Wheely Wonka

Paper Bike & Flag Retrieval System

ME 310: Paper Bike Design Document

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1 Executive Summary

1.1 Background/Context

The paper bike competition has been a longstanding tradition in ME 310, a year-long project class focusing on design innovation. Every year, teams of three to four students work together to make a vehicle out of paper products as a means of having fun while getting to know classmates. The Autumn 2010 paper bike competition was a variation of the “Capture the Flag” game. Offensively, each macro team, consisting of four paper bikes each, must invade the opponent’s territory, obtain the flag, and either carry or launch it back to the team’s own territory without touching the flag. Defensively, each team must protect their own flag through tagging the enemy either by hand or by launching water balloons.

1.2 Vision & Approach

The macro team, named the A-Team, collectively decided to have one bike focused on defense, another focused on offense, and the remaining two capable of taking on either role. The Wheely Wonka team was designated as the last category—equipped to be either offense or defense, depending on what the A-Team needed at the moment. Given this dual role, Wheely Wonka needed to be very versatile, especially allowing for rider mobility, pusher speed, and vehicle sturdiness. Hence, the main focus was primarily on the body of the vehicle. Afterwards, accompanying tools were made to retrieve and launch the flag and to launch water balloons at opponents.

Past designs have shown that a simple frame with two independently rotating front wheels is a successful means of transporting a person. Although Wheely Wonka uses this general template, this paper bike is unique in several ways that cater to the pusher, the rider, and even the spectators. In addition to being a fully-functional, easy-to-push vehicle, Wheely Wonka stands out aesthetically with its hypnotizing wheels and its beautifully arched rainbow handles, making it a sight to behold. The handle allows the pusher to choose whichever hand position feels most ergonomic and comfortable. This new version of the paper bike also allows for easy rider mounting and dismounting, which greatly enhances the user experience. The seat is comfortable and also allows the rider to balance without using his/her hands, giving the rider a sense of security that allows the rider to freely enjoy the experience without a worry about falling off.

1.3 Key Features of Design

The emphasis of Wheely Wonka was to allow the rider to stay on without using his/her hands so that the rider can freely tag other teams when playing defense and use the flag-capturing tools when playing offense. The Wheely Wonka vehicle achieved this objective by allowing the rider to comfortably latch his/her feet behind the sturdy rider support tube, as shown in Figure 1.1, giving the rider a sense of security.

Another important emphasis of Wheely Wonka was to be agile. Whether chasing after invading opponents to tag them or dodging opponents to reach their flag, the vehicle must be able to move fast. To accomplish this, the pusher must not get too tired too fast—in other words, the vehicle must be easy to push. This requirement was accomplished in Wheely Wonka through positioning the seat such that the weight of the rider was slightly in front of the axle to balance out the weight of the vehicle frame behind the axle. With this arrangement, the pusher does not have to carry any of the rider weight and only needs to provide the horizontal force required to move forward. Graphite powder was placed in the axle-wheel connection to further aid in reducing opposing friction forces. Wheely Wonka also has padded, curved handles, which allow the pusher to choose which angle feels most comfortable.

Figure 1.1. Rider uses legs to grip Rider Support Tube for balance.

Wheely Wonka had a bearing system designed to reduce friction between the wheels and axles. Aluminum cans were glued onto the axle, and contact paper was taped to the inner lining of the wheels to provide smoother surfaces than cardboard. Then, graphite powder was used as a lubricant to further reduce the friction between the wheel and the axle.

Since the rider was not allowed to touch the ground, it was also important for Wheely Wonka to have a firm platform on which a rider can stand in order to effectively throw the flag-containing, cardboard football back to the safe side. The back end of the seat doubled as a standing platform when the vehicle was set on the floor.

1.4 Results & Lessons Learned

During the paper bike competition game, Wheely Wonka dominated the field. The agility of the vehicle allowed the pusher to race across the field. Its maneuverability allowed the paper bike to dodge several water balloon attacks by opponents. Its stationary stability allowed the rider to have a steady stance while throwing the flag-containing football back to the A-Team field.

The only significant malfunction with Wheely Wonka during the intense game play was that the bearing materials were ripped and shredded, causing the wheel movement to be constricted. However, having removable external hubs and extra zip ties allowed the team to successfully clear the blockage between the axle and wheel, therefore freeing the wheel to again spin smoothly.

The maneuverability and versatility of Wheely Wonka allowed it to be the highest-scoring vehicle on the field. The simple football launching method ended up scoring the most points. The tube-structure of the Wheely Wonka wheels held up during the intense match. The Wheely Wonka team not only built a successful paper bike, but also learned the importance of extensive brainstorming, early prototyping, manufacturing feasibility, and efficient teamwork.

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2 Glossary

- **Paper Bike:** A vehicle made out of paper/cardboard that is human powered and can carry at least one person at all times
- **The Game:** A game of capture the flag played by 2 teams each consisting of 4 paperbikes each. The goal is to get the opposing team's flag into the home team's half
- **Wheely Wonka:** Our team name as also our rendition of the paper bike this year
- **A-Team (a.k.a. Macro Team):** the 4 paper bike teams comprising of teams 1 to 4
- **Rider Support Tube (a.k.a. The Cannon**): A multipurpose cardboard tube at the base of Wheely Wonka that can support the feet of the rider and store the football and loading spoons (explained below)
- **Flag Spear:** A long cardboard tube with a pointed spear like end that is used to successfully pull the flag out from the pole
- **Spear Holders:** Two small cardboard tubes that can hold the flag spear when it is not being used
- **Loading Spoons:** Cardboard cutout in the shape of a spoon (and reinforced) that is used to hold a part of the flag and force it inside a football (defined below)
- **The Football:** A small cardboard tube that can contain the flag completely and can be launched 80' easily just like a football. It is padded with soft tape on the exterior
- **Gor-wood-lla Glue:** An indestructible combination of Gorilla and Wood glue, this has been a key component of our joint designs. The Gorilla glue component expands as it hardens, helping to add rigidity to joints where tolerances are otherwise loose.
- **Rainbow Handle:** A rainbow shaped handle at the head of Willy Wonka than allows the pusher to have a better grip over the bike frame
- **Concentric Tube Wheels:** Large diameter wheels made of an outer 30" ring whose internal area is reinforced by 25 smaller 3-5" diameter tubes arranged in concentric circles about a filled 10" Inner Wheel.
- **Inner Wheel:** A 6" long x 10" diameter tube reinforced with cardboard sheets that houses the axle. It is contacted by reinforcing tubes on the outside
- **Internal Hub:** A retaining cardboard ring placed inboard of the wheel that keeps it constrained laterally on the axle. Acts as a thrust bearing.
- **External Hub:** A retaining cardboard ring placed outboard of the wheel that keeps it constrained laterally on the axle. Acts as a thrust bearing.
- **Seat:** A rounded piece of cardboard, from a 36" diameter tube, on which the rider can comfortably sit at all times.

3 Context

3.1 Need Statement

Versatility is the buzz word in today's competitive world that embraces adaptability. Stanford University, realizing this, has tailored its Masters program so that a Grad student will gain both depth and breadth in Engineering. In the niche market of sports entertainment there is a great demand for varied activities such as dirt track racing, bull riding, mobile sunbathing and just cooling off in the hot sun. Moreover, realizing that people who like some of the above mentioned activities is usually a superset of people who are actually able to do them, Wheely Wonka was created. Simple and elegant in its design, easy to maneuver and varied functionality, it's the most versatile paper cart ever built. Moreover, it is great value for your money. With Wheely Wonka, a user can get a taste of bull riding, racing, sunbathing and either pushing hard or dozing off all the while playing a sport called capture the flag. The vehicle can also serve alternative purposes such as ferrying off the injured in an accident, transporting the differently abled, etc. Its big wheels make it a makeshift wheelchair in times of emergency. To sum up, the Wheely Wonka is a one stop shop for all your needs in today's world. And it's wheely wheely cheap!

3.2 Problem Statement

Although the paper bike has been a traditional team-building project in ME310, the context and rules of the competition varies each year. This year, the goal is to work with a macro team to play "Capture the Flag" against the other half of the class.

The specific vehicle design constraints can be found at: (310 Teaching Team, 2010)
Bicycle Design Constraints (https://310content.stanford.edu/node/335)

The details for the rules of the game can be found at: (310 Teaching Team, 2010)
Capture the Flag Rules (https://310content.stanford.edu/node/337).

In particular, this year's Paper Bike "Capture the Flag" competition presents a few noteworthy and unique design challenges. These include the following:

- All bikes must be resistant to water balloon impacts from close range, as well as water resistant to the drenching that may ensue
- All bikes have the opportunity to launch water balloons at one another, and thus may be built with integrated launching capabilities in mind.
- All bikes must facilitate the recovery of a small green flag from atop 9-foot pole without touching the flag. By definition, this must include some 9 foot tall device and some rider controllable manipulator for handling the flag.
- Finally, all bikes are allowed to launch the flag across an ~80ft distance to score extra points for their team. Like the water balloon launcher, this provides an opportunity for an integrated launch solution that is critical to competitive game play.

4 Design Requirements

The main design requirements of the paper capture the flag vehicle are to safely, comfortably, and effectively mount the rider in a position in which they are able to actively participate in a game of paper bike capture the flag while continuously adapting to the actions of the other team; this must all be done under the physical power and quick decision making capabilities of a human pusher. A successful design will integrate numerous rider positioning and pusher aiding requirements into a vehicle which is effective and user friendly. Additionally, a successful design must be both robust and durable enough to successfully withstand a few rounds of intense testing along with two one-hour game play sessions, the Local Rally and the Global Rally.

The design requirements are broken down into Functional, Physical and User Requirements. In addition, constraints, assumptions and opportunities of each category are listed below. For more reference about Design Requirement, see the "Requirements" handout. (Cutkosky, 2010)

4.1 Functional Requirements

4.1.1 Functional Constraints

- The vehicle must be human powered (No stored energy is allowed).
- The rider must not touch ground during the game.
- The vehicle, water-balloon launcher, the Football and flag spear poses no danger to any riders or pushers (No sharp object, pinch points or heavy objects that can injure players.)
- The vehicle is endurable and stable during the game.

4.1.2 Functional Assumptions

- The game will be played on a relatively dry field.
- The vehicle will survive the game in good enough condition to test for next year's game.
- Supporting a portion of the passenger's load would detract substantially from maneuverability and playability.
- All the pushers are healthy and strong/fit enough to push/pull the vehicle for 10 minutes at competition speed (around 7.7 ft/second).
- Collisions will occur, but not serious.

4.1.3 Functional Opportunities

- The human power source can push/pull the vehicle.
- Footseats, handholds or other features could be added to stabilize the rider and prevent accidental ground contact.
- Both rider and pusher can control steering.
- The vehicle can be aesthetically pleasing.
- Team 1 to 4 (A Team) can share defense/offence strategies before and during the game.

Table 4.1. Functional Requirements

Functional Requirements	Metrics	Rationale
Vehicle is sturdy/strong enough to support a rider during game play	Vehicle holds 400 lbs at standstill and 150 lbs with side loads. Vehicle at 7.7 ft/second speed will not exhibit structural failure confronted with sudden acceleration and deceleration within 1 second.	The rider's weight must not break the Vehicle. We are assuming rider is <200 lbs and that the perceived weight during (vertical) acceleration is 2g.
Allow rider to balance without using hands	Rider does not need to use hands for balance during 85% of the duration of a trial run[1]. Rider only needs hands during a collision or rush turn.	Rider needs hands to grab flag, tag opponents, use a shield, or launch or dodge water balloons.
Can withstand water balloon impacts	Vehicle will not exhibit structural failure after 20 balloon impacts worth of water contact per match.	Assume we will be hit with (quite) a few water balloons per round.
Can withstand frequent collisions	Vehicle can withstand 10 collisions with other vehicles per match or 1 collision per minute at speeds of up to 15 ft/second.	Assume we will collide with other vehicles several times per round.
Keep lifting effort low for the pusher and let the rider participate in balancing the vehicle.	Rider can balance by shifting his/her weight even when pusher is not putting vertical force on handles.	This stability will remove the need for the pusher to exert effort vertically, thus increasing their efficiency and endurance.
Vehicle should not require significant vertical force from pusher	Vertical force from pusher is less than 20N with rider on the vehicle at some angle within reasonable range.	Want all of the pusher's force to move the Vehicle horizontally so that minimal force is wasted in the vertical direction.
Little friction between wheels and axle	Wheel can spin for at least 2.5 seconds when lifted off the ground and spun with hand spinning motion.	Less friction will reduce the force necessary to move the vehicle.
Easy for one pusher to push/pull the vehicle	All team members can push/pull any other team member 20 ft within 3 seconds.	The vehicle is powered by one pusher, and we do not want him/her to get tired too fast.
Easy for one pusher to turn vehicle	Can turn vehicle 360o in 5 sec while moving forward at 7.7 ft/seconds.	The vehicle is powered by one pusher, and we do not want him/her to get tired too fast.
Easy for one pusher to stop vehicle	Can stop vehicle within 3 ft when travelling >7ft/second.	The vehicle is powered by one pusher, and we do not want him/her to get tired too fast.

[1] A trial run is defined as three minutes of pushing a rider that includes sharp turns, sudden stops, sudden acceleration, and going backwards.

Vehicle is comfortable for the rider	All team members agree that vehicle is comfortable enough that they are willing to ride for every round of competition.	Rider does not want to feel sore after the game.
Vehicle positions rider such that he/she is able to tag opposing team members	The rider is able to reach up to 1.25 arms length in any direction while vehicle is in motion.	The Game rules necessitate tagging as a basic defensive strategy in order to be competitive.
Vehicle is maneuverable enough to aid in tagging opposing teams	Vehicle is easy to push, pull and turn with restrictions stated above.	We want to help our team not lose!
The flag spear is easy to use for flag capture	Each team member as a rider can catch flag within 30 seconds.	We must retrieve the flag in order to place it in the football and throw it back to our side.
The Football is capable of being thrown far enough	50% of team members rider can throw at least 80 ft for 80% of throws.	A good Football helps with more odds to score per flag capture.

Figure 4.1. Wheely Wonka team closing in on the flag.

4.2 Physical Requirements

4.2.1 Physical Constraints

- The vehicle fits in 3' x 3' x 5' box.
- Approximately 5 minutes for quick repairs in between rounds of the game.
- Total bike cost should not exceed $50 for the entire team

4.2.2 Physical Assumptions

- The paint is water-resistant.
- The materials (mostly paper) designed for the vehicle can be found within a 30 mile radius of the Stanford campus.

4.2.3 Physical Opportunities

- Zip-ties, tapes, ropes, glue and screws which are lightweight can be counted toward the 500g non-paper material limit to increase durability.
- The vehicle can carry an unlimited number of water balloons.
- The flag pole used in the game is available for testing before the game.

Table 4.2. Physical Requirements

Physical Requirements	Metrics	Rationale
Vehicle is constructed such that rider does not touch the ground.	Rider does not touch ground during standard vehicle operation.	It's harder this way. And it's in the rules.
Vehicle is primarily constructed out of paper-product materials.	No more than 500 g of non-paper products[2].	Again, those pesky rules. We still maintain helium balloons should count for negative weight. :-)
Vehicle can be transported to the playing field	Must be able to move from the loft to the field for multiple times under the power of 1-2 team members within 15 minutes without damage to the vehicle.	We do not have superpowers (that we tell people about).
Vehicle must be made with a sum BOM that is affordable	We'll shoot for under $50 total.	We are college students.
Wheel must be novel and beautiful.	We'll say that a wheel made of 25+ circles should qualify.	Beauty + innovation = cool.
The vehicle can transport water-balloon launcher and/or flag spear during the game	The vehicle enables enough room for water-balloon launcher or flag spear without affecting the normal use of the vehicle.	Rider can easily access the tools while in need and should not be disturbed (also for pusher) by the tools otherwise.

[2] In general, any product for which the mass of binder or resin is substantial (let's say greater than 50%) in comparison to the mass of paper will be designated as a "composite" and subject to the non-paper material limit.

4.3 User Requirements

4.3.1 User Constraints

- Rider cannot step on the ground at any time.
  Rider has limited arm length.

4.3.2 User Assumptions

- Rider can throw the football at least 80 feet.
- Rider is able to transition to the standing position on a stationary bike without touching the ground.

4.3.3 User Opportunities

- Rider can use a shield to block opponent's flag launching.
- Rider can use a cushioned shield to prevent water balloons from popping.
- Pusher can choose to act as an obstacle to protect the main offensive bike.

Table 4.3. User Requirements

User Requirements	Metrics	Rationale
Untrained rider is able to ride safely	Spectators can ride our vehicle without signing a waiver and we don't break a sweat.	Law suits are expensive.
Untrained rider is able to become proficient quickly.	Spectators become proficient riders in 1 minute of practice.	Games you can't play are no fun.
Untrained pusher is able to push effectively.	Spectators should want to keep pushing our vehicle for at least 2 minutes after they first start playing with it.	This game is supposed to be fun, and smoother vehicles are just more fun to push.
Every member of team participates as a pusher or rider during games	All team members have tried being both pusher and rider during trial runs.	There's no "i" in team.
Rider is safe	Rider wears a helmet.	Helmets protect from head damage. College education * 4 years = a lot of money.

5 Design Development

5.1 Design process tools

Overall, extensive team discussion aided by individual sketching and white-board drawings was our primary method for generating and evaluating ideas in the early stages. Moreover, our team leaned heavily on rapid prototyping as a method for "getting physical" with our brainstormed ideas and allowing us to come to conclusions about the effectiveness of a design very quickly. In general, our ability to churn out crude but rapid prototypes paid dividends by allowing us the confidence to try out novel concepts such as our concentric tube wheel design. Additionally, it allowed us to identify unrealistic design goals–such as a standing rider position—with ample time to adjust our solution and meet our fundamental criteria via other methods. Finally, our group engaged in numerous verbal discussions where we actively weighed the pros and cons of a given solution possibility; team members made an agreed upon, active, and concerted effort to facilitate the promotion of radical new ideas and innovative concepts, which figures prominently in our novel approach to wheel design and effective rider positioning. As a ream, no idea was too crazy or too strange to discuss, and this openness to new solutions promoted fun and interesting team discussion sessions, and helped push us into a whole new realm of Paper Bike design options.

5.2 Initial Testing and Design Evolution

5.2.1 Pretesting

As part of ME310 Paper Bike tradition, three of our team members spent an afternoon testing and evaluating previous Paper Bike designs. This testing involved taking out three bikes from previous years to Roble Field and pushing them around for a few hours while we evaluated what aspects of their designs worked and didn't work. As a result of this exercise, our team came to the following conclusions:

- Small wheels are not a good option because they get stuck on the uneven grass surface and generate large amount of friction located at the bearing circumference relative to the force applied to the ground located at the wheel circumference.
- Therefore: Wheel to axle ratio is extremely important, so we should strive to develop a large diameter, small axle wheel.
- Pushing and pulling can be very different across various bikes. Stable bikes tend to be relatively decent at both, but we should be very careful to test both modes of locomotion and have an idea ahead of time of how our bike would operate.

Additionally, our team came up with the following criteria based on physical interaction with real-world locomotion systems, some of which were similar to the paper-bike geometry:

- Considered a pogo-stick or stilts like design, but rejected it based on the materials difficulties of withstanding high stresses using cardboard members.
- Ruled out unicycle and a one wheeled wheel-barrow based on anecdotes of extreme difficulty in balancing single wheeled wheel-barrows in the lateral direction.

5.2.2 Design Evolution of bike structure

Section I: Frame Layout, Rider Position and Balance Considerations

Based on a strategic assessment of our expectations for game-play amongst the eight teams, as well as the physical interaction with previous paper bikes and wheel-barrows, our team determined quickly that creating a stable and balanced bike design was of the utmost importance. We believed that balancing the bike about a single axle supporting two wheels by correctly positioning the rider would get the most out of our pusher's effort since they wouldn't have to exert a balancing force in the vertical direction. Additionally, we believed that this balance and stability would aid in making the bike more maneuverable since it would operate well in both the pushing and pulling direction, as well as aid in maintaining constant rider position during high-g turning situations, and thus reducing weight transfer and other instabilities in the dynamic modes of our vehicle. Overall, our initial design was predicated upon this desire to maintain stability: we aimed to position the rider with one leg on either side of the main axle so that each foot rested on a curved platform approximately 1-2 feet *below* the main axle. We believed that lowering this point of contact between the rider and bike would place our center of mass below the axle, thus increasing stability about that axis; moreover, we also thought that even if the center of mass was above the axle, this would still place the center of mass directly above the axle and keep the system balanced. In general, sitting provides more stability, but standing allows the rider to be able to reach flag easier and dodge bullets. Therefore we decided to require that the rider be able to both sit and stand easily on the paper bike; additionally, this approach afforded a high probability of sufficient range of motion for the rider.

Although we proposed, sketched, and prototypes several strategies to realize this standing/seated requirement, the standing-rider positioning concept was eventually dropped for the final prototype. Ultimately, the 3' wide constraint on our bike design, and our decision that 6" wide wheels were a necessary component, left us with a limited amount of lateral space for rider positioning. Additionally, the cross beams that we had proposed for attaching a curved "floor board" for the rider to stand on added an extra volume consuming element to our design, and left virtually no useable space for the rider.

Therefore, faced with these volume constraints and an ever-approaching deadline, we decided to instead position the rider seated above the main axle, with their legs wrapped around a rider support tube. As part of this strategy, the rider was able to position their legs directly below the rear axle and wrap them around the lower portion of the rider support tube. The support tube provide excellent rider stability with minimal volume costs as it complemented the natural body position of a seated rider and gave them a surface to grip tightly with their thighs and feet. Overall, allowing the rider to wrap their feet around the tube provided a strong leg hold for the rider to hold themselves in place with minimal effort and a wide range of motion, especially in the upper body. Additionally, placing the rider's legs and feet below the main axle like this helped locate our center of mass lower in the vehicle, and thus aided greatly in stability. In the end, although we did not realize a standing-rider position design, our large wheels in tandem with the rider support tube positioning method provided the same stability, wide range of motion, and low center of gravity that we had been seeking to achieve with the standing rider design.

The following sequence of images captures the design evolution from a standing to seated frame design based upon the assumptions of a 36" wheel and single main axle as discussed above:

(1) Frame Design I

Figure 5.1. Curved Cardboard Platform and V-shaped Tube Supports

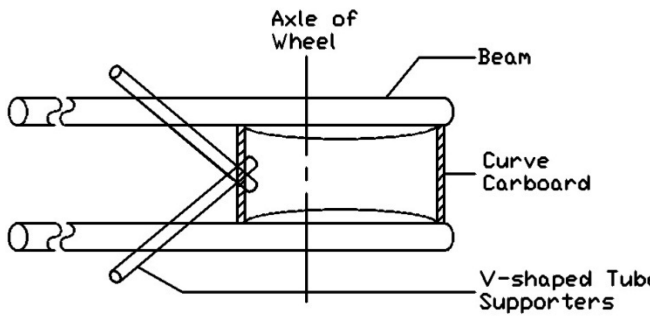

Figure 5.2. Top view of paper bike frame in Design I, Configuration A

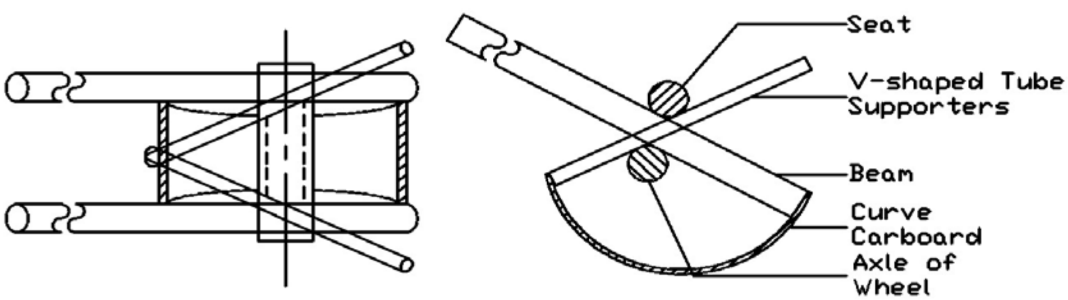

Figure 5.3. Top and Lateral View of paper bike Design I, Configuration B

Our initial strategy for constructing the standing platform was to join several curved cardboard platforms cut from a 36" tube with V-shaped tubes and the beam as shown in Figure 5.3. In this design, the rider would sit with one foot in front and the other in back of the axle (located below the seat) so that it would be easy to stand up while in motion, and would help maintain a low center of mass for the rider + vehicle combo.

However, with zip-tied prototypes of these configurations, we found out that it was hard and uncomfortable to stand one foot in the front and the other in the back because of the limited room wherever we chose to pace the V-shaped support tubes. Additionally, it became increasingly clear that the platform to support tube joint would be one of extreme stress and dynamic loading; given our materials and space constraints, as well as an unclear strategy as to how we would reinforce the cardboard platform, we decided to investigate a few other designs in hopes of simplifying our joint requirements.

(2) Frame Design II

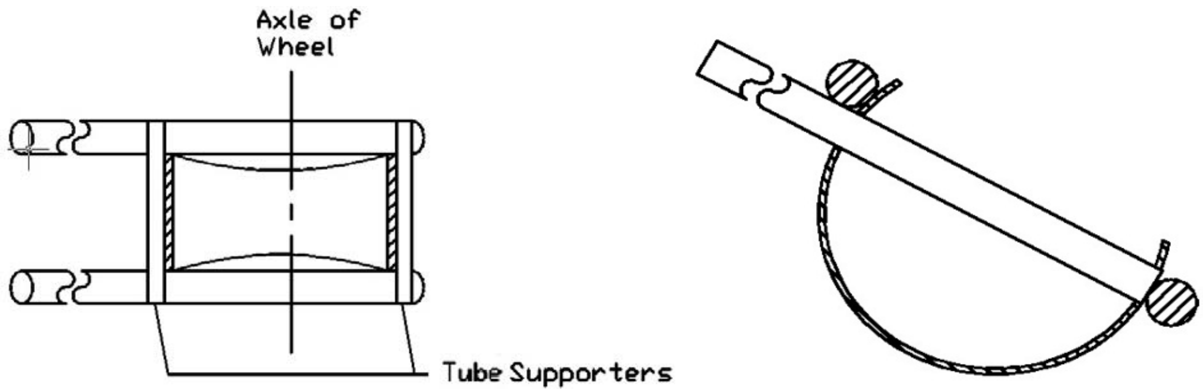

Figure 5.4. Top and Lateral View of Design II

Our subsequent strategy took into account the standing room of the rider and attempted to simplify our frame, as well as allow for easier joint realization. We lengthened the curved cardboard platform to reach the beams; as a result, the protruding parts of the curve cardboard above the beams provide easier joint solutions with gluing, nailing, or possibly tying with rope.

However, this did not eliminate the problem of the cardboard platforms load-bearing requirement. As a result, we considered Design III, which utilized a simpler and hopefully sturdier tube based standing platform:

(3) Frame Design III

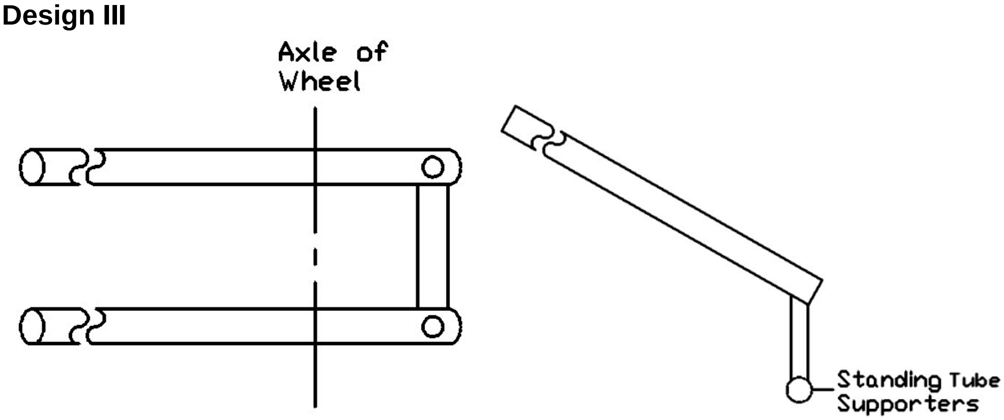

Figure 5.5. Top and Lateral View of Design III

While using a thick, strong tube for the support bar here would solve our load-bearing problem, we had come right back to the problem of manufacturing a joint that could withstand the necessary loading. Since the vertical bars here would be directly loaded in tension, any joining method between them and the cross bar would have been tenuous at best, and without any brilliant ideas clearly in mind, we moved on to conjuring up Design IV.

(4) Frame Design IV – Joint Design

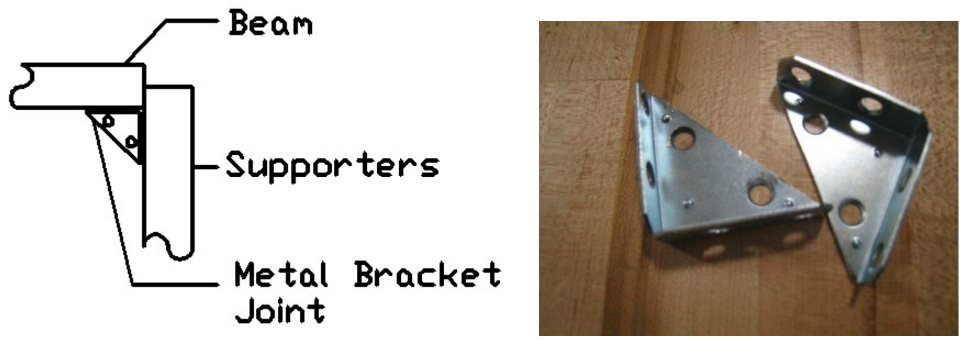

Figure 5.6. Joint Realization for Curved Cardboard Platform to Tubular Crossbars

In our fourth design iteration, we focused primarily on how to achieve the joint itself. As a possible option, we considered the metal bracket shown in Figure 5.6 above. The lateral extension of the bracket could be utilized to interlock with our cardboard platform by cutting slits on corresponding positions on the cardboard, and we believed this would achieve a satisfactory joint.

However, at this point in the evolution of our standing frame design process we realized that (1) it would be much more comfortable and flexible for the rider to put both feet in front of the axle, considering that the rider has to tag opponents and launch water balloons during the game and (2) the standing platform capability is really necessary only when the rider catches and launches the flag. Consequently, we chose to switch over to a seated design, incorporating a rider support tube. We stole this idea from numerous other teams, but improved it with our selection of a tube diameter optimally sized for the natural gap between two human legs (as opposed to the very small and very large diameter support tubes implemented by other teams).

Additionally, the geometry of our construction and large clearance width below our main axle allowed our rider to situate themselves directly above the main axle with their legs tucked beneath as seen in Figure 5.7.

Figure 5.7. Rider uses legs to grip Rider Support Tube for balance.

Section II: Wheel Design – Rationale and Development behind an Innovative Concept

In order to allow room for the placement of a standing platform below the main axle, we choose to develop 30" diameter wheels, giving us approximately 12-14" of clearance between the outer surface of our main axle and the ground. Additionally, this choice incorporated our major learnings from the hands on testing with previous bikes as it met our requirement that the bike possess a high wheel diameter to bearing diameter ratio (30" : ~4"). However, the construction of 30" diameter wheels had rarely been attempted (to our knowledge) in recent Paper Bike Competition, which we determined was largely in part to the large deflection and lack of durability exhibited by typical Paper Bike wheels, which involve numerous sheet of corrugated cardboard cut into circles, stuffed inside an equivalent diameter tube, and all laminated together to form a wheel.

Additionally, cutting and combining such large pieces of cardboard would have proven laborious and we also desired to come up with an innovative manufacturing process that might be repeated for years to come. Thus we decided to reinforce the interior area of our wheels using a geometric configuration of small diameter tube cross sections, as shown in the rendering below:

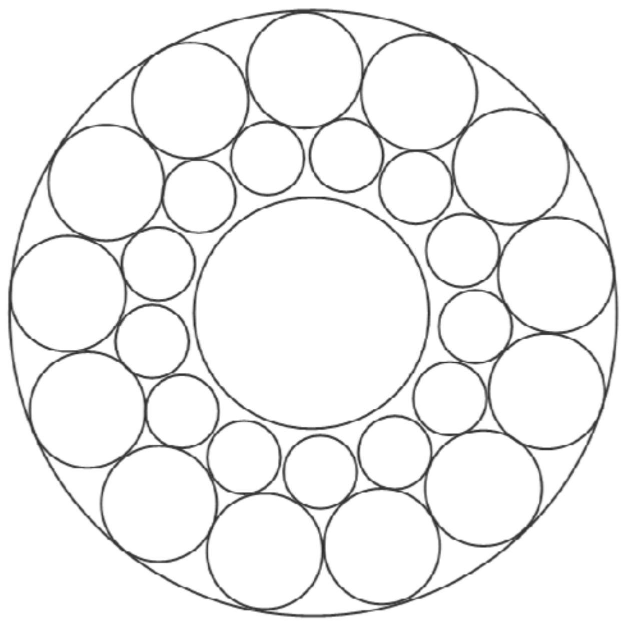

Figure 5.8. Computer sketch showing proof of concept geometry for Concentric Tube Wheels.

After discussing the concept with one of the TA's, we learned that previous year's teams had managed to create such a design using approximately 5-6 large diameter inner tubes to reinforce a larger outer tube. However, we also learned that these designs had experienced failures near the outer rim where the necessary large gaps between large diameter tubes created unreinforced locations and the external rim deformed to create a hexagonal "wheel." Overall, this discussion pushed us towards our 25+ concentric circle design because using more small circles eliminates these large gaps in reinforcement. Additionally, the smaller circles allowed us to utilize our very prevalent and very strong 4" and 5" diameter tubes. In the center of the wheel, we placed a 10" diameter wheel with "traditional" ME310 paper bike wheel cardboard sheet laminate that created an ideally sized hole in the middle of our wheel for a tube picked specifically because it interfaced well with the axle bearing tube. This "inner wheel" drew heavily on the wheel designed for our CFP and thus leveraged prior knowledge that we had gained in order to facilitate the construction of a novel wheel form factor.

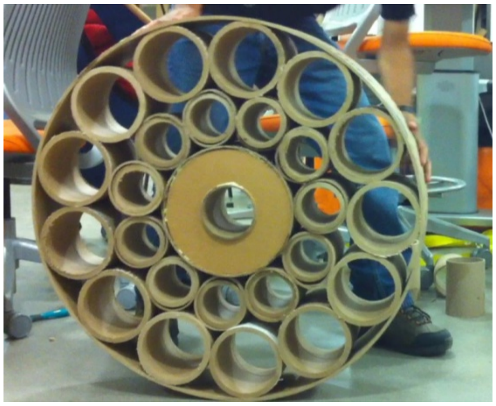

Figure 5.9. Concentric Tube Wheel Design being tested for possible run out (eccentricity) in the location of the axle

When manufacturing the concentric tube wheels, we found it to be relatively straightforward to fill a 30” wheel with the proper geometric pattern, due largely to the considerable time and effort determining that geometry ahead of time. As a result, when we laid out our wheel components before gluing, the 25+ circles fit together very nicely. However, this “very nice” fit was ultimately not the best solution; in order to provide rigidity in the wheel, what we really needed was a “super-tight” fit. In order to achieve this super tight, self-reinforcing fit, we squeezed a few 5” diameter tubes into locations where we had previously had to settle for 4” ones. Though this required some deformation in the smaller tubes, it created a spring like effect that kept everything snuggly together. Additioanlly, we placed narrow shims in any remaining gaps in the wheel pieces in order to get the outer tube to inner tubes connection to be as snug as possible. Finally, we applied our Gor-wood-lla glue mixture to all of the small gaps between tubes and allowed this to dry for several hours. Fortunately, and as predicted, significant expansion of the Gorilla glue added even more rigidity to our wheels, to the point where their rigidity far surpassed that which could be achieved via “traditional” ME310 Paper Bike wheel designs. All in all, this manufacturing process proved extremely successful in producing a very large, extremely rigid, and extremely robust wheel structure.

Figure 5.10. Concentric Tube Wheel construction—shimming the gaps between internal tubes.

Section III: Critical Function Component and Axle Development

For many reasons, this section should be entitled “Show Us Your Failure.” In order to meet our emphasized goals of speed, efficiency, and maneuverability, we chose to investigate low friction, high durability bearing solutions for our Critical Function Prototype. And as luck would have it, we came up with what we thought was a very effective solution: We reinforced our central axle with an extra cardboard tube, and then wrapped the outer tube with a super thin layer of aluminum (from soda cans) in order to create a low friction bearing surface. The cans were affixed to the main axle using Gor-wood-lla glue, and throughout testing seemed to stay in place and function very effectively. Next, we placed a layer of slick plastic contact paper over the inner surface of our internal wheel tube, so that we ended up with a slick plastic on slick aluminum connection. Under test conditions for our CFP, this achieved a “free spin time” (aka, length of time that the wheel would continue rotating after being spun up by hand and then left alone) of approximately 1.5-2s. Next, we added some graphite to lubricate the bearing, and then achieved even better free spin times of 1.8-2.5s. Overall, we were very pleased with our solution and presented this well designed CFP during our initial CFP design review with satisfaction.

Figure 5.11. Close up of aluminum can surface on CFP. Blue tape is keeping tension on aluminum while the glue dries.

Now fast forward a week to PB Local Rally day. After proving the effectiveness of our aluminum can solution previously, we chose to carry this design forward for the final bike, and did so with little trouble due to our prior experience. And during initial testing it held up great… until the competition rolled around. Then, during the competition, the contact paper layer inside of our bearings, coated in graphite, became mildly shredded; so we removed as much as we easily could and continued playing. However, over time, the repeated loading and accelerations experienced by our axle bearings caused the aluminum to catch on the cardboard outer layer of the wheel tubes, and eventually shredded the aluminum layer into a horrifying and friction inducing mess of shrapnel. In particular, we believe loading when travelling in the ‘reverse’ direction, for which we had done comparatively little testing before the competition, was the main culprit. While this problem proved fixable by simply removing the wheel, clearing out the aluminum shrapnel, and then playing on with a simple cardboard-graphite-cardboard interface, we were still very surprised that a previously “tested” design could fail so miserably. Overall, this experience brought about a renewed appreciation for even more thorough testing, particularly noteworthy since our vehicle had been one of the more well tested prototypes in the class! However, it also gave us a sense of appreciation for the modular design we had employed to attach our wheels in an easily removable and re-attachable way; by making our bike easily serviceable without even meaning to, we managed to create a bike which survived an otherwise catastrophic event during game play.

Figure 5.12. Photo (left) showing shrapnel from aluminum cans and shredded cardboard pulled from axle during break in PB Local Rally and additional photo (right) showing removable hub-cap design (zip ties), which allowed for quick serviceability during game play.

Section IV: Pusher Positioning and Handle-Bar Development

In order to meet our key criteria of pusher efficiency and ease of use, we spent a good deal of time developing different hand hold points for the pusher. This began with simple user tests to determine the optimal angle at which our main support bars should be positioned in order to make for the best pushing experience (we settled on a range of about 15-30^{o} depending on how the pusher is holding the handlebars at a given time). By having such a flat angle, we realized this would cause the pusher to exert force primarily in a horizontal direction, and thus waste less valuable energy pushing the bike "into the ground." In order to further optimize our vehicle frame design, we incorporated a beautiful and ergonomic "Rainbow Handle" (pictured below). This handle was essentially a large diameter arc placed above a handlebar tube, and wrapped with paper towels in order to make it soft to the touch and improve grip. Overall, this designed improved ergonomics and gave the pusher a variety of options when positioning their hands. Other hand positioning options also included a grip on the butts of the main cross beams running directly up from the axles, or a grip on the connecting handle bar tube, further increasing the flexibility of our design and affording a comfortable pushing position to pushers of various heights and body types.

Figure 5.13. Photo Showing Rainbow Handle and Handle Bar Tube Assembly

5.2.3 Offensive/Defensive Tool Design Evolution

The key strategy of our team was to be flexible in terms of the role (defense vs. offense) to be played during the game. Once the maneuvering aspect was looked at, the bike needed to have a mechanism to either launch the balloons for tagging or capture the flag and launch it across.

A lacrosse stick prototype was built to try out the balloon launching process and after a few iterations that modified the form of the balloon holding cup of the stick, the final form of the stick 'launcher' looked like Figure 5.14. The stick could launch 4 out of 5 balloons at a bike sized target within a distance of 15-20 feet. A key requirement that was registered at this point was that storing water balloons on board would need a special location close to the axle to prevent unbalanced loads that could make pushing difficult.

Figure 5.14. Lacrosse stick launching device for water balloons.

However, on game day, after consultations with the macro team, it was decided that our team would focus on using the flag retrieval mechanism and assume an 'offensive' role as part of the macro-team strategy.

"Capturing the flag" had two aspects to it. First, take the flag down, and then, without touching it, launch the flag across to the other side, run it over to the other side, or just pass it on to another macro-team member. Some of the ideas discussed for the retrieval included, but were not limited to, the following:

(1) Attaching the flag to helium balloons and let it 'fly' across the field as a team member back on our side reeled it in.

We did not prototype this on the grounds that the string tying up the balloons together would be hard to protect/oversee/control. Another team used this concept as their retrieval mechanism, to great success during testing, but no success during game-play.

(2) Taping the flag to a soccer ball and kicking it across.

Figure 5.15. Soccer Ball 'launcher' with Flag taped to it and kicked across

We also tried this method, but the results (distance and accuracy) were not consistent. Also it was difficult for the rider to maintain balance while kicking the soccer ball.

(3) Making a Frisbee out of cardboard and flag and throwing it across.

Figure 5.16. Frisbee made from Cardboard Ring and Flag. The cardboard ring is along the underside of the circumference of the Frisbee.

We successfully validated this concept but eventually abandoned it due to the fact that it was not possible to chuck the Frisbee without actually touching the flag. Specifically, taping the flag involved some amount of touching it.

(4) Final Solution: Shoving the flag inside a container and throwing/chucking it across.

This idea had a lot of potential because of the fact that the flag container also called The Football could be thrown across the field as also passed on to macro team members in case of a time crunch. The initial container was a small tube zip tied at one opening that acted as a stop for the flag. The size of the tube evolved based on the distance to which it could be thrown standing up on the bike. For safety concerns, the final design involved covering the container in soft tape giving it the shape of a football!

Figure 5.17. The flag spear used to remove the flag from the 9-foot tall pole.

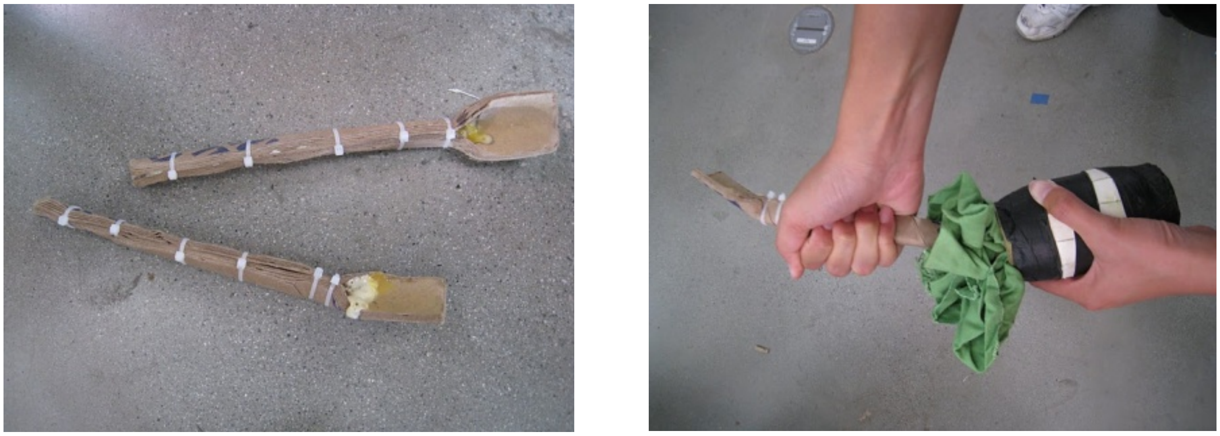

Figure 5.18. The components of the flag launching system. The figure on the left shows the loading spoons, which were reinforced with glue. The figure on the right shows the process of using the loading spoons to shove the flag inside the football.

As for the flag removal process, a flag spear was made to lift the flag and place it inside the football. So that the flag fit would snugly inside the football it was essential to force it in without touching it. Loading spoons made out of cardboard were used for the same. After finding out that they buckled under pressure, they were re-made out of double layered cardboard and Gor-wood-lla.

The flag spear needed to be stored on board so that the hands of the rider would be free for tagging. One possible locations considered was the rider support tube ('the cannon'), but we soon learned tat placing the spear in between the riders legs, directly within his/her needed range of motion, disturbed the ergonomics of the bike. Ultimately two short cut tubes (ie, rings) were used as spear holders to do the job of storing the flag spear when it was not needed; these small rings were mounted onto one of the main support beams of the bike, and thus kept the spear running parallel and next to these beams, and thus out of the way. Fortunately, freeing up the cannon provided an ideal location to store the football and the loading spoons, which rested gently inside its central cavity in a location perfect for rider access.

5.3 Key findings and failures

The cardboard shield was a key finding of the paper bike game. The shield proved affective against the water balloons. It also proved to be a deterrent for flags launched with catapults on board vehicles. The soda cans and contact paper combination proved to be a failure in the actual field conditions. It was realized that inter team communication helped as much as intra team communication especially in strategic design. Another key finding later on in the design process was the lack of space available to seat the rider (because of the constraint that the bike should fit inside a 5' X 3' X 3' box. Also, the need to take the varying loads of the water balloon basket and its location close to axle on the bike was realized much later in the design process.

6 Design Description

6.1 Physical Specifications

6.1.1 Flag Spear:

Spear 'tool head':	5"
Total Length:	47"

6.1.2 Concentric Circle Wheels:

Wheel OD:	30"
Wheel Width:	6.5"
Hub Width:	1-1.5"
Axle OD:	4"
Inner Wheel OD:	10"
Internal (Structural) Tube OD:	4.5", 5"

6.1.3 Bike Frame/Body:

Bike Area:	3' x 5'6" in the inclined plane
Main Frame Area:	18" x 5'
Seat:	1/6th circle of 36" diameter tube, 10" width
Spear holders:	4.5" diameter, 6" length
Cannon:	29"

6.1.4 Other Tools:

Balloon Launcher	3' long pole, 14" x 8" head
Football	2" diameter X 5" wide
Spoons	9" long, with 2" X 1" flats
Handle arc is	Max Distance of 1' from the frame

6.1.5 Various Metrics:

Pushing Speed	~7.7 ft/sec
Pulling Speed	~7.7 ft/sec
Rider Space	22" lateral x 24" longitudinal
Intended Rider Weight	< 200 lbs.
Expected Life Span (w Collisions)	~4 hours continuous use
Expected Life Span (Collision Free)	~12 hours continuous use

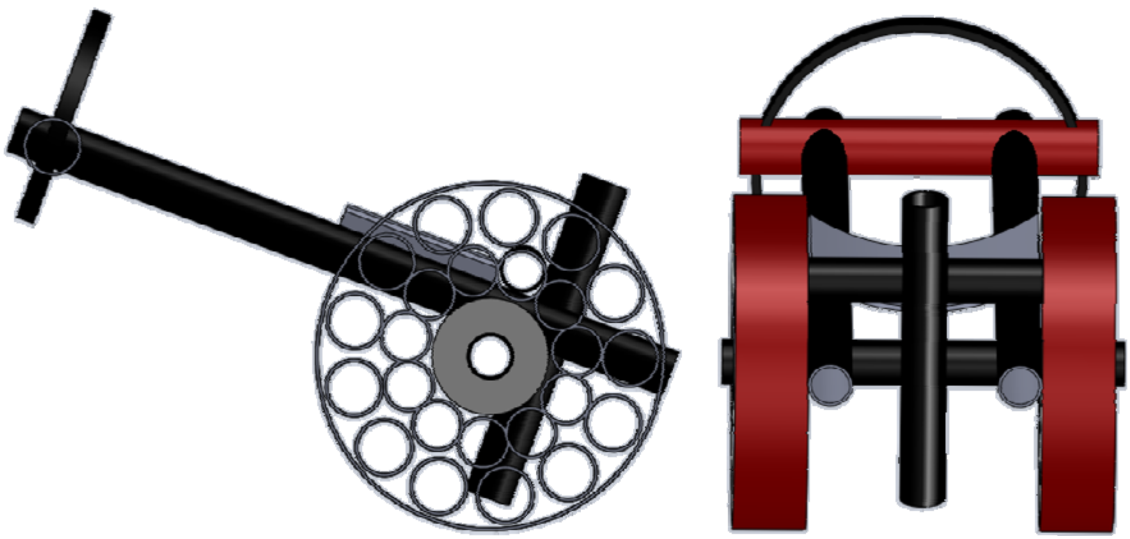

Figure 6.1. A SolidWorks model of our final design: side view and front view.

6.2 Non Paper Materials Break Down

Table 6.1. Record of non paper weight (Quantities are approximate. But they are well within the allotted quota of 500 grams.

Material	Approximate quantity	Approximate weight* (grams)
Zip ties - short	20	60
Zip ties - long	15	40
Aluminum cans	6 cut soda cans	30
Twine	2 strings of 4' each	60
Gorilla Glue	2 bottles	-
Wood glue	2 bottles	-
Foam tape	1' in length, 1" cross-section	20
Paint	1 spray paint can and about 200 ml of enamel paint	-
Total non paper weight		**210**

* According to design constraints, glue in small amounts (not used for material stiffening purposes), paint would not count towards the non paper weight.

6.3 Functional Specifications – Final Design

Requirement	Specification	Discussion
To provide the pusher with different grips so as to be able to pull/push the bike	The rainbow handle, hollow longitudinal tubes making up the frame allow for different grips to be able to pull and push	Overall, the bike was easier to push than pull given a choice to the pusher
To provide a stable seating platform for the rider with the possibility of standing inside the safe zone	The seat was made of a rounded cardboard with a cross bar as an end stop to snugly fit the rider inside it.	This was achieved quite satisfactorily
A new user (rider or pusher) should be able to learn to ride/ push easily	The loading, unloading processes of the rider by raising the bike up are very intuitive and there are multiple grips for the pusher. The process can be learnt in less than a minute	This was tried out in the design review and was agreed upon by the teaching team
To be able to get the bike moving and stop it as easily as possible	Should not take more than 2 seconds to get the bike running at 6-7 ft/sec and bring it to a stop	Having designed bigger wheels this requirement was changed to 3 seconds. However, once the bike was 'started' it was fairly smooth in its operation
Mechanism to launch water balloons	A lacrosse stick with cardboard paws can throw balloons after being manually loaded	The stick worked fairly accurately but in the absence of a water balloon carrier, was not used in the game
Mechanism for removal of flag without touching it	A flag spear that can lift the flag out of its place and place it inside the football	The length of spear chosen such that this requirement can be met even with the rider sitting
Mechanism to bring the flag across the half line	A football into which a loading spoon can shove the flag after it is placed there by the flag spear. The football can then be chucked across the half line	The distance travelled by the football is a user dependent function which makes the distance travelled by it variable
Place to hold the flag spear when not being used (Discovered Reqt!)	Two small cardboard tube holders zip tied to the main frame hold the spear in place	The holders worked well for most of the game. Could be glued down for future tune-ups to the bike
Place to hold the football and the loading spoons	The cannon is used for this purpose. The football can fit inside the cannon and the spoons can rest inside the football	The spoons can fall during the game. future designs can look into securing them more safely

6.4 Recommendations for Future Work

Balloon launching was dropped after macro team consultations However, in the altered version of the game where only balloon tagging was possible, a balloon basket became a requirement. Future work could involve integrating a balloon basket with the design keeping in mind the rider stability and pusher comfort at balancing the bike. Also, the bike should also ideally be able to carry the lacrosse stick made for chucking water balloons. Future work could involve figuring out a way to store both the spear and the lacrosse stick on board while making it fairly accessible to the rider.

The bearing surface was prototyped for wheels of smaller size and tested without factoring in sudden reverses in motion of the bike. This led to shredding of the bearing surface. For future designs, this needs to be sorted out. Perhaps instead of gluing cans together, it would be a good idea to fit an exact size can both at the inner and outer wall of the axle wheel joint. Another option is to steer clear of glue at the bearing surface and use graphite to assist cardboard on cardboard motion. That way generation of shrapnel is avoided.

7 Resources

Tube Service Co. | Milpitas, CA | 408.946.5500 | Lots of free medium diameter (2"-6") tubes. Very friendly. The tubes are 12'+ long, but they cut down tubes to whatever size fits in your car.

Muller Construction Supply | San Jose, CA | 408.279.7050 | Limited supply of free large diameter (10"-36") tubes. Very generous. It is helpful to know what sized tubes you want.

JoAnn Fabrics | Mountain View, CA | 650.948.5300 | Friendly, but did not have much cardboard.

Carpet Mart | Mountain View, CA | 650.941.1536 | Lots of free 4" diameter tubes; some were thick and useful, but others were not quite round. They let us take as many as we wanted; they throw them away otherwise. The tubes come 12' long; bring a hand saw to cut tubes so that they fit in your car.

Costco | Mountain View, CA | 650.988.1841 | Lots of flat cardboard in between stacks of product. Push a flatbed cart inside, and collect whatever cardboard sheets are not needed.

Ace Hardware | Palo Alto, CA | 650.327.7222 | Lots of general supplies for purchase; often out of Gorilla glue.

Home Depot | East Palo Alto, CA | 650.462.6800 | Lots of glues, but not free. Gorilla glue: $$$.

8 Reflections

Xiao Ge

The two-week project is amazing when I look back on it. At the beginning, I was not well prepared to join in Team 2 halfway and not confident in my English communication, but I was very sure of what I wanted to do, that is, to be part of Team 2. We did not have a panorama about what we exactly wanted the bike is, we discussed and prototyped and revised and summarized. This period of time was tough and challenging. I joined in the building process and gave advice and ideas, which worked much better than I thought. When we did the standing platform iterations, I was stuck and frustrated since we built out nothing for five hours in the loft. However, I later realized that it is worth sacrificing for better solutions. I really love the experience! I never had such an experience to spend most time and energy discussing and building among the team till 3:00am in the morning. Of course, I was very excited to see our Wheely Wonka score in the Paper Bike Rally. I have learnt a lot. I can see a clear boundary between the me two weeks before and the me now. I appreciate my opportunity to be in ME310 and want to do better and become better in the near future.

Jessica Ji

Brainstorm extensively, and prototype early. Many times, it seems easier to just go with the normal way of doing things, but more often than expected, those crazy ideas sometimes do work. And even if the idea doesn't work, the experience of failure often teaches as much, if not more, than that of success. I appreciated the fact that everyone on our team was willing to hear new ideas without immediately shooting them down. One person's innovative idea would generate a snowball of even more ideas, some of which were just ridiculous, but super fun to discuss.

On a related note, I am glad our team took the chance in making non-standard wheels. Stacking flat cardboard circle cutouts was the "tried and proven" method of manufacturing paper bike wheels, but we were willing to test a different solution. Although we weren't 100% sure how the tubes would hold up, it was definitely fun to be working on "the bike with the cool wheels." Now that we've shown that they can work, we anticipate many more wheels like this in future paper bike competitions!

Recommendations for future teams: (1) Get tubes early, and get a lot! Tubes are by far the most useful cardboard due to their strength. All the teams used tubes for the main frame of their vehicles. Although in an ideal situation, design should not be limited by available material, oftentimes it does happen. (2) Put on disposable gloves when using gorilla glue. It is an awesome adhesive that foams up when it dries, but it also sticks to your skin until you shed that layer. (3) Try to do something crazy—it might not work, but you'll have a lot of fun trying!

Peter Kardassakis

Paper Bike was an awesome project! Like most design projects, it's the Gorilla glue of academia: however much time I had left in my schedule, PB was there to expand and fill it up. Which is why my teammates were so great… they were willing to put in tons of hours and work around my admittedly annoying schedule. We all worked really well together and had a ton of fun. Like Jessica notes, we were great about accepting and fostering crazy ideas, and the innovation showed in our result. I think the hands on nature of the project made for really fast turn-around on the learning process, and it was awesome seeing some group members who'd done less fabrication in the past come alive as they learned to use all of the manufacturing tools, etc. It was also great working with students from other countries and seeing different personalities come out as we worked. Overall, I liked how our design was innovative, but was really sad to see our axle bearings fail so badly after doing so well in initial tests—oh well, I guess that just gives us more to work on for next time. I can't wait for the Global Projects to start… Paper Bike was a great way to kick off the year! My key takeaway, which everyone in the group seemed to realize, was not to stress too much about specific project minutiae and instead make sure we're building good team bonds and enjoying the time together, as this made everything else smoother and more successful.

Abhishek Shiwalkar

I had an awesome time throughout the roller coaster ride of the paper bike exercise. I was particularly happy about the way we handled the work allocation in the team and ironed out scheduling issues. We had a lot of fun brainstorming some of the most outlandish ideas for a paper bike though time constraints didn't allow us to pursue some of them. In hindsight, the decision to put off a flag launching mechanism to the end was a great one because it allowed us to explore the user interfacing of the bike as also its mobility in greater detail. The multiple user grips and the simple yet effective rider seating were central to our design. The idea of notching tubes and then using twine proved vital. Also, the simplicity of the launching mechanism led to its extreme effectiveness. I am glad we went in for a different technology for strengthening the wheels. I wish we had brainstormed the standing rider design. I also wish we had more to prototype some ideas that seemed promising. My key takeaway from the project was learning to think ahead in the rapid prototyping process so that valuable time and material could potentially be saved. Ultimately I loved the way in which we coordinated with the macro team and offloaded some ideas and requirements to make it truly a team effort

Figure 8.1. Wheely Wonka's factory workers.

9 References

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10 Acknowledgements

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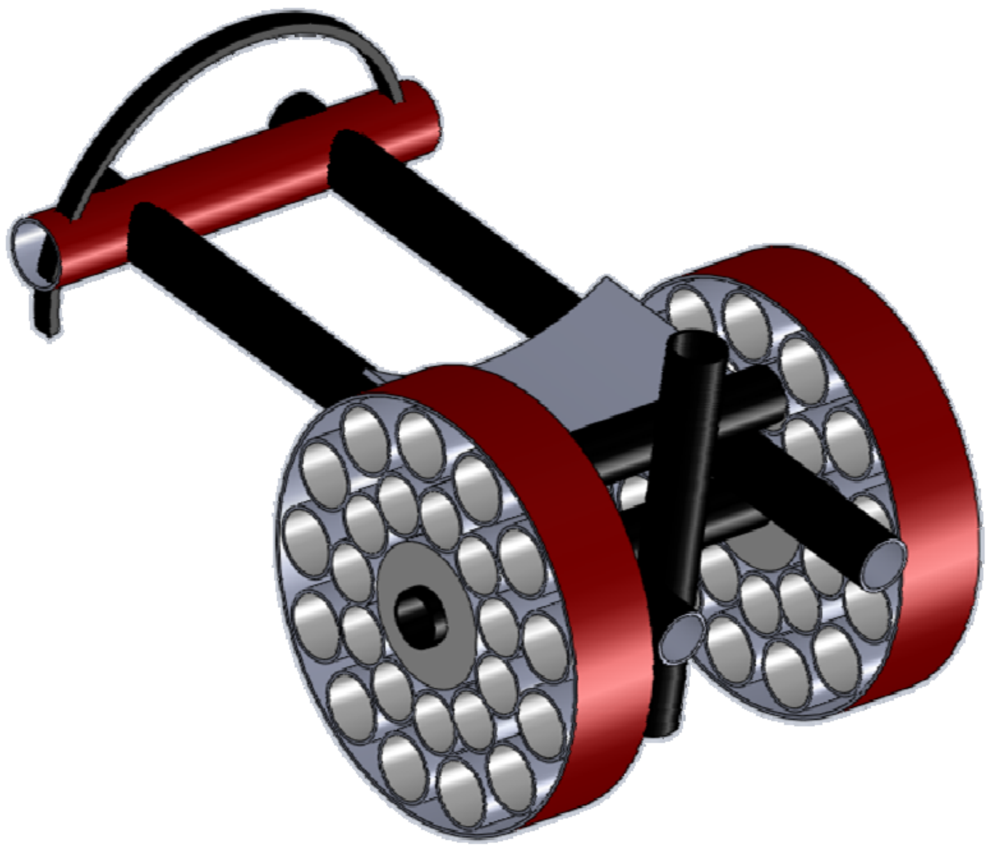

Figure 10.1. SolidWorks model of Wheely Wonka!