Physics Extended Essay
Jason Vincent
St. Julian's School
Supervisor: Mr. G. Atkinson - Physics

Abstract: 299
Essay: 3947

Excluding abstract, contents, appendixes, bibliography and definitions, tables and diagram labels.

1

'Investigating the Limitations affecting maximum braking on a freeride bicycle'

Abstract

It is common when beginning an investigation to start out with a broader view of the topic and then to elaborate on more specific foci as the research progresses. This was the case with my investigation into the physical factors affecting optimum braking which led to 'Investigating the limitations affecting maximum braking on a Freeride bicycle' as my research question.

The scope of this essay is to, through the means of experimentation and theoretical models, investigate to what extent a rider can increase his maximum deceleration achievable on the bicycle before either the bike starts to skid, or the rear wheel starts to lift off the ground in what is known as an 'endo'.

This is then further elaborated on by considering the ground gradient and how this would affect the maximum deceleration attainable, and also the point on a downhill slope where it's possible to travel at a constant velocity, thereby being able to cancel the acceleration due to gravity acting on the bike and rider by braking.

The conclusions drawn from this investigation by considering the theoretical models and the experimental data is that there is a definite correlation between weight distribution and maximum deceleration achievable, and in essence the further back the rider the more he/she can decelerate without the bike tipping over. However, data has also shown that a riding position which is too far back will result in the front wheel skidding. The conclusions point towards a braking position where the combined centre of mass is approximately 96cm from the front wheel contact point as being the optimum braking point on flat ground, since the bike first skids very slightly and then as the apparent weight shifts forward the bike will start to tip – though at this point it will have already decelerated substantially.

0

Contents

Introduction

Though the theory covered in the body of this essay can be applied generally to bicycles and motorbikes the focus will be on a Freeride[I] bicycle. The sophistication that has arisen throughout the past few years in this sport, which has become increasingly more common, cover not only personal safety equipment but also the components of the bike itself. Though this sophistication is outside the scope of this essay, one element worth mentioning is the brakes, which have been the focus of many companies in an aim to obtain the best braking efficiency and modulation[II].

The research question that I have developed in order to determine to what extent the brakes are effective in the conditions a Freeride bicycle is subjected to is 'Investigating the limitations affecting maximum braking on a Freeride bicycle'. I aim to go into depth both by hypothesising at a theoretical level but also by collection of data through experimental means and thus investigate how these factors can be controlled to obtain the optimum braking, whilst also determining the brakes' physical limits.

Evidently simply by considering the situation various factors come to mind almost immediately. These include the weight distribution of the rider on the bicycle – representing a shift in the centre of mass - the load and weight transfer during braking, and the resulting frictional forces acting on the bicycle's tyres, on a constant ground surface.

Evaluation which is essential will be done throughout the essay as opposed to at the end in order to aid in subsequent interpretations etc.

Body

Theoretical Mathematical Hypothesis

FACTOR 1: STATIC FRICTIONAL FORCES

A moving bike, though dynamic, is subject to static friction whilst rolling, and dynamic friction once the force of static friction has been exceeded and the bike starts to skid[III]. This is thus a definite limitation for braking, since entering into a "skid phase" would be considered ineffective braking for two reasons:

- The coefficient of kinetic friction is less than the coefficient of static friction.
- The steering of the bicycle is impaired severely.
- It is not possible to balance (or at least extremely difficult)

In order to determine the maximum force of friction present the following can be used:

$$f_{fr} = u_s f_n$$

Where u_s = the coefficient of static friction

and f_n = the normal force.

Initially let us consider that the bicycle is on flat ground and thus the normal force is perpendicular to the ground. I can then state that the sum of the frictional forces acting upon the bike (front and rear tyres) can be expressed as follows:

2

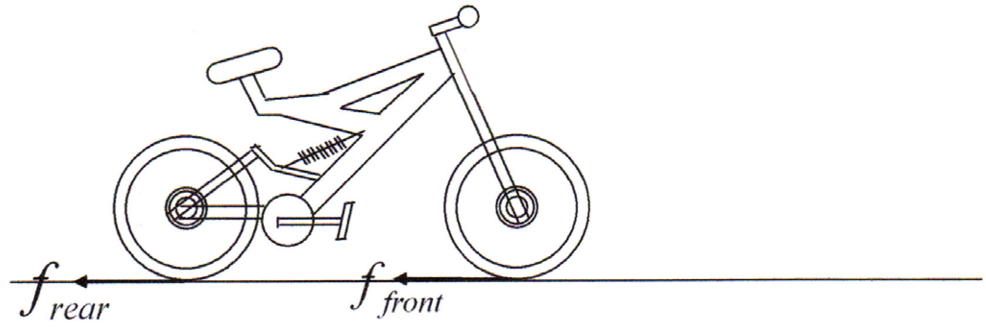


Figure 1

$$f_{f(rear)} = u_s f_{rear-weight}$$

$$f_{f(front)} = u_s f_{front-weight}$$

Therefore $\sum f_f = u_s f_{weight}$

FACTOR 2: DECELERATION LIMITED BY TIP-OVER[IV]

In investigating factors affecting braking, the deceleration at which the bicycle will tip over, or rather, where the rear wheel will lift off the ground, is important to find, since any deceleration greater than this is no longer efficient braking, given that it could potentially lead to an accident.

The following is a theoretical model to find the maximum deceleration before tip over occurs:

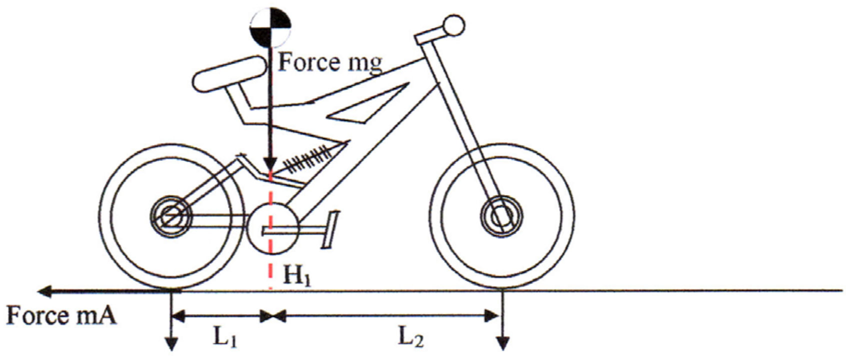


Figure 2

When the rear wheel just starts to lift off the ground the clockwise moment force is equal to the counter clockwise moment force. Thus the following can be deduced:

The moment forces will be Moment Force = Force x Perpendicular Distance

Therefore the clockwise moment force can be derived considering F=ma, where F is the braking force, M is the combined mass (rider and bike) and a is the acceleration due to braking. The clockwise moment will be $f_{cw} = maH_1$ where H_1 is the perpendicular distance to the line of action.

The counter clockwise moment force will be $f_{ccw} = mgL_2$ where *mg* is the weight and L_2 the perpendicular distance to the line of action.

By equating the two you get: $mgL_2 = maH_1$

And by rearranging for A (the maximum acceleration [in this case deceleration] permitted) I will have a moment equation to model tip-over.

$a = \dfrac{gL_2}{H_1}$ Where G= the Acceleration due to gravity $= 9.81\text{ms}^{-2}$ $\therefore A = \dfrac{9.81 \times L_2}{H_1}$

This is true because the centre of mass represented in the diagram is where the combined weight is said to act vertically down from.

Experimental Variables

INDEPENDENT VARIABLES

- Weight distribution

CONTROLLED VARIABLES

- Tyre air pressure (2.5psi)
- Brakes (Front brake, same regulations[I])
- Brake force (maximum braking force sought after)
- Surface conditions – dry
- Surface – Concrete / Tarmac – flat gradient

DEPENDENT VARIABLES

- Maximum deceleration before either skid or tip-over

Overall Experimental Apparatus

- Freeride bicycle with front functioning brake
- Tape measurer
- Newton scale
- Acceleration sensor and relevant software
- Laptop computer
- String
- Backpack
- Air pump
- Wooden board

[I] Regulations refer to the same settings as in modulation and sensitivity.

4

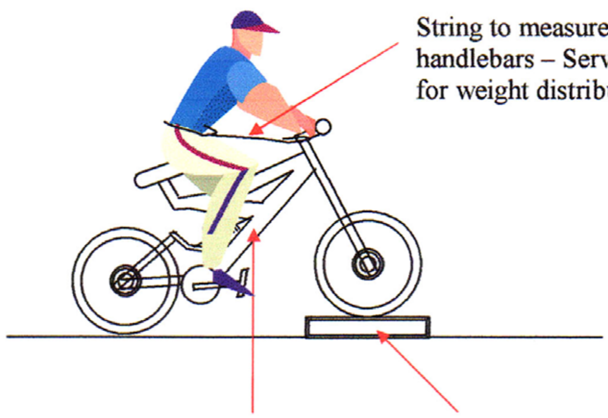
Experimental Methods

The fundamental assumption made in the theoretical model above is that the positioning of the centre of mass is known, whilst in actual fact this is not the case. Thus the first step is to find the position of the centre of mass. In order to do so I will split the problem up into two parts. Firstly, I will locate the horizontal positioning of the combined centre of mass (ignoring height), and second, the vertical location of the individual centres of mass.

Procedure – Horizontal positioning of the Centre of Mass:

1. Measure the bicycles wheelbase (distance between both points of contact)
2. Measure the mass of the bicycle using a scale.
3. Measure the mass of the rider using a scale.
4. With the rider standing on the bicycle whilst at rest – supported by an assistant, a string is to be tied around the riders' waist at one end and the stem[V] of the steering tube[VI] at the other end. The length of this piece of string from the stem to the riders' waist is to be measured and recorded.
5. A scale is to now be placed under the front wheel, whilst the rider ensures the string remains stretched. The reading is to be recorded.
6. Steps 4 and 5 are to be repeated using 8 different lengths of string and the results recorded accordingly, always with the rider standing in different positions.

Experiment / Apparatus Diagram



String to measure distance to handlebars – Serves as reference for weight distribution later

Freeride Bicycle

Newton Scale

Figure 3

Having carried out this experiment the following data was collected: (Uncertainties are shown where relevant and these are then processed accordingly for the remaining of the essay – this could involve converting the absolute uncertainties to percentage uncertainties and this will be done by taking the average reading and then finding the absolute uncertainty as a percentage of this average.)

5

Reading Number	Length of String (m) ± 0,05m	Front Force (N) ± 5N
1	0,3	440
2	0,4	360
3	0,46	305
4	0,49	295
5	0,55	230
6	0,64	175
7	0,72	125
8	0,87	75
	Average: 0,55	
	% Uncertainty: ± 9,09%	
	Bike Mass (kg) ± 0,5kg	23
	Rider Mass (kg) ± 0,5kg	75
	Combined Mass (kg) ± 1,0kg	98
	Combined Mass (kg) ± 1,02%	98
	Bicycle Wheelbase (m) ± 0,02m	1,17
	Bicycle Wheelbase (m) ± 1,71%	1,17

Table 1

Having collected this data it is now possible to process it and establish a ratio to determine the horizontal positioning of the Centre of Mass. By dividing the front force by the total weight (combined mass x G = 9.81M) it is possible to get a ratio which represents what percentage of the centre of mass is at the front half of the wheelbase.

By then multiplying this value as a decimal by the wheelbase I can attain a value for the distance of the centre of mass from the rear wheel contact point with the ground.
The following table shows this data:

Length of String (m) ± 0,02m	Front Force (N) ± 5N	Centre of Mass % distance from Rear ± 10%	Centre of Mass distance from Rear (m) ± 11.82%
0,30	440	45	0,53
0,40	360	37	0,43
0,46	305	31	0,36
0,49	295	30	0,35
0,55	230	23	0,28
0,64	175	18	0,21
0,72	125	13	0,15
0,87	75	8	0,09
			Average: 0.30

Table 2

Now that I know the horizontal position of the centre of mass I need to find the vertical position. Initially, I had devised a method for finding this using trigonometry. This method was not used but can be viewed in Appendix I.

Since this was important for the success of this investigation I devised another method with the aid of some research. It involves measuring the centre of mass of the rider individually, the centre of mass of the bicycle, and then using some basic mathematics to work out the vertical positioning of the combined centre of mass.

6

Procedure – Vertical positioning of the Centre of Mass (rider):

1. Using a board, place one end on a scale.
2. The rider is to lie down on this board with the end of his head at the end of the board on the side with the scale.
3. Place rider in riding position (knees slightly flexed to approximately 100°).
4. Place object the same height as the scale under the board where the riders' feet end.
5. Record the value visible on the scale.

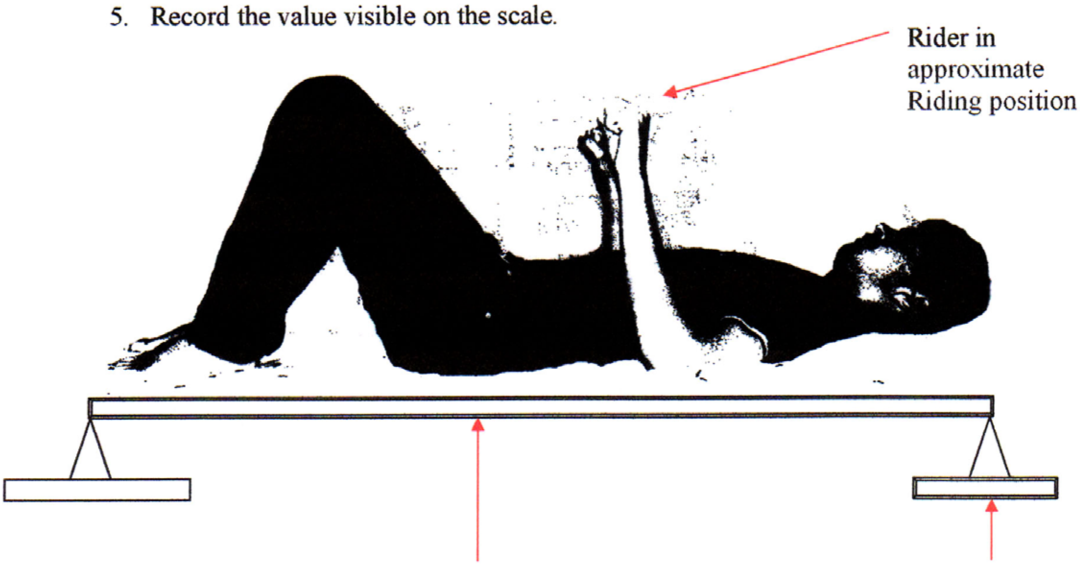


Figure 4

After having carried out the experiment the data collected from the scale was as follows:

Value on scale (N) ± 5N or ± 1,11%:	450
Length of rider in riding position (m) ± 0,05m or ± 2.86%:	1.75

Since I already know from the previous experiment that the riders' weight is 750N ± 5N or 0,67%, the ratio of weights from the top of the board where the riders' head rests to the bottom is 450:300.

$$\frac{450}{750} = 0.6 \pm 1{,}78\%$$

$$\therefore 0.6 \times 1.75 = 1.05\text{m} \pm 4{,}64\%$$

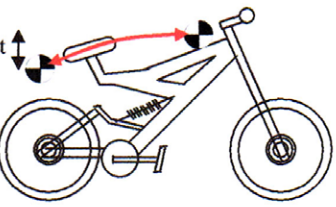


Figure 5

Therefore the height of the riders' Centre of Mass is 1.05m ± 4.64% above the ground when in the riding position. However this is the height for a set riding position. When the rider is working through all the different weight distributions the riding position changes slightly. The rear-most distributions for instance will have the knees flexed less than 90°. This will lead to a parabolic shape for the centre of mass as the rider moves through the different weight distributions and gives rise to a significant uncertainty in the height of the centre of mass which is extremely hard to quantify.

Procedure – Vertical positioning of the Centre of Mass (bike):

1. Hang the bike from one point and drop a piece of string with a weight. Mark generally the line on the bike frame (adding paper below the bike frame may be necessary).
2. Repeat step 1 twice from different points.

Having used this method to establish where the centre of mass is on the bike, I then measured the height of it from the ground, and determined it was 0,48m (see Img. 1 in appendix).

➢ There is however a problem with this method which is the fact that since no rider is on it, the method doesn't take into account the geometric change which brings about a shift in the centre of mass due to the compression of the suspensions. This gives rise to an uncertainty of ± 0.066m since suspension compression is about 1/3 of the total travel when the rider is on it, and the total travel is approx. 200mm. Or: ± 13,75%

Knowing the two Centres of Masses I can now combine them and determine the overall height.[II]

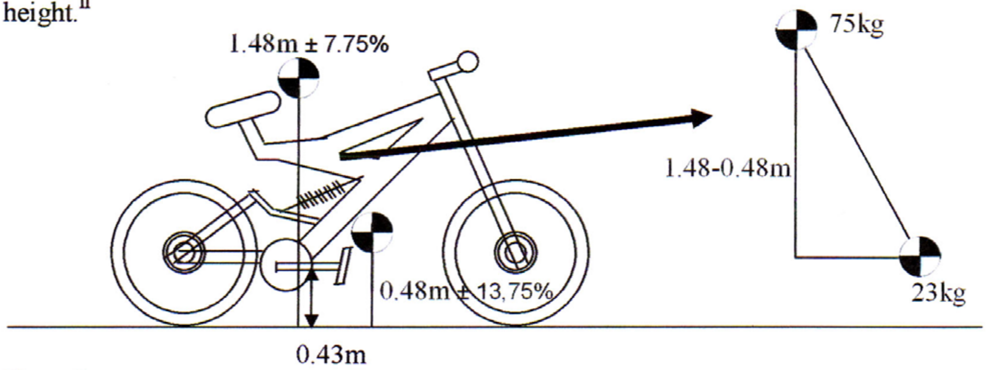


Figure 5

$1.48 - 0.48 = 1$ ± 18,07%

$\frac{23}{98} = 0.235$ ± 3,19%

$0.235 \times 1 = 0.235$ m ± 21.26%

$1 - 0.235 = 0.765$ m ± 23.07%

Therefore the overall vertical height of the Centre of Mass is 0.48+0.765 = **1.25m** ± 19,48% from the ground.

Having established this, I can now hypothesise a theoretical line for the maximum decelerations the bike should be able to endure before tip-over begins to occur, using the theoretical equation for the acceleration derived previously $A = \frac{9.81 \times L_2}{H_1}$

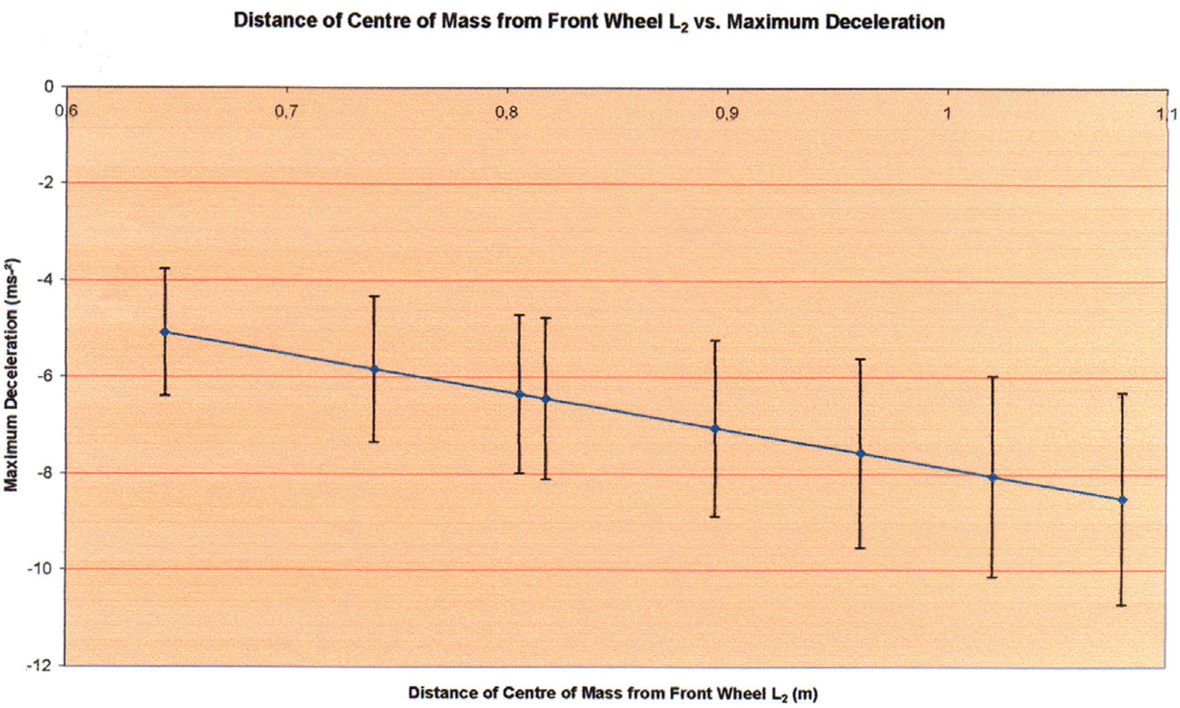
[II] The height of the rider Centre of Mass is 1,48 because the pedals are 0,43 m above the ground and the rider's Centre of Mass is 1,05m above the ground. This **assumes** flat pedals and the suspension implies an uncertainty of ± 0.066m

8

Centre of Mass distance from Rear L_1 (m) $\pm 11.82\%$	Centre of Mass distance from Front L_2 (m) $\pm 6.37\%$	Maximum Deceleration Possible ($-ms^2$) $\pm 25.85\%$
0,525	0,645	$\frac{0.645\times9.81}{1.245}=5.082$
0,430	0,740	$\frac{0.740\times9.81}{1.245}=5.831$
0,364	0,806	$\frac{0.806\times9.81}{1.245}=6.351$
0,352	0,818	$\frac{0.818\times9.81}{1.245}=6.445$
0,275	0,895	$\frac{0.895\times9.81}{1.245}=7.052$
0,209	0,961	$\frac{0.961\times9.81}{1.245}=7.572$
0,149	1,021	$\frac{1.021\times9.81}{1.245}=8.045$
0,090	1,080	$\frac{1.080\times9.81}{1.245}=8.510$

Table 3

By plotting this on a scatter graph it will be easier to see the trend that hypothetically should occur (processed uncertainties are shown for the most significant axis).



Graph 1

9

Clearly the main fallacy of this hypothesis is that it assumes there will be sufficient friction for the bike to tip-over, which in reality it might not. In order to determine the deceleration at which the bicycle will skid I will refer back to the theoretical result for the frictional force acting on the bike, $\sum f_f = u_s f_{weight}$.

The surface that the experiment is to be performed on is concrete / tarmac and the tyres of the bicycle are rubber. By researching relevant literature[III] I have found the coefficient of static friction for tarmac/rubber to be between 0.6 and 0.85. I will use a mid-value of 0.725 ± 17,24%. This is clearly a major uncertainty and could have been reduced immensely if an experiment had been carried out to determine the coefficient of static friction.

I will use Newton's first law $F = MA$ once I have the frictional force to find the maximum deceleration permissible.

By rearranging I get $\frac{F}{M} = A$

I will assume that all the weight of the bicycle is being used as the normal force about the front wheel since when the bicycle tips over all 980N of the bike will be on the front wheel. I will not be using the rear brake in this experiment.

$f_{fr} = 0.725 \times 980$

$f_{fr} = 710.5\text{N} \pm 18.26\%$

$A = \frac{710.5}{98}$

$A = 7.25ms^{-2} \pm 19.28\%$

Therefore any deceleration greater than this should cause the bike to skid.

III http://www.engineershandbook.com/Tables/frictioncoefficients.htm

10

In a dynamic scenario, there is physical shift in weight transfer since the bike is not static. This is due to:

- The suspensions which will compress during accelerations. This implies that the geometry will have changed and the physical location of the centre of mass will move.
- Tyre compression from braking independently of air pressure will lead to a shift in geometry.
- The riders' body will inevitably shift during braking even if the rider tries to preserve the weight distribution.

These all contribute towards uncertainties.

Procedure – Collecting data – Maximum Decelerations

1. Calibrate and level the acceleration sensor on the handlebars so that it is pointing forwards (detecting positive accelerations) and is not influenced by the acceleration due to gravity.
2. Using the weight distributions stipulated earlier via the 'string around waist' method, the rider is then to ride at each weight distribution on flat ground and then apply the front brake to the maximum. The rider is then to release immediately after the bike either starts to skid with the front wheel, or alternatively starts to tip-over.
3. The rider is to repeat this reading 3 times with each weight distribution.
4. The rider is then to repeat step 2 and 3 using the other weight distributions.

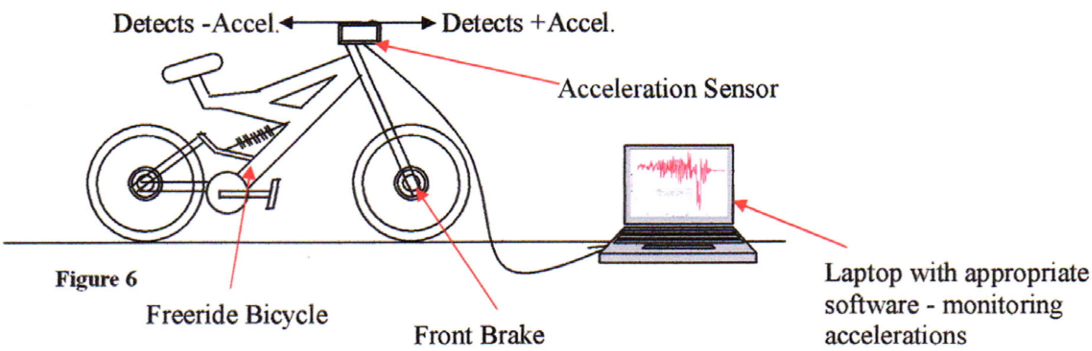
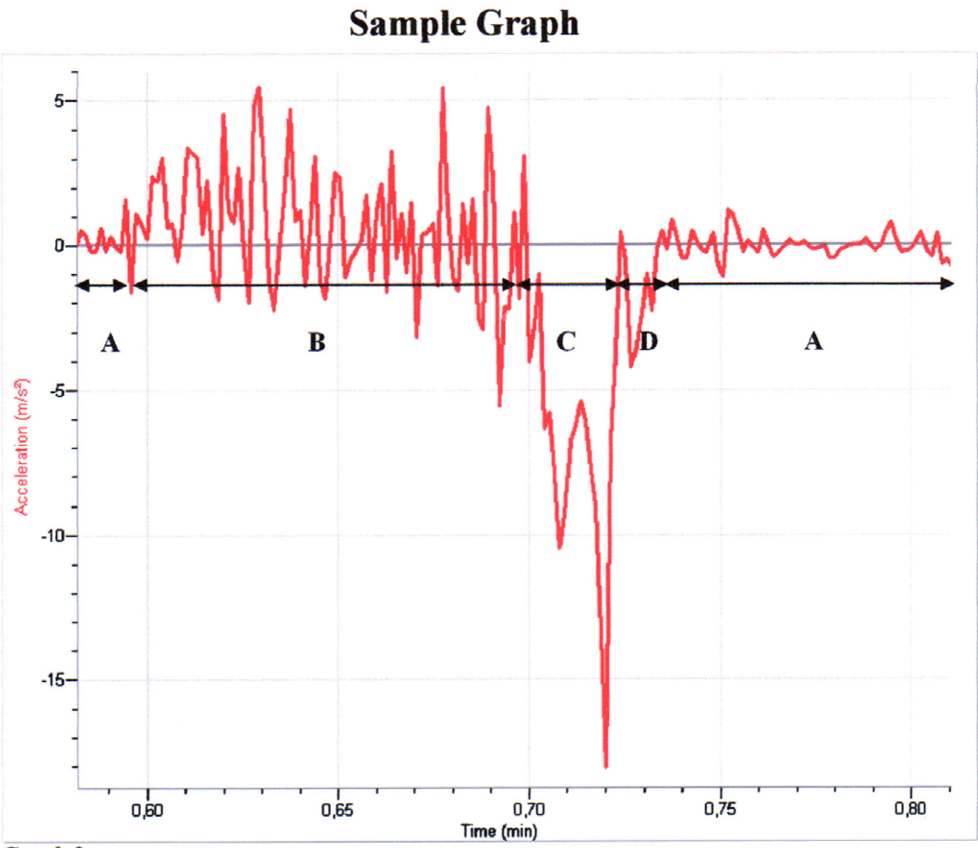


Figure 6

A test run is carried out in order to explain and clarify the various sections of the graphs generated:

11



Graph 2

The sampling rate for the data collection software is set the maximum rate in order for the data to be as reliable and accurate as possible

A	This area merely represents noise whilst the bike is stopped with me on it before the run begins.
B	This section represents the pedal strokes whilst increasing velocity before braking occurs.
C	This is the deceleration due to the braking force exerted with the front brake.
D	This is the rider letting go of the front brake to prevent a complete tip-over but braking right after to come to a stop.

The graphs from which I have extracted the data to base my experiment on can be found in Appendix II.
However, a problem did become evident at this stage. Since for readings where the bicycle doesn't skid, the bicycle starts to tip over it will start to record part of the acceleration due to gravity. In order to attempt to reduce this, and also the fact that there is a significant amount of noise in the data, I will take an **average of the entire deceleration period** as opposed to focusing on minimum values. I will also let go of the front brake immediately when it starts to tip in order to reduce the uncertainty.

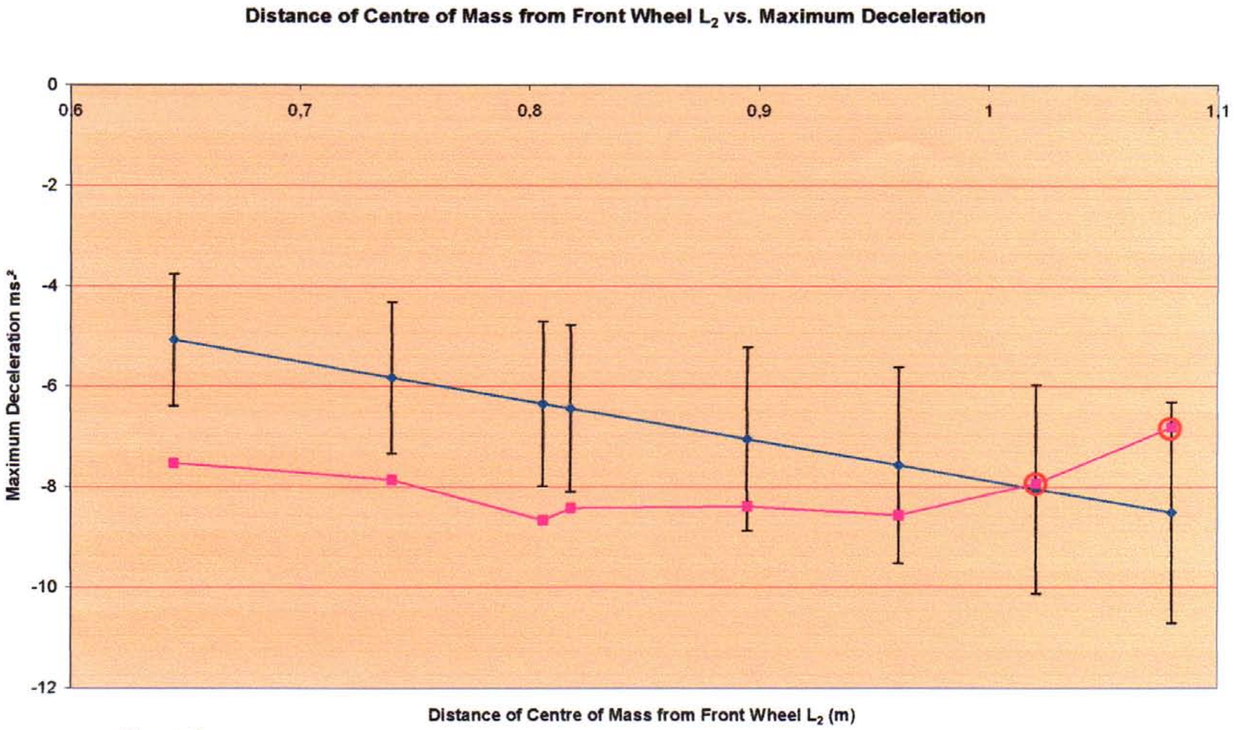
The data I collected is summarised in the following table:

12

Acceleration Averages (From Acceleration/Time graphs)				
Centre of Mass distance from Front L_2 (m) ± 6.37%	Attempt1 (ms^{-2})	Attempt2 (ms^{-2})	Attempt3 (ms^{-2})	Average (ms^{-2})
0,645	-7,543	-7,506	-7,553	-7,534
0,740	-7,107	-8,948	-7,528	-7,861
0,806	-7,965	-8,400	-9,637	-8,667
0,818	-9,184	-8,353	-7,747	-8,428
0,895	-7,826	-8,215	-9,144	-8,395
0,961	-8,659	-8,649	-8,404	-8,571
1,021	-8,852	-7,897	-7,047	-7,932
1,080	-6,998	-5,766	-7,699	-6,821

Table 4

It is complicated and difficult to quantify an uncertainty for the acceleration average from the graphs. Clearly the noise gives rise to a substantial uncertainty but this is hard to quantify.
I will now compare the data without uncertainties to my hypothetical prediction by plotting the data on the same graph. The following graph illustrates this[IV]: (I have taken an average of the decelerations collected from the experiment for each weight distribution shown in the table above)



Graph 3

[IV] Circled data readings imply that the bicycle was skidding, as does red data in the table.

13

Interpretation of the graph (data collected) vs. the Hypothesized results

It is clear from the graph that the data collected does not fit the theoretical prediction very accurately. The following will help to explain this:

- Firstly, the data point which represents the largest distance $\mathbf{L_2}$ is substantially less negative than the predicted result. This is because the theoretical line assumes infinite friction whilst in actual fact for this reading the bike was skidding. Skidding implies the bike has a dynamic coefficient of friction, which is less than the static, so it will permit smaller decelerations.
- The next data point meets the predicted data point. This was an interesting reading, since when maximum braking force was applied with the front brake, the bike would start to skid and then tip as the geometry would change. (Due to suspension compression, tyre deformation etc.)
- After this the data points get progressively further from the theoretical prediction. This is because the acceleration sensor that was mounted on the bicycle was reading positive accelerations that occurred when the bike was moving forwards, though when tip-over begins, the orientation of the sensor is no longer 180° or flat. This implies that it is going to start recording a percentage of the component of the acceleration due to gravity.

The following diagram illustrates this concept.

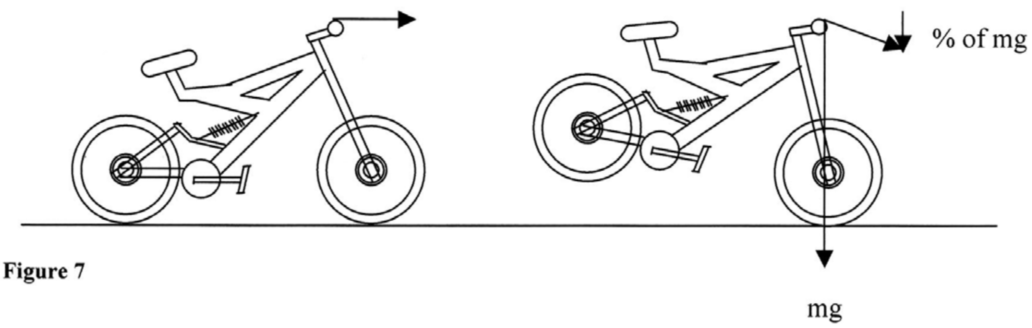


Figure 7

This implies that for all the readings where the bike starts to tip-over the average acceleration will be including part of the acceleration due to gravity. **This is a systematic error and thus will shift all the values to be more negative than the supposed prediction.**

- However why is this **systematic error not consistent** throughout all the data points? Despite releasing the brake as soon as tip-over began, for readings where the Centre of mass was closer to the front wheel it becomes **increasingly harder to control how much the rear wheel lifts off the ground**. This implies it will tip more before I can react and thus will record a greater % of the acceleration due to gravity. This justifies the experimental data which shows that the readings get further and further from the theoretical prediction.

14

Tip-Over On Slopes Hypothesis

I will now investigate how the tip-over deceleration is affected by the ground gradient, using θ as the angle of the ground in degrees.

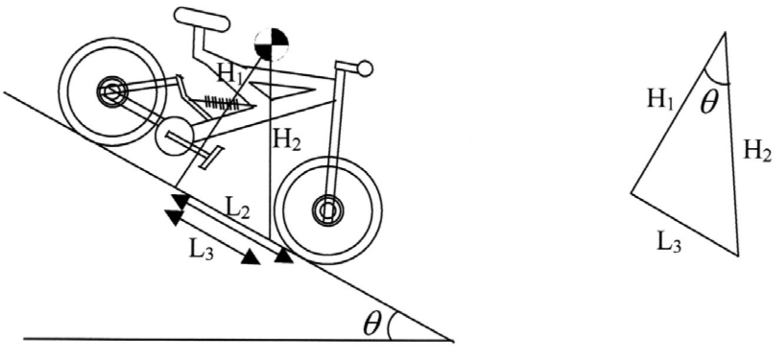


Figure 8

Therefore based on this model I can derive the following:

$$Tan(\theta) = \frac{L_3}{H_1}$$

Therefore $H_1 \cdot Tan(\theta) = L_3$

Taking moments about the front contact point of the bike with the ground again I get the following:

$$f_{cw} = maH_1$$

This is from previous investigation where braking Force = ma, where a is the deceleration from braking.

$f_{ccw} = mg(L_2 - L_3)$ where mg is the weight and $L_2 - L_3$ is the perpendicular distance to the line of action

Therefore since $f_{cw} = f_{ccw}$, $mg(L_2 - L_3) = maH_1$

Since $H_1 \cdot Tan(\theta) = L_3$ then: $mg(L_2 - H_1 Tan(\theta)) = maH_1$

Expanding gives: $mgL_2 - mgH_1 Tan(\theta) = maH_1$

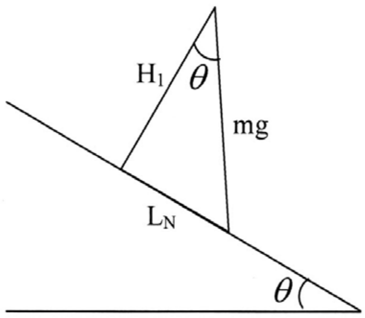
The mass now cancels down leaving: $gL_2 - gH_1 Tan(\theta) = AH_1$

15

Dividing by H_1 gives: $\dfrac{gL_2 - gH_1 Tan(\theta)}{H_1} = A$

This simplifies to $g\left(\dfrac{L_2}{H_1} - Tan(\theta)\right) = A$

Another important aspect to mention is that it is possible to calculate at what point the bicycle can travel at a constant speed, and the point past which the bicycle will not necessarily tip over, but won't be able to cancel the component of acceleration due to gravity.
This is possible by considering the acceleration due to gravity. On a slope, this will be equal to the following:



L_N represents the force accelerating the bike down the slope due to the acceleration from gravity. In order to calculate this I simply use trigonometry and know that

$Sin(\theta) = \dfrac{L_N}{mg}$ and therefore $mgSin(\theta) = L_N$

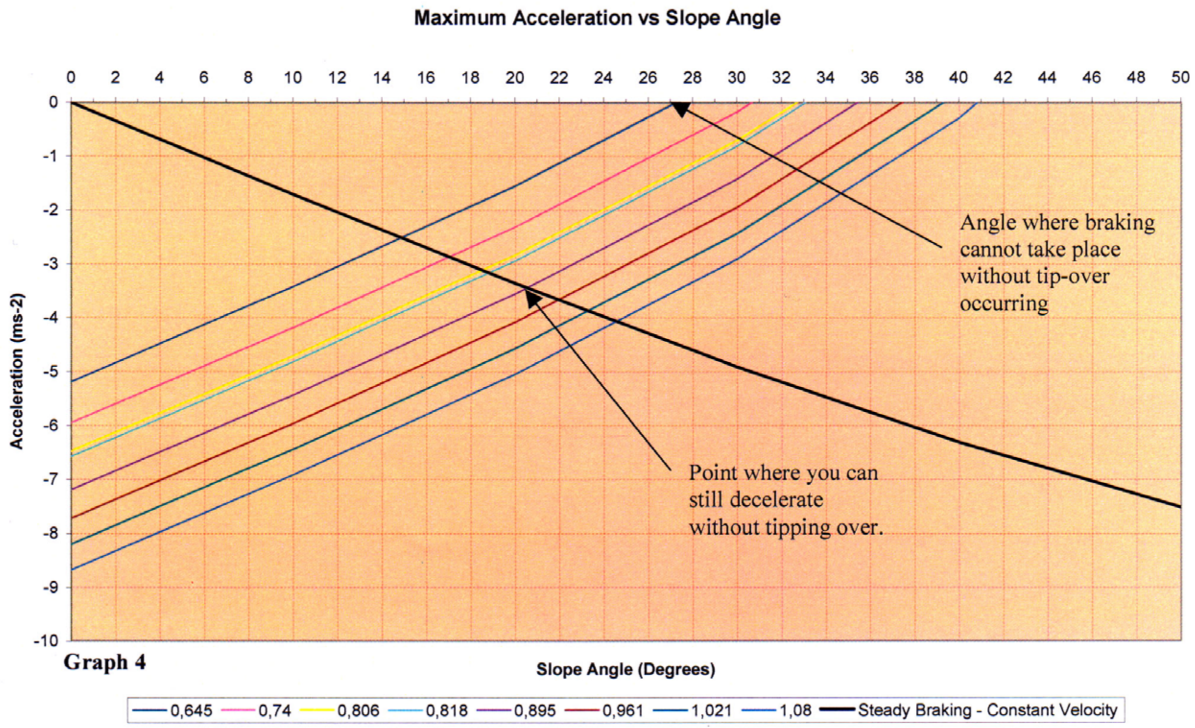
Figure 9

Thus a braking force when the bike is travelling on a slope θ at a constant velocity will be equal to $mgSin(\theta)$, and the acceleration will be $gSin(\theta)$.

Therefore if I plot this acceleration on a graph, against the deceleration by braking it will give me the point where the bike travel at a constant speed without tipping. It will also show the acceleration the bike must have in order to not tip at greater angles.
I have included different weight distributions on the same graph in order to aid comparison. Each coloured line represents a different weight distribution. The key shows the distributions as "distance from Front L_2 (m)".

Values Plotted are as follows:	**Value**
H_1	1.25m ± 19.48%
L_2	Weight distribution from front (variable) ± 6.37%
g	$9.81ms^{-2}$
θ	The slope angle (variable)

16



Graph 4 *distance from front L_2 (m) (uncertainties not shown)*

Interpretation of the Graph

This graph however was slightly controversial to reality given that from personal experience I know for a fact that it is possible to travel down terrain with a ground gradient of over 50° without tipping over. One factor contributing to this graph not being truly representative of real life situations is that the centre of mass for the rear most position is in actual fact a lot lower due to the parabolic shape of the riders' centre of mass – described previously. A lower centre of mass implies a greater deceleration before tip-over, and also a greater ground gradient before natural tip-over. Also, the reason tip-over occurs is because of the reaction force about the front wheel (mainly) that is making it rotate and tip. However, as the ground angle increases, this reaction force decreases allowing for steeper slopes to be tackled without tip-over.

Conclusion – Including 'Areas for Further Research'

Given the constraints imposed by this essay, several areas cannot be fully explored. Areas which deserve attention and which would be interesting to investigate include:

1. Investigating the frictional forces…:
   - On wet surfaces
   - In mud
2. Different types of bikes[V] with different combined centres of mass, and how this would affect the results.
3. Determining this reaction force in relation to the ground angle.

Improvements could have been achieved by:

[V] Such as XC, BMX, road etc. (see Definitions)

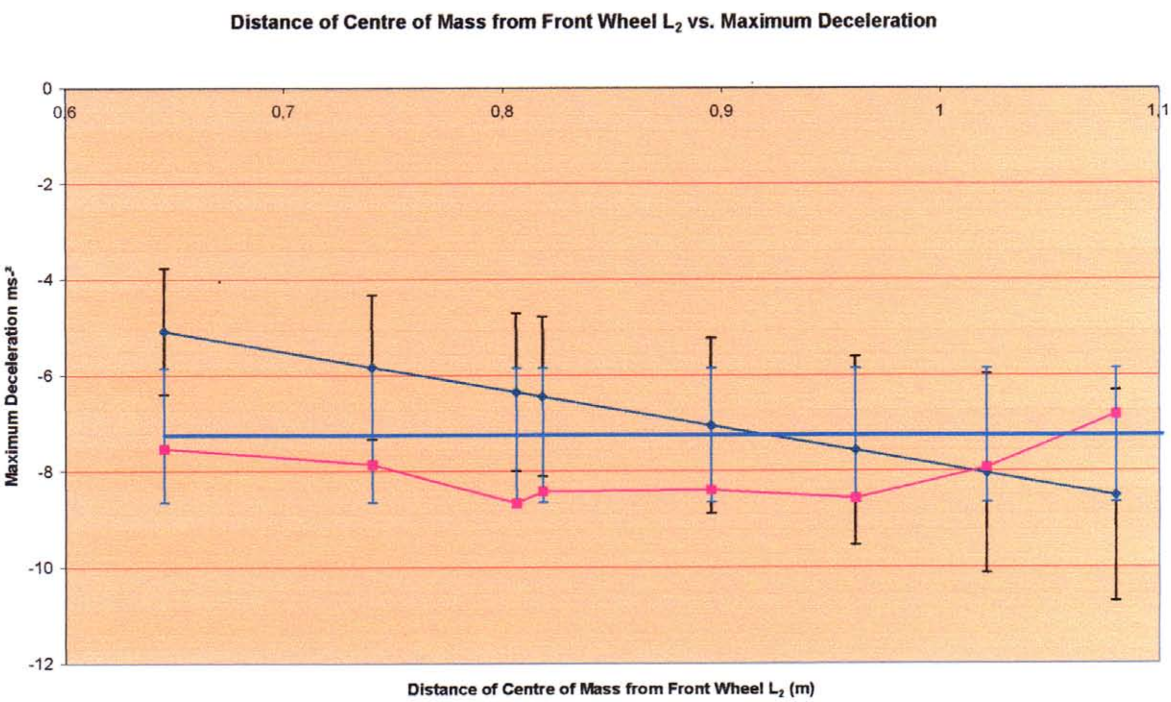
17

1. Using a method that is effective to find the vertical positioning of the combined centre of mass for different weight distributions, such as a functioning version of that proposed in Appendix I. This would reduce the rather significant uncertainty present in the height of the centre of mass (which was not included in the processing of uncertainties since it was so hard to quantify).
2. Finding the coefficient of friction by experiment to reduce the uncertainty. This could have been achieved by using a Newton meter to pull a wheel along the ground (tarmac). Given the mass of the wheel it would then be possible to calculate the coefficient of static friction by recording the force required for the tyre to 'skid' on the ground (not rotate). Using $f_{fr} = u_s f_n$, given that I would know the normal force and the force of friction (meter reading) I could find the coefficient.
3. Using a greater range of different weight distributions and recording more attempts for each weight distribution would also reduce the uncertainty.

Through experimentation I have found that there is a **definite correlation** between weight distribution and maximum deceleration. The limitations for braking however are:

- Coefficient of static friction that allows the bike to skid
- Tip-over

By looking at the graph below with the limitation due to static friction illustrated (blue line) it is possible to find a conclusion regarding the optimum braking position:



18

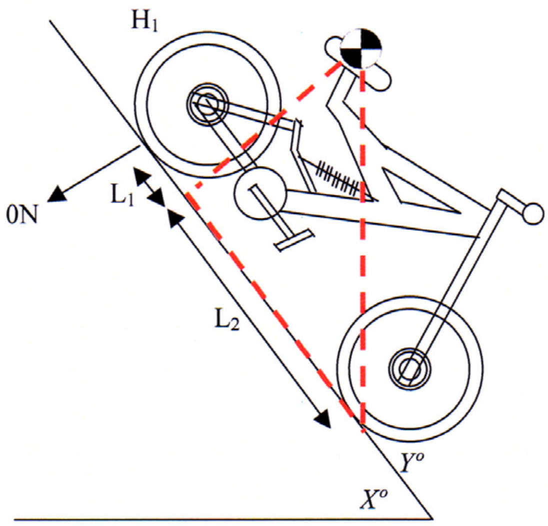
1. One data point differs from the others by lying above the blue line. This is because this limit is for all the weight of the bike being used as the normal force, but for this reading the bike didn't even begin to tip, thus a great deal of weight was about the rear wheel and the normal force was not being exploited for decelerating – this made the bike skid at a lower deceleration.
2. The fact that most experimental data points lie below the line is due to:
   a) the uncertainty in the static friction limit
   b) the uncertainty in the collected data which is not quantified (hard to set an uncertainty given all the problems with the graph such as noise)

Given the uncertainties in the experiments, from what is available for interpretation the maximum deceleration appears to be attainable at a weight distribution where the centre of mass is approximately between 1.02m and 0.96m from the front wheel contact point. Though 0,96m appears to yield a greater deceleration this could be because of the significant amount it would tip-over and thus could include a component of 'g'. On the other hand, for 1,02m the bike would barely tip since it would decelerate enough by skidding to only tip a small amount before the brake was released – and thus could be a more accurate reading for the maximum deceleration attainable.

Appendix I - Method for calculating Centre of Mass

The centre of mass always acts directly down, and the centre of mass when an object is at rest is always in the same place. Having said that, once the centre of mass is in front of the front most contact point of the object, in this particular case the point where the front wheel contacts with the ground the bike will inevitably flip forwards, even at rest.

Theoretically the following is true:



Y = 90-X

$Y^\circ = 90^\circ - X^\circ$

Therefore if I know X from experimentation, I can find Y.

Figure 10

Based on this, I can calculate the height H_1 of the Centre of Mass.

$$x + y = 90$$

Given that $Tan(y) = \frac{H_1}{L_2}$

$$Tan(90 - x) = \frac{H_1}{L_2}$$

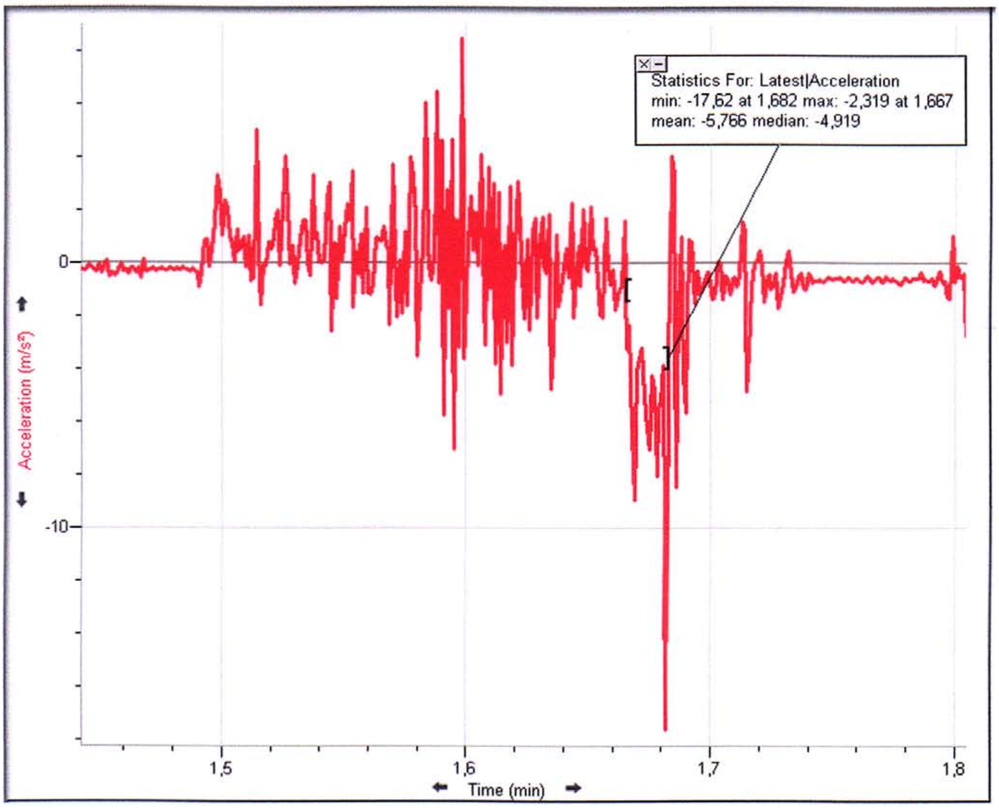
Therefore $L_2 Tan(90 - x) = H_1$

By finding the angle X where the bike tips over it will be possible to determine the perpendicular height H_1.

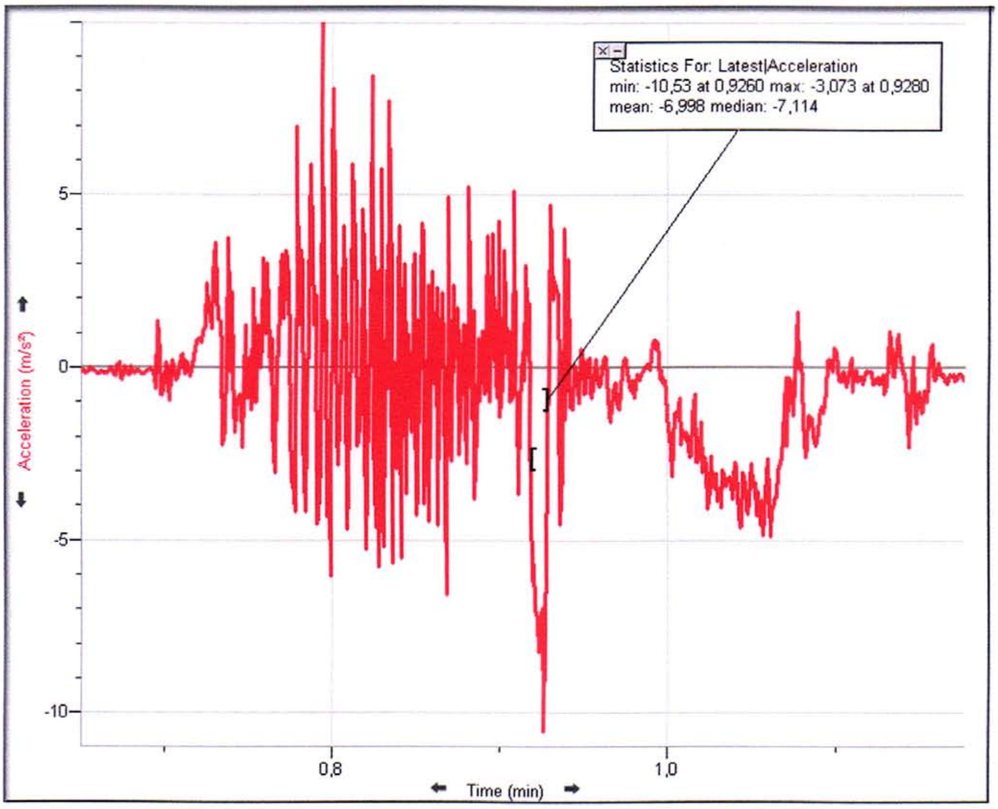
[This method was not used however due to complications which arose related to constructing a support that would allow this experiment to be conducted without the bicycle slipping down the slope first]

Appendix II – Acceleration/Time Graphs

Weight Distribution

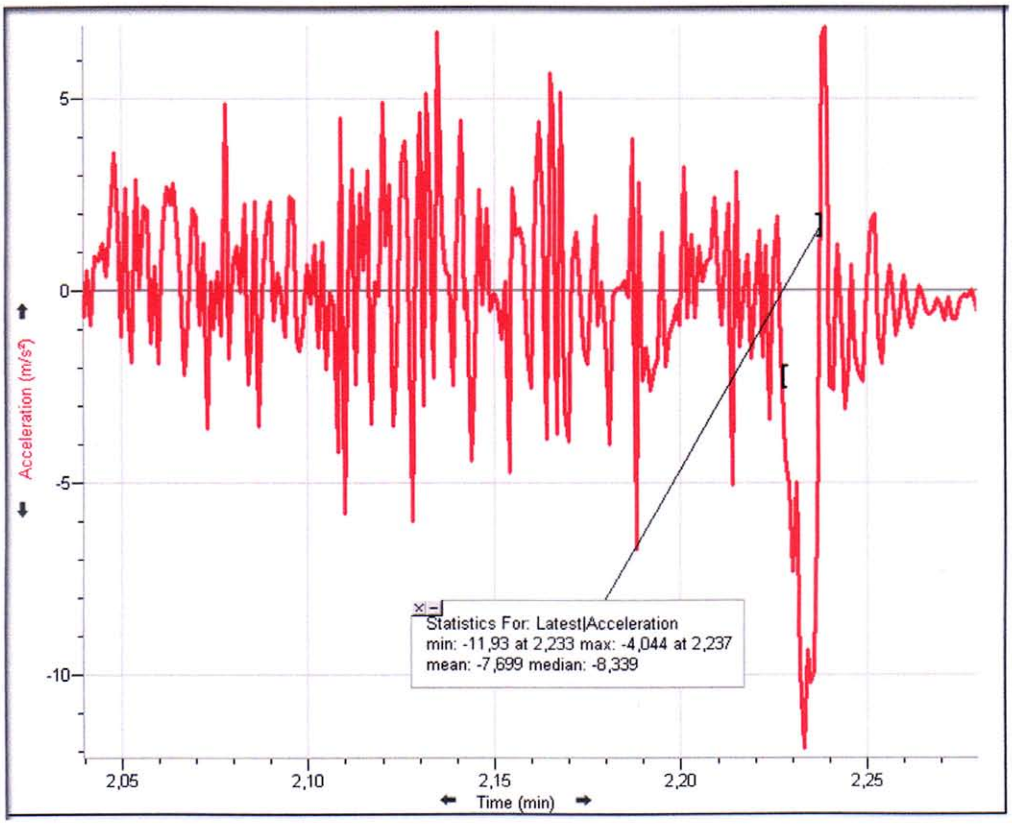


1.080m



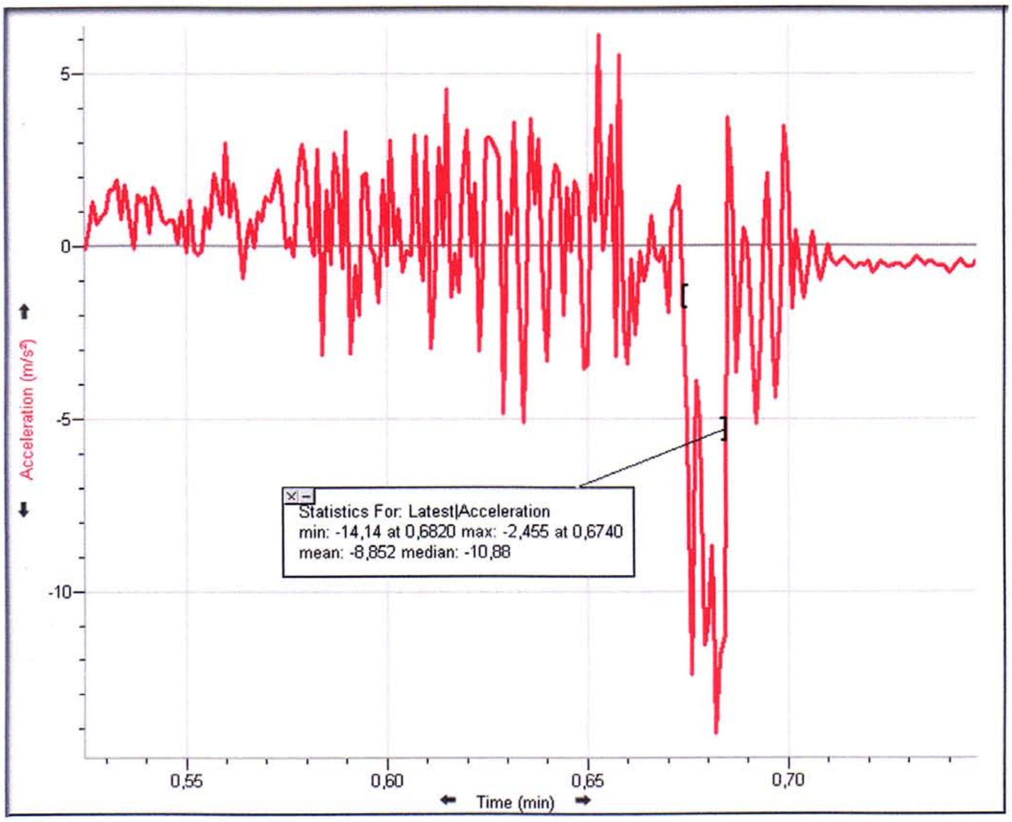
1.080m

21



Weight Distribution

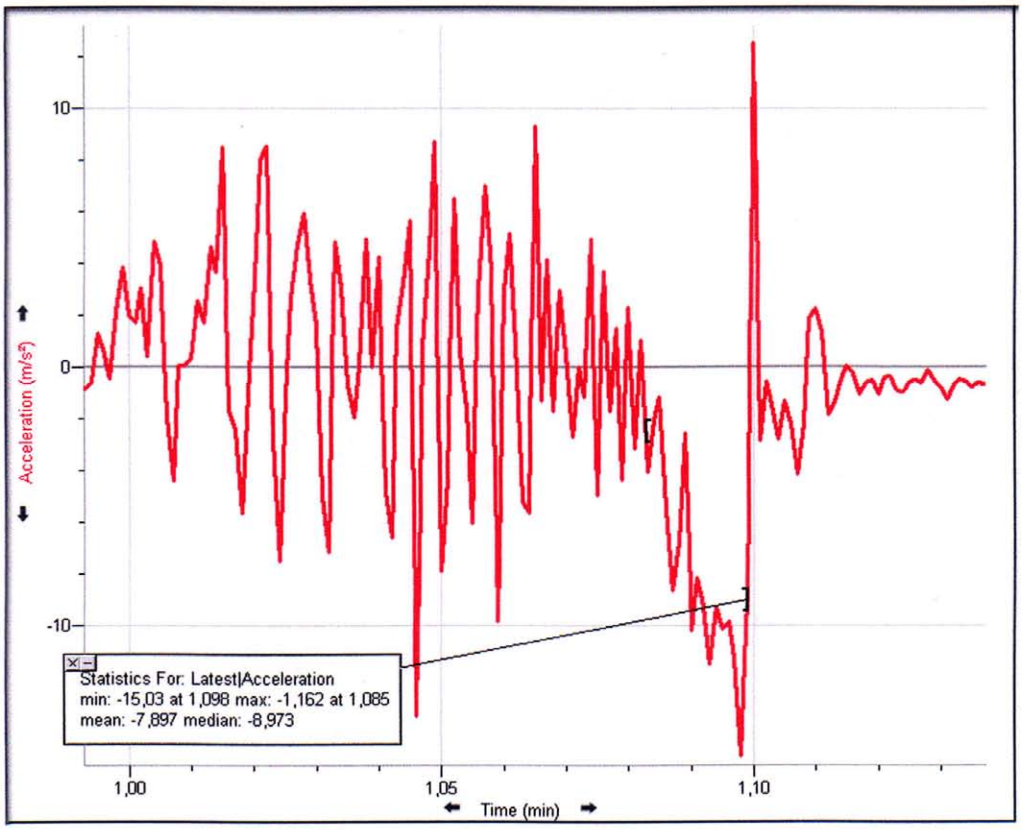
1.080m

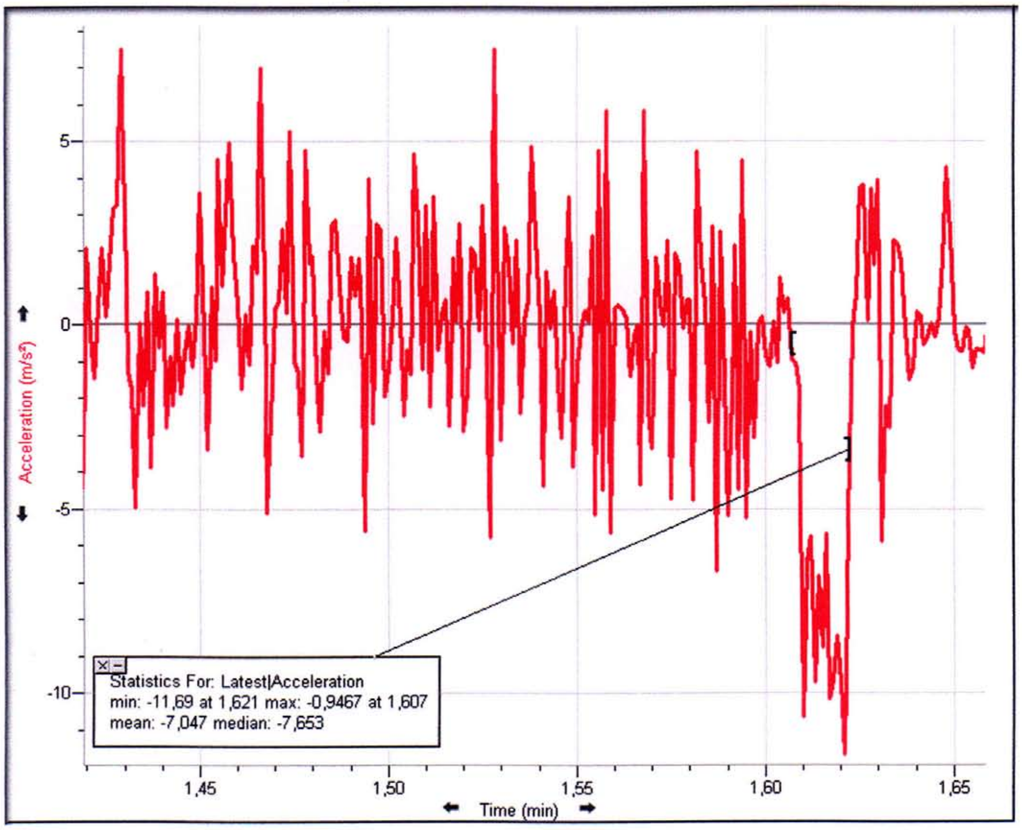


1.021m

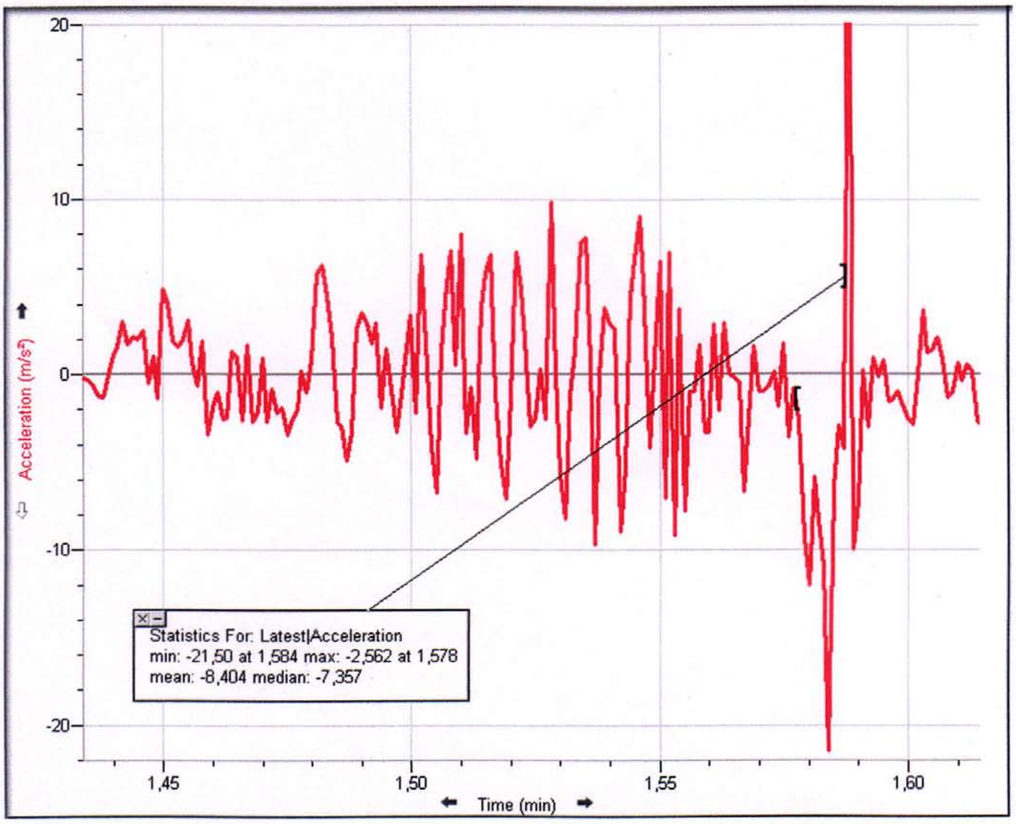
22

Weight Distribution

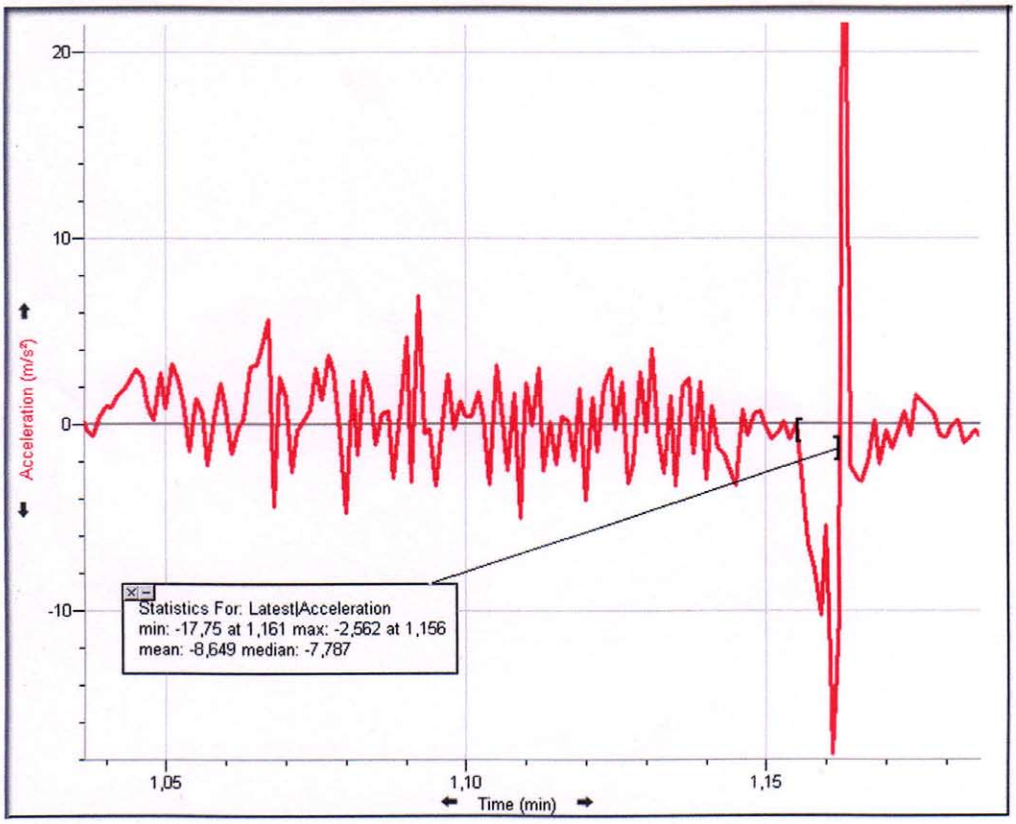




23

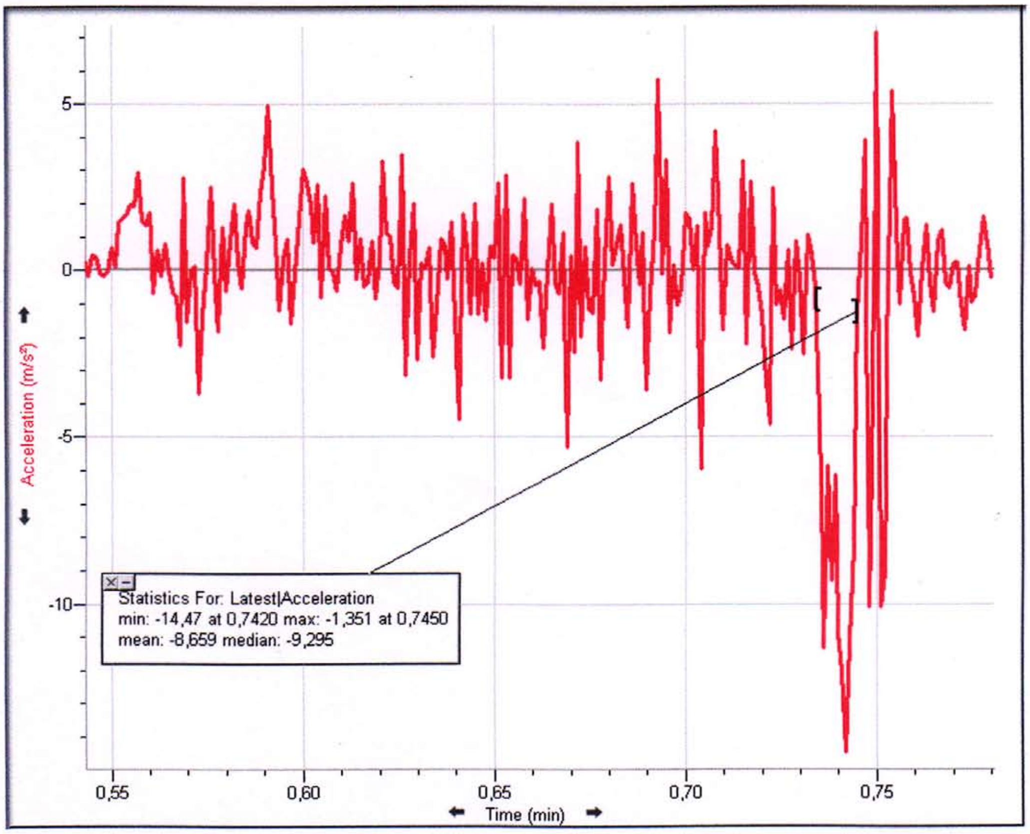

Acceleration (m/s²)
Time (min)
20
10
0
-10
-20
1,45
1,50
1,55
1,60
Statistics For: Latest|Acceleration
min: -21,50 at 1,584 max: -2,562 at 1,578
mean: -8,404 median: -7,357


Weight
Distribution
0.961m
0.961m

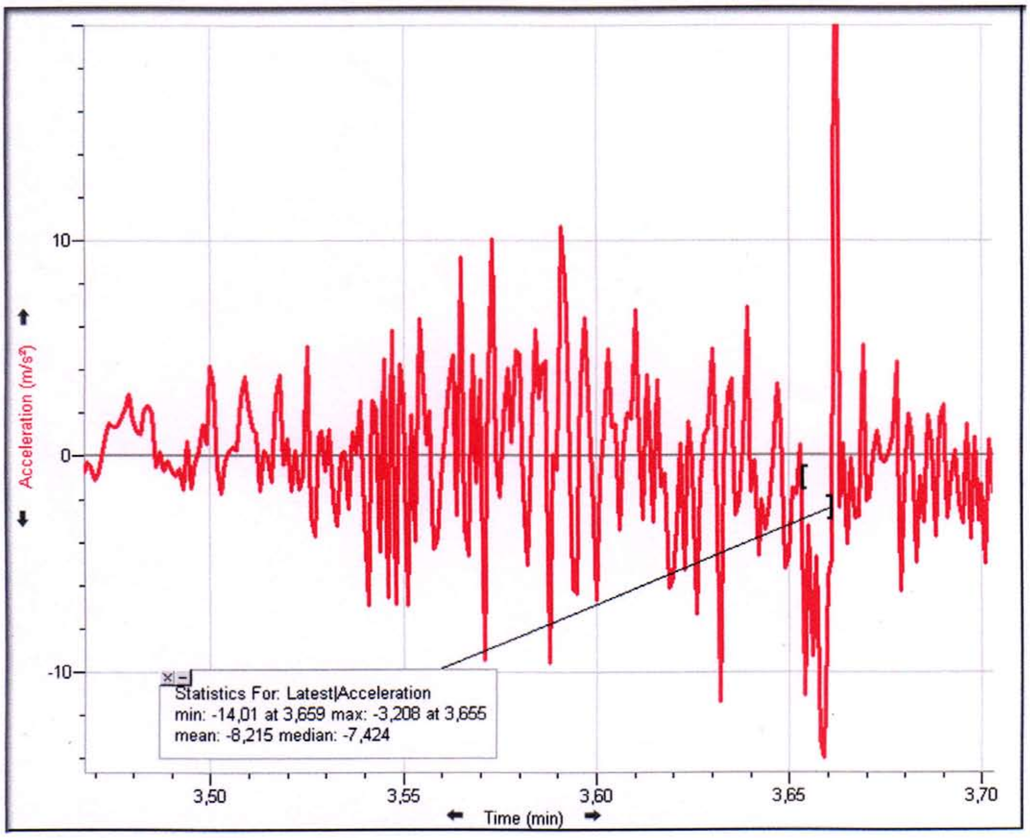

Acceleration (m/s²)
Time (min)
20
10
0
-10
1,05
1,10
1,15
Statistics For: Latest|Acceleration
min: -17,75 at 1,161 max: -2,562 at 1,156
mean: -8,649 median: -7,787

24

Weight Distribution

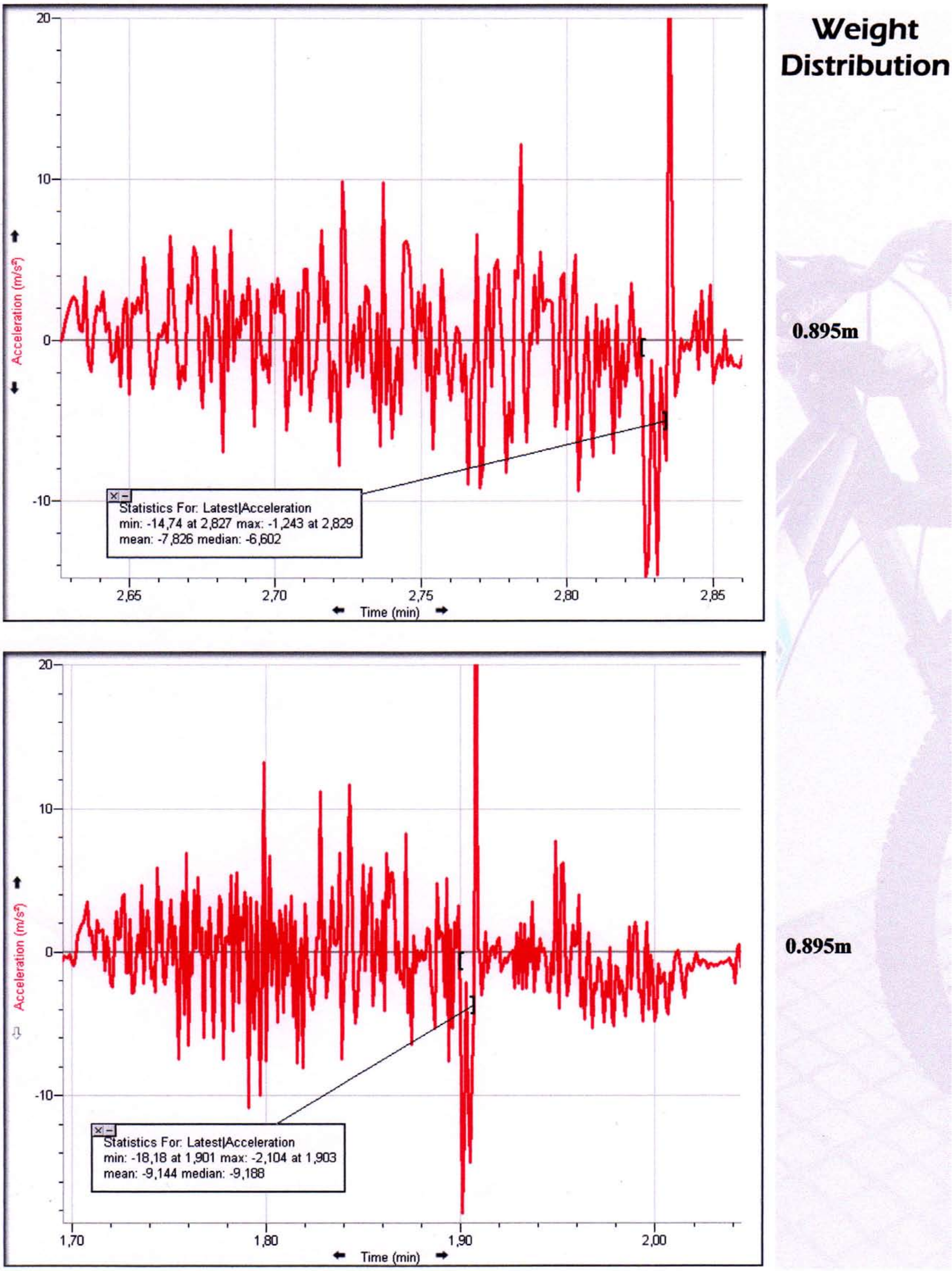


0.961m



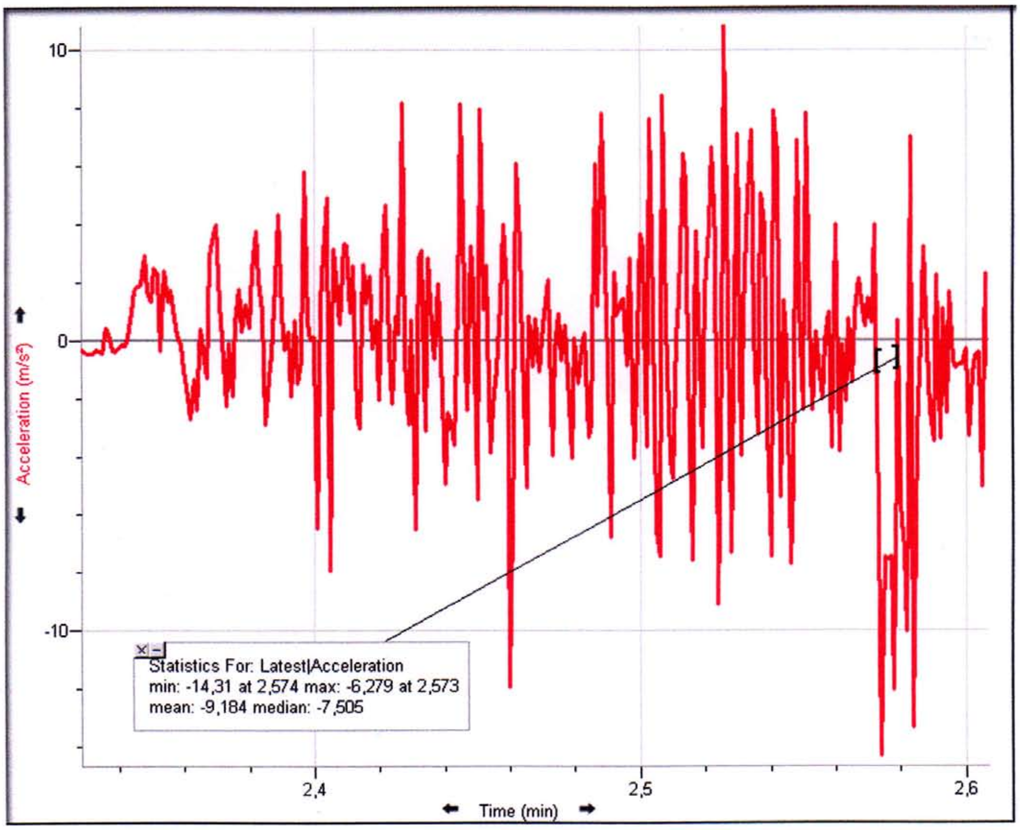
0.895m

25

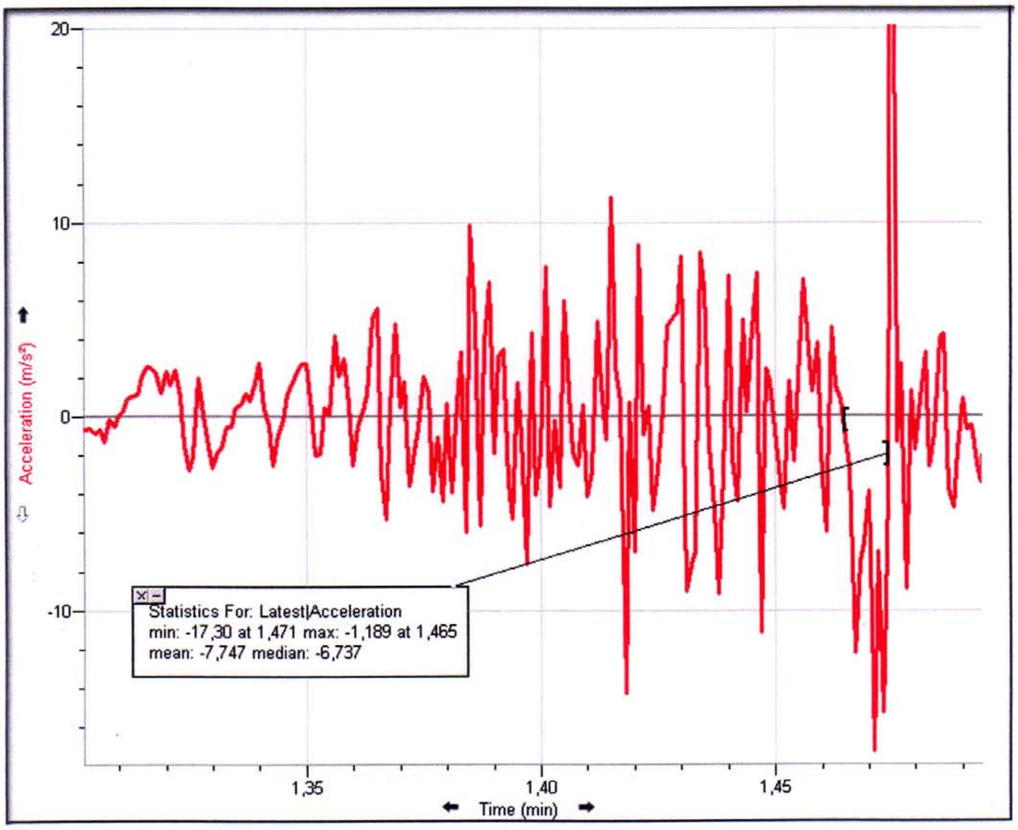

Weight Distribution
0.895m
Statistics For: Latest|Acceleration
min: -14,74 at 2,827 max: -1,243 at 2,829
mean: -7,826 median: -6,602
Acceleration (m/s²)
Time (min)
20
10
0
-10
2,65
2,70
2,75
2,80
2,85
0.895m
Statistics For: Latest|Acceleration
min: -18,18 at 1,901 max: -2,104 at 1,903
mean: -9,144 median: -9,188
Acceleration (m/s²)
Time (min)
20
10
0
-10
1,70
1,80
1,90
2,00

26

Weight Distribution



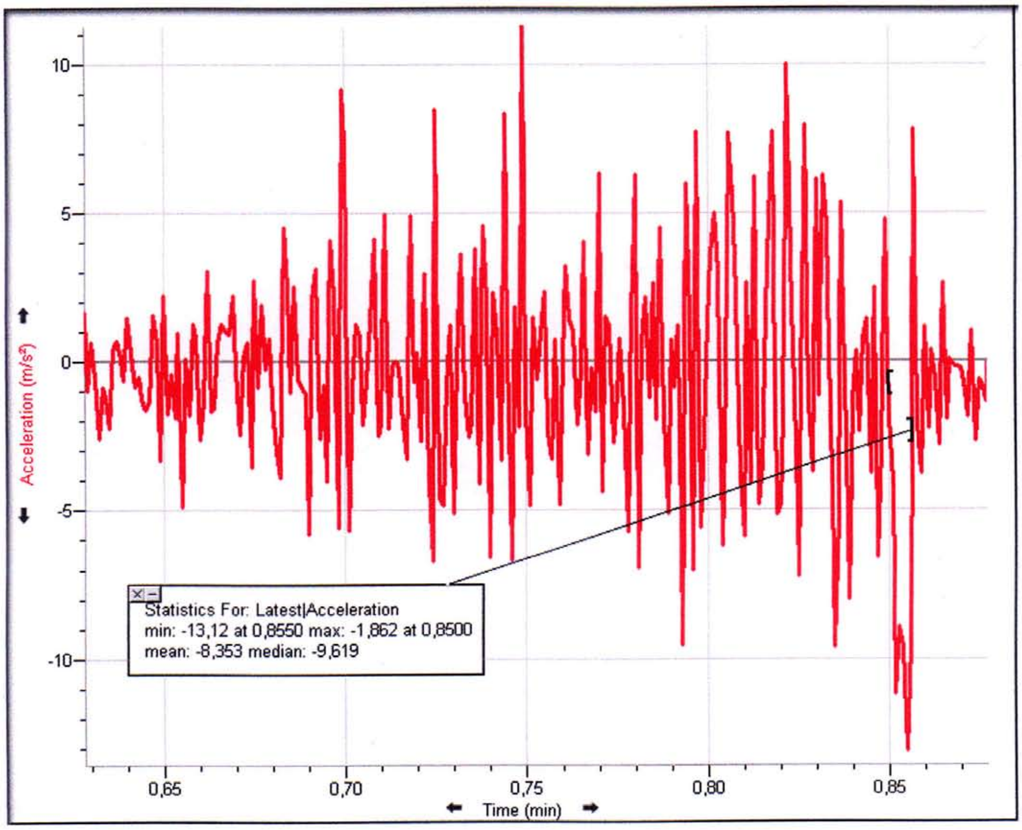
0.818m



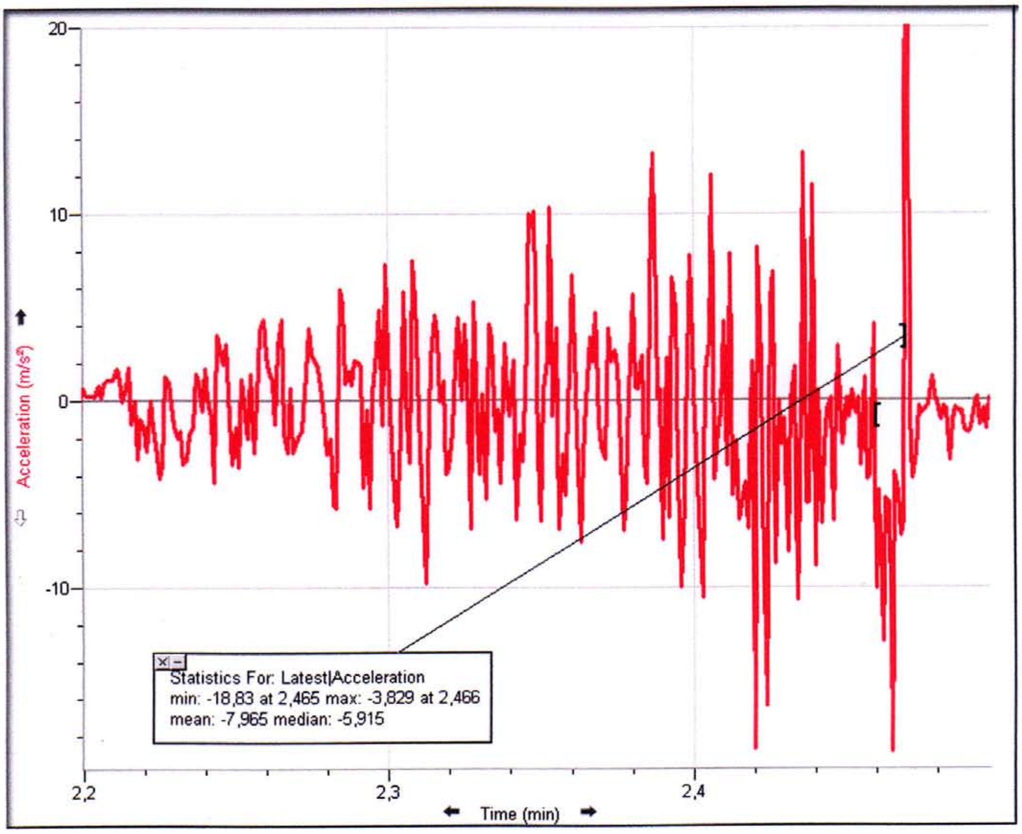
0.818m

27

Weight Distribution



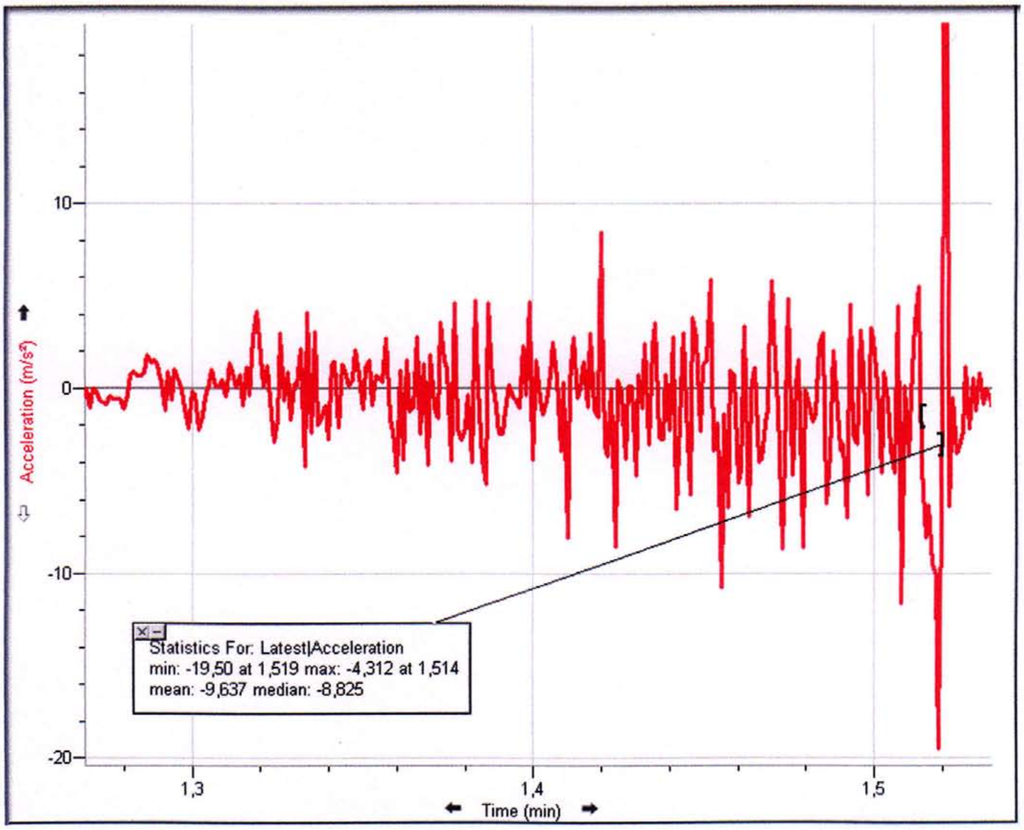
0.818m



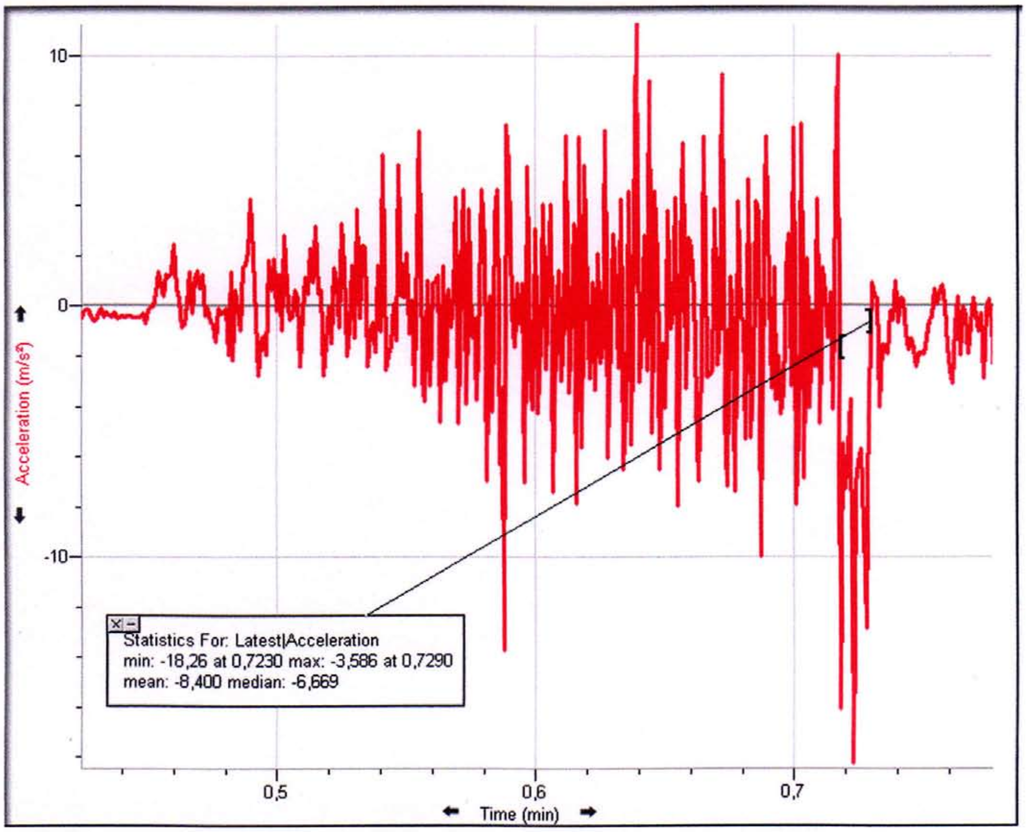
0.806m

28

Weight Distribution

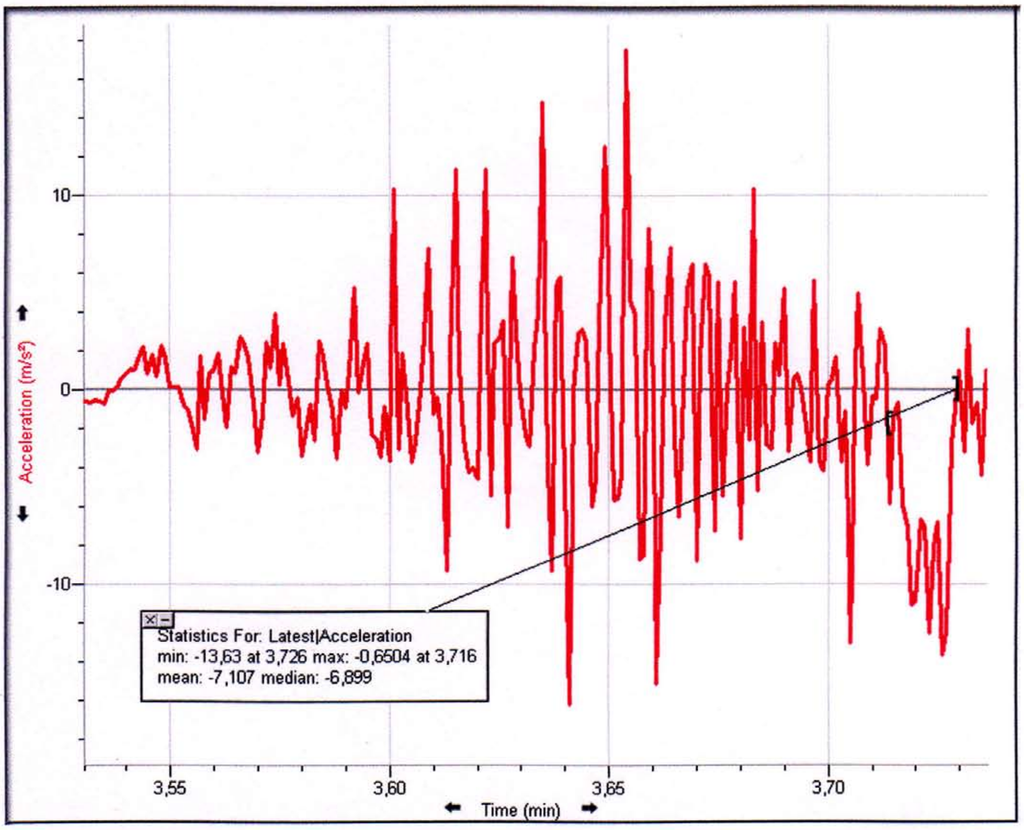


0.806m

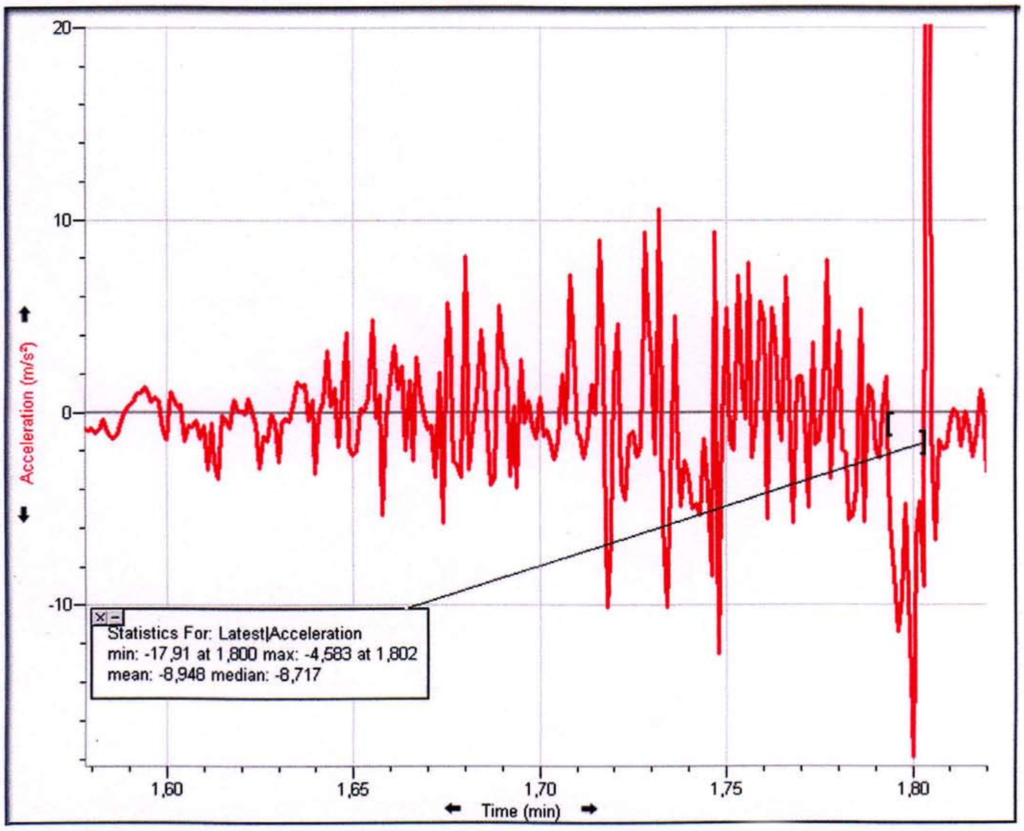


0.806m

29

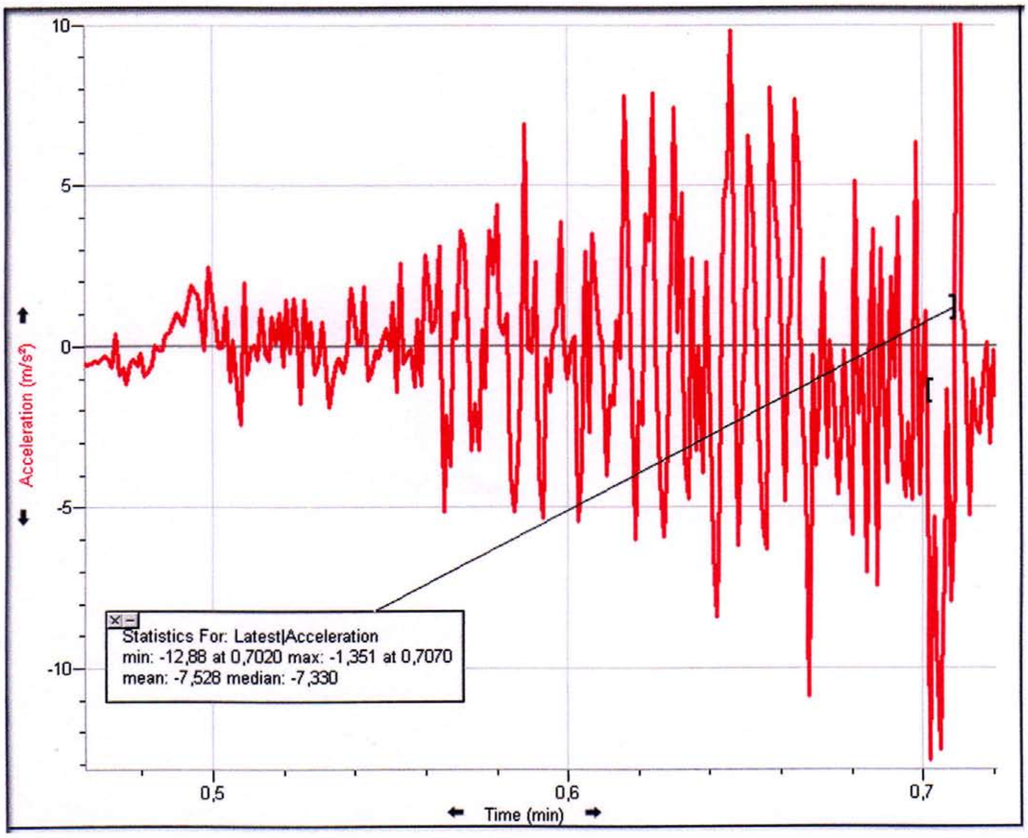

Statistics For: Latest|Acceleration
min: -13,63 at 3,726 max: -0,6504 at 3,716
mean: -7,107 median: -6,899
Acceleration (m/s²)
Time (min)
3,55
3,60
3,65
3,70
10
0
-10


Weight Distribution
0.740m
0.740m

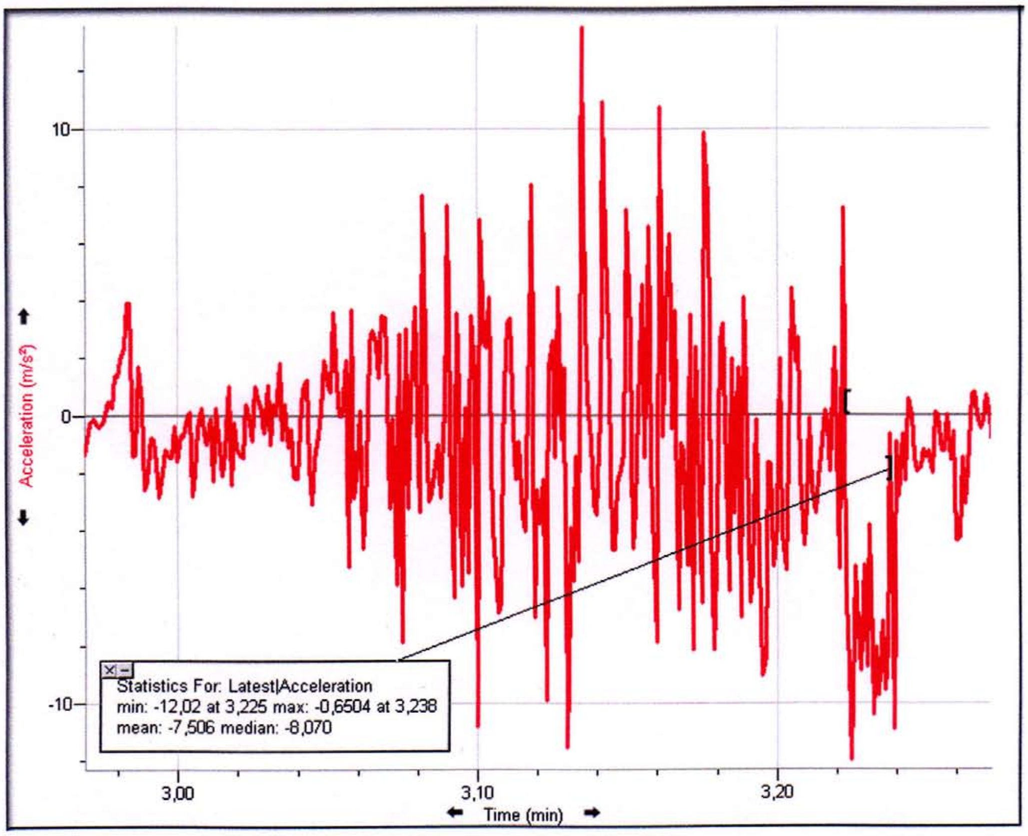

Statistics For: Latest|Acceleration
min: -17,91 at 1,800 max: -4,583 at 1,802
mean: -8,948 median: -8,717
Acceleration (m/s²)
Time (min)
1,60
1,65
1,70
1,75
1,80
20
10
0
-10

30

Weight Distribution

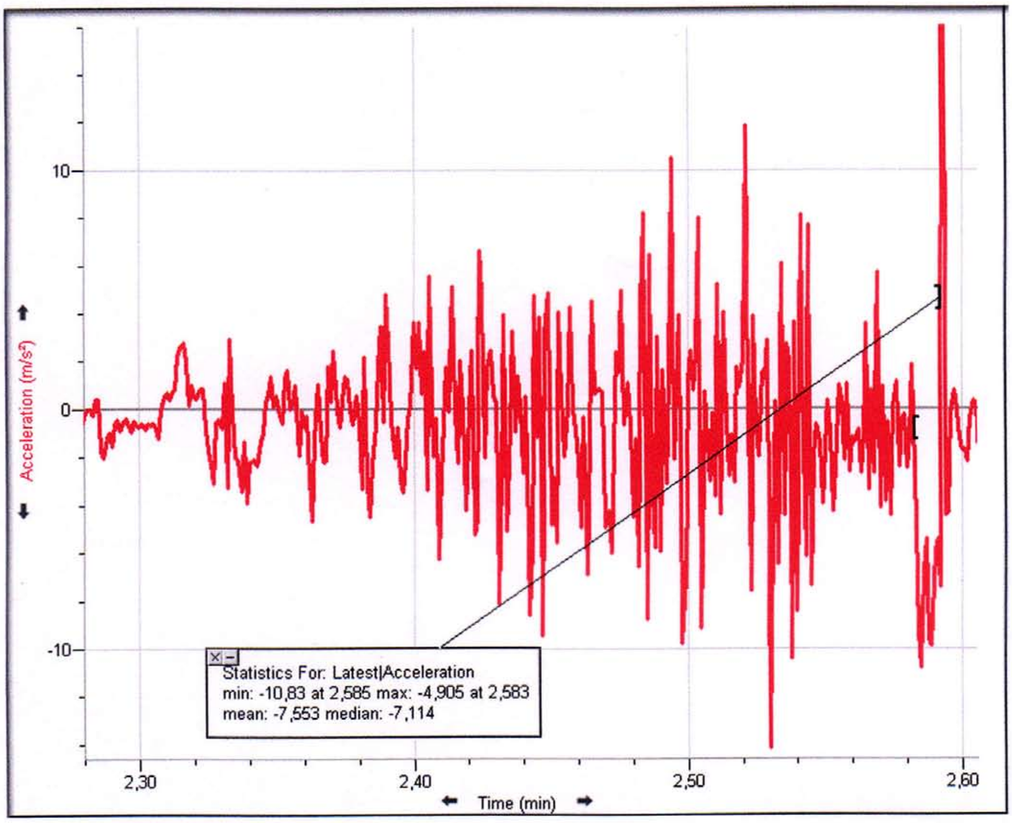


0.740m

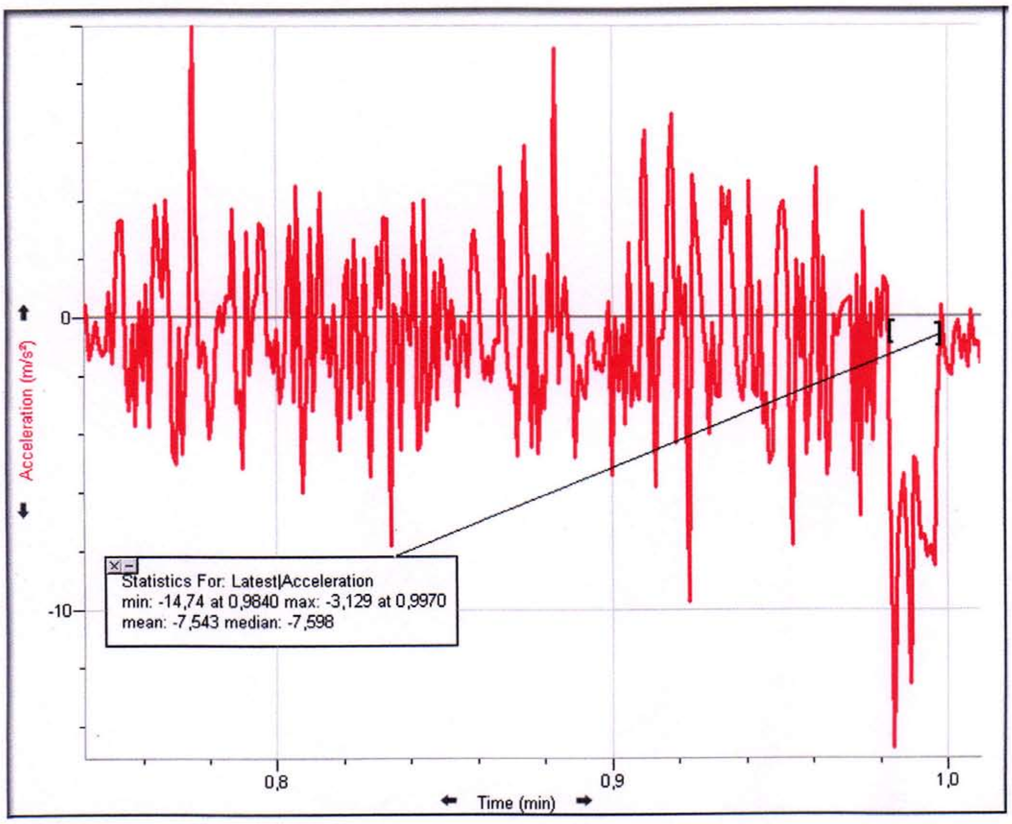


0.645m

31


10
0
-10
Acceleration (m/s²)
Statistics For: Latest|Acceleration
min: -10,83 at 2,585 max: -4,905 at 2,583
mean: -7,553 median: -7,114
2,30
2,40
2,50
2,60
Time (min)

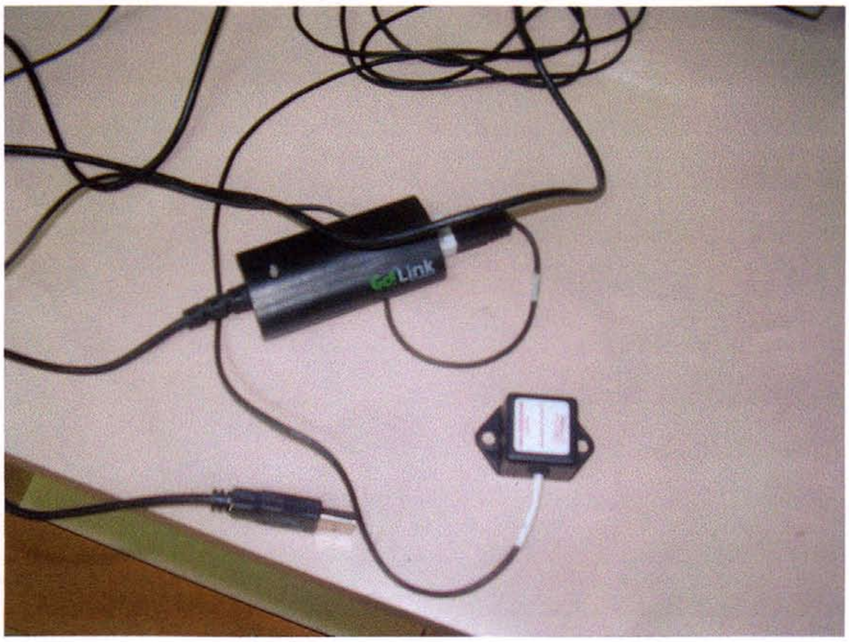

Weight Distribution
0.645m
0.645m


0
-10
Acceleration (m/s²)
Statistics For: Latest|Acceleration
min: -14,74 at 0,9840 max: -3,129 at 0,9970
mean: -7,543 median: -7,598
0,8
0,9
1,0
Time (min)

32

Appendix III – Photographs of the Experiments

Finding the centre of mass of the bicycle by hanging it from 3 points and drawing lines.



The hardware used to measure the accelerations when braking on the bicycle. The small sensor would be mounted on the handlebar, whilst the rest would be in the backpack.

Appendix IV - Figures/Graphs/Tables Explained

	Explanation
Figure 1	Diagram of bicycle showing frictional forces acting upon it on both points of contact.
Figure 2	Diagram of bicycle showing forces acting upon it and the positioning of the combined centre of mass.
Figure 3	Apparatus diagram of experiment to measure weight on each wheel at different weight distributions in order to subsequently find the horizontal positioning of the centre of mass.
Figure 4	Apparatus diagram of experiment to measure weight distribution on each extremity of the human body in order to find an approximation of the location of the centre of mass for the rider.
Figure 5	Diagram illustrating the parabolic motion of the centre of mass through different weight distributions.
Figure 6	Diagram illustrating individual centre of masses and subsequently showing how this leads to a calculation for the combined centre of mass.
Figure 7	Apparatus diagram of experiment to measure maximum deceleration at various weight distributions.
Figure 8	Diagram to illustrate how the uncertainty in tip-over decelerations arises due to the acceleration due to gravity as the bike starts to tip.
Figure 9	Diagram to illustrate situation for tip-over on slopes of varying gradients.
Figure 10	Simplified diagram of Figure 8 to aid in hypothesising via mathematical methods the maximum deceleration permitted at various ground gradients and the maximum ground angle before tip-over occurs independently of braking.
Figure 11	Alternative method for calculating the height of the centre of mass, which theoretically would allow this to be calculated for various weight distributions. (This was NOT done however – and this method was therefore not used)
Graph 1	Graph showing theoretical maximum decelerations for different weight distributions, assuming infinite static friction when braking.
Graph 2	Sample graph to show graphs generated by the acceleration monitoring software and how these will be interpreted to generate the relevant data.
Graph 3	Graph comparing theoretical maximum decelerations assuming infinite friction with the average of the three attempts for each weight distribution of the actual experimental maximum decelerations obtained via data collection.
Graph 4	Graph illustrating different weight distributions (each coloured line) with maximum slope angle vs. maximum deceleration achievable before tip-over. It also compares this line with the black line representing the point where the bike will not tip-over but deceleration is still possible.
Graph 5	This graph shows the maximum deceleration permitted by the frictional force acting on the bike together with graph 3.
Table 1	Data collection for how the weight is distributed between the two wheels of a bicycle for different rider weight distributions.
Table 2	Table 1 data processed to show forces and the distance of the centre of mass from the rear wheel (first as a percentage of the total wheel base and then as a value in 'm')
Table 3	Theoretical calculations for the maximum deceleration possible assuming infinite friction.
Table 4	Data collection for experiment to measure maximum deceleration achievable on a Freeride bicycle. This value represents an average of the deceleration period on the graph in order to reduce uncertainty due to noise and spikes.

34

Bibliography

Note on the sources:

The sources presented below were used for theoretical knowledge, and given the nature of this essay for confirmation of conjectured ideas and calculations, and no content was copied or transcribed directly.

Sources:

- **TOPIC:** Coefficients of Friction
  PURPOSE: Finding a value for the coefficient of friction Concrete / Rubber
  AUTHOR: N/A
  PUBLISHER: N/A
  PAGE NUMBER: N/A
  WEBSITE/OTHERS:
  http://www.engineershandbook.com/Tables/frictioncoefficients.htm
  Last checked: 21:49 on 11/05/06

- **TOPIC:** Weight Transfer
  PURPOSE: General research into weight transfer in dynamic systems
  AUTHOR: N/A
  PUBLISHER: Wikipedia Online Encyclopaedia
  PAGE NUMBER: N/A
  WEBSITE/OTHERS: http://en.wikipedia.org/wiki/Weight_transfer
  Last checked: 21:50 on 11/05/06

- **TOPIC:** Load Transfer
  PURPOSE: General research into load transfer in dynamic systems
  AUTHOR: N/A
  PUBLISHER: Wikipedia Online Encyclopaedia
  PAGE NUMBER: N/A
  WEBSITE/OTHERS: http://en.wikipedia.org/wiki/Load_transfer
  Last checked: 21:50 on 11/05/06

- **TOPIC:** Tip-Over on Slopes Hypothesis
  PURPOSE: Research into tip-over on slopes
  AUTHOR: Frederick H. Matteson
  1874 Cushman Street
  Hollister, CA 95023-5525 USA
  Phone: 831-637-6598
  PUBLISHER: IHPVA (International Human Powered Vehicle Association)
  PAGE NUMBER: 6-8
  WEBSITE/OTHERS: Edition 51, Fall 2001

- **TOPIC:** Bicycle Brake Systems
  PURPOSE: General research into bicycle brake systems
  AUTHOR: N/A
  PUBLISHER: Wikipedia Online Encyclopaedia
  PAGE NUMBER: N/A
  WEBSITE/OTHERS: http://en.wikipedia.org/wiki/Bicycle_brake_systems
  Last checked: 21:52 on 11/05/06

Definitions

XC – Shorthand for cross-country bikes that are usually lightweight and have a higher combined centre of mass, since it is not likely to have to overcome steep descents or large obstacles etc.

BMX – A type of bicycle used for skateparks or street variants of cycling.

[I] **Freeride –** Freeride is considered to be an extreme variant of mountain biking, which consists mainly in the overcoming of obstacles, be they jumps or man-made constructions, commonly at high speeds, and on substantial downhill gradients.

[II] **Modulation** - To regulate by or adjust to a certain measure or proportion; soften; tone down.

[III] **Skid** – An unexpected or uncontrollable sliding on a smooth surface by something not rotating, esp. an oblique or wavering veering by a vehicle or its tires.

[IV] **Tip-over** – The point of tip-over is also known as an "endo" which is the act of lifting the rear wheel off the ground on a bicycle or motorbike by means of using the front brake.

[V] **Stem –** The piece on a bicycle which connects the handlebar to the frame or front suspension.

[VI] **Steering Tube** – Another name for the handlebar of a bicycle which is used to steer whilst riding.