How Center of Mass Affects the Acceleration and Final Velocity of a Pinewood Derby Car

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The purpose of this experiment was to examine if the location of where weights were added to a Pinewood Derby Car would affect the acceleration and final velocity of the car as it raced down the track. To determine this, an unshaped car was run multiple times in the same lane with weights placed in different locations on the car. The goal was to see how the acceleration and velocity changed in conjunction with the alteration of the position of the weights. Through the use of photogates, the car's velocity and times were recorded at two points along the track and then used to calculate the acceleration for the first part of the track. The data collected from this experiment showed that the car had the greatest acceleration when all of the weight was in the front of the car, but had the greatest final velocity when the weight was in the middle to back of the car, as long as it was not directly above an axle. This was different from the expected outcome with the placement of the weights predicted to be near the back of the car. Further testing would be needed to see if the shape of the car with varying weight placement would affect the acceleration and final velocity of the car.

I. INTRODUCTION

Every year thousands of young boys and today a few girls work together with an adult to build a Pinewood Derby Car. These cars and their designers then gather together and race on a specially designed track. This tradition was started by Don Murphy, Cub Master for Pack 280C in 1953. Cub Scouts is the division of Boy Scouts for boys between 1^{st} and 5^{th} grade, but too young to be Boy Scouts. Murphy was looking for an activity that he could organize with his son who was too young to participate in the Soapbox Derby. The Soapbox Derby races cars that are actually manned by a young person, while the Pinewood Derby races model cars. The Pinewood Derby is designed for children aged six to twelve. Murphy created this activity to help draw fathers and younger sons closer together while participating in a safe activity. He designed the template for the cars and had them built. He selected pinewood because it was soft and could easily be carved to a shape. The original cars came with a shape already given to them and a cockpit in them.[**?**] The cars today come as a solid block of pinewood ready to be shaped however each scout desires. Most are painted reflecting the scout's personality as well. Even though each car today reflects an individual personality, it must also meet certain criteria. The most important of these criteria is the actual weight of the car. Confirming that each car falls into a specific weight range ensures that the race is completed as fair as possible. Weights can be added to each car so that each individual car falls into this specific weight range.[**?**]

In this experiment I focused only on how where the added weights were placed on the car would affect the acceleration and the final velocity of the car. I ignored what affect the shape and aerodynamics of the car would have. To do this, the car was raced in as close to its original shape as possible while the mass was placed in the car in such a way that it did not change the shape of the block.

II. THEORY

The principle of the Pinewood Derby track is that gravity is the only force acting on the car to make it travel down the track. Any outside force in or on the car was cheating. In this case the only way to change how fast the car will go was to change its potential energy, because the car equates energy with gravity and height. The idea behind the potential energy was that if an object could be made heavier or higher then it would have more energy at the bottom. In this experiment, the weight of the car was a fixed number not allowed to exceed 141.74 grams. That meant that only the height could be changed. This experiment was testing to see what difference the location of the center of mass on the car made to its acceleration and final velocity. The center of mass location was how the height of the car would be determined. Since the car cannot be started farther back or further forward, the height of the physical car was fixed. By using the the center of mass as the height, moving it will affect the amount of time that the car is accelerated by gravity, which is comparable to the amount of potential energy the car had. If the center of mass were to be entirely located at just one end of the car, then the height difference from one end of the car to the other would be 7.493 cm, which means a change in potential energy of 0.1103 $\mathrm{kgm^2/s^2}$. This extreme case was not possible because there was no way to put the center of mass on the extremes of the car. This meant the differences between the centers mass was small.

The car could be run down the track in two different orientations. The first was when the front axle was only 2 1/4 cm from the front of the car. This orientation left more of the car hanging after the rear axle, and the second orientation was reversed. The reason for running the

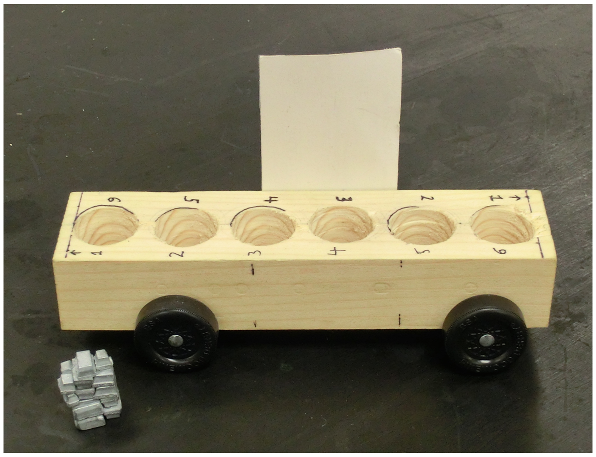

FIG. 1: This is the design I used for my car in order to just test how where the weight was would affect the acceleration and final velocity of the car. The moveable weight can be seen sitting by the car. The car could be run two ways down the track. Most of the sample cars I brought from home had the left side being the front of the car, but both directions were tested.

car down the track both ways was to see if the location of the center of mass from the front of the car made a difference in the speed and acceleration.

To find the center of mass of the car, it was placed on two scales to measure the weight on each axle. With the distance from the axles to the front of the car and the weight on each axle, the center of mass for the particular spot could be calculated using

$$X_{cm} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2}, \tag{1}$$

where m_1 and m_2 were the weight measurements for the front and back axles and x_1 and x_2 were the distance from the front of the car to the axles. By moving the majority of the weight being added to the car, the weight over each axle would change with the different locations, moving the center of mass closer to where that weight was placed.

This race relies on gravity to move the cars down the track. The track is 9.75 m long, the first three metes is a downward sloped ramp at a 25 degree angle. The remaining 6.7 m is a flat section leading to a foam stopper. The photogates were placed at the bottom of the sloped section and right before the car would reach the stopper. The energy for the entire system was conserved and the potential energy at the top of the track would equal the kinetic energy which aided in predicting the final velocity of the car at the bottom of the track. The potential energy was solely dependent on the height of the center of mass because the weight of the car was not changed. That equation was

$$PE = mgh, \tag{2}$$

where m was the mass of the car, g was the acceleration from gravity and h was the height. In the extreme case presented earlier, the height changed, at most, by 7.49 cm. In the actual experiment, that difference was only about 2.5-3 cm which meant that the change in potential energy was very small from one center of mass point to the next.

Since the acceleration at the beginning of the track was something that would influence what the final velocity of the car was, measurements were made using the data recorded by the first photogate. Using the velocity and the time recorded at the photogate the acceleration could be calculated using

$$v_f = v_0 + at, \tag{3}$$

where v_f was the final velocity, v_0 was the initial velocity, a was acceleration of the object, and t was time. Since the car was starting from a resting point, v_0 was zero, so it can be removed, and the photogate gave the final velocity and time for this part of the track. Rearranging Eq. **??** for acceleration gave

$$a = \frac{v_f}{t}. \tag{4}$$

Using this equation, the center of mass position that had the fastest acceleration could be calculated. Since the photogate gave the velocity of the object passing through, there was no calculation needed to find the final velocity. However, using the velocity from the first potential energy the velocity at the end of the track could be predicted. Then using the recorded velocities from the photogates, the total drag forces on the car could be calculated.

III. PROCEDURE

In this project, I was testing how changing the center of mass in a Pinewood Derby Car would affect the acceleration and final speed of the car. In order to only test how the weight changes would affect the car, I did not change the original shape of the car, a rectangular cube, to cause it to have less air drag as it moved down the track. The Pinewood Derby Car came as a rectangular block of wood 17.78 cm long and 4.44 cm wide. The pinewood derby kit comes with four wheels and two axles (which are just nails). These are both official pieces and cannot be substituted for other parts. Many people add powdered lubricants to the axles, and try to smooth out the axles and wheel wells to make the wheels spin faster. In order to be consistent to other modifications I had done to the car, all of the axles and wheels remained exactly as they were when they came out of the box.

There are three standard lengths for a Pinewood Derby Track. The one that was used in this experiment was a 9.75 meter track, the shortest of the three track lengths.

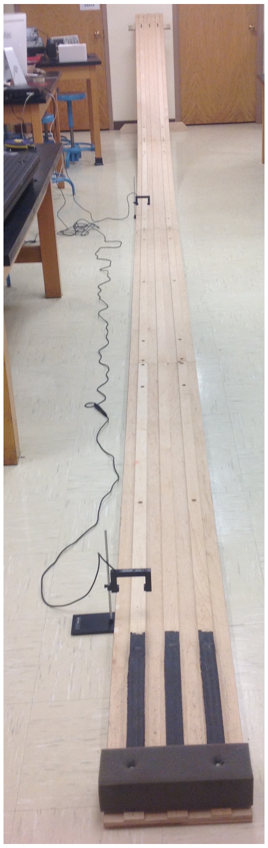

FIG. 2: The full length of the track. with the photogates next to it and the stopping mechanism at the bottom of the image.

This meant that the final velocity for this track was going to be higher than it would be for other tracks because there was less time for the friction of the track and air resistance to slow the car. To record the velocity of the car and the time it took for the car to reach specific points on the track, I used Data Studio and two photogates.

To measure how changing the center of mass would affect the acceleration and final velocity of the car, while not changing friction and drag on the car, I had six holes drilled in the top of the car. Each hole was about 2.22 cm wide so that a stack of weights could be easily placed into different spaces on the car. Each hole ran about 3/4 of the way through the car so that the weights would sit down in the car and minimally affects drag force of the car while allowing for the weights to be easily moved.

At two points along the track, photogates were placed to record the time it took to get to that gate and the velocity at that gate as seen in Fig. **??**. For finding the acceleration and final velocity, I placed one photogate at the bottom of the curved part of the track because that is the point where the car stops accelerating and before the car starts to slow down. To measure the final velocity, I put the other photogate at the end of the track, right before the stopping mechanism, in order to measure the last possible velocity.

In this experiment I selected six different locations to place the weights to test for the difference between acceleration and final velocity as seen in Fig. **??**. When I dropped the starting gate as shown in Fig. **??**, I also would also start the run in Data Studio to record the velocity and time. At each of the locations, I performed several runs in order to diminish any differences that would happen from me starting the clock and releasing the car. The data collected for each run was put into Igor and the acceleration of the car in the first part of the track could be calculated. The data in the graphs is the averages of both the final velocity and the acceleration. The error was calculated by moving the end photogate to the beginning of the track to find the time difference between the clock starting and the gate dropping. The difference in velocity between the first part of the track and the final velocity showed the effect of friction on the car as it traveled and could also be calculated from the data recorded.

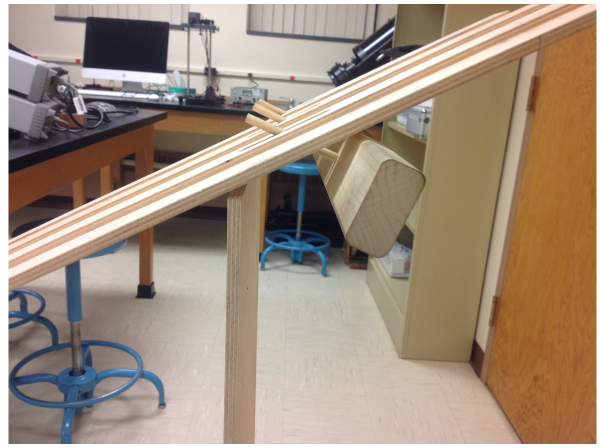

FIG. 3: Image of the starting gate used on this track. In a race setting it would ensure that all the cars started at the same time. For this experiment, the starter lets me start the car the same way every time.

IV. ANALYSIS

The goals of this experiment were to determine how weight placement on a Pinewood Derby Car would affect the acceleration and final velocity of the car. Moving the center of mass on the car to different locations tested this. By simulating different weight locations, it was expected that when the center of mass was located closer to the back of the car, a higher starting point, that the car would have a faster acceleration. This could be equated to a higher velocity at the bottom of the curved section of the track, which meant that the final velocity of the car would also be faster. The average acceleration and average final velocity were graphed with respect to the location of the additional weights. From the theory, it was expected that the car would have the greatest acceleration when the weights were farthest back on the car.

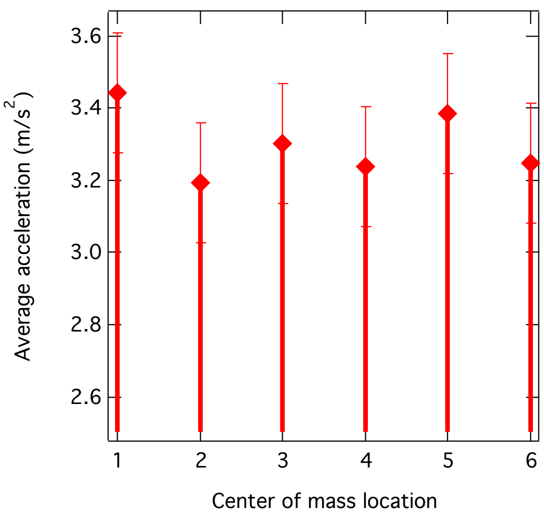

FIG. 4: This is a graph of acceleration vs. center of mass. This graph shows that the acceleration of the car is fastest when the weight is located at the very front of the car. The x-axis represents the locations on the car where the weight was placed. The numbers corresponding to which run it was. 1 and 4 were the front of the car, 2 and 5 were the middle, and 3 and 6 were the back. 1, 2, and 3 are the car oriented forward while 4, 5, and 6 are the reversed orientation.

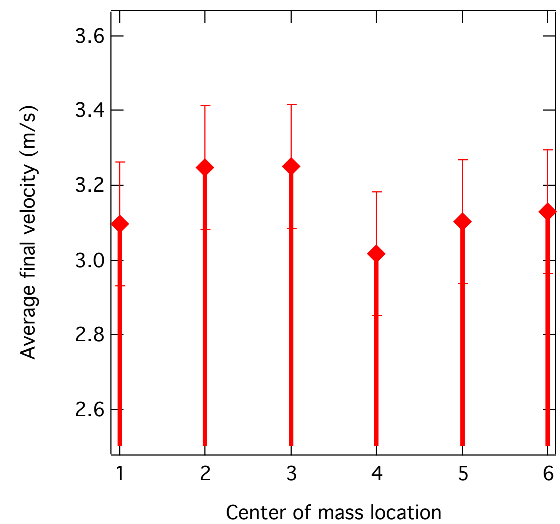

FIG. 5: This is a graph of final velocity vs. center of mass. The final velocity is fastest when the mass was located in the middle to back section of the car. The x-axis represents the locations on the car where the weight was placed.

However, from Fig. **??**, it was clear that when the weights were in the front of the car, it actually had the best acceleration. This was the opposite of the theory and may be due to the cars shape, because the car was not shaped to be aerodynamic. If the car had some shape to it, then the center of mass could have been moved much farther back on the car. Because the car was uniform in shape and weight distribution, placing all of the mass in the front caused it to accelerate faster. The uncertainty in the graphs comes from not being able to release the car and start the timer at exactly the same time. To account for this each weight placement was run several times so that an average could be calculated. A photogate was also placed directly after the starting gate so that an average time for the car to travel the length of the curved section of the track could be found. Using theses two times the difference in the gate dropping and the clock starting could be minimized, and was found to be 0.165 seconds difference between the clock and the car starting on average.

Although there are three standard lengths for a Pinewood Derby Track, the one that was used in this experiment was a 9.75 m track, the shortest of the three track lengths. This meant that the final velocity for this track was going to be higher than it would be for other length tracks because there was less time for the friction of the track and air resistance to slow the car down. The final velocity of the car was graphed against the position of the weights and the fastest final velocities were measured when the weight was near the middle or back of the car as seen in Fig. **??**. Since the track was shorter, it provided less time for the car to slow down so it could be expected that for longer tracks the final velocity would be even slower.

If the car had been made to be more aerodynamic in shape and the axles and wheels had been prepared in a way that reduced drag, then the acceleration of the car as well as the final velocity would be faster since it would lose less energy to the forces slowing it down. In this experiment, the final velocity does not coincide with the weight placement for the fastest acceleration, which was against the proposed theory. More potential energy would be equal to having more velocity at the beginning of the flat section of the track. This meant that when the car had the fastest acceleration, at the flat section, it lost the most velocity. This was probably due to how the car was balanced. When a majority of the weight was placed directly over the wheels, the downward force at that point was higher, which would mean the drag on those wheels and axle was greater than when the weight was more centered on the car.

V. CONCLUSION

The goal of this experiment was to determine if where weight was placed on a Pinewood Derby Car would affect its acceleration and final velocity. Using potential energy, it was predicted that the car would have the greatest acceleration and final velocity when the weight was placed closer to the back of the car 3 and 6 on the x-axis of Fig. **??**, however, this was not the case. The car had the greatest acceleration when the weight was in the very front of the car specifically in hole one. This fast acceleration did not coincide with the fastest final velocity, which happened when the mass was more centrally located on the car seen best in 2 and 3 of the x-axis of Fig. ??. The inconsistency from this theory probably came from the shape of the car. Since the car was still a rectangular block, there was no reduction on drag forces that the car encountered, and no modifications were made to the wheels or axles to reduce friction making all of the runs the same.

When the weight was placed directly over one of the axles it put more force on that set of wheels and since friction was not reduced, that force lead to extra drag in that situation. Some potential errors in this lab may include the inconsistency in the release of the car and starting Data Studio recording. This made all of the times to the gate a little shorter than they actually were. To reduce this factor, in the future an electronic starting system should be used. In this experiment, I relocated one of the photogates to the very beginning of the track to measure the time from the start of the track to that gate and then the time to the bottom of the curve. These times were then added together and the times from the prior corresponding run were subtracted from them. The average of these times was the difference between when the clock was started for the data runs. This gave an error of 0.165 seconds between the gate dropping and the clock for Data Studio starting, about as fast as a person can start and stop a stopwatch. Additional error came from the track itself. If any of the joints were not firmly connected to each other or there were bumps in the track, the car may have slowed down. Also, if the car did not travel down the track straight, then the wheels would drag on the edge of the track further slowing it down.

This experiment showed that the placement of the weight does not greatly affect the acceleration or final velocity of a Pinewood Derby Car. The causes for uncertainty in the data are from inconsistent starting of both parts of the experiment, as well as how straight the car traveled down the track, if it collided with the guide rail of the track this would also slow the car down. The difference in velocity and acceleration from the starting method is not a significant amount added or subtracted from the acceleration and velocity. Since it was consistent in all the runs and if it had been a race all cars would have been equally affected in the end. This could be different if the car were shaped and designed in a more aerodynamic way than it was for this experiment. Any changes to the shape of the car would change the weight distribution and would affect how the weight of the car rested on the wheels and axles as it was raced. Additional testing would be needed to examine how the shape and weight placement would affect these parts of the race.

VI. ACKNOWLEDGEMENTS

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[1] Don Murphy *Pinewood!: The Story of the Pinewood Derby* (Torrance, CA: Murphy Enterprises, 2001. Print.)

[2] MeritBadgeDotOrg RSS. BSA, *Pinewood Derby Official Rules*, (2009).

[3] Gargiulo, Joseph, and Stephen Gargiulo *Winning Pinewood Derby Secrets* (Trumball, CT: Pinewood Pro, 2001. Print.)