Understanding Physics Concepts through Project Based Learning

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***Abstract*— Project Based Learning has been researched and practiced at many high schools as well as colleges. Union County Magnet High School is one of 15 schools in New Jersey awarded the Blue Ribbon School Award of Excellence by the United States Department of Education. The students in the Union County Magnet High School strive under the guidance of a group of motivated instructors who are actively involved in innovative teaching pedagogies. Project based learning has been in practice for a number of years at Union County Magnet High School. Since becoming freshman in the fall of 2012 at Union County Magnet High School, the author has been participating in project based learning in various classes. In the sophomore year 2013-2014, the Physics I instructor at Union County Magnet High School led his class to design an innovated practice in order to enhance the comprehension of the fundamental physics concepts – a project to design and build car in which only mechanical forces were allowed for propulsion using the application of the concepts covered in class. Through the process of building a mechanically powered car, some problems aroused that led to consideration of friction force, material weight, and stability control, etc. To calculate the distance the car traveled and average velocity of the car, a number of concepts and mathematical equations must be used correctly. In this paper, the design of a mechanically-powered car which won in the categories of farthest distance traveled and fastest speed will be described along with its related physics concepts. It also demonstrates a series of mathematical calculations. The data recorded through a series of experiments and its comparison with theoretical calculations is presented.**

***Index Terms*— project based learning, physics concept, and mouse trap car**

I. Introduction

The Union County Magnet High School (UCMHS) is a magnet public high school located in Scotch Plains, New Jersey on the Union County Vocational Technical Schools Campus, serving the vocational and technical educational needs of students throughout Union County, New Jersey. The Mission Statement of the school states that the school's goal is to prepare students for college/vocational training utilizing technology through problem solving, project-based learning and interdisciplinary education. The Union County Magnet High School is one of fifteen schools in New Jersey awarded the Blue Ribbon School Award of Excellence by the United States Department of Education. In addition, according to *The Daily Beast*, Union County Magnet High School is currently ranked twenty-seventh in the nation. The students in the Union County Magnet High School strive under the guidance of a group of motivated instructors who are actively involved in innovative teaching pedagogies. Project based learning has been in practice for a number of years at Union County Magnet High School. The Physics I course is offered to junior year students and sophomore students who are in a pre-calculus or higher level mathematics course. It is an algebra-based honor's level course which covers mainly the topics of Mechanics and Electricity. The instructor also emphasizes the development of reasoning and problem solving abilities through both class and lab work. Toward the end of the course, a project assignment is assigned which incorporates the concepts of basic mechanics acquired throughout the year. The project requires students to build a mechanically powered car and conduct a series of experiments with the goal of calculating the average velocity as well as the distance traveled for the mechanically powered car to be later compared to measured values. Throughout the process of the experiment, students are also required to calculate frictional force, spring constant, spring force, and average acceleration. After successful completion of pre-calculus during freshman year, the author enrolled in the Physics I class while taking AP Calculus I/AB during sophomore year. In the academic year, the author led a team in the project to brainstorm, design, manufacture, test, and analyze a car in which only mechanical forces were allowed to propel it.

II. Design and Construction of a Mechanically Powered Car

Having learned from Newton's First Law that an object in motion will stay in motion, and an object at rest will stay at rest, unless acted upon by another force, along with a plethora of other physics concepts acquired through Physics I, in order to demonstrate how physics concepts are applied to real life, the team came together to apply their acquired knowledge and problem solving skills to meet the several design requirements given to them and create a mechanically powered car.

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In competition with many other teams, the mouse trap car traveled the farthest. Initially, before coming up with final design, the team brainstormed a myriad of simple designs. These designs included the standard mousetrap powered car, a spring powered car, a balloon powered car, and finally a combination of two or more of the previously mentioned designs. Initially the design choice was to go with a hybrid of the first two ideas; however in lieu of a spring, a rubber bands would be used. In doing this, assumingly having two forces propelling the car would increase the velocity and distance travelled. However, after thorough contemplating on each part, a mouse trap car was chosen for implementation. One of the forces may have overpowered the other rendering one of the forces useless in the propulsion of the car. In addition, having two different forces of propulsion would make calculations much more difficult than necessary. The final AutoCAD drawing of the manufactured car is seen in Figure 1a. and Figure 1b.

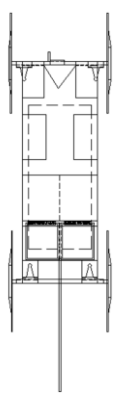

Figure 1a. The top view of the mousetrap car

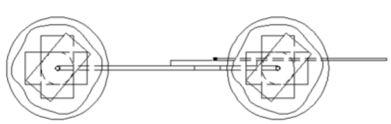

Figure 1b. The right side view of the mousetrap car

During the manufacturing stage, the focus was given on how the car could be fine-tuned to travel the farthest. It came to realization that with a small axle, large wheels, a long lever arm, and a strong propulsion force, the car would have a strong chance to compete for farthest distance. This works because with a long lever arm, the number of revolutions the axle goes through increases. In addition, because the axle and wheels have the same number of revolutions, making the axle smaller and the wheels larger would provide more translational displacement of the wheels, thus making the car travel farther. To account for a larger propulsion force, a test was conducted using two mousetraps attached to the same lever arm so they would act as one. In addition, it was also taken into consideration to make the car light so there would be less kinetic friction; as a result, a foam board was chosen as the body of the car (parts of it were 2ply so it could withstand the force of the mousetraps). To assemble the car, a combination of glue and duct tape was used, as both are very reliable adhesives.

A. List of materials for the Mouse Trap Car

3.5” x 10” Foam board (chassis)
4 CDs (wheels)
2 mouse traps (source of propulsion)
16” of 3/8” Grosgrain Ribbon (used to turn the rear axle system)
1 Straw (used to stabilize the axles)
Duct tape
Glue
4 Binder Clips (used to stabilize the axles)
4 Bamboo Skewers (axles)
1 Chopstick (lever arm)

III. Experiments

The purpose of this experiment is to calculate the average velocity for a mouse (or rat) trap car as well as calculate the distance for a mouse trap car to travel. Afterwards, the average velocity and distance travelled will be measured and compared to calculated values. During experiments, a spring scale attached to the lever arm of the mousetraps was used to calculate spring constant and in turn, propulsion force. Additionally, using a tilted dynamic track, the coefficient of kinetic friction was calculated by rolling the car down at a constant speed and was later used to calculate the kinetic frictional force. After massing all the components of the wheel and axle system, the moment of inertia was calculated and used, along with kinetic frictional force and propulsion force, to find the translational acceleration. The average time was found by measuring the time it took for the mousetraps to complete a full rotation when the car had been wound up and set free.

During testing, several setbacks were encountered which led to conduct some reconstruction. The main setback was that, albeit oblivious to the team at the time, the car exceeded the length constraint! The modification of design was done and another car was built to meet design constraint of eighteen inches. The calculations and measurements were re-conducted. In addition, solving for the translational acceleration proved to be quite a difficult task. Every time the team tried to calculate the translational acceleration, the torque generated by the mousetrap was calculated to be less than that of the kinetic friction thus resulting in a *negative* acceleration. After consulting with each other and the instructor Mr. Pantaleo, the team was able to identify the problem: the frictional force measured was not of the wheels, but of the axles. Therefore, in lieu of the radius of the wheel, the calculation used the radius of the axle and gave a positive, more reasonable answer. Also, during experiments, the car had a tendency to swerve to the right. As a result of its constant swerving, testing for velocity and distance became painstakingly difficult because it kept crashing into the surroundings and would not travel straight. It is resulted in that the axle system kept shifting while the car was running and that this was the source of the problem. To solve this problem, small binder clips were added and tested to prevent this movement. Finally, after taking care of the obstacles and setbacks, the car performed outstandingly!

A. Instructions of calculations

If a car is placed on a Dynamic Track and the track is tilted so that the car rolls down the track at a fairly constant velocity, then the coefficient of kinetic friction (μk) of the car can be calculated. It can be calculated with equation 1 below, where θ is the angle between the track and the table top. :

$$\mu_k = \tan\theta \tag{1}$$

The angle can be found either by measuring it with a protractor or by calculating it by measuring the height of the track (y) at some point and then measuring the length of the track from the point at which the height was measured to the end (x). Use equation 2 to solve for the angle.

$$\theta = \sin^{-1}\left(\frac{y}{x}\right) \qquad (2)$$

Now, that the coefficient of kinetic friction was found, the kinetic friction (fk) can be calculated. Since the car will be operated on a horizontal surface than the normal force (Fn) will be equal to the weight force (Fw). The mass of the car (mc) must be taken and then equation 3 can be used to calculate the normal force and then fk can be calculated using equation 4.

$F_n=m_c\times g$ where g is equal to 9.8 m/s^2 (3)
$F_k=F_n\times\mu$ (4)

The next thing to figure out is the spring constant of the spring in the mouse traps. To do this use a spring scale on the lever arm that is attached to both mouse traps and a protractor to measure the angle that the lever arm is pulled back. First, measure and record the distance in meters from the center of the spring to the lever arm where the spring scale will be pulling, this is the radius of the lever arm (r_L). Readings will be taken every 10° so to figure out the arc length (d_L) for each reading that the spring is pulled back, use equation 5.

$$d_L = \theta \times \frac{\pi}{180} \times r_L \qquad (5)$$

Pull back the lever arm with the spring scale to about 10° and measure the spring force (F_s) in Newtons. Make sure that the spring scale is perpendicular to lever arm. Take angle readings (θ) and spring force readings every 10° up to the maximum angle. Use this data to plot the force vs. arc length (d_L). The slope of the line is the spring constant of the mouse trap spring (k_{MT}). In this case, force of propulsion can be calculated by using equation 6 (where d_L is the arc length of corresponding to the angle the mouse trap lever arm is pulled back):

$$F_p = \frac{1}{2}k_{MT}d_L \qquad (6)$$

The inertia of the driven wheel and axle assembly (I_{WA}) must be calculated using equation 8. Note: This may require you to take apart your wheel assembly to measure the mass of the wheel and the axle. The radius of the axle (r_{axle}), the radius of the wheel (r_{wh}), and the radius of the tape (r_{tape}) will also have to be measured. Using the net torque equation 9 and breaking it down into its variables we are left with equation 10. Re-arrange equation 10 and solving for translational acceleration of the wheel (a_{wh}), results in equation 11.

$$I_{WA} = 2(I_{wheel}) + I_{axle} + I_{tape} + I_{hook_1} + I_{hook_2} \qquad (7)$$

$$I_{WA} = 2\left(\frac{1}{2}m_{wheel}r_{wheel}^2\right) + \frac{1}{2}m_{axle}r_{axle}^2 + m_{tape}r_{tape}^2 + \frac{1}{3}m_{hook1}L_{hook1\&axle}^2 + \frac{3}{2}m_{hook2}r_{hook2}^2 \qquad (8)$$

$$\tau_{NET} = \tau_{MT} - \tau_{FRIC} = I_{WA} \times \alpha \qquad (9)$$

$$(F_p \times r_{tape}) - (f_k \times r_{axle}) = \left(I_{WA} \times \frac{a_{wh}}{r_{wh}}\right) \qquad (10)$$

$$a_{wh} = \frac{[(F_p\times r_{tape})-(f_k\times r_{axle})]\times r_{wh}}{I_{WA}} \qquad (11)$$

In order to calculate average velocity, the time for the mousetrap's lever arm to move through its complete travel must be measured. Pull back the bail of the mousetrap and time how long it takes for the lever arm to go through its complete travel. Repeat this several more times, making sure the bail of the mouse trap is pulled back to the same position each time. Take about 5 trials then average the value (t_{avg}).

Solve for average velocity, with equation 12:

$$v_{avg} = \frac{v_f}{2} = \frac{(a_{wh}\times t_{avg})}{2} \qquad (12)$$

In order to calculate the distance travelled, break up the calculations into the two distinct parts of the movement. In the first part for the full travel of the mousetrap lever arm, the kinematics equations can be used. Since the a_{wh}, v_o and t_{avg} are known, the distance for the first part can be calculated using equation 13. Also, calculate final velocity (v_f), which will be used later, with equation 14.

$$x = v_o t + \frac{1}{2}a_{wh}t^2 \qquad (13)$$

$$v_f = v_o + a_{wh}t \qquad (14)$$

After the mousetrap has gone through its complete travel, frictional force will slow down the car until it stops. We can analyze this part by using conservation of energy. Once the mousetrap has gone through its complete travel, the only energy the car possesses is kinetic energy (translational and rotational). Since friction is acting on the car there is non-conservative force on the car therefore non-conservative work. The final kinetic energies will be equal to zero since the car stops. The movement is therefore defined by equations (15) and (16).

$$W_{nc} = KE_0 + KE_{0r} - KE_f - KE_{fr} \qquad (15)$$

$$f_k \times s = \frac{1}{2}mv_0^2 + \frac{1}{2}I_T\omega^2 - 0 - 0 \qquad (16)$$

The frictional force (f_k) was calculated before when finding average velocity. The total inertia (I_T) will be the inertia of the driven wheel assembly and the non-driven wheel assembly. The inertia of the driven wheels was calculated before when calculating average velocity, but this time the inertia of the non-driven wheels must also be found. Use (18) to calculate the inertia of the non-driven wheels. The initial velocity (v_o) will be the final velocity from the section above when calculating final velocity equation (14). The initial angular velocity (ω_o) can be calculated using equation (19).

$$I_{WA} = 2(I_{wheel}) + I_{axle} \qquad (17)$$

$$I_{NON} = 2(\frac{1}{2}m_{wheel}r_{wheel}^2) + \frac{1}{2}m_{axle}r_{axle}^2 \quad (18)$$

$$\omega_0 = \frac{v_0}{r} \text{ where r is the radius of the wheels} \quad (19)$$

With all of the variables of equation 16 found, the only variable left will be distance (s). So, the equation can be arranged to solve for distance, equation (20).

$$s = \frac{\frac{1}{2}mv_0^2 + \frac{1}{2}I_T\omega^2}{F_k} \quad (20)$$

Take the distance in equation (13) and add it to the distance in equation (20). This should be the total calculated distance.
To measure average velocity, use a stop watch and ruler. For each run, record several points of distance and time so they can be plotted on an x vs t graph. The line of best fit on the graph will indicate average velocity.
Between the measured data and the calculated data, calculate the % error by equation (21) and (22) below.

$$\%\,error\,(v_{avg}) = \left(\frac{v_{avg\,calculated} - v_{avg\,actual}}{v_{avg\,calculated}}\right) \times 100\% \quad (21)$$

$$\%\,error\,(dist.trav.) = \left(\frac{distance\,trav._{calc} - distance\,trav._{meas.}}{distance\,trav._{calc}}\right) \times 100\% \quad (22)$$

B. Procedure of Calculating Frictional Force

1. Set up a Dynamic Track so that it can be tilted
2. Place the car on the track and tilt it so that the car rolls down at a constant velocity
3. Take a protractor or use equation 1 to find the angle of the track (repeat for at least 3 times and take the average)
4. Use equation 1 to calculate the coefficient of kinetic friction (using the average found in step 3)
5. Take the mass (mc) of the car
6. Use equation 3 to calculate the normal force
7. Use equation 4 to calculate the kinetic frictional force
8. Record the data in Table 1

C. Procedure of Calculating Spring Constant and Spring

1. Measure the distance in meters from the center of the spring to the tip of the lever arm (rL)
2. Obtain a spring scale and attach it on the lever arm of the mousetraps
3. Pull back the spring scale so that it remains perpendicular to the lever arm
4. Use a protractor to measure the angle that the mousetrap arm is pulled back for every 10° from 10° to 50° and 90° and 180°
5. Use equation 5 to calculate the arc length (dL) for the reading
6. Measure the spring force (Fs) displayed on the spring scale
7. Use the data obtained to plot the force vs. arc length graph
8. Find the slope of the line. This is the spring constant (kMT)
9. Calculate the force propulsion (Fp) using equation 6
10. Record the data in Table 2

D. Procedure of Calculating Average Acceleration

1. Measure the mass of the wheel, the axle, the tape, and the two parts of the hook in kilograms
2. Measure the radius of the wheel, the axle, the tape, and the hook
3. Measure the distance from the tip of the hook to the axle
4. Use equation 8 to calculate the inertia of driven the wheel and axle system
5. Use equation 11 to calculate the translational acceleration of the wheel
6. Record the data in Table 2

E. Procedure of Calculating Average Velocity

1. Wind up the string around the axle and release the car. Measure the time (in seconds) it takes for it to go through its entire rotation
2. Repeat this for 5 trials and then take the average value of the time (tavg)
3. Use equation 12 to calculate average velocity
4. Record the data in Table 3

F. Procedure of Calculating the Distance Traveled

1. Use equation 13 to calculate the displacement of the first segment of movement (distance when car is being pushed by the mousetrap)
2 .Use equation 14 to calculate the final velocity (v_f)
3. Calculate the inertia of the non-driven wheels using equation 18
4. Use equation 19 to calculate the initial angular velocity (ω_o)
5. Use equation 20 to calculate the displacement of the second segment (distance when car is coasting to a stop)
6. Find the total displacement by adding the values from equation 12 and 20
7. Record the data in Table 4

G. Procedure of Measuring Velocity and Distance

1. Using strips of tape, mark points of distance from the starting point to a distance of 30 meters using increments of 3 meters
2. Wind up the car and release it
3. Using a stop watch, record the elapsed time at each respective point of distance
4. Plot the data in a distance vs. time graph and find the line of best fit. This will be the average velocity
5. Measure in a straight line from where the car starts and stops (the car must travel within a lane of 2.00 meters wide). This will be the displacement
6. Repeat this three times and average the obtained values
7. Use equations 21 and 22 to calculate the % error between the measured and calculated data
8. Record the data in Table 5a and Table 5b

IV. Observation Data

Following the instruction and procedures, the following data was collected:

TABLE 1: FRICTION FORCE

.Mass of mc (kg) (5D): 0.17720

Trial	1	2	3
Height of track(m)(y)	0.0200	0.0325	0.0220
Length of track (m)(y)	1.3000	1.3000	1.3000
Angle of track (degrees)	0.881	1.43	0.970
Avg angle of track	1.09		
Coef. of Kinetic Friction	0.0191		
Normal Force(Fn)	1.7366		
Kinetic Frictional Force (fk)	0.0332		

TABLE 2 Spring Force, Average Acceleration

Angle of Lever Arm (degree) – θ, Arc Length -(m) (d_L), Spring force -(N) (F_s), Spring Constant (N/m)-(k_{MT}), Force of Propulsion (N) $- F_p$, Inertia of Wheel and Axle (kg·m^2)- (I_{WA}), Translational Acceleration (m/s^2) $-(a_{wh})$

(θ)	(d_L)	(F_s)	(k_{MT})	(F_p)	(I_{WA})	(a_{wh})
10.00	0.03433	1.60	5.13	1.60	7.6 x 10^{-5}	4.5
20.00	0.06946	2.00				
30.00	0.1042	2.00				
40.00	0.1389	2.40				
50.00	0.1737	2.40				
90.00	0.3126	2.80				
180.00	0.62518	4.20				

TABLE 3 AVERAGE VELOCITY

Trial #	Time (seconds)	Average Time (seconds) (t_{avg})	Average Velocity (m/s) (v_{avg})
1	2.31	2.36	5.3
2	2.61		
3	2.25		
4	2.35		
5	2.28		

TABLE 4 DISTANCES TRAVELED

Car is being pushed by mousetrap	Initial Velocity (m//s)	0
	Translational Acceleration (m/s^2) (a_{wh})	4.5
	Average Time (seconds)	2.36
	Final velocity	11
	Displacement	12
Car is coasting to a stop	Inertia of non-driven wheels	7.6×10^{-5}
	Inertia of Wheel and Axle (kg·m^2) (I_{WA})	7.6×10^{-5}
	Total Inertia (kg·m^2) (I_T)	1.5×10^{-4}
	Initial Angular Velocity (rad/s) (ω_0)	170
	Displacement (m) (x_2)	360
	Total Displacement	370

TABLE 5A: EXPERIMENTAL RESULTS

Distance	Time		
0.0000	0	0	0
3.000	2.26	2.25	2.22
6.0000	3.42	3.39	3.41
9.0000	4.01	4.02	4.01
12.0000	5.58	5.57	5.59
15.0000	7.13	7.12	7.14
18.0000	8.90	8.91	8.89
21.0000	10.26	10.25	10.26
24.0000	14.81	14.82	14.80

TABLE 5B: EXPERIMENTAL RESULTS

Trial	1	2	3
Theoretical Average Velocity (m/s) (v_{avg_T})	5.3		
Experimental Average Velocity (m/s) (v_E)	1.762	1.761	1.595
Experimental Average Velocity (m/s) (v_{avg_E})	1.706		
Theoretical Total Displacement (m) (x_{Total_t})	370		
Experimental Total Displacement (m) (x_{Total_E})	25.54 00	25.12 00	27.13 20
Avg Experimental Total Displacement (m) (x_{Total_E})	25.9307		
% Error of (v_{avg})	68		
% Error of (x_T)	93		

V. Conclusion

Using the fundamental concepts of mechanics, the team successfully designed, produced, and tested a self-powered, mechanically-driven car. The idea of a mousetrap car was taken and adapted to travel far. With understanding of the concepts of Kinematics, Conservation of Energy, Newton's Laws, and Rotational Dynamics, the team was able to construct a procedure finding the average velocity and distance travelled of the car. Albeit difficult at times, the team was able to unite, and withstand the various problems and setbacks presented to it. Combining their knowledge of classic mechanics and their dexterity, all the team members created a car that not only met every constraint; they created a car that exceeded them.

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