**Advanced Mechanical Design, University of Rochester**

**Final Design Report**

**Spring 2023**

DRILL-POWERED CART

| **Ahmed Abdalla** | **Samantha Dinhofer** | **Lingyun Huang** | **Ihab Youssef** |
| --- | --- | --- | --- |

**ABSTRACT**

*Vehicles are a great showcase of many different feats of engineering. From creating power to drive the vehicle, to designing parts which can withstand various forces, manufacturing a vehicle requires ample knowledge of mechanics. It also requires machining skills and creativity. The goal of this project is to create a vehicle powered by a battery-powered drill. On design day, this cart will compete in an endurance race, against two other carts, that will test its efficiency and ability to properly complete the design objectives which were decided based on the maneuverability requirements dictated by the course. All teams must follow the same rules, requirements, and specifications, but creativity from each team has led to three very different approaches at creating the most efficient drill-powered cart.*

**PROBLEM DEFINITION**

* Air pollution is a significant problem facing the world today, with a wide range of negative impacts on human health, ecosystems, and the economy.
* Air pollution adversely affects the health of human beings causing respiratory ailments and other diseases. It also contributes towards global warming and climate change.
* The problem addressed by our project is air pollution from CO2 emissions caused by gas-powered vehicles. The electric-powered cart is a sustainable and affordable alternative to traditional gas-powered vehicles, reducing the number of pollutants released into the air.

**REQUIREMENTS, SPECIFICATIONS, DELIVERABLES**

Deliverables:

The project has a timeline to follow as it must be done by the end of April on design day. To complete the project, a drill powered cart must be built. The cart and a driver from the team must be ready to race on design day. A project technical report must be written to document the project including testing data. Lastly, a presentation about the project. must be prepared and presented to faculty. To achieve the goal deliverables, the cart is built following a WBS shown in appendix H figure 14 that splits the project into five major categories: Frame, steering, usability, drive train, and project management. This will be achieved in time following the CPM.

Requirements

* The vehicle will be powered by a single electric drill, each team will use the same drill
* The vehicle body will be made from plywood
* The vehicle can be optimized by each individual team
* The vehicle must have a lap style safety belt and horn for safety
* Pinch points must be guarded and pass inspection by Professor Muir
* Payload will be standardized
* Cart must sustain the weight of the heaviest team member
* The vehicle must utilize a non-traditional steering system
* The vehicle must be able to maneuver the course

Specifications:

* The vehicle cannot exceed 25 MPH
* Payloads must be within 5 lbf of each other
* Maximum brake distance of 15 feet at maximum speed
* The vehicle must have more or less than 4 wheels
* The vehicle must have minimum turn radius of less than 11 ft
* Vehicle must fit within a 6ftx4ftx4ft volume

**concepts**

Steering:

|  | Lever one wheel | Lever two wheels | Pedal one wheel | Pedal two wheels |
| --- | --- | --- | --- | --- |
| Ease of assembly | + | 0 | + | - |
| Cost | + | 0 | 0 | - |
| Familiarity to user | + | + | - | - |
| Preventing Slippage | + | 0 | + | 0 |
| total | 4 | 1 | 1 | -3 |

Table 1: concept selection for steering

One of the requirements is to steer the cart using an unconventional steering system. This means not using a steering wheel that controls the steering column. Different methods were considered to control steering, including hand levers and pedals. Table 1 shows the Pugh concept selection matrix for possible steering systems. Different options were rated based on manufacturability, cost, and ease of use. Overall, using levers as input is easier to assemble than using pedals. Although steering with 2 wheels could produce tighter turn radius, creating an Ackermann or rack and pinion system is more expensive and harder to manufacture than steering one wheel. Steering using hand levers through one wheel proved to be the most suitable option for steering. As can be seen in appendix D figure 8, The system uses the movement of two levers pushed by the driver's hands to push and pull two bars that rotate the wheel swivel caster. Steering was decided to be done through the front to separate from the drive train   
system applied on the back wheels for ease of assembly and troubleshooting. The cart must have a steering radius of less than 11 ft. The calculation shown in Appendix D figure 9 shows the calculation for the steering angle required for the car to clear the course. The steering system was designed using ball joints that can fulfill the required steering angle.

Braking**:**

| Braking Criterion | Conventional/Cable Disk Brake | **Hydraulic Disk Brake** | Band Brake | Stick in Ground |
| --- | --- | --- | --- | --- |
| Cost | 0 | **+** | 0 | - |
| Manufacturability | 0 | **0** | + | + |
| Ease of Assembly | 0 | **0** | - | + |
| Applied Force Required | 0 | **+** | - | - |
| Total | Baseline | **+2** | -1 | 0 |

Table 2: Braking Selection (Pugh) Matrix

Table 2 shows the concept selection matrix for the braking system. The criteria considered are cost, manufacturability, ease of assembly, and braking power.

Calculations to determine the braking force needed to stop the cart at its top speed of 25 MPH in 15 feet can be seen in Annex B. This braking force was determined to be 1598.168 N. This is equivalent to 359.281 lbf, thus making the stick in ground concept not feasible. This force can be produced by both the conventional/cable disk brake system and the hydraulic brake system. The main difference between these two systems is reactivity. Ultimately, the hydraulic system was chosen as the pricing is not much different and it is more reactive than the conventional/cable system. A concept drawing of this braking system can be seen in Appendix\ G Figure 13.

Body frame:

|  | **Triangle** | Rectangle | Others |
| --- | --- | --- | --- |
| Ease of cutting | 0 | +1 | -1 |
| Cost | 0 | -1 | 0 |
| Weight | 0 | -1 | -1 |
| Total | Base line | -1 | -2 |

Table 3: Body Frame Selection Matrix

Table 3 refers to the selection matrix of the shape of body frame. To find out the best selection, the cost, ease of cutting, and weight are considered. According to the table, triangle shape is the best choice.

To complete the finite element analysis of body frame, the sitting area of the driver was measured in NX. Specifically, a human body model with driver’s dimensions was placed onto the frame model. Then, draw a rectangle at the human model’s sitting area. To process the FEA of the frame model, a distributed load was assigned to the sitting area. The total load in that area was assumed to be the weight of the driver. Also, the weight of the plywood was embedded into the model analysis.

To calculate the stiffness of material, two tables were used to support a piece of rectangle plywood which has thickness of 0.465 inch. Then, different loads were placed onto the middle of the plywood. Deformations of the plywood under corresponding loads were recorded. In this case, the plywood was approximately a beam structure with center load and two-end supports. Using the equation in Table A-9 (APPENDIX F), Young’s Modulus of the plywood was calculated.

Drivetrain:

| Drivetrain Criterion | **RWD (Rear Wheel Drive)** | FWD (Front Wheel Drive) | AWD (All wheel drive) |
| --- | --- | --- | --- |
| Practicality | **0** | - | - |
| Ease of Manufacturing | **0** | 0 | - |
| Size | **0** | 0 | - |
| Efficiency | **0** | 0 | + |
| Total | **0** | -1 | -2 |

Table 4: Drivetrain Selection Matrix

Table 4 shows the selection matrix for drivetrain mechanism, where RWD, FWD, and AWD were considered. AWD is the most efficient, but the manufacturing and implementation would be complicated in terms of the scope and timeline of project. Rear Wheel Drive (RWD) was selected as it is the most practical and compatible with other systems. Another major deciding factor is that steering is determined to be using the front wheel, so RWD is the best choice overall.

Additionally, figure 6 in Annex C shows the proposed mechanism for drivetrain that will implement a centrifugal clutch connected with a chain to a sprocket attached on the rear axle to transmit power to cartwheels.

Wheels are to be connected using an aluminum plate fixed to the axle by collars and two connecting threaded rods that connect to the plate in one end and to the wheel on the other.

Calculations for needed gear ratio that will provide the necessary torque to allow the cart to climb up the ramp is shown in figure 7 in Annex C. Using a centrifugal clutch allowed us to base our calculations upon the torque of the drill at selected speed avoiding the limitations regarding the stall torque of the drill due to the engaging mechanism of the centrigual clutch.

Exact torque values couldn’t be confirmed since the torque changed according to the speed, so the calculations provided were used as a guideline and upon testing a gear ratio of 1:3 was sufficient to power the cart.

**MECHANICAL ANALYSIS**

Tolerance Issue:

One tolerance issue faced during manufacturing was during milling the top rod to make a keyslot for the centrifugal clutch built-in machine key. There were no dimensional drawings for the clutch inner parts so a claibar was used to get the measurements that turned to be width of 0.185 in. and depth of 0.087 with tolerance of 0.01 due to the position of the machine key in the clutch which didnt allow for an accurate measurement. A drill bit of 0.18 in was used but the machine key in the clutch was closer to 0.19, so a bigger brill bit was used to solve the issue.

Another tolerance issue was during mounting the top axle through the bearings as the diameter of the rod was three thousands of an inch from the intended diameter of 0.625 in. The rod was sanded multiple times to resolve the issue.

Fatigue Analysis:

A fatigue analysis is a crucial part of the engineering design process, as it helps predict the lifecycle and potential failure points of a material or component under cyclic loading conditions. In our project, a fatigue analysis was performed on rhe bottom ⅝ rod made out of carbon steel which connected the two wheels. The analysis is in APPENDIX A. Result shows that failure will not occur in the future whether using Goodman’s standard or Soderberg’s standard.

Torque Fastener Analysis:

The front wheel is assembled to the frame using four ⅜ in-16 bolts that are fixed in place using hex nuts. An analysis was done to calculate how much force it would take to tighten and unscrew the wheel as can be seen in Appendix D Figure 11. This is an acceptable range as the vibration of the frame wouldn’t produce enough force to unfasten the bolts while it is easily controllable by human hand.

Material Selection:

For drivetrain, material selection was a crucial factor on the design and the plan. The rear axle bears most of the weight of the cart and transfers torque to the wheels. The axle needed to be robust enough to support the car's weight, resistant to torsion when torque is applied, and lightweight to decrease the moment of inertia and enhance the efficiency of torque transmission from the drill to the cart. To satisfy these requirements stainless steel rod was chosen due to its strength and durability.

Another choice was for the supporting beams for the drivetrain, Plywood was chosen because it was abundant, lightweight, highly machinable particularly when cutting the parts at angles, and provides the needed force and torque resistance needed from the supports.

Spring Sizing Discussion:

For the assembly of power pedal and the trigger in the drill box, two springs were used. Multiple samples were obtained from rettner fabrication lab and tested by applying the driver foot load on the pedal to see if the spring returns to its original position without deforming. Two springs were tested and assembled successfully for the power pedal and the trigger.

Bearing Analysis:

Bearing analysis for the top axle in the drivetrain was done to ensure that the bearing will not fail due to load and speed. The top axle is connected directly to the drill, so it is rotating at 1800 rpm and the weight of the cart plus the driver was estimated to be 190 lbf. Factor of safet of 2 was used during the calculations and failing load was found to be 1140 lbf at 500 hours as the desired life, which is much higher the desired load even with the factor of safety of 2. Detailed calculations are shown in figure 5 in Annex C

NX Displacement Analysis:

During the execution of this research project, a comprehensive structural Finite Element Analysis (FEA) was carried out utilizing the Nastran computational software with the aim of analyzing the structural integrity of a cart frame. The overarching objective of this analysis was to ascertain the deflection behavior of the cart frame under various loading conditions, thereby simulating the forces exerted on the frame during standard operational activities.

To achieve this, a three-dimensional (3D) computational model of the cart frame was meticulously constructed. Subsequent to this, a simulation was devised to incorporate the pertinent material properties and geometric constraints. In particular, the material properties of plywood, encompassing mass density and Young's modulus, were employed in the analysis. The boundary conditions were defined as fixed constraints at the locations of the wheels, specifically at three edges of the frame. The computational model was discretized into 3D tetrahedral mesh elements with an approximate size of 10 millimeters (equivalent to approximately 0.39 inches). The implementation of this refined mesh facilitated the precise computation of stress, strain, and displacement distributions throughout the structure. The loading condition was formulated to simulate a realistic driving scenario, specifically by applying a distributed load on the rectangular surface segment corresponding to the seating area for the driver.

The resultant data acquired from the FEA simulation were thoroughly scrutinized, yielding key insights that were instrumental in evaluating the structural behavior of the cart frame. Furthermore, this analysis enabled the identification of potential areas of concern and provided valuable recommendations for design enhancements to augment the performance and safety of the cart. In summation, the maximum theoretical deflection of the frame, as deduced from the analysis upon the driver's seating, was determined to be 17 millimeters (FEA can be found in Appendix).

When designing the brake bracket, the shape of the forked piece had multiple design options. Design one was two thin rectangles which would be individually welded to the upper support. This would be easiest to manufacture as it would not require plasma cutting. Design two has a rectangular portion which then splits into the fork shape. This design is more robust but would require plasma cutting to manufacture due to the complicated shape of the forked piece. In order to analyze the strength of the two design geometries, each was tested in NX. The mounting holes in each were fully constrained and the required braking force, 1598.168 N, was split evenly between the two holes in the forks and was applied in the opposite direction of disk movement. It was found that design one displaced 0.0459 inches while design two only displaced 0.0162 inches. Ultimately, design two was chosen in order to reduce the possibility of a large deformation, leading to misalignment of the brake caliper, due to displacement of the bracket. The NX results can be seen in Appendix B.

Static Analysis:

In order to calculate the needed torque to allow the cart to move in a straight line and up the ramp, a free body diagram of the cart on the ramp was drawn and analyzed. The base equation used was

∑𝞽 = 𝑇𝑎𝑝𝑝𝑙𝑖𝑒𝑑 - 𝑊𝑐𝑎𝑟𝑡 ( 𝜇𝑠 × 𝑟 + Rr × r) = 𝐼𝛼 (1)

where Tapplied is the torque applied to the rear axle, Wcart is the weight of the cart, 𝜇s is the coefficient of static friction between the tires and the road, “r” is the radius of the rear tires, Rr is the rolling resistance, I is the moment of inertia of the tires and the rear axle, and α is the angular acceleration. Figure 7 shows the detailed calculation of this static problem

**MANUFACTURE**

Steering:

The steering system required the manufacturing of four rods to transmit the force input of the driver to the front wheel. PVC was the material of choice to manufacture the rods from. This was after consideration of cost, weight, and manufacturability compared to other options like steel and aluminum. The other components of the system were bought. This includes the front wheel swivel caster, ball joints, and bearings. To minimize the weight, it was decided to use tubes instead of solid rods and create threaded corks to be glued on each end of the tube for installation of the ball joints.

To fit all the rods to length, the horizontal band saw was used. Afterwards, a solid PVC rod was cut into 2.5 inch pieces to be manufactured into the rod end plugs. Along 2 inches of each piece, the outer diameter was reduced on the lathe to either 0.70 inch or 1.05 inch depending on the rod it connects to. This made sure that the plug touches the interior wall and the edge of the rod which provided enough surface area to be glued using PVC cement to the rods. The lathe was then used to drill holes through the center of the plugs using 29/60 inch drill bit. The holes were tapped with a ½ inch 20 tapper using the lathe as a holder to ensure the tapper moves precisely in the hole.

To install the rods on the frame, two of the rods needed to be installed on bearings on both side of the driver. The two other rods needed to connect to the front wheel. The drill mill was used to create ¼ inch holes on both of the driver rods. It was also used to create two ½ inch holes on the sides of the swivel caster that houses the front wheel. The swivel caster is made out of steel so the holes were done over 4 steps. The hole location was first pinned on the caster with a center drill bit to guide the drill bits after. Then a ¼ , 3/8 , and ½ inch drill bits were used to create the holes step by step as going through directly with the ½ inch drill would not be possible. A threaded shaft was installed through the 2 holes to allow for the ball joints to be installed in a neutral position compared to installing them directly on the swivel caster which would reduce the range of movement of the steering system. Two two-inch long pieces of PVC rod were cut then placed on the lathe to create threaded ½ in 20 center holes that are used to connect the threaded shaft and ball joints. This ensures that the ball joints are in neutral position as the wheel faces forward which maximizes turn degree and also reduces the force required to steer by increasing the arm moment.

Braking:

The braking system was designed around a bike disk brake system. This part was purchased from JFOYH on Amazon as it would be too complicated and expensive to manufacture within the scope of this project. To modify the bike brake system to fit the needs of the cart, a bracket had to be made to hold the brake caliper above the disk and a shaft collar had to be machined to attach the disk to the rear axle of the cart. The bracket was manufactured by plasma cutting 0.25” steel into three pieces: a 2” x 4” rectangle, a 0.8” by 4” rectangle, and a 3” x 4” piece with a fork in it.. Once the steel was plasma cut, four thru holes were drilled into the base plate for the purpose of bolting the bracket to the cart frame. Next, 2 holes were drilled and tapped in the end of the forked piece to accommodate the M\_ fasteners that came with the brake caliper. Finally, the three bracket pieces were welded together by a friend. This was free and chosen over welding in-house due to budget constraints. Steel was chosen for this part because of its high tensile strength.

Body Frame:

A piece of 4’’ x 8’’ plywood was selected as the ideal material for creating the base of a cart frame. The first step in the process involved designing a profile, which was essentially a digital blueprint, to guide the ShopBot cutting machine in carving out the desired shape. This profile was meticulously crafted to ensure that the final cut would precisely conform to the intended design. Once the profile was ready, the plywood was transported to the Rettner fabrication facility, where the ShopBot machine was located. With the help of skilled operators, the ShopBot was programmed to follow the profile's guidelines, and the plywood was expertly cut to produce the desired cart frame shape. Remarkably, the entire cutting process took less than two hours to complete.

Drive Train:

The drive train manufacturing involved multiple parts and steps. Two 5⁄8 in. diamter steel axles were cut to size of 24 in and 52 in accordingly. The top 24 in. axle had a key shaft machined using the mill to create a groove for the centrifugal clutch to fit. Also, the end attached to the rod was machied using the lathe to a diameter of 0.4 in. to fit in the drill head.

The skeleton for the drivetrain was made out of plywood since it can be mounted easily particularly at angles and is easy to machine to the needed dimensions. Two 10 x 17 in. side walls were cut and aligning holes were drilled to fit the top axle and house the bearings. Four supporting beams were cut at 45 degree angle to fit on the side wall and the frame. Bearings were mounted on the sidewalls and the frame bottom to allow the axles to rotate and eliminate friction.

The mounting plates for the tires were machined out of

aluminum. Holes were drilled in the plate to align the plates with the holes that were already drilled in the wheels and the holes drilled in the shaft collars.. Two threaded connecting rods were used to fix the plate to the wheels using 5/16”-18 fasteners. Plates were mounted to the axle using shaft collars. To prevent any slipping a bolt and a nut were used that held the plate securely between the two collars making use of the threaded holes in the collars.

A similar connection method was used to fix the sprocket in the rear axle as well. A 3x3 in. aluminum plate was manufactured amd drilled to be placed between the two shaft collars for a better grip on the sprocket. The plate was center drilled to fit in the axle and had two other holes alignin with the shaft collar holes. The sprocket was drilled as well to fit a bolt and nut that goes through the two collars, the aluminum plate, and the sprocket to ensure there are no power lost in transmission.

The centrifugal clutch is connected to the sprocket using a #35 chain. The chain couldn’t be cut to the exact length needed so an intermediate pulley was assembled to ensure that the chaiin is tighty connecting the clutch and the sprocket to reduce power losses as much as possible.

The total cost of materials bought can be seen in appendix E Table 1, the estimated hours and cost of labor of team members are listed below:

Development Time:

| Ahmed Abdalla | 22 |
| --- | --- |
| Ihab Youssef | 28 |
| Samantha Dinhofer | 20 |
| Lingyun Huang | 21 |
| Total Hours | 91 |

Manufacturing Time:

| Ahmed Abdalla | 40 |
| --- | --- |
| Ihab Youssef | 47 |
| Samantha Dinhofer | 30 |
| Lingyun Huang | 35 |
| Total | 152 |

Total cost of Manufacturing:

| Purchased Hardware | 1079 $ |
| --- | --- |
| Labor cost | 15200 |
| Total | 16279$ |

**TEST PLAN AND RESULTS**

Max Speed:

The intended approach to determine the maximum speed of the cart was to drive it at full throttle over a distance of 60 feet (marked with a measuring tape) in the Eastman Quad. A team member would record the time taken, which would then be divided by the distance covered to obtain the average maximum speed (distance / time). This test would be carried out three times, and the average of the outcomes would be considered as the cart's maximum speed

Payload:

To ensure the payload is equal for all carts, all drivers will be weighed on a scale on race day. The driver weight will then be equalized by adding additional weight to carts with lighter weight drivers.

Number of wheels:

By visual inspection it can be confirmed that the cart does have only three wheels, thus satisfying the specification.

Vehicle size:

The dimensions of the cart were measured using a tape measure. the dimensions of the car turned out to be 4 feet and 5.15 inches long, 3 feet and 10.5 inches wides, and 1 foot 11.6 inches high. This fits the design envelope of 6x4x4 feet.

Breaking Distance:

To test the breaking distance of the car, two lines are drawn on the ground that are set to be 15 feet apart measured by a tape measure. The car is then accelerated to top speed while approaching the lines and the driver fully presses the breaks while over the first line. The car must fully come to a stop before the second line is passed.

Turning Radius:

To test the turning radius, water or colored powder can be applied to the front wheel. The car is then directed to turn to the maximum angle possible in a set direction either right or left. The car is then driven around in a circle and the radius of the trail the car leaves on the ground is measured as the turn radius.

Results:

Initial testing for maximum speed and breaking distance was performed. However, we experienced an accident while driving that prevented further testing currently. The initial values collected for Maximum speed and braking distance are provided below , the turning radius was calculated using steering system geometry and the range of motion of ball joints used.

| Test | Result |
| --- | --- |
| Maximum Speed < 25mph | 7.5 MPH |
| Braking Distance < 15ft | 11.3 ft |
| Maximum Turning  Radius > 11ft | 10 ft |

**INTELLECTUAL PROPERTY**

The cart's design and manufacturing process are not eligible for patent protection since most of its features are not novel. The use of power drills to create motion is a well-established practice in the development of vehicles, and there are existing patents that cover similar innovations. For instance, US Patent No. 8,753,041 by John M. Ferguson describes a power drill-powered vehicle with an adjustable drive mechanism. Another patent by Anne E. O'Donnell (US Patent No. 9,018,492) discloses a drill-powered cart with a collapsible frame. These and other patents illustrate that the application of power drills in vehicle drivetrains, braking systems, and steering connections is not a novel concept and therefore not patentable.

**SOCIAL AND ENVIRONMANTAL IMPLICATIONS**

This project was modeled around goals which aim to have a positive impact on society and the environment. Conventional modes of transportation burn fossil fuels, releasing carbon dioxide, a greenhouse gas, into the atmosphere as a byproduct. This carbon dioxide depletes the ozone layer. Utilizing battery power to run a small-sized vehicle is a much more environmentally friendly alternative to vehicles that utilize gas or diesel power and pollute the environment and atmosphere.

The small size and relatively low cost of manufacturing, compared to conventional vehicles, make the drill-powered cart affordable and more accessible than the conventional car.

In the future, further improvements that can be made to lessen the environmental impact of the drill-powered cart include utilizing recycled materials and materials that are stronger and therefore less likely to need replacement.

**RECOMENDATIONS FOR FUTURE WORK**

If more time were allotted to work on this project, we would suggest that a more comprehensive NX design and analysis be completed before beginning manufacturing in order to better optimize the design and avoid flaws that might be discovered post-manufacturing without this analysis. Further, a more detailed design would allow the team to know what parts should be ordered early in the design process which could reduce the difficulty caused by shipping delays.

**ACKNOWLEDGMENTS**

Drill-Cart Bravo would like to thank our sponsor, Professor Muir, and our TA, Jamie, for their support and guidance over the course of this project. We would also like to thank Chris Pratt, Jim Alkins, and Peter Miklavcic for providing their expert knowledge and materials. Finally, we would like to thank the other drill-cart teams for pushing us to create the best possible product.

**REFERENCES**

Budynas, R. G., Nisbett, J. K., & Shigley, J. E. (2015). *Shigley's Mechanical Engineering Design*. McGraw-Hill Education.