Investigating the Effects of Pedaling Faster and Gear Changing of a Bicycle

I. Introduction

Bicycles have always been an excellent source of exercise and a method of transportation that does not produce harmful emissions. As someone who loves to ride their bicycle for exercise and recreational purposes, the ability to increase the speed of the bicycle by simply changing the gears amazes me. This ability allows the bicycle to travel uphill, but to also terrain over grass, dirt, and pavement. Anyone who has ridden a bicycle would observe the difference in pedalling resistance with the gear they are pedalling at. Additionally, one would also observe the change in speed with the rate at which they are pedalling. These observations made while riding my bicycle on numerous recreational trails have enlightened me to find a definitive answer:

Research Question: How does changing the pedalling frequency and gears of a bicycle affect its constant speed?

To answer my research question, I will be using my bicycle and my driveway to conduct my experiment. I decided to use a start and finish line as a set distance to avoid the hassle and inaccuracy of using a bicycle tracker app which I would normally use on my bike rides. Additionally, I will be using my phone to video record straight down toward the ground to determine the time taken for the bicycle to travel the set constant distance.

II. Hypothesis

I hypothesize that as the frequency of pedalling increases, the bicycle wheels would rotate at a greater speed thus covering the same distance in less time resulting in a faster velocity. Since a higher pedalling frequency would result in a faster speed, I hypothesize that this relationship is linear. Additionally, as changing the gears affects the effectiveness of each pedal on flat terrain, and ultimately the top speed of the bicycle, I hypothesize that this relationship will also be linear.

III. Variables

<u>Controlled Variables</u>

- The distance that the bicycle travels.
- The air pressure in the bicycle tires.
- The bicycle ensures constant mass, wheel diameter, and other properties.

<u>Dependent Variable</u>

- The time it takes for the bicycle to travel the set distance.

<u>Independent Variable</u>

- The pedalling frequency of the biker.

IV. Equipment and Materials

- Bicycle (helmet recommended)
- Device Capable of Video Recording (Smartphone)
- Measuring Tape
- Chalk (or equivalent to mark start and finish line)
- Clear and Flat Pavement (driveway, parking lot, etc.)
- Bicycle Phone Mount (alternative: zip-ties or string)

V. Procedure

<u>Setting up the Experiment</u>

1. Count the number of teeth on all the gears at the chain wheel (center) and cog (rear) of the bicycle. Record these numbers as they will be required to calculate the gear ratio later.
2. Using the chalk, mark a start and finish line in a straight orientation on the pavement. Ensure that the pavement is clear of any obstacles such as twigs and that there is sufficient space for acceleration and breaking at the start and end points.
3. Measure the distance between the start and finish lines with the measuring tape. Record this distance.
4. Mount the phone onto the bicycle with the phone mount ensuring that it is facing downwards, towards the pavement. If you are using string or zip ties, a criss-cross “X” tying method is recommended. A cushioning object (i.e., Styrofoam, foam) may be used to absorb the shocks and vibrations exerted from the bicycle onto the phone. Ensure that the phone is sufficiently charged.
5. Pump both bicycle tires to the same PSI. Throughout the experiment, ensure that the air pressure in the bicycle tires is constant. This is to ensure that the circumference and traction of the wheels stay consistent.
6. Ensure that the bicycle brakes, chain, and gear shift are functional. Wearing a helmet is recommended for your safety.

<u>Conducting the Experiment</u>

1. Beginning behind the start line (3-5 meters), set your gears and determine the pedalling rate that you will be pedalling at. Record the gears set.
2. Start pedalling at a constant rate and begin video recording on the phone.
3. Once you cross the starting line, count the number of pedals (half a rotation) until the finish line. Record this number down.

4. Come to a stop after the finish line (not before to ensure constant velocity) and stop the video recording.
5. Review the video recording to determine the start and finish times. Record the times down.
6. Repeat steps one through five, varying the gears and pedalling speed. Ideally, use three different pedalling rates (slow, medium, fast) per gear ratio with five different gear ratios for a total of 15 trials.

VI. Raw Data

Qualitative:

Table 1: Qualitative Observations

Observations	Description
Pedals	When going at a faster pedalling rate, the number of pedal cycles was sometimes higher by 1 compared to the other trials of the same gear configuration.
Acceleration	When using a gear configuration capable of travelling at a higher maximum speed, the time and space needed to accelerate to the desired pedalling frequency were greater.

Quantitative:

Constant Variables

Bicycle Tire Pressure: 35 PSI   Distance: 18.80m ± 0.03   Wheel Diameter: 0.60m ± 0.01

Table 2: Raw Data Collected

Trial	Center Gear (chain wheel)	Rear Gear (cog)	Pedal Cycles	Start Time (s) ± 0.01	Finish Time (s) ± 0.01
1	1	6	11.0	4.53	10.13
2	1	6	11.0	3.03	6.54
3	1	6	11.0	4.31	13.12
4	1	3	15.0	4.50	14.08
5	1	3	15.0	4.14	10.29
6	1	3	16.0	3.40	7.52
7	2	5	10.0	3.23	9.28
8	2	5	10.0	5.03	12.11
9	2	5	10.0	5.06	9.05
10	3	1	13.0	4.27	11.28
11	3	1	13.0	3.31	8.48
12	3	1	13.0	4.25	7.47
13	3	5	7.0	3.50	10.27
14	3	5	7.0	4.05	9.30
15	3	5	7.5	5.00	8.35

Table 3: Number of Teeth per Gear Counted (Center and Rear Gears)

Center Gear (chain wheel)	Number of Teeth
1	28
2	38
3	48

Rear Gear (cog)	Number of Teeth
1	28
2	24
3	20
4	18
5	16
6	14

VII. Processed Data

<u>Calculating the Difference in Time (Δt)</u>

To calculate the time taken for the bicycle to travel the distance of 18.80m, the difference between the start and finish times is required by subtracting the finish time from the start time. Since my video recording was performed in 60 frames per second (FPS), I must find the difference in frames according to 60 rather than 100. Therefore, an extra calculation is required to convert the frames to seconds. This can be done by dividing the remaining frames by the number of frames per second, in my case, 60.

Finding the time difference (Δt) for Trial 1 in seconds:

$$\Delta t = 10.13s - 4.53s$$

$$\Delta t = 5.00s + \left[\frac{(0.13) + (0.60 - 0.53)}{0.60}\right]s$$

$$\Delta t = 5.33s$$

Finding the uncertainty in Δt:

Uncertainty for Δt = 0.01 + 0.01 = 0.02s

Therefore, for Trial 1:

$$\Delta t = 5.33\text{s} \pm 0.02$$

$$\Delta t = 5.33\text{s} \pm 0.4\%$$

Repeating the process above, the following data table is created.

Table 4: Processed Time Data

Trial	Δ Time (s) ± 0.02
1	5.33
2	3.85
3	8.68
4	9.30
5	6.25

Trial	Δ Time (s) ± 0.02
6	4.20
7	6.08
8	7.13
9	3.98
10	7.02

Trial	Δ Time (s) ± 0.02
11	5.28
12	3.37
13	6.62
14	5.42
15	3.58

Calculating the Speed of the Bicycle

Calculating the speed at which the bicycle was travelling during each trial is accomplished by dividing the total distance travelled by the time taken to travel said distance. As the recorded time taken for the bicycle to travel the set distance changes with each trial, the uncertainty would vary as a result. Thus, I will calculate the uncertainty for the mean value of time (Δt) from Table 4.

Finding the speed of the bicycle during Trial 1:

$$v = \frac{18.80\text{m}}{5.33\text{s}}$$

$$v = 3.53\text{ms}^{-1}$$

Finding the mean uncertainty in speed:

% Uncertainty for Speed = % Uncertainty in Distance + % Uncertainty in Time

$$\text{Uncertainty in Distance} = \frac{0.03\text{m}}{18.80\text{m}} \cdot 100\% = 0.2\%$$

$$\text{Uncertainty in Time} = \frac{0.02\text{s}}{\left(\frac{\text{Max} + \text{Min}}{2}\right)\text{s}} \cdot 100\% = \frac{0.02\text{s}}{\left(\frac{9.30\text{s} + 3.37\text{s}}{2}\right)} \cdot 100\% = 0.3\%$$

$$\text{Uncertainty for Speed} = 0.2\% + 0.3\% = 0.5\%$$

Therefore, for Trial 1:

$v = 3.53\text{ms}^{-1} \pm 0.5\%$

$v = 3.53\text{ms}^{-1} \pm 0.02$

Calculating the Pedaling Frequency

Calculating the pedalling frequency at which the biker pedalled during each trial is accomplished by dividing the total number of pedals during the trial by the time taken to travel the distance of 18.80m. To calculate the uncertainty, I will be using the same approach from earlier.

Finding the pedalling frequency for Trial 1:

$$\text{Pedaling Frequency} = \frac{11}{5.33\text{s}}$$

$$\text{Pedaling Frequency} = 2.1\text{Hz}$$

Finding the uncertainty in pedalling frequency:

% Uncertainty in Pedaling Frequency = % Uncertainty in Time + % Uncertainty in Pedaling

Uncertainty in Time = 0.3%

$$\text{Uncertainty in Pedaling} = \frac{0.5}{\left(\frac{\text{Max} + \text{Min}}{2}\right)} \cdot 100\% = \frac{0.5}{\left(\frac{16 + 7}{2}\right)} \cdot 100\% = 4.4\%$$

Uncertainty in Pedaling Frequency = 0.3% + 4.4% = 5%

Therefore, for Trial 1:

Pedaling Frequency = 2.1Hz ± 5%

Pedaling Frequency = 2.1Hz ± 0.1

Calculating the Gear Ratio

To calculate the gear ratio, the number of teeth on all the gears on the chain wheel (center) and cog (rear) will be required from Table 3. This gear ratio value will help to calculate the diameter and circumference of the bike wheel during each trial. Additionally, this helps determine the relationship between the gear ratio and bicycle speed. The formula for calculating the gear ratio is the following:

$$r = \frac{F}{R}$$

r = gear ratio value	F = number of teeth on the chain wheel	R = number of teeth on the cog

Finding the gear ratio used in Trial 1:

$$r = \frac{28}{14}$$

$$r = 2.0$$

Therefore, the gear ratio used during Trial 1 was a value of 2.0.

Processed Data Summary

By using the methods above, the raw data collected in Table 2 can be processed into Table 5 below.

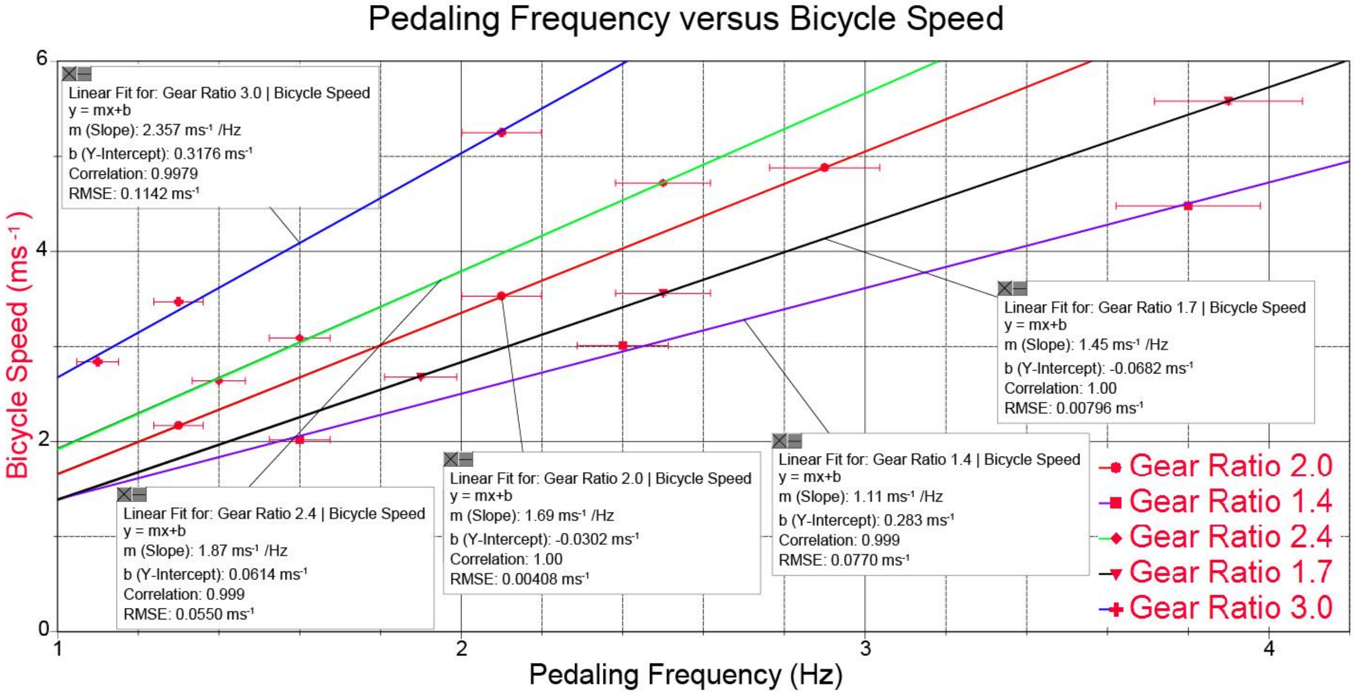
Table 5: Processed Data Summary

Trial	Δ Time (s) ± 0.02	Speed (ms^{-1}) ± 0.5%	Pedaling Frequency (Hz) ± 5%	Gear Ratio
1	5.33	3.53	2.1	2.0
2	3.85	4.88	2.9	2.0
3	8.68	2.17	1.3	2.0
4	9.30	2.02	1.6	1.4
5	6.25	3.01	2.4	1.4
6	4.20	4.48	3.8	1.4
7	6.08	3.09	1.6	2.4
8	7.13	2.64	1.4	2.4
9	3.98	4.72	2.5	2.4
10	7.02	2.68	1.9	1.7
11	5.28	3.56	2.5	1.7
12	3.37	5.58	3.9	1.7
13	6.62	2.84	1.1	3.0
14	5.42	3.47	1.3	3.0
15	3.58	5.25	2.1	3.0

VIII. Data Analysis

From the summarized data in Table 5, it is apparent that pedalling frequency does influence the speed of the bicycle when the gear ratio remains constant. Additionally, changing the gears does affect the speed of the bicycle, however, it is not as significant as the pedalling frequency. To confirm these observations, I will graph this data in Graphical Analysis 3 by having the pedalling frequency as the independent variable and the speed as the dependent variable.

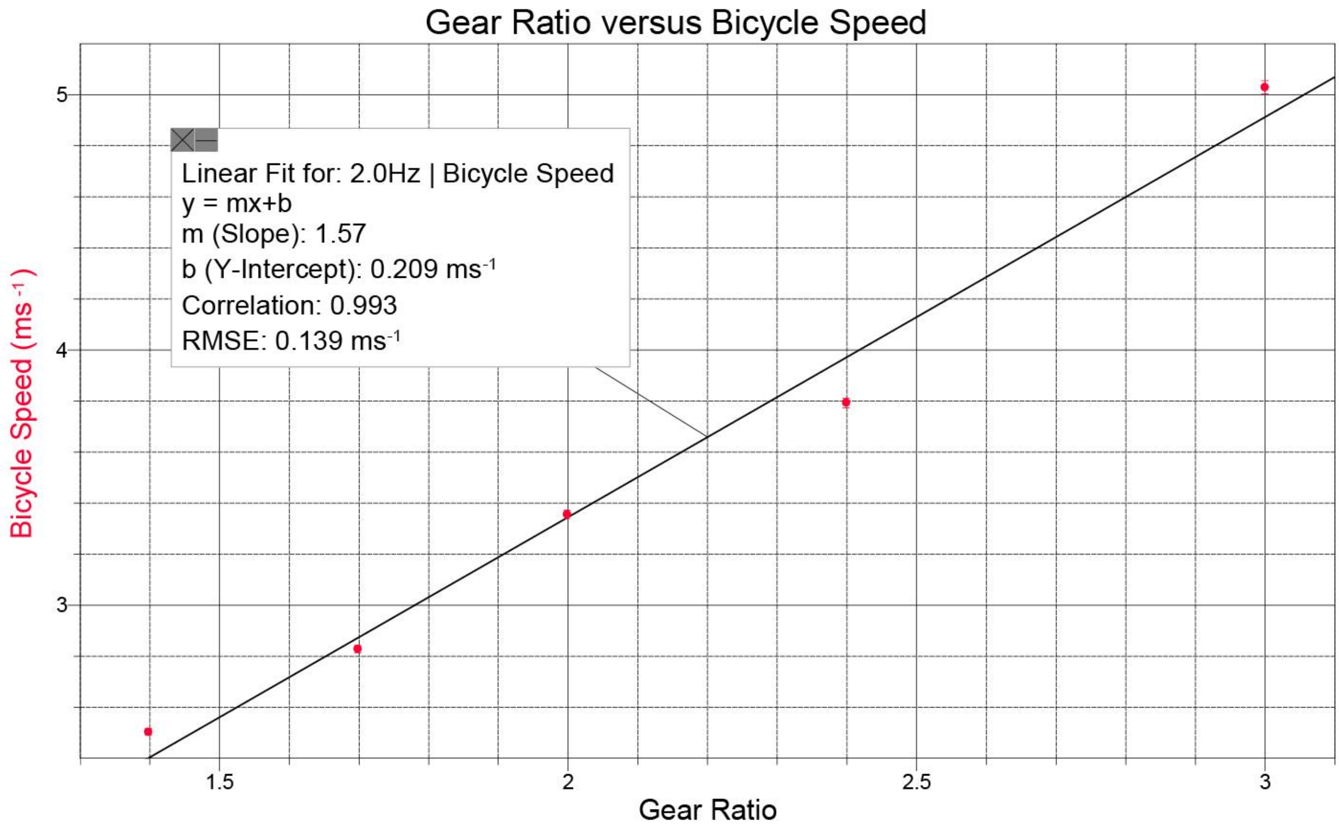
Graph 1: The Relationship Between Pedaling Frequency and Bicycle Speed



Graph 1 displays five different data sets; these are the five different gear ratios used while experimenting. Within each data set, there are three data points and that is the number of trials done per gear ratio. Upon observation, the relationship between pedalling frequency and bicycle speed is indeed a perfect positive linear correlation as all five data sets have a linear fit with a correlation coefficient value (r) of 0.99 or greater. The closer the r value is to 1.00, the stronger of an influence the variables hold in relation to each other whereas the closer it is to 0, the opposite is the case.

Another observation from the graph would be the different magnitudes of the linear fits of the different data sets. As the gear ratio increases, so does the slope of the line. To confirm that this is a positive linear correlation, I will graph the bicycle speeds of the different gear ratios at the same pedalling frequency. To accomplish this, I will be using a pedalling frequency of 2.0Hz and taking the bicycle speed values directly from Graph 1 above. I picked the frequency of 2.0Hz as there is no extrapolation in any of the five gear ratio data sets.

Graph 2: The Relationship Between Gear Ratio and Bicycle Speed



While I was conducting my experiment trials, I was particularly confused as to why the number of pedals stayed the same despite the different pedalling frequencies that I was pedalling at. I believe this is because each pedal cycle generates enough power to travel a set distance based on the gear ratio and wheel circumference. This caused me to view the rotation of a bicycle wheel as an example of simple harmonic motion (SHM). The motion of a set point on the rotating wheel travels to and from an equilibrium position and if graphed, it would result in a sinusoidal function. This made me think about whether the formula for calculating the speed of a wave would work for determining the speed of the bicycle in my experiment. The formula for calculating the speed of a wave is as follows:

$$v = f \cdot \lambda$$

v = speed f = frequency λ = wavelength

However, since the wavelength (λ) is represented by the circumference of the wheel, a slight modification is required to take the different gear ratios into account. The modified formula is as follows:

$$v = f \cdot C$$

v = speed f = pedalling frequency C = wheel circumference

The formula for determining the wheel circumference is as follows:

$$C = D \cdot r \cdot \pi$$

C = wheel circumference D = diameter of the wheel r = gear ratio

Finding the speed of the bicycle in Trial 1 using the speed of waves method:

$$v = 2.1\text{Hz} \cdot C$$

$$C = 0.60\text{m} \cdot 2.0 \cdot \pi = 3.77\text{m}$$

$$v = 2.1\text{Hz} \cdot 3.77\text{m}$$

$$v = 7.92\text{ms}^{-1}$$

However, since I counted both the left and right-side pedals when pedalling the same oscillation, I need to half the speed.

$$v = \frac{7.92\text{ms}^{-1}}{2} = 3.96\text{ms}^{-1}$$

Finding the uncertainty in speed:

$$\%\ \text{Uncertainty for Speed} = \%\ \text{Uncertainty in Pedaling Frequency} + \%\ \text{Uncertainty in Circumference}$$

$$\text{Uncertainty in Pedaling Frequency} = 5\%$$

$$\text{Uncertainty in Circumference} = \frac{0.01\text{m}}{0.60\text{m}} \cdot 100\% = 2\%$$

$$\text{Uncertainty for Speed} = 5\% + 2\% = 7\%$$

Therefore, for Trial 1:

$$v = 3.96\text{ms}^{-1} \pm 7\%$$

$$v = 3.96\text{ms}^{-1} \pm 0.28$$

By using the methods above, the following data tables and graphs are produced below.

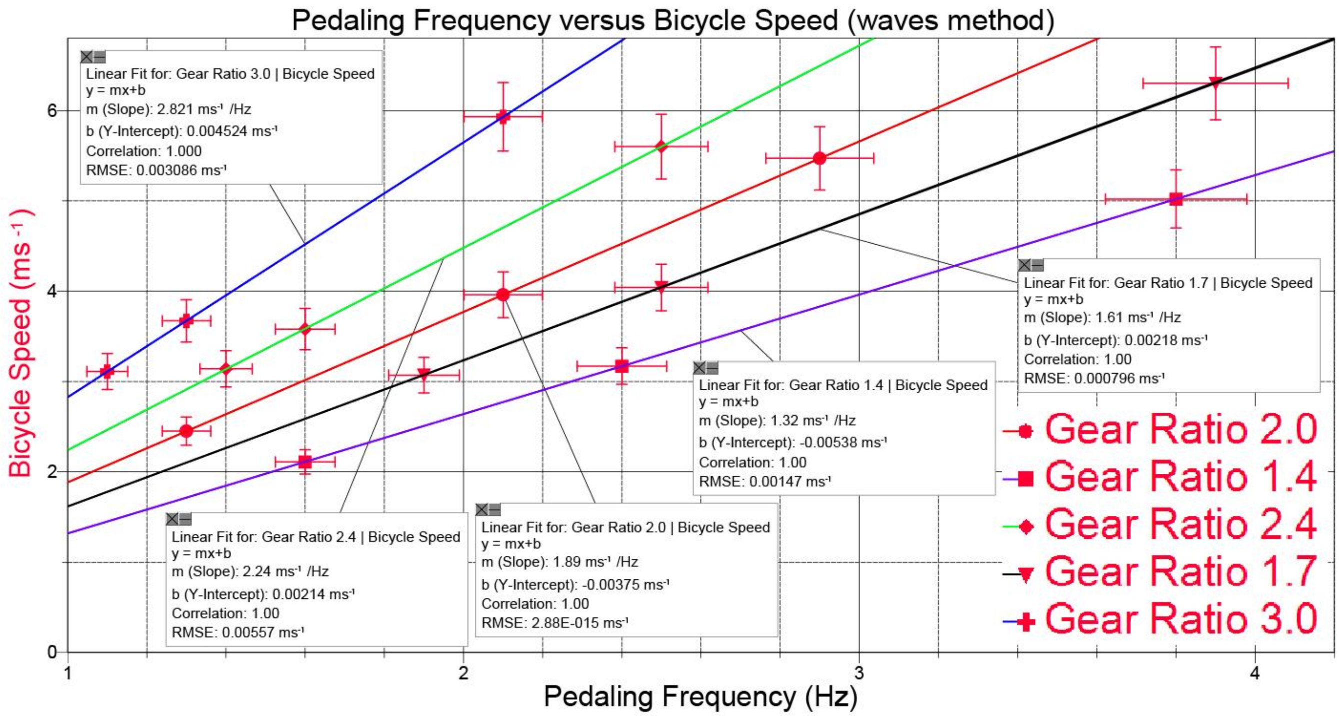
Table 6: Speed of Waves Method Calculations Summary

Trial	Gear Ratio	Wheel Circumference (m) ± 2%	Pedaling Frequency (Hz) ± 5%	Speed (ms^{-1}) ± 7%
1	2.0	3.77	2.1	3.96
2	2.0	3.77	2.9	5.47
3	2.0	3.77	1.3	2.45
4	1.4	2.64	1.6	2.11
5	1.4	2.64	2.4	3.17
6	1.4	2.64	3.8	5.02
7	2.4	4.48	1.6	3.58
8	2.4	4.48	1.4	3.14
9	2.4	4.48	2.5	5.60
10	1.7	3.23	1.9	3.07
11	1.7	3.23	2.5	4.04
12	1.7	3.23	3.9	6.30
13	3.0	5.65	1.1	3.11
14	3.0	5.65	1.3	3.67
15	3.0	5.65	2.1	5.93

Table 7: Two Speed Calculation Methods Comparison

Trial	Speed $\left(\frac{\text{distance}}{\text{time}}\right)$ (ms^{-1}) ± 0.5%	Speed $(f \cdot C)$ (ms^{-1}) ± 7%
1	3.53	3.96
2	4.88	5.47
3	2.17	2.45
4	2.02	2.11
5	3.01	3.17
6	4.48	5.02
7	3.09	3.58
8	2.64	3.14
9	4.72	5.60
10	2.68	3.07
11	3.56	4.04
12	5.58	6.30
13	2.84	3.11
14	3.47	3.67
15	5.25	5.93

Graph 3: The Relationship Between Pedaling Frequency and Bicycle Speed Using Wave Speed Method



Graph 4: The Relationship Between Gear Ratio and Bicycle Speed Using Wave Speed Method

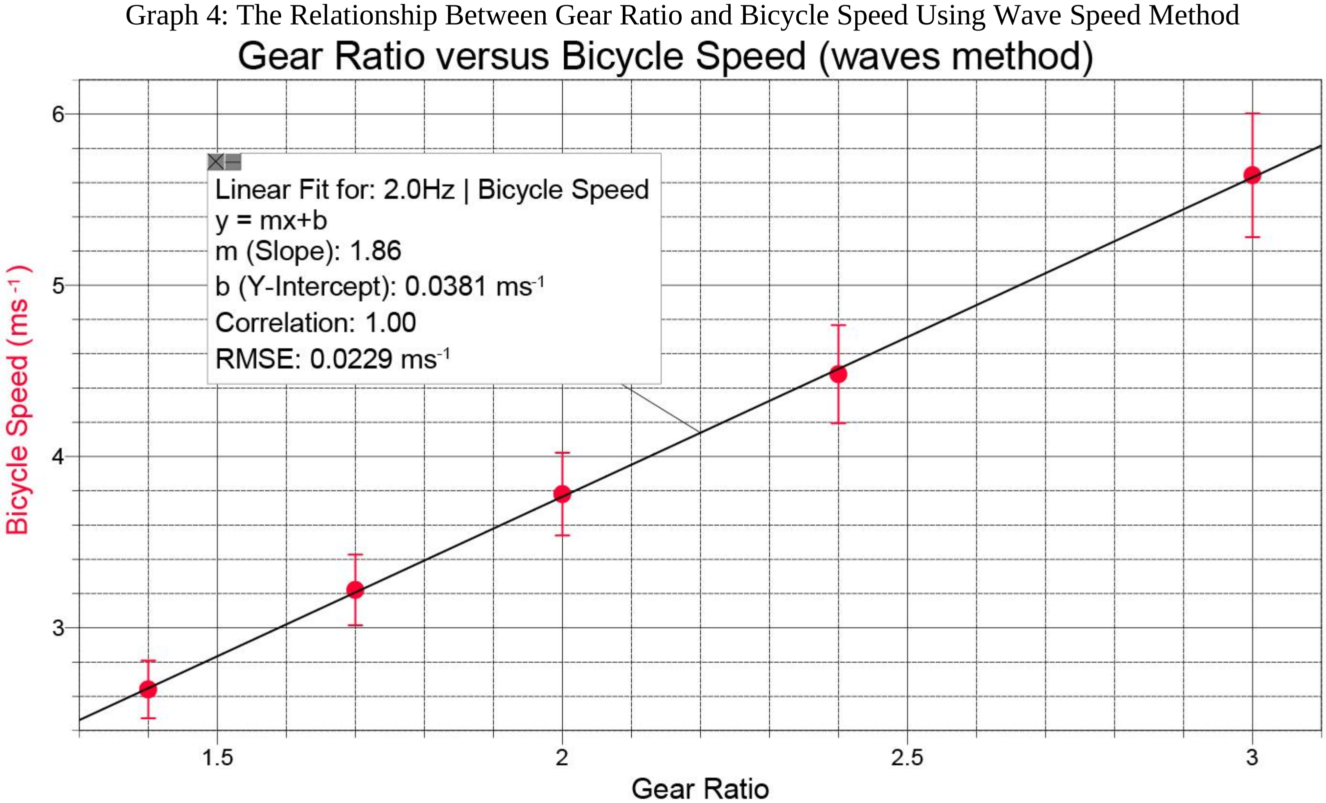
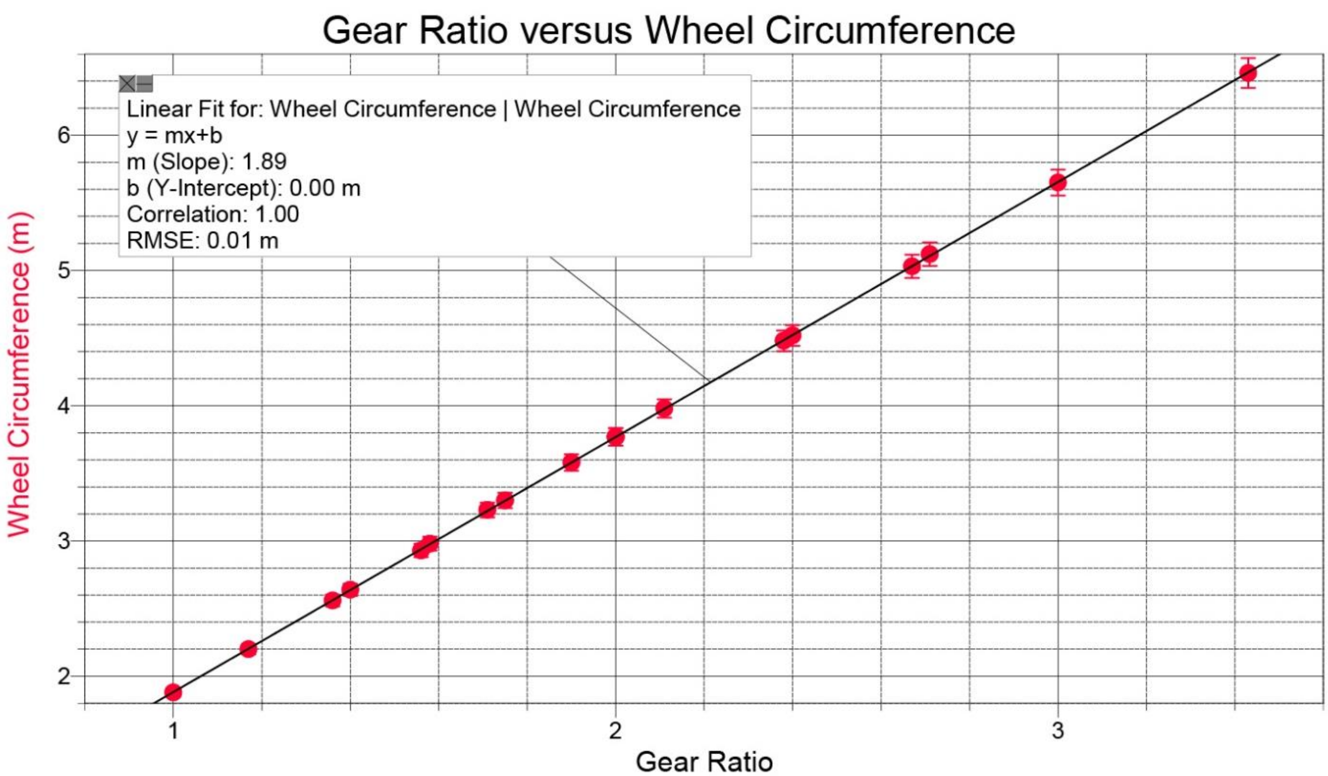


Table 8: Summary of Gear Ratio Affect on Wheel Diameter and Circumference

Gear Ratio	Actual Wheel Diameter (m) ± 2%	Actual Wheel Circumference (m) ± 2%
1.00	0.60	1.88
1.17	0.70	2.20
1.36	0.81	2.56
1.40	0.84	2.64
1.56	0.93	2.93
1.58	0.95	2.98
1.71	1.03	3.23
1.75	1.05	3.30
1.90	1.14	3.58
2.00	1.20	3.77
2.11	1.27	3.98
2.38	1.43	4.48
2.40	1.44	4.52
2.67	1.60	5.03
2.71	1.63	5.12
3.00	1.80	5.65
3.43	2.06	6.46

Graph 5: Gear Ratio versus Wheel Circumference



Upon observation of the concluded data, it is apparent that the uncertainty in using the speed of a wave method to calculate the speed of the bicycle is noticeably greater than the more conventional approach of dividing distance by time to calculate speed. While some of the speed values given by both methods were somewhat close to each other, others were not making the speed of a wave method unreliable given its 7% uncertainty, which could be much greater. In addition, while the linear trend of each data set displays the same relationship compared to Graphs 1 and 2, the difference in the value of the slopes was quite significant. Ultimately, the great uncertainty creates the information produced using the wave method to be unreliable, mainly due to the 5% uncertainty in pedalling frequency.

From Graph 5, the linear relationship that the gear ratio has on the circumference of the wheel is displayed. This further confirms the hypothesis of gear ratio linearly affecting the speed of a bicycle. As each pedal is capable of covering a greater distance as the gear increases, which is also experienced by the biker whenever changing gears as greater resistance to pedalling is felt, the bicycle can travel at a faster speed on flat, smooth terrain.

IX. Conclusion

Overall to conclude, this experiment has answered my research question and has confirmed my hypothesis to be correct. The effects of changing the gear ratio and pedalling frequency do linearly affect the speed of the bicycle positively. This is clearly shown in Graphs 1, 2, and 5. This is because the pedalling frequency linearly affects the period, the time that is taken for the wheel of the bicycle to make one complete rotation, while the gear ratio changes the circumference of the bicycle wheel which linearly changes the distance one full wheel rotation would travel. The movement of a set position on a bicycle wheel is a form of SHM. While using the waves method to calculate the speed of the bike is possible, a more precise method of determining the pedalling frequency is needed to lower the 7% uncertainty. Nonetheless, the same conclusions are drawn from both speed calculation methods.

X. Discussion

During this experiment, uncertainties were kept quite low by utilizing various methods such as video recording to track time instead of a stopwatch, setting a start and finish line to keep the distance travelled constant, and keeping the tire pressure at the same PSI. There are areas for improvement which will be discussed in this section.

Table 9: Random Errors and Suggested Improvements

Random Errors		
Limitation	Significance	Improvement(s)
Rate of Pedaling: Pedaling at a constant rate is difficult and thus resulted in fewer trials per gear ratio as varying speed was a challenge.	Creates inconsistency in the bike speed, limits the number of trials able to perform, and decreases the precision of the experiment.	Increase the distance travelled to allow for greater flexibility with pedalling speed. With a larger distance, the implications of inconsistent pedalling are smaller and additionally give more room to pedal at different rates while resulting in a significant difference in travel time to create adequate trials and data samples.

A critical issue with this experiment would be the lack of trials with only three being performed per gear ratio. This is because while experimenting, besides pedalling at a slow, medium, and fast pace, it was difficult to pedal at a speed in between. This was partially due to the short distance available to travel. Additionally, pedalling at a constant rate is extremely difficult at slower speeds as the bike requires acceleration to maintain balance. By using a greater distance, the implications of inconsistent pedalling are scaled down, and allow more room to perform different pedalling rates as the resulting time taken to travel the distance will be marginally apart from another trial with a slightly slower or faster pedalling rate. Access to a long piece of pavement is difficult, however, it would allow more trials to be performed which overall improves the consistency and precision of the gathered data.

Table 10: Systematic Errors and Suggested Improvements

Systematic Errors		
Limitation	Significance	Improvement(s)
Number of Pedals: Counting the number of pedals performed mentally is difficult.	Creates uncertainty and reduces the accuracy of the number of pedals performed to travel the distance as, especially with the higher gear ratios, a quarter of a rotation can cover a good amount of distance.	Use a video recording device to record the rotations of the pedals or use a sound indicator to signal a complete rotation. Another option would be to have someone else keep track of the number of rotations, however, this is prone to human errors.
Video Recording: When reviewing the video playback, the start and finish lines would be passed mid-frame. This is especially evident on a lower framerate (ex: 30FPS).	This slightly reduces the accuracy of measuring the time taken to travel the distance.	Record at a higher framerate or in slow motion to capture the exact moment the wheel crosses the start or finish lines will improve the accuracy of when exactly the wheel crosses the lines.
Diameter of Wheel: The thread of the tire will be worn, and	This changes the diameter and circumference of the	Use a fresh tire that is fully pumped and kept at a constant PSI. Use the

the tire is compressed ever so slightly by the weight of the biker.	wheel which reduces the accuracy of the circumference measurements and thus the speed calculations.	same biker to ensure the weight placed on the wheel and compression enacted is kept to a constant amount.

The most significant problem and source of uncertainty with this experiment would be the method of counting the number of pedals per trial. Counting the number of pedals mentally while riding a bike and operating the video recording device is mentally draining that not everyone can perform simultaneously. Moreover, the entire counting of the left and right foot pedals in addition to half-pedal rotations made it very confusing to process. Using a video recording device to record the pedal would be the most accurate method as even half or quarter pedals can be taken into consideration, however, mounting a camera to the side of a bike or having someone run with it poses challenges of its own. Using a sound indicator for when a full pedal rotation is complete would help, however, it does not consider half or quarter rotations, and someone would still have to mentally keep track of the number of sound indications. Using another human to track the number of pedals would relieve some stress from the biker, however, this does not mitigate the risk of human errors.

While using a video recording device to record the time needed to travel the set distance greatly reduced the uncertainty of using a human timer and dealing with human reaction time, it still presented the problem of uncertainty when the bike was travelling at a faster speed. This was because sometimes the crossing of the start or finish lines would happen in between frames. This is especially evident on lower framerates such as 24 or 30. While this does create slight uncertainty, this method is still more accurate than using a human timer. To improve upon this, recording at a higher framerate such as 60, or in slow motion, would reduce the chances of the bike crossing the lines mid-frame as the video playback will have more frames to display.

With the diameter of the wheel, the weight of the biker would compress the tire ever so slightly and thus affect the diameter and circumference of the wheel. This created a slight uncertainty in the diameter measurement. To mitigate the effects of this, fully pumping the tire will reduce the amount of compression on the tire. Additionally, it is important to keep the PSI of the wheels constant and to keep the biker the same to keep the change in tire compression to a minimum.