PHYSICS HIGH LEVEL EXTENDED ESSAY

INVESTIGATION OF FACTORS AFFECTING FORCE OF KINETIC FRICTION: MASS, SURFACE AREA AND SPEED

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Word Count: 3854

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ABSTRACT:

The objective of this report is to investigate the effects of mass, surface area and speed of a moving object on force of kinetic friction as underlined with the research question as "How do mass, surface area and speed of moving object affect the force of kinetic friction?" Therefore, the method employed in this research has three parts: In Part A, effect of mass is investigated using 1 to 15 wooden blocks that are put on top of each other and on the same surface area in each trial. Initial push was given to the blocks, and the acceleration was recorded with the help of Lab Quest Interface and Vernier Accelerometer. In Part B, effect of surface area is investigated using 6 wooden blocks that are put in variety of surface areas in each trial. Again, initial push was given to the blocks, and the acceleration was recorded with the help of Lab Quest Interface and Vernier Accelerometer. In Part C, effect of speed is investigated using a shoebox, in which there is a certain mass, which is fastened to a treadmill, and speed of the treadmill was increased up to $25ms^{-1}$. Lab Quest Interface and Vernier Force meter was used in measuring the force exerted on the shoebox. The results show that mass has a direct proportional effect on force of kinetic friction, while surface area has no effect; and as speed increases, force of friction first begins to increase but then decrease.

Word Count: 244

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1. INTRODUCTION:

In physics classes, we have been taught that there is a force called friction and in motion problems, we would just concern with the mathematical operation of coefficient of friction and the normal force. I wanted to investigate the factors affecting force of kinetic friction experimentally, so I chose this topic for my extended essay. The essay consists of three parts, in which 3 factors are observed: In Part A, effect of mass; in part B, effect of surface area; and in part C effect of speed is investigated. The aim, research question, variables and the method will be presented including all of the parts, but data collection and processing will be presented individually. In order to observe these effects, it would be useful to know the following information about kinetic friction.

To begin with, kinetic friction is defined as *"The force that resists motion when the surface of one object slides over the surface of another."* [1]. It is basically a resistant force acted upon a surface that is in contact with another one. Even the smoothest looking objects have a frictional surface on the microscopic scale. They have microscopic bumps that when they are in contact with another surface's bumps, small electric forces result in chemical bonds. While moving across this surface, some bonds are broken; some of them are made which eventually results in what we call "frictional force".

As friction is a resistant force, its magnitude will be in the opposite direction of object's velocity, depending on the nature of two surfaces and the normal force:

$$Ff = \mu_k F_n$$

where μ_k is the coefficient of friction and F_n is the normal force.[7] Normal force can be explained by Newton's Third Law of Motion: *"Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first"*[2]. When an object is at rest, there is only gravitational force acted on it, towards the ground. As a result, due to Newton's third law of motion, a normal force acts on it in opposite direction to its weight but equal to its own weight. This ultimately shows the relationship between the mass of the object and the force of friction: This will be observed in this essay's **Part A: Effect of Mass**.

Apart from mass, coefficient of kinetic friction is also in direct proportion with friction. For example, Teflon's coefficient of kinetic friction is 0.05 while smooth tire on wet pavement is 0,4.[3] Teflon is used so that no food stays stuck to the pan, as it's slippery due to its small coefficient of friction. But wire's coefficient is much bigger than that of Teflon's as in order for the car to move or stop, there should be a bigger force of kinetic friction than that of Teflon's apart from the brake, otherwise although the brake was pulled, if the wheels were as smooth as Teflon or any kind of substance having a small coefficient of kinetic friction, then it would be impossible for car to stop when the gas pedal is released. That's why; coefficient of kinetic friction also determines the friction's being big or small directly.

Secondly, surface area, on the other hand, has no effect on frictional force as it neither affects coefficient of friction nor the normal force. [4] This will be observed in this essay's **Part B: Effect of Surface Area** part.

Lastly, velocity, is told to have no effect on force of friction in some sources[4] but in some others, the effects of high velocities on friction are also mentioned. According to these sources, *"at low velocities the friction is independent of the relative surface velocity, at higher velocities the coefficient of friction decreases."*[5]. That is; if velocity is high, this will decrease the coefficient of friction and thus the force of kinetic friction, as well. This information is for the dry surfaces. When the surfaces are well lubricated, *"at low pressures the friction varies directly as the relative surface speed. At high pressures the friction is high at low velocities falling as the velocity increases to a minimum at about 0,6m/s. The friction then rises in proportion the velocity ^{2}."* [5] In this experiment, dry surfaces will be used to investigate the effect of speed in **Part C: Effect of Speed** part.

1.1. Aim:

Friction allows us to do lots of thing in our daily lives, even in walking. Most of the people are not aware of this force acting upon us. The main reason of this is not being properly acknowledged about this topic or what we know is only in theory, rather than in practice. The main aim of this experiment is to investigate the effects of mass, surface area and speed of a moving object on force of kinetic friction.

1.2. Research question:

How do mass, surface area and speed of moving object affect the force of kinetic friction?

1.3. Hypothesis:

When mass increases, as the normal force increases, force of kinetic friction will increase.

When surface area increases, as the interaction site between the object and the table increases, the object will be faced by a greater force of friction. Hence when surface area increases, force of kinetic friction increases, as well.

When speed increases, the force of kinetic friction will decrease as the object's increasing speed causes decrease in coefficient of friction and thus force of kinetic friction, as well.

1.4. Key Variables:

 1.4.1. Constants:

(The variables which are controlled during the experiments are listed below. Some of them were kept constant during overall experiment, and some were controlled in specific parts. These variables are specifically titled as "Part ..." referring to the part it is controlled.)

- Temperature (The experiment is held during the day, so the temperature is at room temperature $25 \pm 1 \ ^{o}C$)
- Atmospheric pressure (assumed to be constant ≈ 1021 mbar in Ankara)
- Type of track (The track used in each of the parts are kept constant so that the coefficient of kinetic friction remains the same within the parts. The track used in Part A and B is a table. In Part C, it is the treadmill)
- Type of blocks and box (The blocks used in each trial are identical in shape and material they are made from in Part A and B. The box is a cardboard box strengthened by tape so that it won't fall apart while moving. The same cardboard box is used in each trial in Part C)

- *Part A and B:*
  - The place of the accelerometer (The accelerometer is fixed at same position, in the middle of the upper block)
- *Part B and C:*
  - Mass of the system (As effect of surface area and speed are investigated in these parts, mass of the system will be kept the same by using same number of blocks in each trial in Part A and the same masses in the box in Part C)
- *Part A and C:*
  - Surface area of the blocks (As effect of mass and speed are investigated in these parts, base surface area of the blocks will be kept the same by putting the blocks on top of each other on their same side every trial in Part A and the same base area of the box is used in every trial in Part C)
- *Part C:*
  - Place of force sensor (It is fixed at the same point, see figure 2 in Method)

1.4.2. Independent variables:

- *Part A*: Mass of the system
- *Part B*: Surface area of the system
- *Part C:* Speed of the system

1.4.3. Dependent variable:

- *Part A and B:* Acceleration of the system (as accelerometer is used)
- Force of kinetic friction

1.5. Materials:

- 12 x 5 x 2.2 cm wooden blocks (x15)
- 28.3 x 19.5 x 10 cm Shoe box (cardboard) (x1)
- Logger Pro 3.8 Software
- Lab Quest Interface
- Accelerometer (x1)
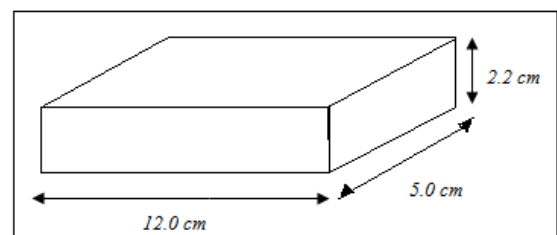
Figure 1: Dimensions of one wooden block

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- Force sensor (x1) (±0.01 N)

- Ruler (x1) (±0.1 cm)

- 5 kg Dumbbell (x2)

- Hook (x1)

- Tape (x1)

- 1m track

- Treadmill

- Pilates Matt

- Scale (x1) (±0,5 g)

- 1.5 kg Soil (±0.5 kg)

- Thread

- Scissors

- Camera

1.6. Method:

- *Calibration of the data collection equipment for Part A and B:*

1. Computer is turned on and Logger Pro 3.8 is connected. The lab quest is opened. The accelerometer is plugged. Graph of acceleration versus time will be displayed.

2. [Data Collection] button at Logger Pro is clicked on and the values below are entered:

    a. Mode: Time Based

    b. Length: 10 seconds

    c. Sampling Rate: 20 samples/second

    d. A tick on the sample at time zero option is put.

- *Procedure for Part A:*

Figure 2: Apparatus and summary of the part

1. Mass of one wooden block is measured with a balance and the mass is recorded.
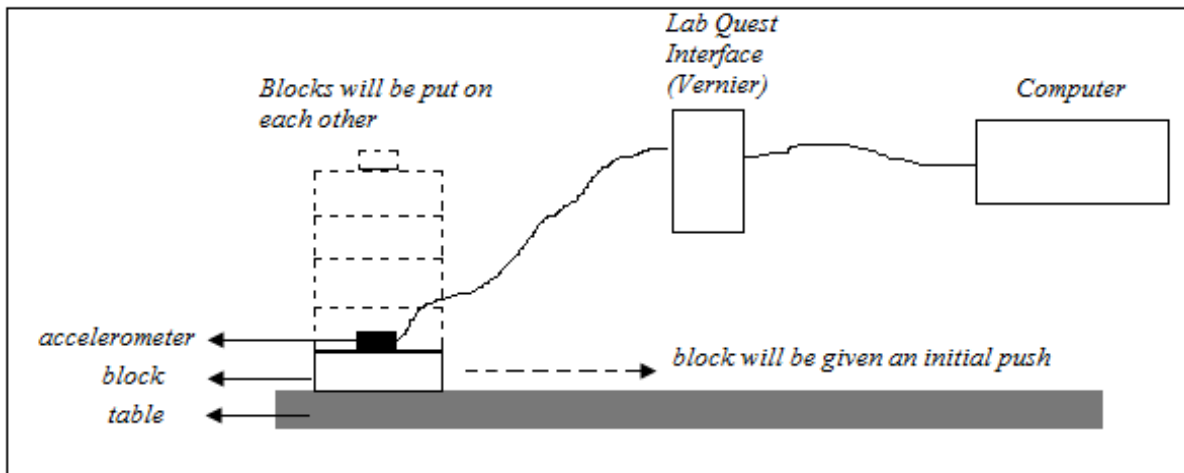2. Each dimension of block is measured in order to calculate the surface area of the side that will be used throughout this part (the side that the block will be put on the track) to monitor any variations. (12x5 cm area would be the best surface area in this experiment as it is big enough for the blocks not to fall when pushed.)
3. The accelerometer on the block is fixed with the help of tape so that it won't slide away when the block is moving.
4. The block is placed on a surface (e.g.: table)
5. [Collect] button at Logger Pro is clicked. As soon as data collection starts, the block is pushed. It will stop eventually and the data collection will stop after 10 seconds automatically.
6. [Autoscale Graph] button is clicked. The region where acceleration is negative is selected. (See Appendix D) Click on Analyze → Linear Fit and Analyze → Statistics.
7. The mean value is recorded.
8. The procedure is repeated for 10 more trials. The average mean value of these 10 trials is taken and recorded.
9. A second block is put on the first one, fixed by a tape (make sure that tape doesn't go around the contact area, you can put the tape on the sides) and the mass measured. The steps 1-7 are repeated.

10. A third block is put on the remaining blocks and the mass is measured. The steps 1-9 are repeated. This will go on until data for 15 different masses have been taken.

- *Procedure for Part B:*

1. 6 blocks are taken and weighed to monitor any variations.

2. By using a tape, the blocks are stuck horizontally. (So the surface area is **12 x 30** cm²)

3. The accelerometer is fixed on the block with the help of tape so that it won't slide away when the block is moving.

4. [Collect] button at Logger Pro is clicked. As soon as data collection starts, the blocks are pushed. It will stop eventually and the data collection will stop after 10 seconds automatically.

5. [Autoscale Graph] button is clicked and the region where acceleration is negative is selected (See: Appendix D) Click on Analyze → Linear Fit and Analyze → Statistics.

6. The mean value is recorded.

7. The procedure is repeated for 10 more trials. The average mean value of these 10 trials are taken and recorded.

8. The last block is taken off from the system and fixed on top of the 5 remaining blocks with tape. (It should be in the middle of the system, not on one side so that the mass is uniformly separated). (By putting the block on top of 5 blocks, surface area is changed to **12x25** cm² while mass is kept constant as it is still 6 blocks)

9. The steps 1-9 are repeated. Then the last block on the bottom is taken, and fixed next to the block which has been put on top of the blocks at step 10. So the surface area is **12x20** cm². The steps 1-9 are repeated.

10. The procedure is repeated with following surface areas (see Appendix A: Part B) (Numbers in the brackets show the number of blocks at the bottom):
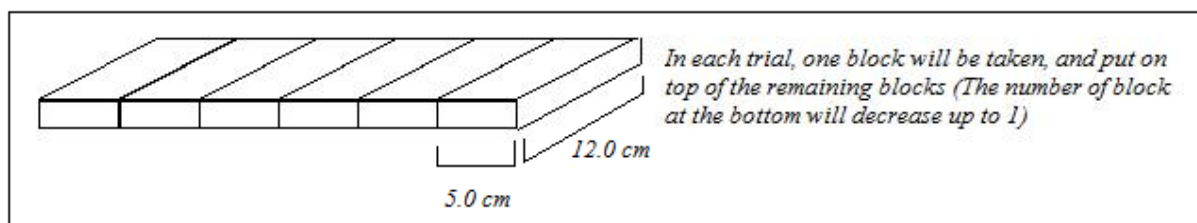
Figure 3: Apparatus

- 12.0 x 15.0 (3)
- 12.0 x 10.0 (2)
- 12.0 x 5.0 (1)

The bottom blocks are put on one side to get the following surface areas:

In each trial, one block will be taken, and put on top of the remaining blocks (The number of block at the bottom will decrease up to 1)

12.0 cm

2.2 cm
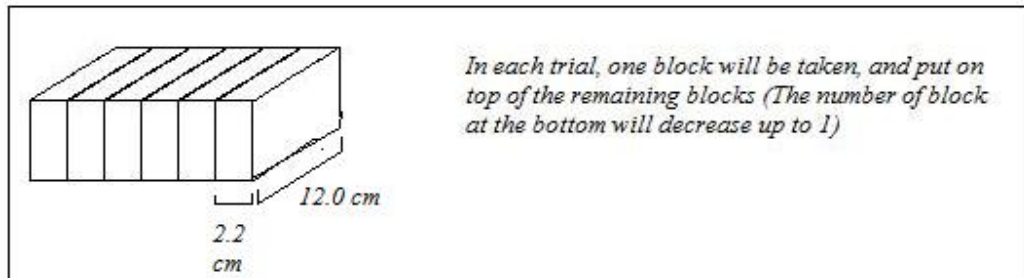
Figure 4: Apparatus

- 12.0 x 2.2 (1)
- 12.0 x 4.4 (2)
- 12.0 x 6.6 (3)
- 12.0 x 8.8 (4)
- 12.0 x 11.0 (5)
- 12.0 x 13.2 (6)

The bottom blocks are put vertically to get the following surface areas:

In each trial, one block will be taken and put on top of the remaining blocks (The number of blocks at the bottom will decrease up to 4 because after that, when they are given an initial push, they fall down)

5.0 cm

2.2 cm
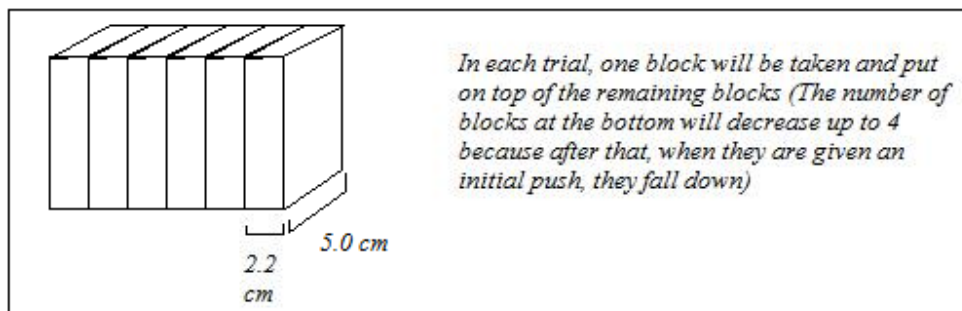
Figure 5: Apparatus

- 5.0 x 13.2 (6)
- 5.0 x 11.0 (5)
- 5.0 x 8.8 (4)

- *Calibration of the data collection equipment for Part C:*

1. The computer is turned on and Logger Pro 3.8 is opened. The lab quest is connected, with the force sensor being plugged in. Graph of force versus time will be displayed.

2. [Data Collection] button at Logger Pro is clicked and the values below are entered:

   - Mode: Time Based

   - Length: 10 seconds

   - Sampling Rate: 20 samples/second

   - A tick on the sample at time zero option is put.

- *Procedure for Part C:*
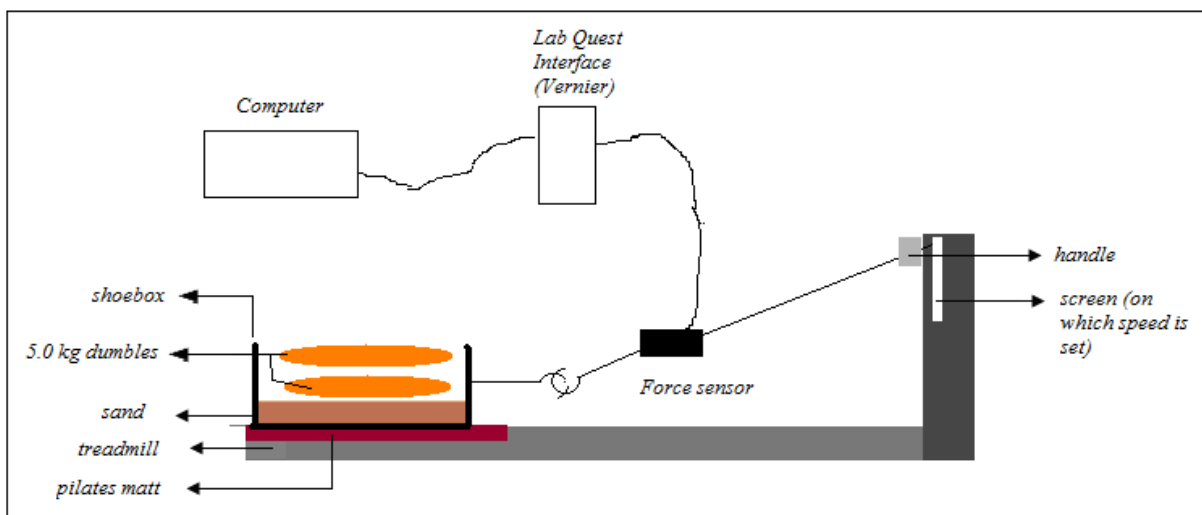
Figure 6: Apparatus and summary of the part

1. The shoebox is taken and taped across the sides, inside and the base of the box so that it won't rip apart later on.

2. On the 19.5 x 10 cm side, the middle of the side is marked by drawing two diagonal lines. A hole in the middle is pierced using scissors, and the hook is fixed there with the help of tape.

3. The soil is taken and put in the box, distributed every side of the box homogeneously.

4. The dumbbells are taken and put on top of the soil.

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5. On the treadmill, the rubber pilates matt is put diagonally in order to stabilize the shoebox. (It can be stabilized with two heavy objects, or two people standing on each side)

6. On the matt, the box (prepared at step 2-4) is put.

7. The force meter is taken and the hook of it is hung to the hook of the box.

8. The 4meters thread is steered through the hole of the force meter and winded around the handle of the treadmill. The rope should be stiff. If not, the position of the box should be changed.

9. The speed is set to 3 ms^{-1} and the treadmill is started to work. Then it is waited until the speed reaches this value.

10. [Collect] button at Logger Pro is clicked when it reaches 3 ms^{-1}. After 10 seconds, it will stop automatically.

11. [Autoscale Graph] button is clicked. Click on Analyze → Linear Fit and Analyze → Statistics.

12. The mean value is recorded.

13. The procedure is repeated for 4 more trials.

14. Steps 1-13 are repeated for varying speeds of 6, 9, 12, 15, 18, 21, 24 and 25 ms^{-1} (the maximum speed of treadmill).

2. DATA COLLECTION AND PROCESSING:

The raw data collected throughout the experiment is presented in Appendix: A

2.1. Part A: Effect of Mass:

10 data for each mass are collected (See Appendix A: Part A). Average of these data is taken. Then, net force is calculated. Below are the average acceleration, net force and uncertainty in net force values for 15 masses:

Trials	mass (kg) ±0.0005	a (ms²)±0.001	Fnet (N)	ΔF (N)
1	0.1100	3.032	0.33352	0.00163
2	0.2205	2.832	0.62446	0.00164
3	0.3305	2.759	0.91185	0.00171
4	0.4410	2.803	1.23612	0.00184
5	0.5510	2.637	1.45299	0.00187
6	0.6620	2.717	1.79865	0.00202
7	0.7690	2.536	1.95018	0.00204
8	0.8760	2.691	2.35732	0.00222
9	0.9850	2.569	2.53047	0.00227
10	1.0930	2.311	2.52592	0.00225
11	1.2025	2.219	2.66835	0.00231
12	1.3135	2.179	2.86212	0.00240
13	1.4250	2.122	3.02385	0.00249
14	1.5350	1.978	3.03623	0.00252
15	1.6450	1.591	2.61720	0.00244

Table 1: Acceleration, total net force (frictional force) and uncertainty in force values for average mass values.

Surface area of blocks used at each trial: 60 cm^2

Below is the graph showing the relationship between mass and force of kinetic friction:
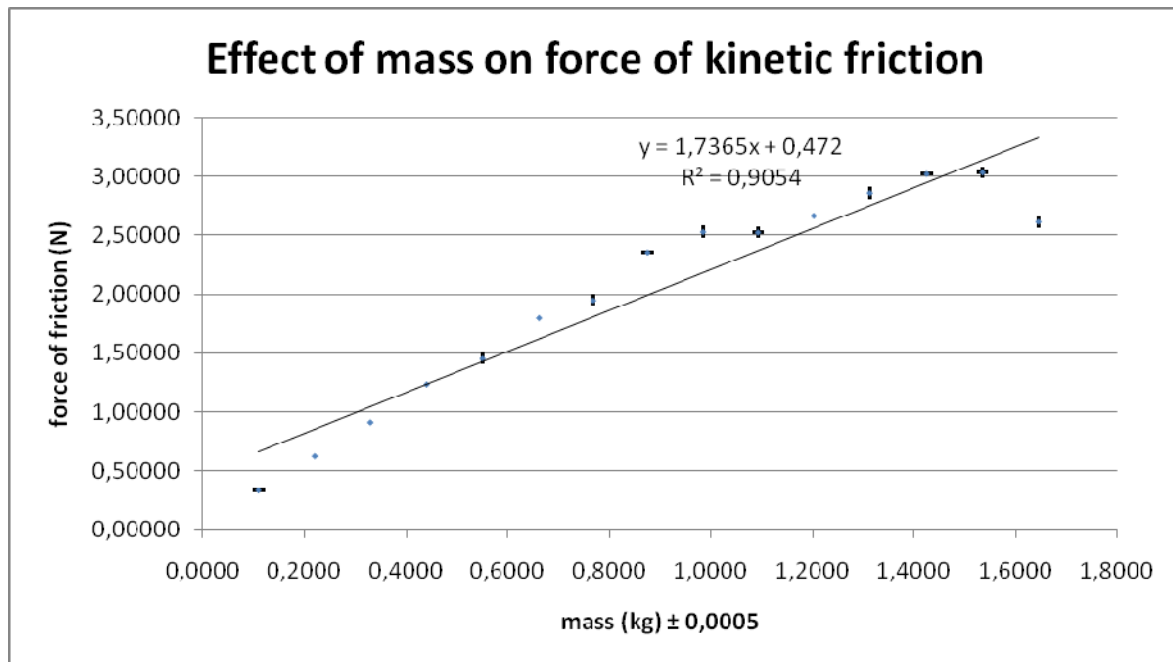
Graph 1: Force of kinetic friction values affected by increasing mass of the system

Note: As the error bars are too small, they are not observed clearly.

2.2. Part B: Effect of Surface Area:

10 data for each surface area are collected (See Appendix A: Part B). Average of these data is taken. Surface are is converted into square meters.. Then, the net force is calculated. Below are the average acceleration, net force and uncertainty in net force values for 15 surface areas:

Trials	surface area (m²)	Δarea(m²)	a (ms²)±0.001	Fnet (N)	ΔF(N)
1	0.00264	0.00014	2.075	4.8036	0.0034
2	0.00440	0.00014	2.496	5.7782	0.0036
3	0.00528	0.00016	2.581	5.9750	0.0036
4	0.00550	0.00016	2.256	5.2226	0.0034
5	0.00600	0.00017	1.765	4.0860	0.0032
6	0.00660	0.00018	2.407	5.5722	0.0035
7	0.00792	0.00019	2.464	5.7042	0.0035
8	0.01056	0.00021	2.453	5.6787	0.0035
9	0.01200	0.00022	1.798	4.1624	0.0032
10	0.01320	0.00023	2.467	5.7111	0.0035
11	0.01584	0.00025	2.512	5.8153	0.0036
12	0.01800	0.00027	2.129	4.9286	0.0034
13	0.02400	0.00032	2.165	5.0120	0.0034
14	0.03000	0.00037	2.439	5.6463	0.0035
15	0.03600	0.00042	2.581	5.9750	0.0036

Table 2: Acceleration, total net force (frictional force) and uncertainty in force values for average surface area values.

Mass of blocks used at each trial: 2315.0 g

Below is the graph showing the relationship between surface area and force of kinetic friction:

Effect of surface area on force of kinetic friction

$y = 13,753x + 5,1566$
$R^2 = 0,0497$
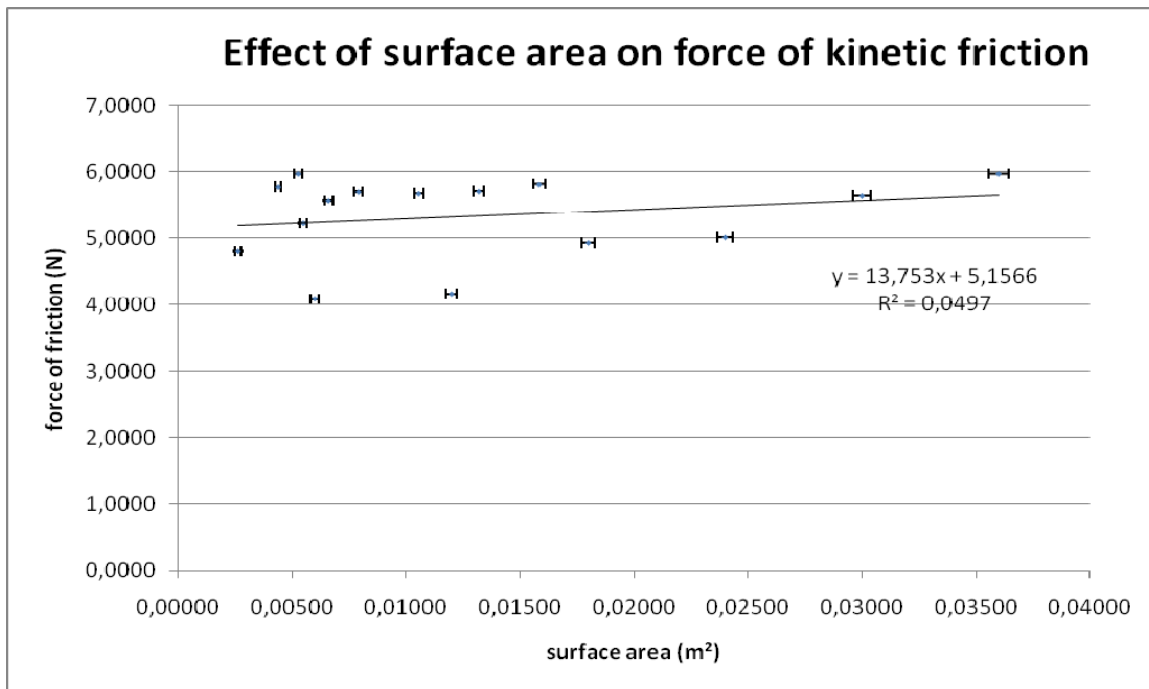
Graph 2: Force of kinetic friction values affected by increasing surface area of the system

Note: As vertical error bars are too small, they are not observed clearly.

2.3. Part C: Effect of Speed:

5 data for each speed are collected (See Appendix A: Part C)**.** Average of these data is taken. Below are the average force values for 9 velocities:

Trials	Speed (ms^{-1}) (±0.1)	force (N) (±0.01)
1	3.0	11.86
2	6.0	11.83
3	9.0	12.45
4	12.0	13.78
5	15.0	14.71
6	18.0	15.33
7	21.0	14.90
8	24.0	13.95
9	25.0	13.28

Table 3: Average force of friction on the system for varying speeds (ms^{-1})

Mass of dumbbells and soil used at each trial: 11.5 ± 0.5 kg

Below is the graph showing the relationship between speed and force of kinetic friction:

Effect of speed on force of kinetic friction

$y = 0,1132x + 11,892$

$R^2 = 0,4656$

force of friction (N) vs *speed (m/s) (±1.0)*
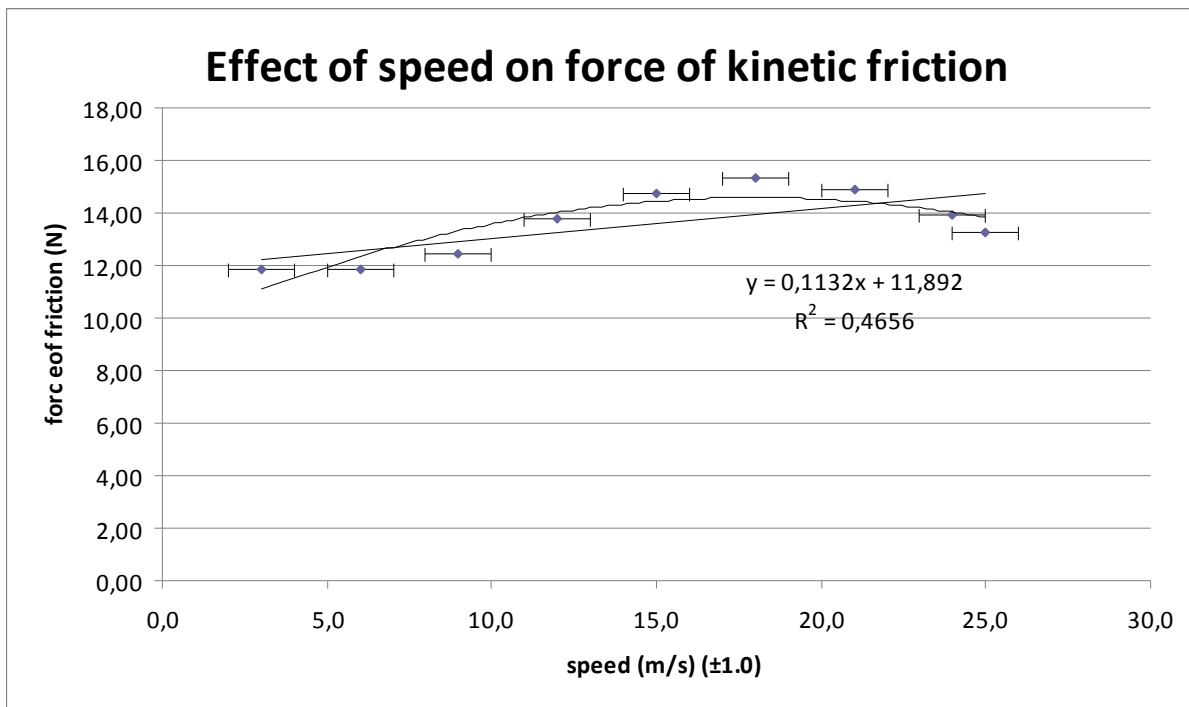
Graph 3: Force of kinetic friction values affected by increasing speed of the system

Note: As vertical error bars are too small, they are not observed clearly.

3. CONCLUSION AND EVALUATION:

In this experiment, effect of mass, surface area and speed on force of kinetic friction are investigated. Effect of mass and surface area was experimented in laboratory conditions, using small wooden blocks which were given an initial push. Effect of speed was observed in a gym, using a box in which there was a certain mass, pulled by a treadmill at various speeds. The results of data analysis provide an evidence to conclude that the magnitude of force of friction exerted on a moving body is directly proportional with its mass and independent of its bottom surface area. In addition, the speed of body has a parabolic effect on force of friction.

Mass' effect on frictional force was obvious as force of kinetic friction is directly proportional to normal: $Ff = \mu.N$ [7] The results of experiment related to effect of mass on force of kinetic friction is in harmony with the literature.

However, surface area's having no effect on kinetic friction force can be explained as; when surface area is increased, pressure decreases. As net force is pressure times surface area [6], it is obvious that small pressure is compensated by bigger surface area, and big pressure is compensated for smaller surface area; resulting in same force. Besides, as pressure time area is equal to weight, as mass remains the same, surface area won't affect the force, as proved in this essay. This supports the literature stating that surface area doesn't affect the force of kinetic friction [4]

On the other hand, investigating the effect of speed gave some non-negligible results. The force increased up to 18 ms^{-1}, after this speed, the force began to decrease. The literature states "*At low velocities the friction is independent of the relative surface velocity. At higher velocities the coefficient of friction decreases.*" [5]. Although it doesn't clearly explain what it's meant by low and high velocity, speed over about 20 ms^{-1} can be considered as high and below it as low; which also proves the hypothesis regarding the effect of speed.

Speed was increased, this might have caused a decrease in coefficient of friction and hence a decrease in force of kinetic friction, which proves the fact that the force decreased after 18ms^{-1}. It would have been better to see the effect of higher velocities (velocities more than 25 ms^{-1}) to be

surer about this deduction. As 25 ms^{-1} was the maximum speed on the treadmill, higher velocities could not be reached. If the object was pulled by a car; so that higher velocities could be reached; then the object would be harmed, worn out and lose its smoothness causing in change in coefficient of friction, which would result in inaccurate results. Besides, the Force meter and Lab Quest (Vernier) is not long enough to make measurements while the box is moved by a car. Pulley system was used to see if the objects could be moved with a higher speed, but the height above the ground was insufficient for the mass hanging from the pulley to fasten more than 25 ms^{-1}. Only about 20 ms^{-1} was reached in the pulley system.

It was hard to calculate the mean from the graphs obtained at each trial as the accelerometer and force sensor are very sensitive measuring devices which measure every single movement of the object. Although the surface the blocks were pushed in Part A and B, there can be some microscopic roughness on the surface. Same thing can be said about the blocks: They had been painted red and blue, and this paint made small roughness on the sides of the blocks. This may caused deviations in the data obtained. Metal objects could have been used instead of wood because they could be sanded to clear any roughness off**.** Wood can both be sanded; however, it wouldn't be as smooth as metal. In Part C, on the treadmill, the merging point of the treadmill affected the data: Although when I touched it, it seemed the same as other parts of the treadmill, however, in the graphs, when that merging point came in contact with the box, the graph made a big remarkable peak point, and it seemed as if it was making a damped harmonic motion (See Appendix D: Part C). This damping also shows the existence of friction.

After this experiment, new questions arises in mind: What would happen if the object's speed was more than 25 ms^{-1}, for example like 80 ms^{-1} ? Would the frictional force be proportional with square of the speed? [5] These could be some topics for a future IB student extended essay.

4. APPENDIX:

Appendix A: Data Collection:

- **Part A:**

mass: 110.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	3.353
2	2.770
3	2.769
4	3.044
5	3.257
6	3.136
7	3.032
8	3.114
9	2.995
10	3.325

mass: 220.5 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	3.082
2	2.941
3	2.501
4	2.828
5	2.832
6	2.666
7	2.966
8	2.675
9	3.001
10	2.386

mass: 330.5 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.618
2	3.417
3	3.328
4	2.638
5	2.865
6	2.759
7	2.122
8	2.890
9	2.823
10	2.433

mass: 441.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.998
2	3.074
3	3.063
4	2.781
5	2.650
6	2.780
7	2.717
8	2.803
9	2.775
10	2.721

mass: 551.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.637
2	2.582
3	3.005
4	2.694
5	2.574
6	2.846
7	2.523
8	2.369
9	2.608
10	2.122

mass: 662.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.401
2	2.231
3	2.796
4	2.359
5	2.726
6	2.717
7	2.839
8	2.892
9	2.742
10	2.914

mass: 769.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.589
2	2.537
3	2.367
4	2.536
5	2.503
6	2.406
7	2.452
8	2.569
9	2.801
10	2.945

mass: 876.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.691
2	2.561
3	2.624
4	2.462
5	2.297
6	2.442
7	2.434
8	2.290
9	2.133
10	2.338

mass: 985.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.199
2	2.869
3	2.383
4	2.477
5	2.299
6	2.682
7	2.316
8	2.896
9	2.569
10	2.146

mass: 1093.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.606
2	2.179
3	2.509
4	2.186
5	1.984
6	2.311
7	2.126
8	2.213
9	2.040
10	2.633

mass: 1202.5 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.086
2	2.078
3	2.121
4	2.417
5	2.381
6	2.298
7	2.219
8	2.343
9	2.487
10	2.496

mass: 1313.5 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.054
2	2.161
3	2.450
4	2.121
5	2.311
6	2.472
7	2.280
8	2.179
9	2.159
10	2.649

mass: 1425.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.480
2	2.357
3	2.209
4	1.866
5	2.355
6	2.296
7	2.122
8	1.849
9	1.628
10	2.400

mass: 1535.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	2.017
2	1.918
3	1.911
4	2.161
5	1.412
6	1.770
7	2.285
8	1.978
9	2.096
10	1.935

mass: 1645.0 ±0.5 gr	
Trials	a (ms⁻²)±0.001
1	1.323
2	1.799
3	1.576
4	1.424
5	1.346
6	1.747
7	1.591
8	1.570
9	1.761
10	1.502

- **Part B:** *("s.a." stands for surface area)*

s.a.: 60.0 cm²	
Trials	a (ms²)±0.001
1	1.825
2	1.765
3	1.818
4	1.704
5	1.904
6	1.435
7	1.819
8	1.293
9	1.408
10	1.998

s.a.: 120.0 cm²	
Trials	a (ms²)±0.001
1	2.181
2	1.841
3	1.068
4	1.970
5	1.850
6	2.242
7	1.798
8	2.087
9	1.567
10	2.101

s.a.: 180.0 cm²	
Trials	a (ms²)±0.001
1	1.974
2	2.124
3	2.127
4	1.744
5	1.932
6	1.977
7	2.122
8	2.139
9	2.122
10	2.129

s.a.: 240.0 cm²	
Trials	a (ms²)±0.001
1	2.492
2	2.175
3	2.282
4	2.204
5	1.946
6	2.311
7	2.048
8	2.165
9	1.978
10	2.043

s.a.: 300.0 cm²	
Trials	a (ms²)±0.001
1	2.953
2	2.611
3	2.576
4	2.378
5	2.074
6	2.583
7	2.566
8	2.689
9	2.382
10	2.439

s.a.: 360.0 cm²	
Trials	a (ms²)±0.001
1	2.665
2	2.172
3	2.923
4	2.948
5	2.442
6	2.500
7	2.257
8	2.254
9	2.469
10	2.581

s.a.: 26.4 cm²	
Trials	a (ms²)±0.001
1	2.107
2	2.409
3	1.687
4	1.651
5	2.385
6	1.746
7	2.893
8	1.357
9	1.748
10	2.075

s.a.: 52.8 cm²	
Trials	a (ms²)±0.001
1	2.209
2	2.175
3	2.581
4	2.168
5	2.620
6	1.756
7	3.072
8	2.662
9	2.817
10	2.341

s.a.: 79.2 cm²	
Trials	a (ms²)±0.001
1	2.126
2	2.676
3	2.883
4	2.800
5	2.464
6	2.501
7	2.771
8	1.895
9	2.583
10	1.735

s.a.: 105.6 cm²	
Trials	a (ms²)±0.001
1	1.701
2	2.407
3	2.683
4	2.909
5	2.731
6	2.453
7	2.606
8	2.842
9	2.367
10	2.413

s.a.: 132.0 cm²	
Trials	a (ms²)±0.001
1	2.241
2	2.177
3	2.279
4	2.262
5	2.747
6	2.637
7	2.650
8	2.467
9	2.633
10	2.684

s.a.: 158.4 cm²	
Trials	a (ms²)±0.001
1	2.587
2	2.512
3	2.534
4	1.768
5	2.686
6	2.252
7	2.265
8	3.021
9	3.391
10	3.123

s.a.: 66.0 cm²	
Trials	a (ms²)±0.001
1	2.397
2	3.118
3	3.424
4	1.719
5	2.930
6	2.407
7	3.314
8	2.350
9	2.945
10	2.233

s.a.: 55.0 cm²	
Trials	a (ms²)±0.001
1	1.874
2	2.020
3	2.587
4	2.361
5	1.709
6	2.256
7	1.831
8	2.247
9	2.599
10	2.278

s.a.: 44.0 cm²	
Trials	a (ms²)±0.001
1	2.064
2	1.628
3	2.931
4	1.924
5	1.980
6	2.268
7	1.783
8	2.496
9	2.861
10	2.566

- **Part C:**

speed: 3 ms^{-1}
Trials	Force (N) ±0.01N
1	12.29
2	11.93
3	11.94
4	11.82
5	11.30

speed: 6 ms^{-1}
Trials	Force (N) ±0.01N
1	11.86
2	11.80
3	11.69
4	11.84
5	11.95

speed: 9 ms^{-1}
Trials	Force (N) ±0.01N
1	12.52
2	12.43
3	12.51
4	12.34
5	12.47

speed: 12 ms^{-1}	
Trials	Force (N) ±0.01N
1	13.70
2	13.76
3	13.83
4	13.83
5	13.76

speed: 15 ms^{-1}	
Trials	Force (N) ±0.01N
1	14.79
2	14.98
3	14.58
4	14.59
5	14.63

speed: 18 m/s^{-1}	
Trials	Force (N) ±0.01N
1	15.48
2	15.28
3	15.18
4	15.13
5	15.56

speed: 21 ms^{-1}	
Trials	Force (N) ±0.01N
1	15.71
2	14.97
3	14.83
4	14.59
5	14.39

speed: 24 ms^{-1}	
Trials	Force (N) ±0.01N
1	14.30
2	14.05
3	13.92
4	13.74
5	13.75

speed: 25 ms^{-1}	
Trials	Force (N) ±0.01N
1	13.50
2	13.54
3	13.06
4	13.06
5	13.25

Appendix B: Data Processing:

- **Part A:**

Mass is converted into kilograms by dividing the values by 10^3, Fnet is calculated by Newton's Second law of motion (F=m x a):

(110 grams will be used as example)

Mass=$110/10^3$=0.110 kg

Acceleration=3.032 ms^{-2}

Fnet = 0.110 x 3.032 = 0.33352 N

- **Part B:**

Surface area is converted into m^2 by dividing the values by 10^4. Fnet is calculated by Newton's Second law of motion (F=m x a):

60 cm^2 will be used as example)

Surface area= $60/10^4$=0.0060 m^2

Acceleration=1.765 ms^{-2}

Fnet= 0.0060 x 1.765 = 4.0860 N

Appendix C: Uncertainty calculations:

- **Part A:**

When mass is converted to kilograms, values and uncertainty is divided by 10^3, which results in uncertainty being 0.0005. Uncertainty in force of kinetic friction is found as:

$$\Delta F = \left(\frac{\Delta m}{m} + \frac{\Delta a}{a}\right) x (mxa)$$

(110 grams will be used as example)

Mass=**0,110 ± 0.0005 kg**

Acceleration= 3.032 ±0.001 ms^{-2}

$$\Delta F = \left(\frac{0.0005}{0.110} + \frac{0.001}{3.032}\right) x (0.110 x 3.032) = \textbf{0.00163 N}$$

- **Part B:**

As surface area is found by multiplying width by length, uncertainty is found by:

$$\Delta A = \left(\frac{\Delta width}{width} + \frac{\Delta length}{length}\right) x (widthxlength)$$

(60 cm^2 will be used as example)

$$= \left(\frac{0.1}{5.0} + \frac{0.1}{12.0}\right) x (5.0 x 12.0) = \textbf{1.7 m}^\textbf{2}$$

Then, as surface area is converted to m^2, uncertainties are divided into 10^4, too. So;

Surface area=**0.0060 ± 0.00017 m$^\textbf{2}$**

Acceleration= 2.453 ±0.001 ms^{-2}
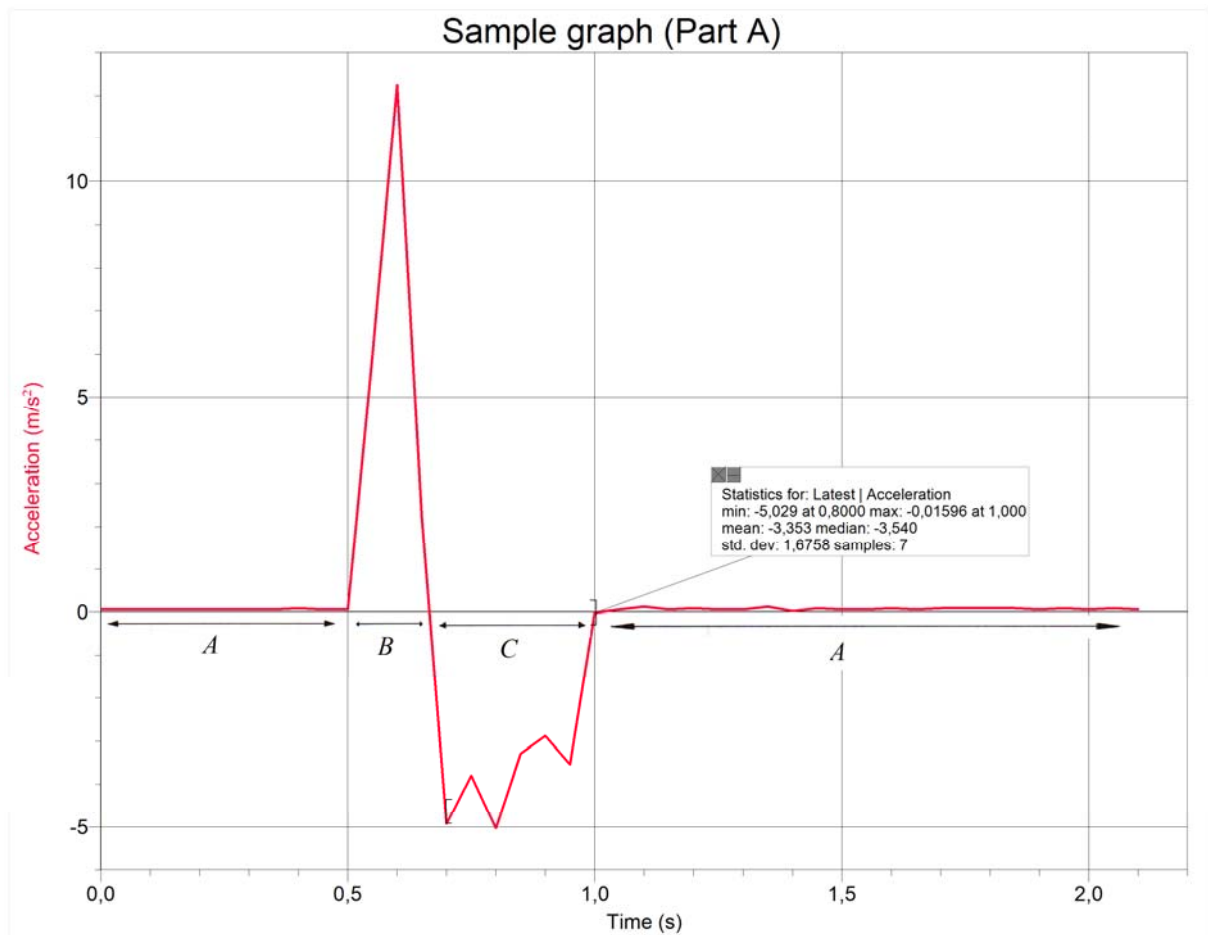
Mass =2.3150 ± 0.0005 kg

$$\Delta F = \left(\frac{0.0005}{2.3150} + \frac{0.001}{2.453}\right) x (2.3150 x 2.453) = \textbf{0.0032 N}$$

Appendix D: Sample graphs:

- **Part A:**

(This graph shows the acceleration values of a 110.0 grams-block (a single block)in its first trial)
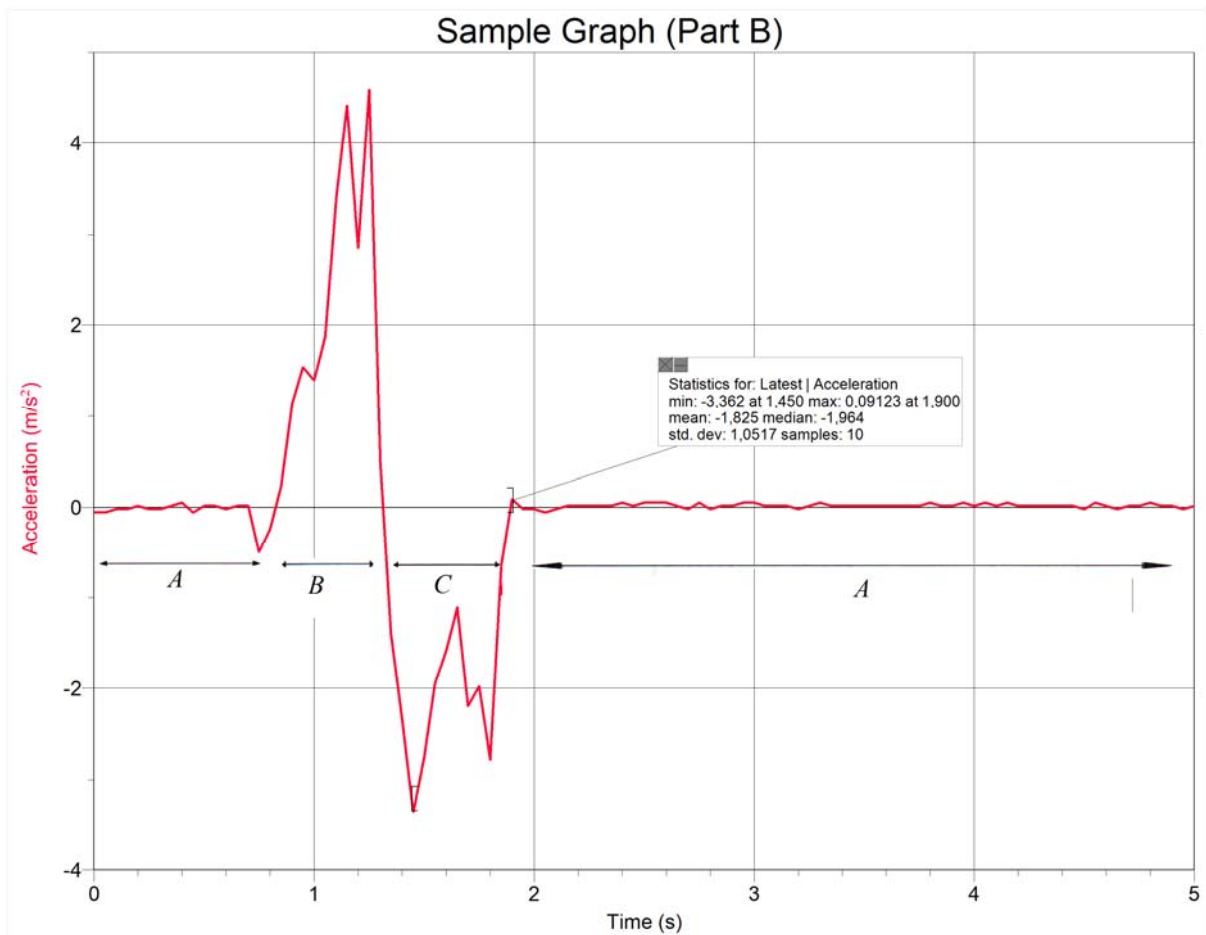

Explanation of the graph above:

A: In these areas, the block stops (The first "A" area shows the time that the object hasn't been pushed yet and the second "A" area shows the time that the object has stopped after its motion due to friction.)

B: At this very incident, the block is being pushed

C: The block decelerates due to the kinetic frictional force.

- **Part B:**

(This graph shows the acceleration values of the apparatus having 60.0 cm^2 surface area (a single block on the bottom) in its first trial.)

Explanation of the graph above:

A: In these areas, the block stops (The first "A" area shows the time that the object hasn't been pushed yet and the second "A" area shows the time that the object has stopped after its motion due to friction.)
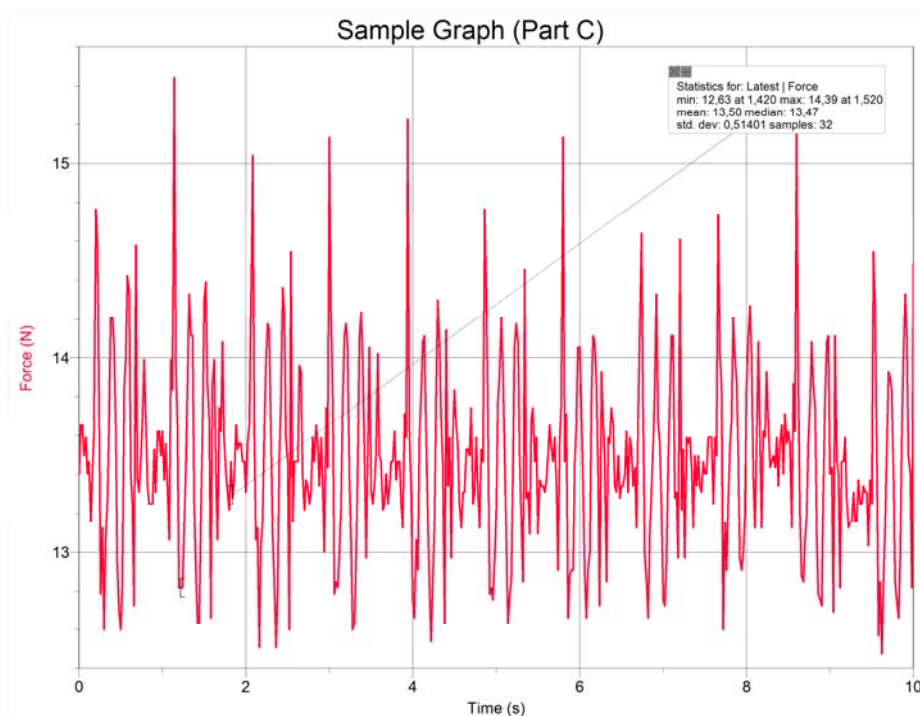
B: At this very incident, the block is being pushed

C: The block decelerates due to the kinetic frictional force.

- **Part C:**
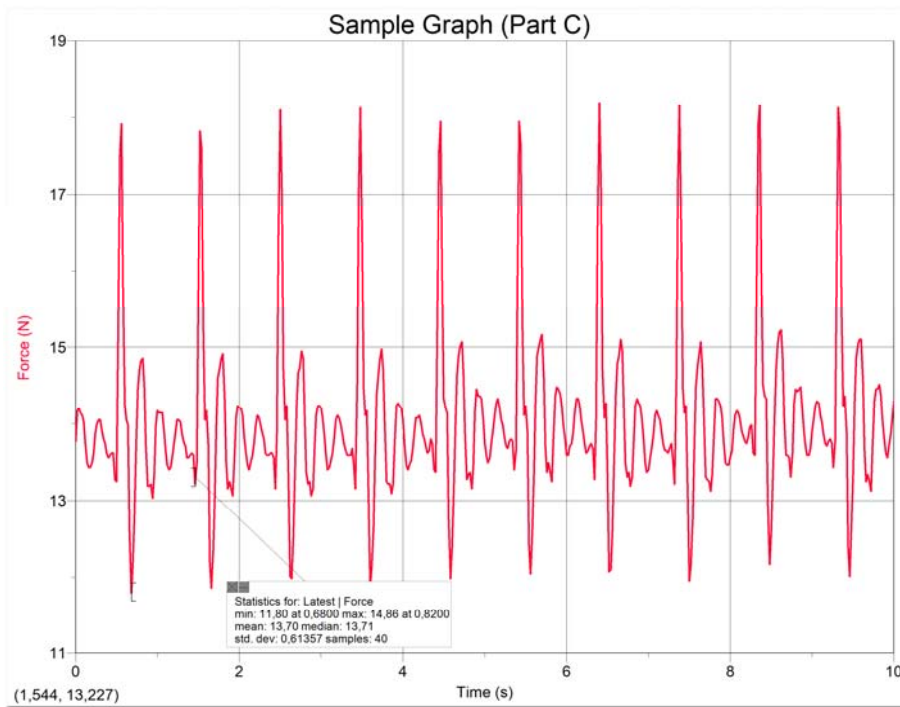
speed = 12 ms⁻¹

speed = 25.0 ms⁻¹

It can be seen from the graphs that the motion of the box is damped harmonic motion. One period of the motion is taken into account.

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