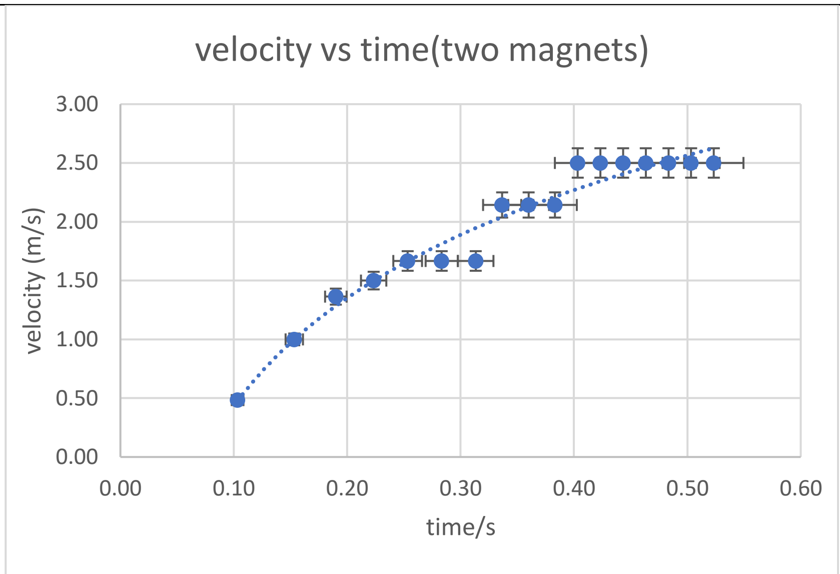
Graphs 3 and 4



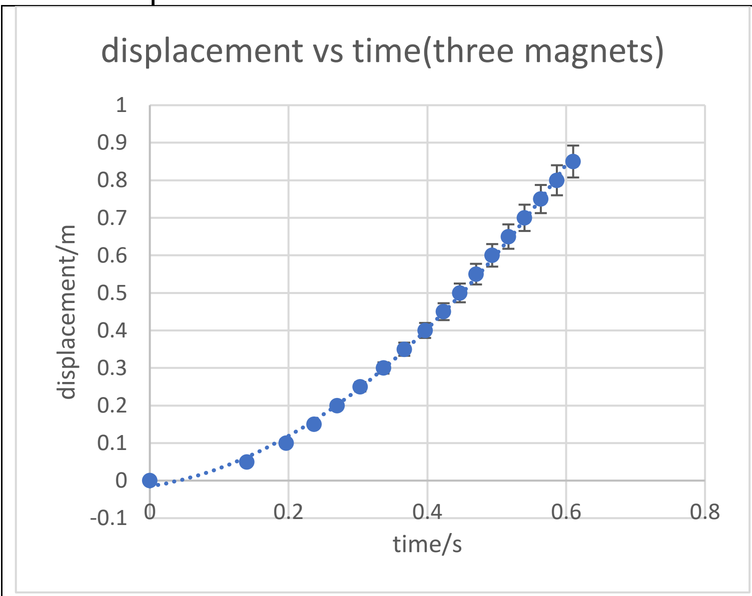


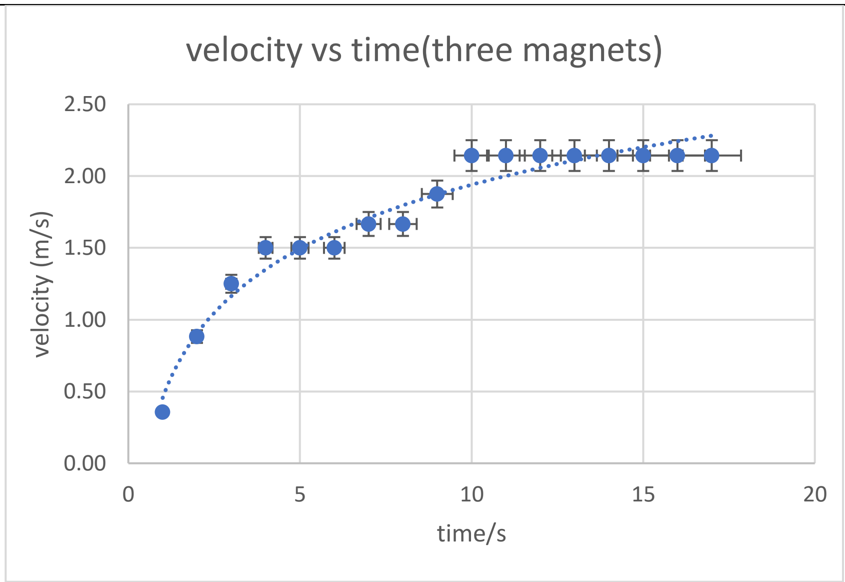
Graphs 5 and 6





Graphs 7 and 8





Analysis

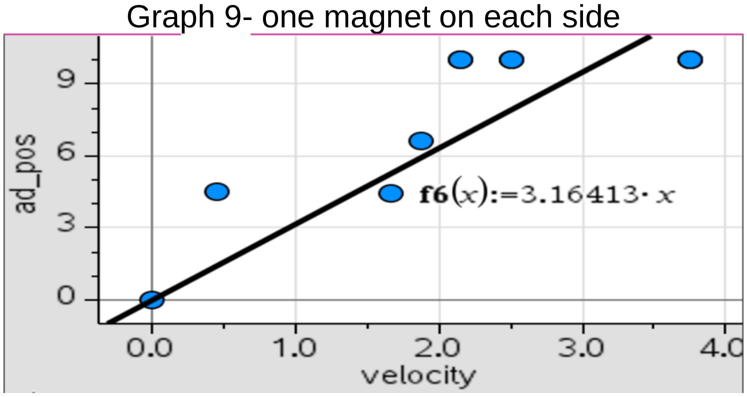
As seen in graph 1, when no magnets are added to the trolley, it behaves like any other free-falling object. The general formula for displacement in terms of acceleration for any object with initial velocity as 0 is $s = \frac{1}{2}at^2$ where a is the acceleration acting on the object which in this case is 9.8 m/s^2, it basically produces a polynomial equation with power 2. If we input 9.8 as "a" in that equation, the equation becomes 4.9t^2 which is very close to the equation of the best fit curve plotted for the data points in graph 1.

Graph 2 shows the relation of velocity against time. Theoretically, velocity is directly proportional to time since it keeps accelerating endlessly if the net acceleration on the body is constant. This is not the case in this experiment since the net acceleration changes as time passes by due to air resistance and friction between the bar and the trolley. The velocity approaches a constant value where the force due to gravity equals the force due to friction and air resistance, this is called its terminal velocity. As observed in graph two, the gradient of the best fit line starts to decrease as the velocity increases. It can be predicted that after a certain period, the velocity will reach a constant value which will be equal to the terminal velocity of the trolley. If the bar was long enough, adequate amount of data could be recorded to calculate the terminal velocity of the trolley.

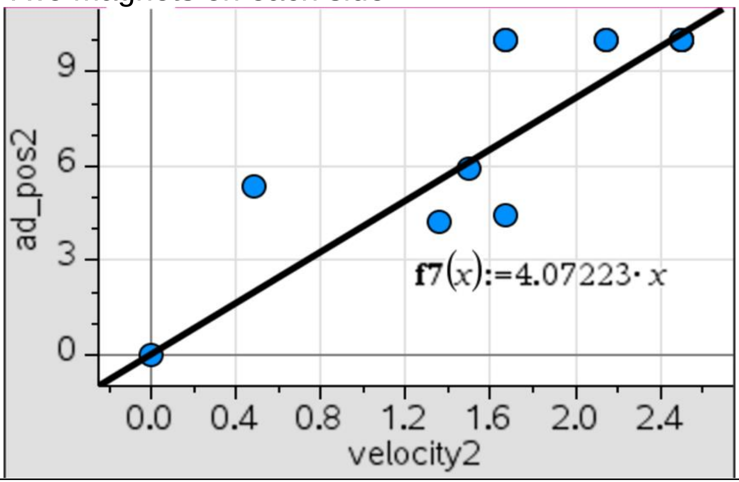
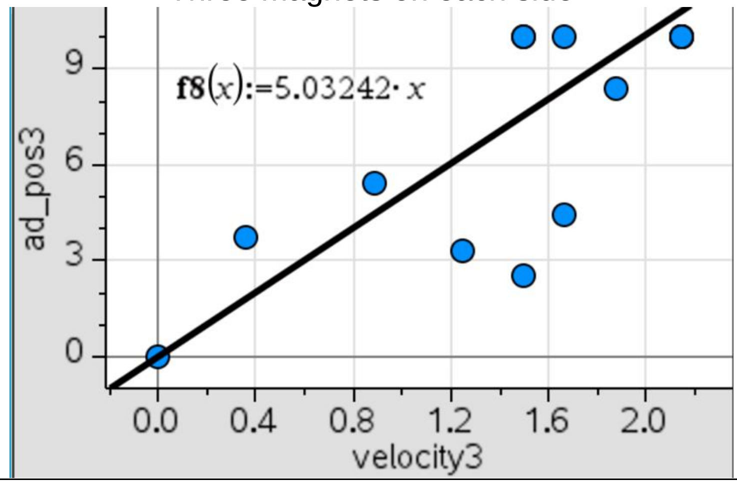
As we start to add magnets to the trolley the immediate observation is that the time taken for the trolley to travel the same amount of distance starts to increase (free fall=0.42, one magnet=0.46, two magnets=0.52, three magnets=0.61). This clearly indicates that apart from friction and air resistance there is another force opposing the motion of the trolley. This opposing force is the drag force due to eddy currents generated in the conductive bar. Furthermore, the equation of the best fit line for graphs 3, 5, and 7 decrease as the magnetic field strength increases which implies that the net acceleration of the body decreases. This trend between the net acceleration and the magnetic field strength indicates an inverse relationship between the two variables. Since acceleration due to the drag force is equal to 9.8-a_{net}, it means that the relationship between magnetic field strength and the drag force is positive as our hypothesis predicts.

Similarly, the graphs of velocity vs time can also be analyzed. As magnetic field strength increases the acceleration due to drag force increases too, this impacts the net acceleration of the body which decreases as a result. The gradient of the best fit curve is the acceleration of the body which as seen in graphs 4,6 and 8 decreases as time velocity increases since velocity and acceleration due to drag force are directly proportional. Moreover, the rate of change of the gradient of the graph is negative, which means that the net acceleration is decreasing as velocity of the body increases. Furthermore, the gradient of the best fit curve for a specific time decreases as the field strength increases, this pattern predicts that the body will reach terminal velocity more quickly for greater field strengths. These trends again indicate an inverse relationship between net acceleration of the body and velocity. Though the graphs show a constant velocity after a certain time period, but this is not the case, it just means that the rate of change of velocity has decreased but is still non-zero.

Graph 9- one magnet on each side



Graph 10 and 11

Two magnets on each side	Three magnets on each side
	

Graphs 9,10 and 11 compares the experimental data with the theoretical formulas I derived earlier for acceleration due to drag force. The graphs ignore the negative values produced by experimental values; these negative values are a result of the inaccuracy of the apparatus used and the systematic errors in the investigation. As expected, the gradient of the theoretical function increases with increasing field strength. This predicts a larger value for acceleration for lower values of velocity. The theoretical function does not consider the existing gravitational force acting on the body which is why it shows a linear relationship between velocity and acceleration. On the other hand, the experimental data shows a constant value of acceleration once the body reaches a specific velocity, at this velocity the drag force and gravitational force cancel each other out. Another important trend evident in the graphs is that as the strength of the field increases, the deviation between the theoretical and experimental data decreases.

Error bars and uncertainties

Overall, the experimental data has low uncertainty as seen in graphs of velocity and displacement. The best fit curve fits inside the error bars of the data points and accurately functions the predicted equation of the curve. To calculate the acceleration from the experimental data, many formulas were used which meant propagation of the uncertainty increased, this resulted in lower accuracy for graphs of acceleration and velocity. The deviation between the experimental and theoretical values observed is majorly due to friction between the body and the bar.

Conclusion

This investigation helped me answer the research question ***"How does varying the magnetic field strength affect the drag force created due to eddy currents when a nonconductive trolley slides through an aluminum bar?".*** The aim of the investigation was to better understand the relationship between magnetic field strength and the drag force generated by it when a changing magnetic field was near a conductive material, which was fulfilled. Additionally, this research proved my hypothesis correct which stated that as the magnetic field strength increased, the body reached terminal velocity sooner, though due to inadequate length of the bar that terminal velocity could not be calculated. To conclude, the magnetic field strength is directly proportional to the drag force induced and inversely proportional to the net acceleration acting on the body.

Evaluation

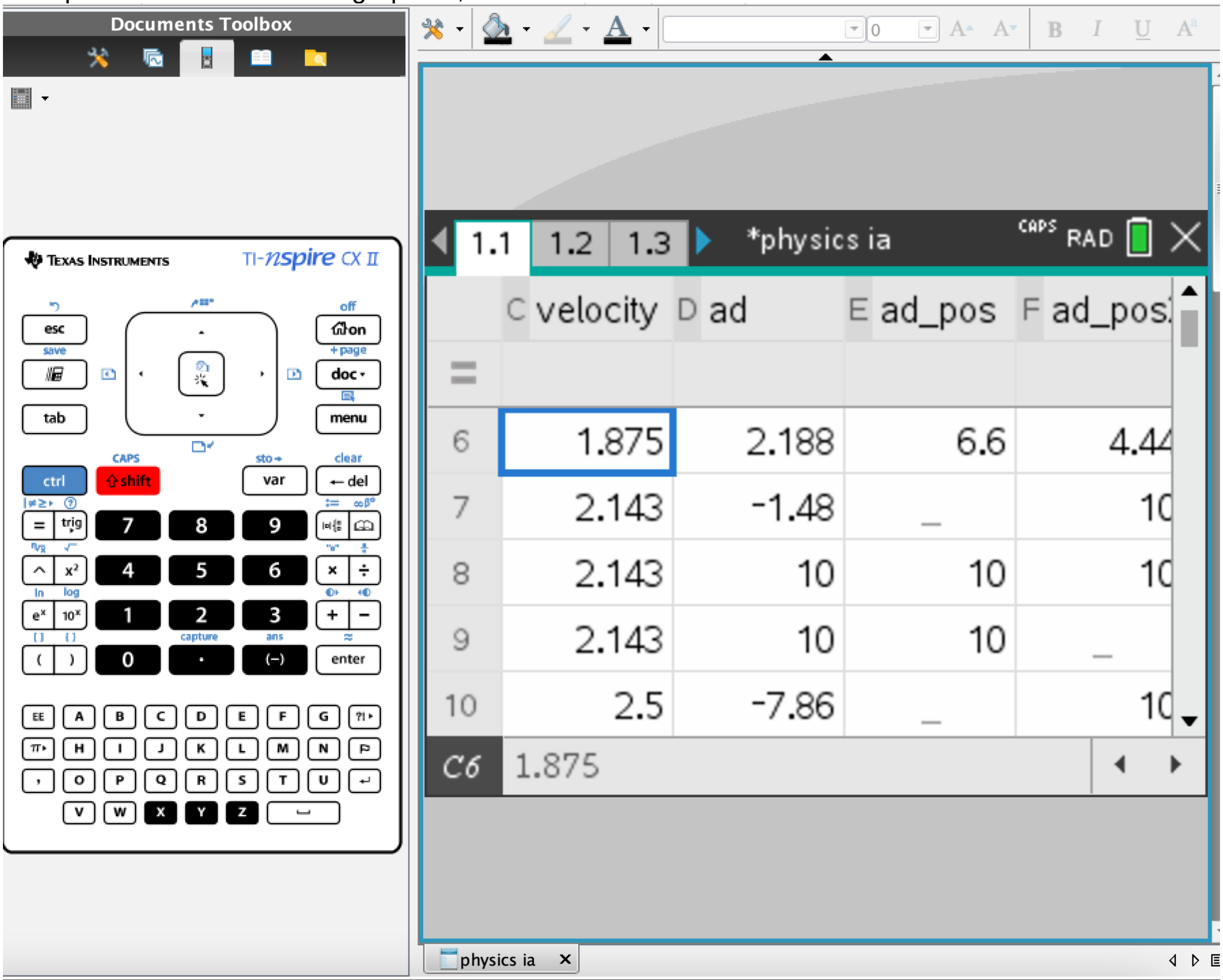
There were several limitations in my investigation which were the product of limited accuracy in the instruments used. In addition to that, multiple assumptions were made to make the calculations easier

Sources of error	**Significance and evidence**	**Improvements**

Inadequate refresh rate of the stopwatch	Refresh rate of the screen determines how fast it can display different characters. A lower refresh rate meant not all the characters are displayed. This resulted in the stopwatch skipping milliseconds, due to this inaccurate data was recorded. This coupled with friction is the reason why I got negative acceleration of the body.	Use a stopwatch with better refresh rate so that all the milliseconds are displayed on the screen.
Assumption about addition of fields and field symmetry	As the magnets are very thin, the field lines might not be symmetrical in the gap. If this is the case, the magnetic fields cannot add together since they are not symmetrical.	More complex formulas should be used to calculate the magnetic field in gap, when magnets are placed on either side of the body.
Poor frame rate of the slow-motion camera	The motion of the body is too fast for the slow-motion camera to record. The camera I used had a frame rate of 240 frames per second. At higher velocities the trolley started to appear blurry which made recording the displacement inaccurate.	A slow-motion camera with higher frame rate should be used so that it can record the position of the trolley accurately.
Friction	The theoretical formula neglected friction which added to the deviation observed in the graphs. In reality, friction existed and to make the gap between the two magnets smaller, the trolley was fit perfectly onto the bar due to which the trolley came in contact with the bar. This again increased friction and slowed down the trolley.	Adding a lubricant onto the bar should decrease friction between the two bodies. Additionally, the gap between the magnets can be increased slightly so that there is no contact between the bar and the trolley.
Insufficient increments in the IV	Due to only three increments, the relationship between the variables was not examined to its full extent. The drag force generated was not enough for the trolley to reach terminal velocity. The graphs give an illusion that terminal velocity is obtained, but if the bar was long enough, an increase in velocity would have been observed. With more increments, terminal velocity could have been corelated to the IV and DV.	Use more increments in the data collection. Also if possible get a longer bar so that the trolley has enough time to reach terminal velocity.

Appendix

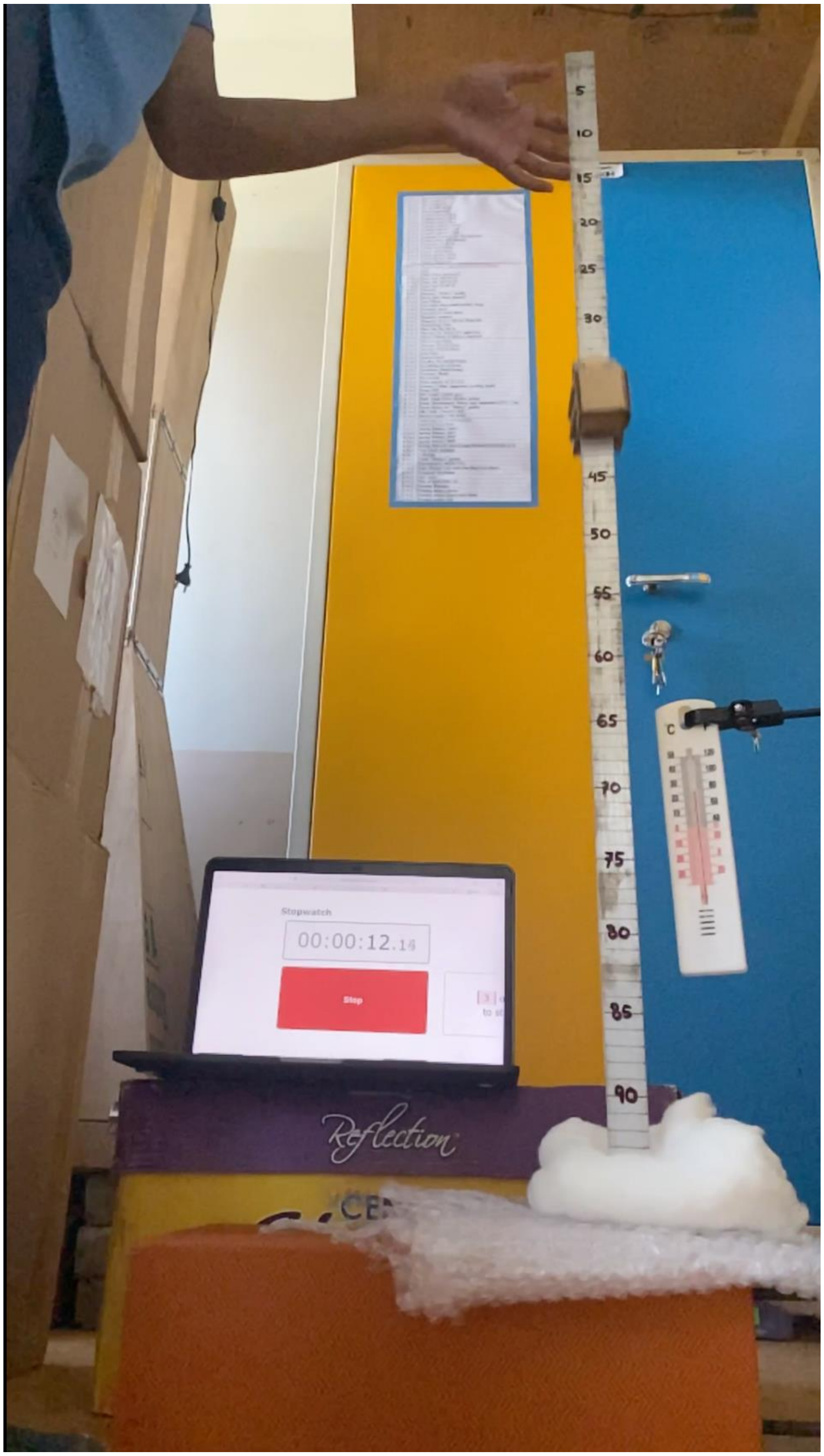
TI-nspire was used to create graphs 9, 10 and 11.



Weight of the empty trolley

Weight of trolley with sand.

Screen shot of the slow-motion video.



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