Sketch Model Challenge

Fast&furious Engineering

***Abstract*—This paper describes the design process behind the creation of a hand-cart made of mostly reusable material such as insulation foam and paper products. The cart had to be manually operated and support one rider, it took place in a dodgeball tournament where it successfully lasted through all of its rounds. The cart built by the team consisted of a one-wheeled device constructed out of mostly cardboard packing tubes and insulation foam (See Fig. 1)**

I. Introduction

This project required the students to come up with creative concepts and design to build a functional human powered cart to play a game of outdoors dodgeball. The challenge would introduce the students to the principles of sketch modeling, from the brainstorming phase, to the specific materials, and also prototyping methods of fabrication.

Constraints were placed on the materials by adding a 30 times weight count for materials that were not paper or insulation foam. Thus penalties were applied to the heaviest contraptions.

The weight penalty was driven by the following equation:

$$Weight_{totalcart} + 30 * Weight_{nonpaper} \quad (1)$$

Requirements were then decided by the team and were as such:

-Must support a 90kg load
-Must accommodate for a 6' tall person
-Must go at least 2m/s
-Must weigh less than 25kg
-Must be able to work in at least 2" of snow
-Must cost less than $75

With these requirements in mind, calculations were made to estimate the dimensions of critical components of the cart, accommodating for both these functional requirements, as well as material requirements.

II. Design Process

A. Concept Generation and Evaluation

Initially, each team member came up with ideas individually and then the team gathered and considered all the different designs. By considering the set requirements, and the different ideas behind the sketches, the list of potential design was progressively reduced to a handful of ideas. One of them was a one-wheeled wheelbarrow where the rider would be sitting near the wheel and thee driver would pull the cart, it was considered because the single wheel could provide great mobility but having one wheel means that all the load would go on it.

Fig. 1. Picture of final prototype

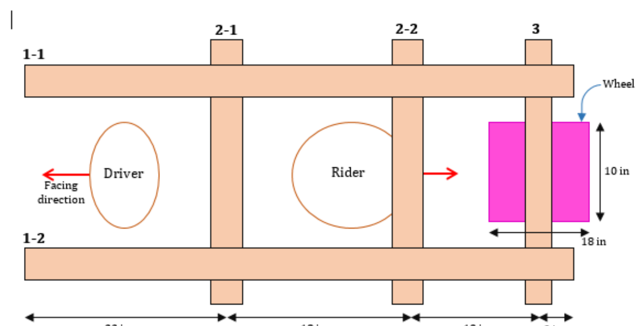

Fig 2. Dimension of cart

Table 1. List of elements

Number	Categories	Outer Diameter	Thickness	Length
1-1, 1-2	Main rod	3 inch	0.15 inch	63 inch
2-1, 2-2	Back supporter, Seat	3 inch	0.15 inch	25 inch
3	Axle	2 inch	0.25 inch	25 inch
N/A	Wheel	18 inch	N/A	10 inch

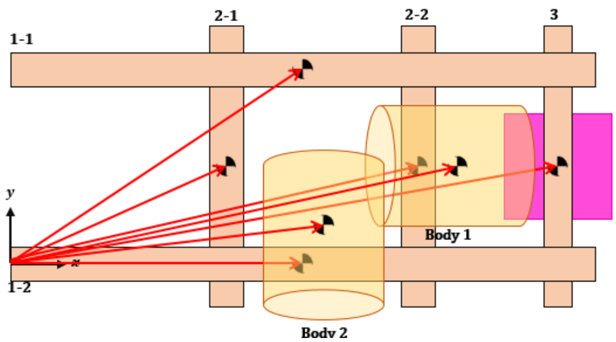

Fig 3. COM analysis

Another design consisted of a 2-wheeled chariot where the two wheels were on the outside of the cart and the driver would pull the chariot forward, it was considered because of the great stability of the two wheels but with this amount of wheels the bearing would need to perform optimally to provide great mobility. Finally a 4-wheeled tank cart was imagined where the driver would be totally enclosed for great protection, however this would require substantial amount of material meaning a lot of weight.

The one-wheeled design was chosen as it seems it would be able to provide great mobility while being the lightest, which would fit the requirements set by the team.

The frame was decided to be built out of cardboard tubes as they are paper based and easy to find. To accommodate a rider, a seat made of a single cardboard tube was imagined where the rider would just sit on top, and then a back support tube would be added higher up in order to give the rider a support to prevent failure and also gave an upright position that was good for throwing the balls.

Additionally a handlebar (see Fig. 7) was thought of, after figuring that it would be easier to pull the cart than push it. Therefore at the end of the side tubes, another tube would be attached to provide the driver with a large surface to grab on and pull.

To allow rotation of the wheel, a fixed axle would be attached to the structure and the wheel would be inserted in with a bigger hole.

By looking at an analysis of the forces, it was determined that the axle and handlebar should be placed on top of the structure since the force was upright and therefore they would not add compression to the structure. The opposite for the seat, since the force was acting down, it was decided to place the seat underneath the frame. For the back support, although the force also points down, it was decided that it would be more beneficial to place it on top to provide a better position to the rider since the force would not be very high.

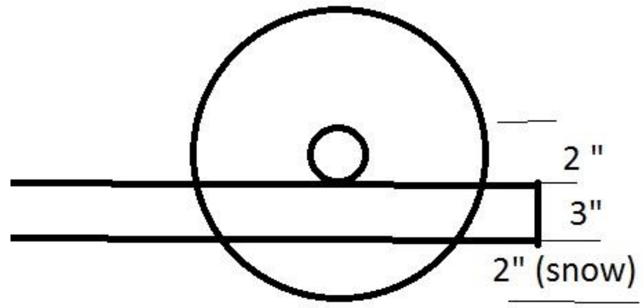

Fig 4. Wheel assembly

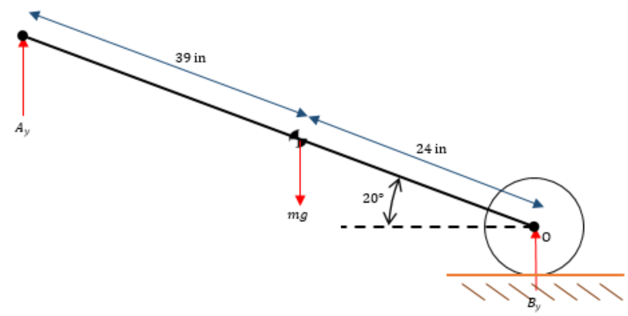

Fig 5. Calculation of load

In order to determine the width that was required for the cart to be stable, an analysis of the center of mass was performed. (See Fig. 3)

With the assumption that in order for the cart not to topple, the center of mass should always remain directly above the wheel. When the rider is located in the middle of the cart, the overall center of mass (COM) is located along the symmetric line. However, when the rider tries to grab a dodgeball, the center of mass of the upper body of the rider will shift. This offset of COM can cause instability of the structure. If the position along y-axis of the overall COM is located within the wheel width, then the total resultant force will act inside the wheel, therefore cannot inflict instability of the structure. To simplify calculation, the body of the rider is assumed as two cylinders. Each cylinder has a mass of 45kg. When the rider tries to grab a ball, upper cylinder will incline long y-axis with 30°.

By the definition of COM is,

$$\vec{r}_c = \frac{1}{m}\sum_{i=1}^{n} m_i\vec{r}_i \;;(i = 1,2,3,\dots) \qquad (2)$$

B. Detailed Prototype Design

Using the data acquired from the simulated seating, it was decided to place the seat about 24" from the bottom, and the back support 20" away from the seat. The axle would rest 3" away from the end to ensure it wouldn't slip off its bindings. (See Fig. 2)

To guarantee that the total force acting on the wheel does not affect its integrity, load test is necessary.

Fig 6 . Picture depicting the square lashing

Based on the calculation of overall COM, with simplification, free body diagram is depicted on Figure 5. Unknown forces, including A_y and B_y is calculated based on the total resultant torque equation.
The angle between the structure and the ground is estimated to be 20° by assuming that point A will rise 35" from the ground by the driver
The calculation of the total resultant torque about point O:

$$\sum M = mg * (24in) - A_y * (39in) = 0 \quad (3)$$

$$A_y = \frac{(187lbf)*(24in)}{39in} = 115lbf \quad (4)$$

$$A_y + B_y = 187lbf \rightarrow B_y = 72lbf \approx 320N \quad (5)$$

So the force felt on the axle is 320N based on a load of 90kg on the seat
As for the wheel, to figure out its diameter, several constraints had to be taken into account. Firstly, according to the requirements, it had to accommodate for at least 2" of snow, since the axle was placed on top and was 2" diameter, and including the 3" diameter of the frame tubing, the wheel would need to be at least 14" diameter (See Fig. 4**)**. Secondly, the maximum diameter was constrained by the placement of the seat, which limits the wheel to less than 24" diameter. It was decided to go with 18" as this would provide additional safety in the case of greater snow on the ground.
Finally to estimate the width needed, using equation (2) and the parameters defined previously, the location of the center of mass when the rider grabs a dodgeball is now

$$\vec{r_c} = 39.4\hat{\imath} + 5.64\hat{\jmath} \quad (6)$$

Fig 7. Picture showing the shoulder straps and handlebar

So in order to have a wheel that covers this maximum center of mass offset, the wheel should be at least 9.72" in diameter. Given that the foam came in thickness of 2", the width was set at 10" width, or five layers of foam.

C. Fabrication of Prototype

The structure of the cart was made of cardboard shipping tubes (See table 1) of various lengths and diameter. The main two lateral tubes were 63" long, with 3.25" Inner diameter and .2" wall thickness shipping tubes. The seat, back support and handlebar were made of 30" long shipping tubes, with inner diameter of 3" and .15" wall thickness. The axle was composed of two 16" long cremation tubes, both with inner diameter of 2" and .25" wall thickness.

These two tubes were joined together with a PVC piece that was inserted and glued onto those two tubes. Since the PVC had a bigger thickness, and to prevent the axle to be only supported on the PVC; paper was wrapped along the surface of the axle in order to make the whole surface flush.
The wheels were made of insulation foam that were 18" diameter and with a hole in them of 3" diameter. The wheels were glued together and were also glued to a 12" long cardboard tube with diameter 3". Those wheels were cut using a CNC machine.
To make sure the wheel would stay in the middle of the axle, holes were drilled through the axle and pencils were inserted to block the wheel in place.
Additionally, the outside of the wheel was covered in a layer of protective duct tape to prevent the foam to enter contact with hard and wet material.

The main method of assembly to connect the various tubes together consisted of using mason twisted rope. Using a square lashing technique (See Fig 6), all the tubes were tightly connected to each other. To prevent any movement of the rope, duct tape strips were added around the connections as well.

To spread the load for the driver, shoulder straps were made connecting the handlebar and back support tubes. Those straps were made of a single layer of duct tape and a layer of cardboard attached to it. (See Fig 7)

For protection, a shield was made using a large cardboard sheet and an unused wheel foam cutout was attached to the back of the shield to provide rigidity. Cardboard straps were added to provide grip points.

Finally the entire cart was decorated with a mixture of wrapping paper and red spray paint

III. RESULTS

Initial experiments were made to test the bearing and its ability to rotate properly under a full load. It was found that the cardboard on cardboard was successful and that the gap size between the 2" axle and 3" wheel hub still allowed the wheel to rotate properly.

Also to test out the strength of the ropes, members of the team sat on the tubes in order to simulate the load of the rider and make sure than it could be supported by the rope lashing.

The only materials purchased were the two long tubes, the foam for the wheels and all the binding materials (glue, rope, and tape), meaning the cost fell under the $75 requirement.

The weight of the cart, including the weight penalty for the PVC, tape and rope was calculated using equation (1) and found that it was 22kg which met the set requirement, and was not the heaviest cart.

The driver was able to pull the cart while running at a jogging speed which is around 4 m/s.

The tallest and heaviest member of the team, 6' tall and with the cart still being intact so the design accounted well for that.

The shoulder straps broke very early in the dodgeball tournament and had to be abandoned which increased the load on the driver significantly but did not hinder the structure of the cart.

Also the shield straps broke very easily which made the shield hard to operate.

However the cart itself remained fully functional throughout the entire competition and its high mobility and maneuverability allowed the team to eliminate a lot of teams and bring victory to its side.

IV. DISCUSSION

It was very important to decide on several key components of the design with the use of theoretical expectations, this way making sure that the design would perform well and thus not wasting any material when constructing the cart. The load and center of mass calculations allowed the team to properly pick the correct size and width of the single wheel, a crucial component of the design.

The only parts that failed were the ones that were added at the last moment to solve problems without taking any technical considerations in account so it should not be surprising that they did not perform well. If it were to be done again, the straps should have been properly tested and their weakness would have been exposed, allowing the team to properly strengthen the component and thus not breaking off midst competition.

Also a more conservative approach should have been done to limit the use of the duct tape by maybe trying to reduce the amount, or find a non-penalized equivalent as the tape with the penalty accounted for more than half the weight, even though in the end the weight requirement was still met.

Overall, the prototype exceeded expectations and felt like a perfect example of simplicity expected from a sketch model, but with its fair share of thought process behind it expected from a well-engineered product.

V. CONCLUSION

With thoughtful design process and choice of material, the initial problem of the human powered cart was solved using techniques of sketch modeling and resulted in a fully functional prototype created in a short amount of time.