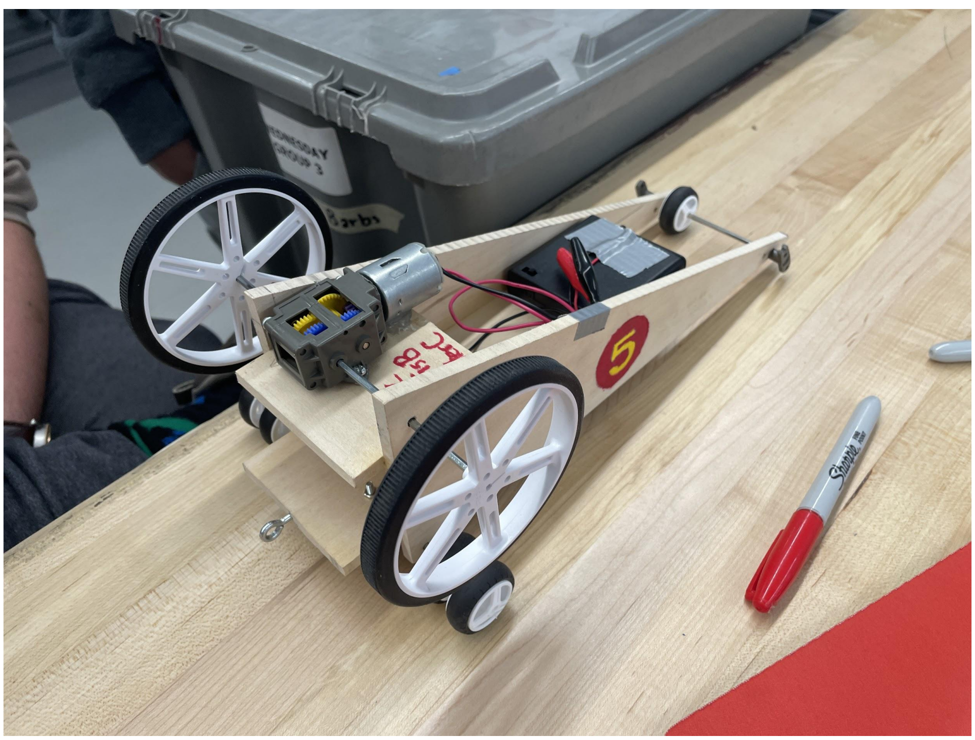
ENGRI 1170 Final Project Design Report
Speed Racers — Ata Zavaro (az335), Chris Bauer (cpb86), Hunter Chubik (htc28)



Development of Design

Overview of Challenges:

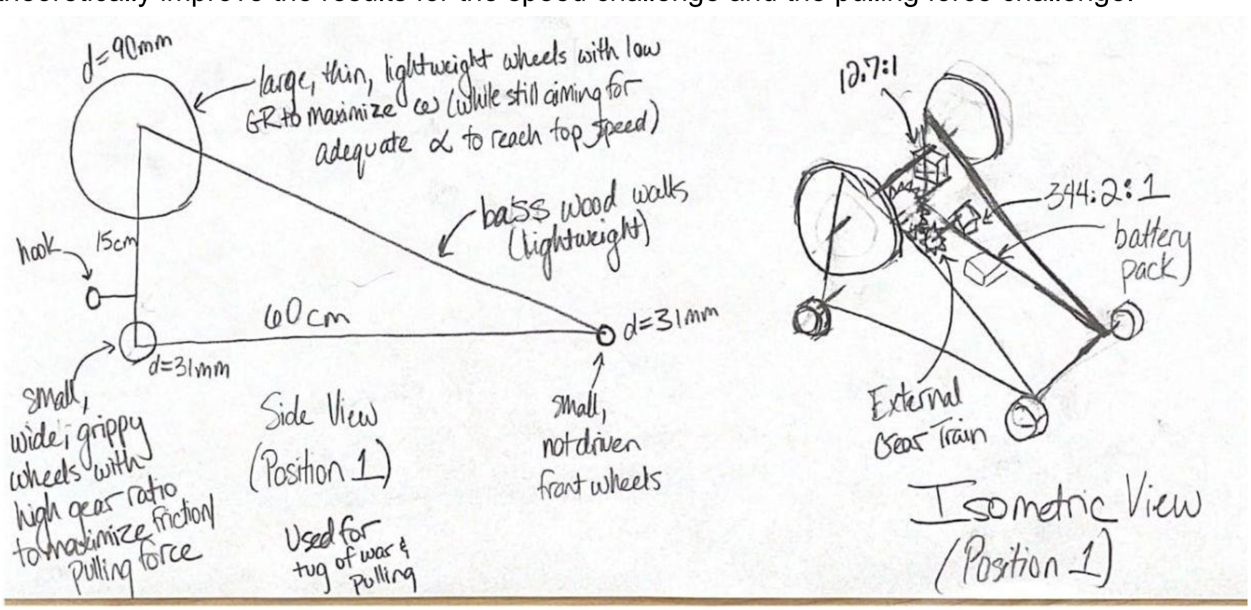
Our group was tasked with building a car that competes in three challenges: a pulling force challenge in which the car must pull with the most force possible per unit weight of the car, a speed challenge in which the car must travel 12 meters as quickly as possible (while staying inside the 1.5 meter track), and a tug-of-war challenge in which the car must try to pull an opposing car out of the competition area.

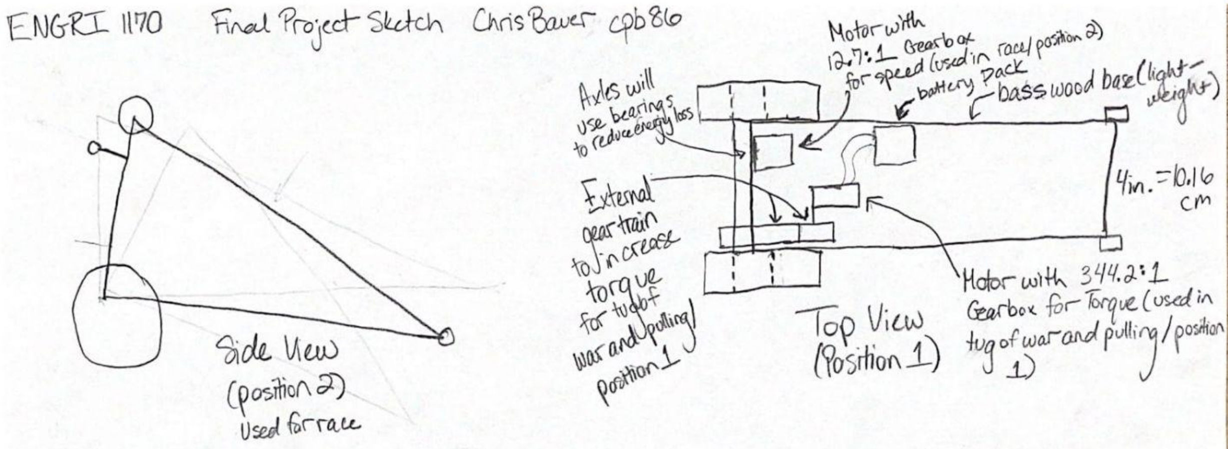
Overview of brainstorming/initial development of design:

Our group chose to determine the final design by creating one preliminary design each and weighing the pros and cons of each design to develop an optimal final design. Below are the sketches, materials, calculated performance estimates, and pros & cons of each design. Overall, we all had the idea of designing a car that excelled in one specific competition while not sacrificing too much from the others.

Chris's Design:

Chris designed his preliminary design to excel in the pulling force competition by aiming for a lightweight body with a lot of torque in position 1 (which would be used for the tug-of-war and pulling competitions). The large theoretical torque was achieved by using wheels that have a small diameter and by using a large gear ratio (344.2:1 gearbox plus an external 2:1 gear train). Chris chose to use wide wheels with a high coefficient of friction to increase friction with the ground to prevent the tires from slipping. For position 2 (which would be used for the speed challenge), Chris chose wheels with a large diameter and a low gear ratio to maximize the theoretical top speed. He chose the 12.7:1 gear ratio for a high top speed but adequate angular acceleration to increase the speed relatively quickly at the start of the challenge. The wheels for position 2 were thinner to reduce kinetic friction a bit so that the car could finish the challenge more quickly. Chris chose to use basswood for the body because it is lightweight, which would theoretically improve the results for the speed challenge and the pulling force challenge.





Free materials used: basswood sheet, 2 motors, hook, ⅛" hollow brass axles (x4), 344.2:1 and 12.7:1 gearboxes, batteries/battery pack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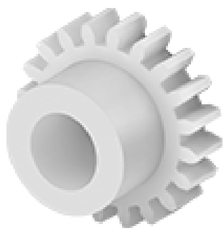
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- (Image 1) 90 mm x 10 mm Pololu wheels = $5.95 for one pair
- (Image 3) 31mm x 10mm Tamiya 70192 Slick Tire Set (4 tires) = $5.25 for 4 tires
- (Image 2) 1" plastic gear (McMaster) = $3.89
- (Image 2) 2" plastic gear (McMaster) = $5.83
- (Image 4) DuraTrax Bearing ⅛" x 5/16" = $2.99 for 2 bearings (x3)

Total estimated cost: $29.89

Estimated top speed calculation:
$v = (\text{no-load speed})(1/GR_{\text{position 2}})(R_{\text{large wheel}})$
$v = (1466.07657 \text{ rad/s})(1/12.7)(45 \text{ mm})(1 \text{ m}/1000 \text{ mm}) = 5.19 \text{ m/s}$

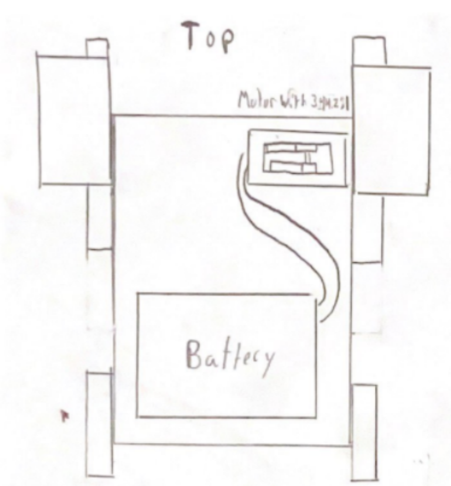
Estimated pulling force calculations:
$F = (\text{stall torque})(GR_{\text{position 1}})/R_{\text{small wheel}}$
$F = (0.01362 \text{ Nm})(344.2)(2)(1/15.5 \text{ mm})(1000 \text{ mm}/1 \text{ m}) = 604.90 \text{ N}$

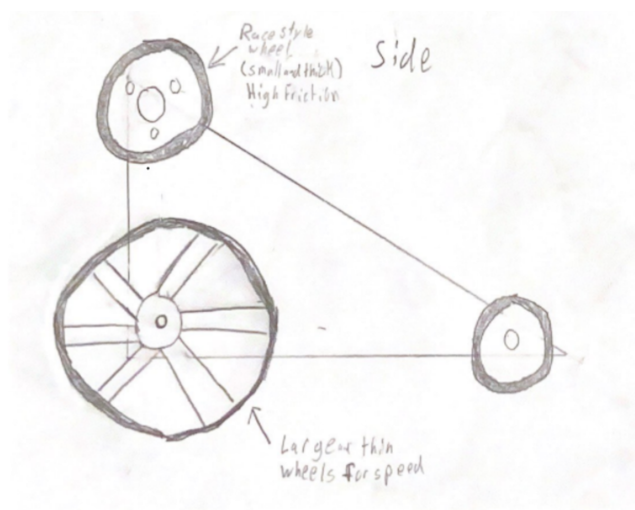
Friction: $F = (0.85)(0.566185 \text{ kg})(9.8 \text{ m/s}^2) = 4.716 \text{ N}$
(Estimate) coefficient of static friction between rubber and concrete = 0.85
(Estimate) mass of car = $43 \text{ g } (2) + 3.2 \text{ oz } (2) (28.3495 \text{ g}/1 \text{ oz}) + 92 \text{ g} + 0.8 \text{ oz } (2) (28.3495 \text{ g}/1 \text{ oz}) + 4.4\text{g } (4) + 300 \text{ kg/m}^3 (1000 \text{ g}/1 \text{ kg}) (1 \text{ m}/100 \text{ cm})^3 (1509.6 \text{ cm}^2)(0.125 \text{ in})(2.54 \text{ cm}/1 \text{ in}) = 566.185 \text{ g} = 0.566185 \text{ kg}$

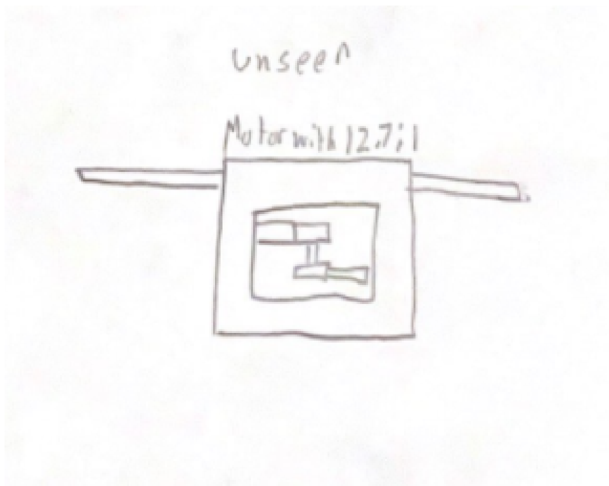
Pros	Cons
● High theoretical max pulling force (604.90 N) ● High theoretical top speed (5.19 m/s) ● Easy to reorient for different events during competition ● Long body is more aerodynamic ● Parts are mostly easy to obtain or in-stock ● Bearings reduce losses in axle rotation	● Barely within budget (estimated cost is $29.89) ● External gear train is difficult to construct properly (requires precise manufacturing) and can cause losses ● Requires switching between two different motors during competition between events ● Long body increases weight ● Gears do not fit ⅛” axles

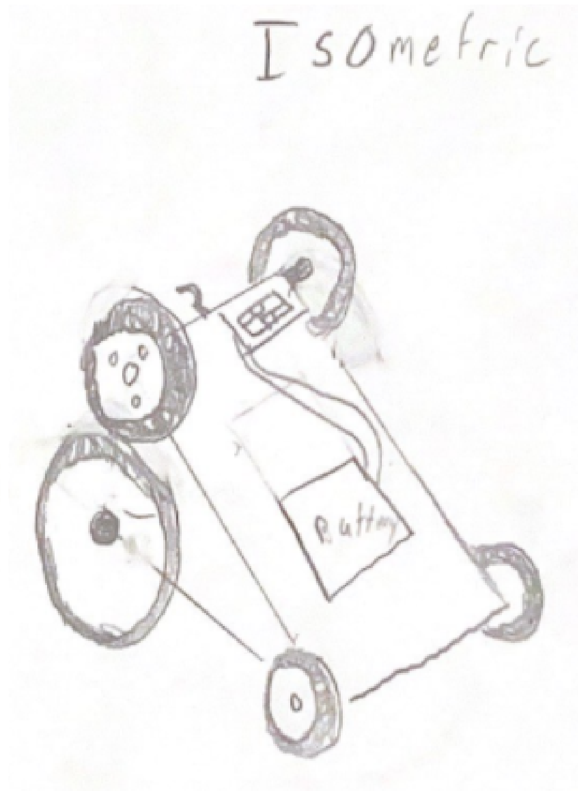
Hunter’s Design:

The main purpose of this design was to optimize torque because two out of the three competitions were about this factor. This design also wanted to be simplistic and also lightweight. We wanted there to be the least complexity so when constructing the car we wouldn’t run into many issues. It included two side pieces that would house the axles and also two smaller pieces in between to house the “guts” of the car. This includes the battery pack, motors, and the two gear boxes. The speed aspect was the same as the other designs utilizing the largest wheel we could find (The 90 mm radius wheel) and using the lowest gear ratio to give us the most speed (12.7:1). For the torque aspect we wanted small wheels in radius and wide so there is the most contact with the floor. The wheels that were chosen were the race style wheels because they had a relatively small radius and also were the widest available. The gear ratio we used was the 344.2:1 gearbox because the larger the gear ratio, the greater the pulling force.

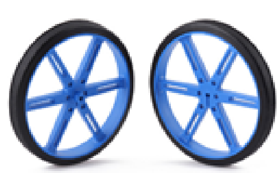








Free materials used: basswood sheet, 2 motors, hook, 344.2:1 and 12.7:1 gearboxes, batteries/battery pack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- (Image 1) 90 mm x 10 mm Pololu wheels - Blue= $5.95 for one pair
- (Image 3) Pololu Wheel 32×7mm Pair – Black = $2.95 for one pair
- (Image 2) Tamiya 70111 Sports Tire Set (2 tires) = $8.75
- (Image 4) Tamiya 70105 3mm Diameter Shaft Set = $6.25

Total estimated cost: $23.9

Estimated top speed calculation:
$v = (\text{no-load speed})(1/GR_{position\ 2})(R_{large\ wheel})$
v =(1466.07657 rad/s)(1/12.7)(45 mm)(1 m/1000 mm) = 5.19 m/s

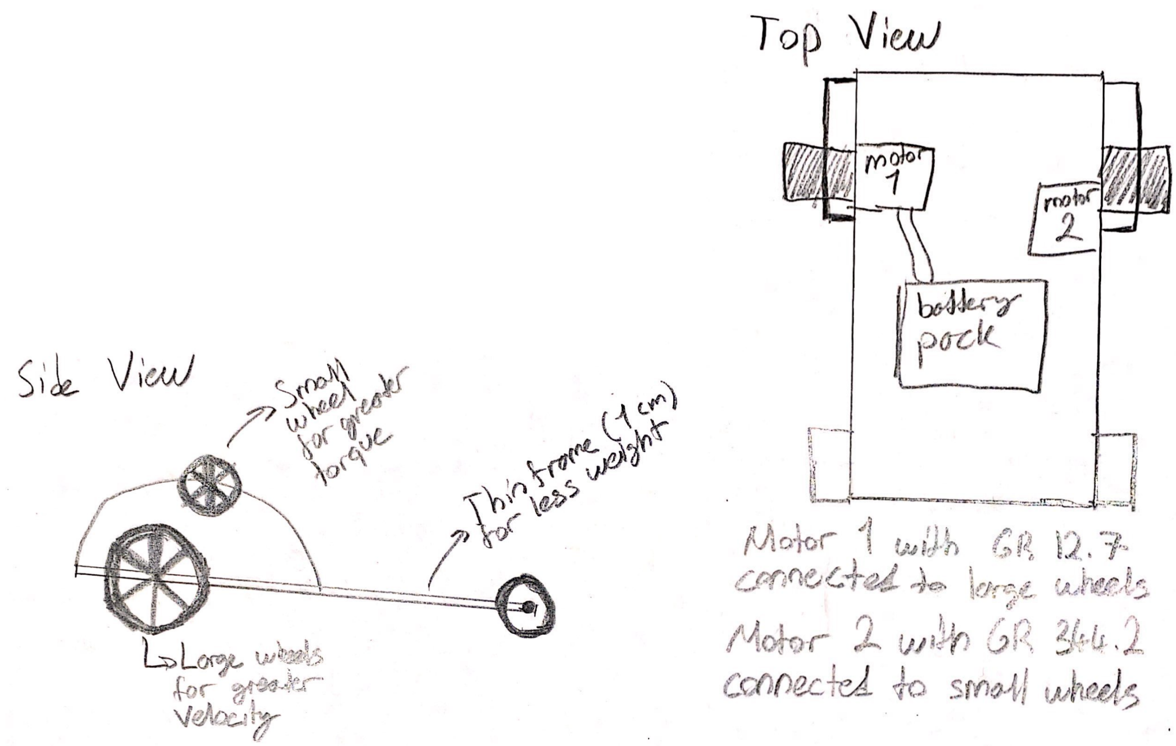
Estimated pulling force calculations:
$F=(\text{stall torque})(GR_{position\ 1})/R_{small\ wheel}$
F=(0.01362 Nm)(344.2)(1/28 mm)(1000 mm/1 m) = 167.43 N

Friction: F=(0.85)(0.609185 kg)(9.81 m/s^2) = 5.080 N
(Estimate) coefficient of static friction between rubber and concrete = 0.85
(Estimate) mass of car = 43 g (2) + 3.2 oz (2) (28.3495 g/1 oz) + 92 g + 0.8 oz (2) (28.3495 g/1 oz) + 4.4g (2) + 25.9(2) + 300 kg/m^3 (1000 g/1 kg) $(1\ m/100\ cm)^3$ (1509.6 cm^2)(0.125 in)(2.54 cm/1 in) = 609.185 g = 0.609185 kg

Pros	Cons
• High theoretical top speed (5.19 m/s) • Easy to reorient for different events during competition • Parts are mostly easy to obtain or in-stock • Wheels used for pulling have large surface area to increase friction • Relatively easy to construct (only gearboxes, axles, and wheels)	• Theoretical max pulling force is relatively low (167.43 N) • Requires switching between two different motors during competition between events • Wider wheels increase weight of car which can reduce speed • Hook will be barely within height limit • Estimated weight is relatively large (compared to other possible designs)

Ata's Design:

Ata's main purpose was to focus on speed while attempting to sacrifice as little as possible from the pulling force. The idea was to put the walls towards the back tires, without adding weight to the front side as much. Hence, the center of mass would be as near the back tires as possible, allowing the car to get more traction due to more force between the back tires and the ground. Hence, the car could have increased traction on the back wheels without adding weight. Furthermore, it also used a two tire setup with a turnable car for the different competitions. For the speed set, it had large wheels(90x10 mm), identical to the one we used finally, combined with the smallest gear ratio of 12.7:1. For the pull test, it had one pair of thick tires(42x19 mm) with the largest gear ratio of 344.2:1. External gears could have proven problematic due to potentially large inefficiencies, which is why they weren't used.



Free materials used: wood, 2 motors, 344.2:1 and 12.7:1 gearboxes, batteries/battery pack

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- (Image 1) Pololu Wheel 90×10mm Pair - Black = $5.95
- (Image 2) Pololu Wheel 42×19mm Pair = $6.98
- (image 3) Pololu Wheel 32×7mm Pair= $2.95
- (Image 4) Tamiya 70105 3mm Diameter Shaft Set = $6.25

Estimated Total Cost: $22.13

Estimated top speed calculation:
$v = (\text{no-load speed})(1/GR_{\text{position 2}})(R_{\text{large wheel}})$
$v = (1466.07657 \text{ rad/s})(1/12.7)(45 \text{ mm})(1 \text{ m}/1000 \text{ mm}) = 5.19 \text{ m/s}$

Estimated pulling force calculations:
$F = (\text{stall torque})(GR_{\text{position 1}})/R_{\text{small wheel}}$
$F = (0.01362 \text{ Nm})(344.2)(1/21 \text{ mm})(1000 \text{ mm}/1 \text{ m}) = 223.2 \text{ N}$

Friction: $F = (0.85)(0.559597 \text{ kg})(9.81 \text{ m/s}^2) = 4.6662 \text{ N}$
(Estimate) coefficient of static friction between rubber and concrete = 0.85

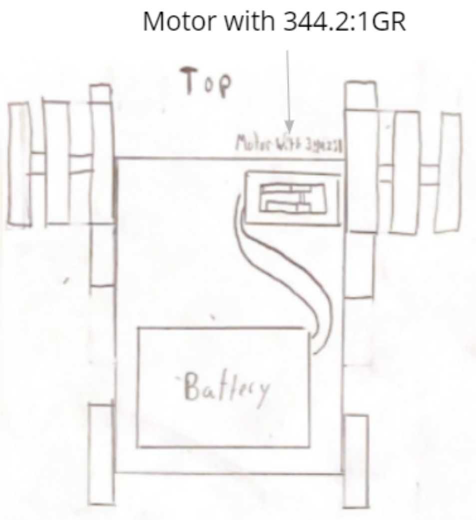
(Estimate) mass of car = (50 g)(2)+115 g + 0.11 oz (2)(28.35 g/oz) + (0.8 oz)(2)(28.35 g/oz) + (19 g)(2) + (30 cm)(10 cm)(1 cm) (0.85 g/cm^3) = 559.597 grams 0.559597 kg

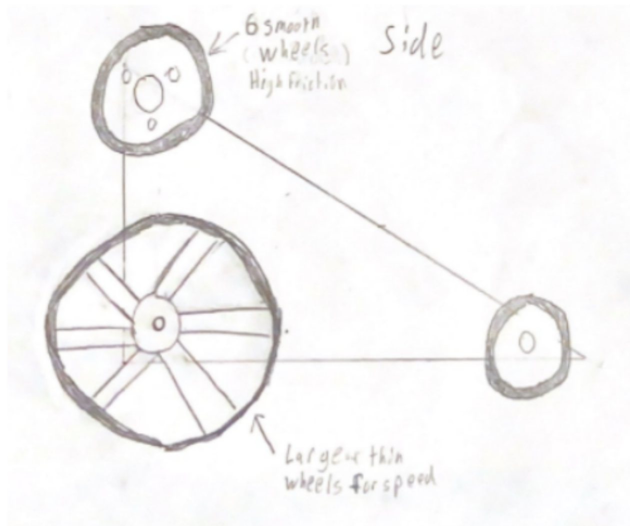
Pros	Cons
• High theoretical top speed (5.19 m/s) • Good theoretical pull force (223.2 N) • Long thin body is aerodynamic • The body has an angle with the ground generating downwards drag and larger traction • Well below the cost limit allowing room for errors or unexpected costs • Simple to reorient for larger speed or torque	• Not especially light (0.560 kg) • Framework is complex and requires very precise craftsmanship • During speed race, too much downwards force may hurt • Large wheels may cause initial acceleration to be low

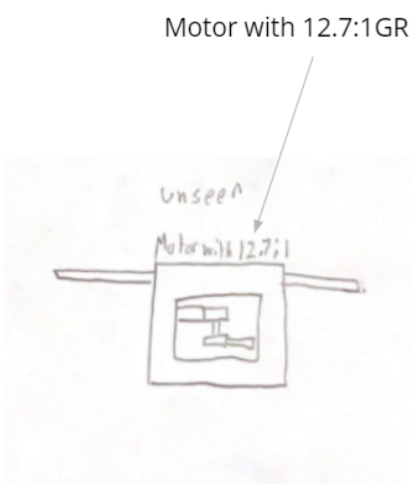
Final Design (Sketches on the next page):

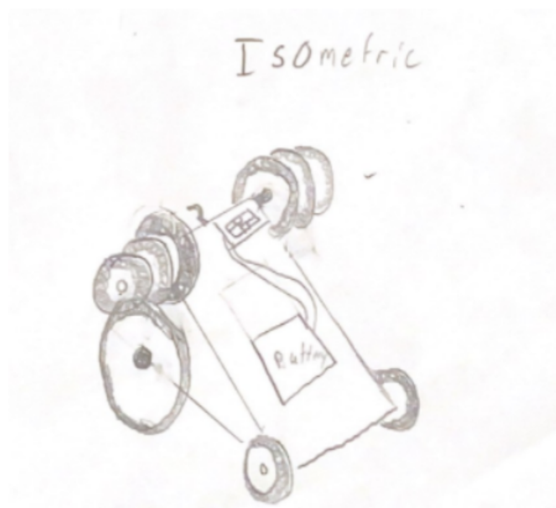
Our final design was very similar to Hunter's design, but it incorporated some aspects of Chris's design in order to take advantage of the pros and cons of each design. Instead of using the wide wheels Hunter proposed for a high pulling force, we decided to use three pairs of Chris's 31 mm x 10 mm wheels on the driven axle. This decision was made because these wheels are cheaper, lighter, smooth instead of treaded, and result in a greater surface area (30 mm total width vs. 25 mm width), which increases the friction with the ground. These wheels also have a smaller radius which increases the theoretical max pulling force. We decided that the external gear train from Chris's design would require too much precision manufacturing to ensure that the gears meshed properly and did not reduce efficiency. We decided to avoid this challenge due to limited time and limited experience with laser cutting, which would be the safest way to ensure that the gears lined up. The gears were also quite expensive and eliminating the external gear train by using Hunter's design saved us room in our budget to spend on other materials that we might need unexpectedly.

Final Design Sketches:









Final Design Initial Materials Plan (Final materials are listed later in the Bill of Materials): Free materials used: basswood sheet, 2 motors, hook, ⅛” hollow brass axles (x3), 344.2:1 and 12.7:1 gearboxes, batteries/battery pack

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- (Image 1) 90 mm x 10 mm Pololu wheels - Blue= $5.95 for one pair
- (Image 2) 31mm x 10mm Tamiya 70192 Slick Tire Set (4 tires) = $10.50 for 8 tires
- (Image 3) DuraTrax Bearing ⅛“ x 5/16” = $2.99 for 2 bearings (x3)

Total estimated cost: $25.42

Calculated performance estimates for the final design can be found below in the “Analysis of Performance” section.

Project Schedule and Planning Evaluation:

Initially, we planned to meet approximately two days each week depending on availability/other classes and progress. If we noticed that we were falling behind the schedule below, we would meet more often to complete the car on time. Although we had an idea of around what time we could finish the car, it greatly depended on the manufacturing process and part shipment time.

NOVEMBER

MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
1st Order Date	2nd	3rd Order Date - Order all initial materials - Start manufacturing body with available materials	4th	5th	6th -	7th
8th Order Date - Order extra materials if needed	9th	10th Order Date - Finish manufacturing and begin testing, order extra materials if needed	11th	12th	13th - Secondary testing, possible improvements	14th
15th	16th Order Date(McMaster)	17th Order Date (McMaster) -Tertiary Testing	18th Order Date McMaster	19th - Final Testing	20th Competition	21st

Therefore, we initially had a best case scenario schedule as above, but were also aware that it was very likely that we would finish in between the 15th and 19th of November. Primarily, we couldn't begin manufacturing on Wednesday Nov. 3rd because the labs were not open yet. Furthermore, we ordered our Tamiya shaft set on the 10th of November because we were unsure if they would be a good fit for our design initially, or if we would want to use the free axles provided. These two events by themselves were enough to push the manufacturing finish day to the 19th of November. However, we were also prepared for such pushbacks, which is why we tried to make a generous initial schedule with room for unforeseeable events. We still had time to test our car and make modifications on Friday the 19th so that we felt confident in our car's capabilities going into the competition on the 20th.

Manufacturing Process

Overall Evaluation:

Overall our manufacturing process went according to plan; however, it gave way to a few significant issues. Primarily, we used the band saw to cut the pieces for the car because we had only four total pieces to connect. Because wood glue takes a lot of time to fully dry, it took a few days to fully prepare the body. Our manufacturing process was successful as it primarily gave us a working, durable car. Furthermore, our design was relatively easy to adjust for issues. This really helped us towards the end of the manufacturing as the wood gluing process caused some of the body to not be level. Nevertheless, our flexibility helped us a lot in optimizing the performance of our car.

Issues and Adjustments:

Although we ran into some issues, we still accomplished all of our goals. Luckily, Chris had experience with most of the machinery available to us in the lab. This helped with our initial cutting and sizing of the parts. One major issue was that while the glue dried, a couple of the pieces in the car's body became slightly misaligned, which made some of our axles crooked and disjointed. This caused us, on the last day of labs, to redrill some of the axle holes and realign our wheels for the speed race. Primarily, we had to redrill the holes on the back wheels because our gearbox was misaligned with the holes. This caused the gearbox to exert force on the axle, which in turn caused force between the holes and axles. Hence, there was significant friction.

Furthermore, our car had a significant tilt towards the left. Therefore, we also drilled new front holes to make the axle more parallel to the back one. Although this made our car go much straighter, we still had a tilt towards the left. Here, we saw the benefit of testing and optimizing. With the help of Jayson, we had the idea of putting our single middle wheel towards the right rather than center, as can be seen in Figure 1. Hence, even though our car had some turn towards the left, it was able to go the twelve meter track without crashing to the wall.

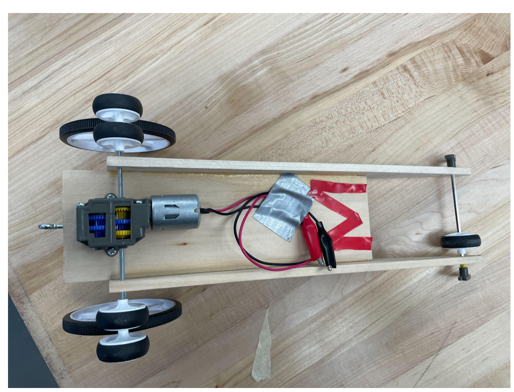


Figure 1: Top view in Speed Position

Another modification we decided upon was to use four small wheels in the back instead of six, because only four fit on the longest axles from our axle kit, and this tradeoff allowed us more time to focus on making our car go straight. We also had to end our manufacturing idea of decorating our car to look fully like the Mach 5 from Speed Racer due to time and the limited white paint on hand.

As you can see in the Bill of Materials below, we decided not to use the bearings as planned for all three axles. Upon drilling the (properly aligned) holes and testing the axles in them, we noticed that the axles spun relatively freely and did not seem to need bearings. However, we still felt that it was important to reduce frictional losses as much as possible for the speed test. For this reason, we used bushings on the axle with the big wheels used for the speed test. These bushings were extras that came with the gearbox, so they did not cost us anything but still allowed us to reduce friction between the axle and the wood.

Bill of Materials

Free materials used: basswood sheet, 2 motors, hook, ⅛" hollow brass axles (x3), 344.2:1 and 12.7:1 gearboxes, batteries/battery pack

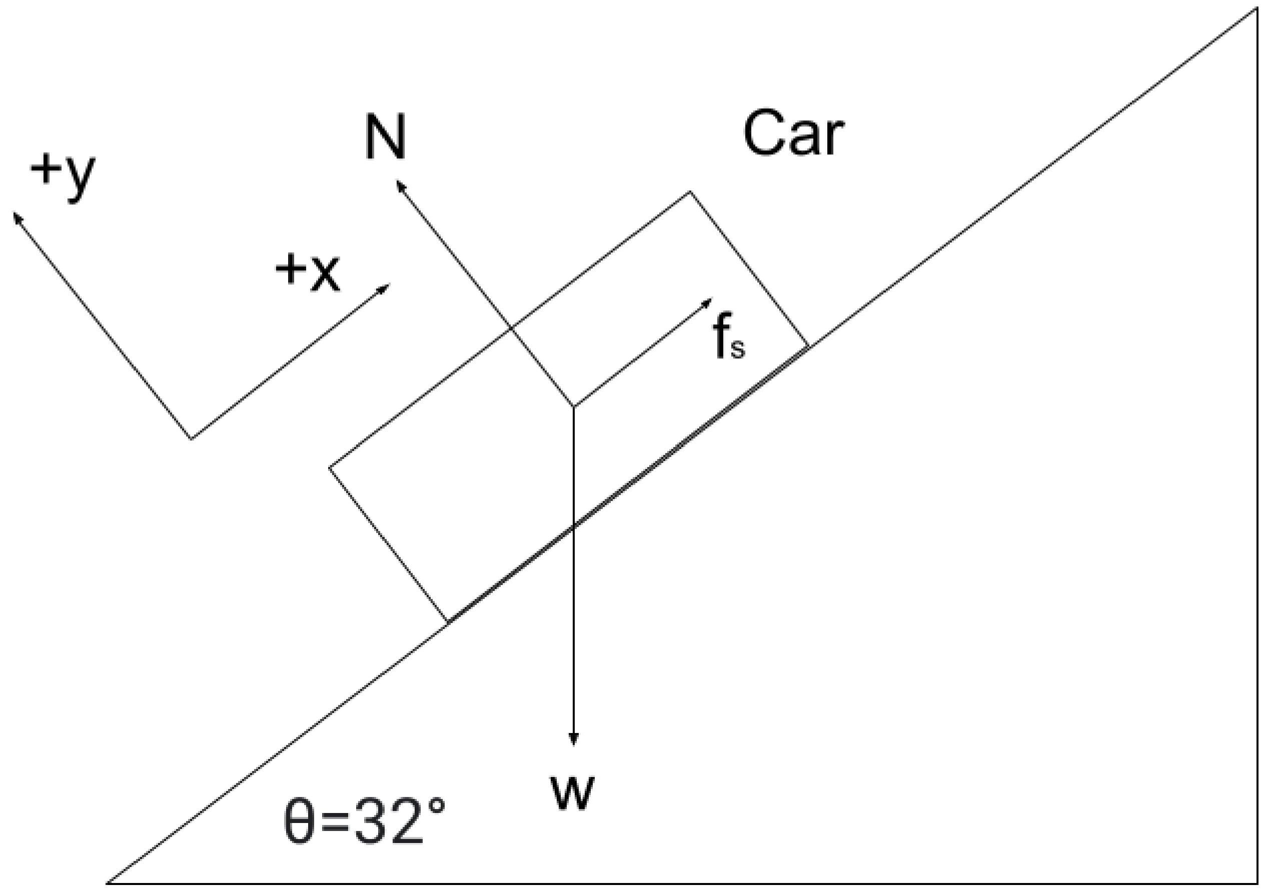
Description	Unit Cost	Quantity	Total Cost
90 mm x 10 mm Pololu wheels - White	$5.95	1	$5.95
31mm x 10mm Tamiya 70192 Slick Tire Set (4 tires)	$5.25	2	$10.50
Tamiya 70105 3mm Diameter Shaft Set	$6.25	1	$6.25
Total Cost	--	--	$22.70

Analysis of Performance

Measured Coefficient of Friction:

Our measured coefficient of friction was 0.625 for both sets of wheels. We measured this by placing the car (in each configuration) on a platform that could be raised to different angles with the tabletop. We jammed the wheels in place with a spare axle to prevent the wheels from rotating so that the car did not roll down the ramp, but would slide instead. We raised the platform to an angle where the car would just barely stay in place and avoid sliding down the ramp. We measured this angle to be 32 degrees for each set of wheels and used the calculations below to determine the coefficient of friction. The calculations for the coefficient of friction are below.

Free Body Diagram:



$\Sigma F_y = N - w\cos(\Theta) = 0 \rightarrow N = w\cos(\Theta)$
$\Sigma F_y = f_s - w\sin(\Theta) = 0 \rightarrow \mu_s N = w\sin(\Theta) \rightarrow \mu_s w\cos(\Theta) = w\sin(\Theta) \rightarrow \mu_s = \tan(\Theta)$
$\mu_s = \tan(32°) = 0.625$

These results seemed reasonable and were similar to other groups who used similar wheels. The coefficient of friction for each set of wheels was the same, which we expected because they both used very similar rubber materials.

Final Design Calculated Performance Estimates:

For the estimated top speed, we multiplied the no-load speed of the motor times the radius of the large wheels (used for the race) and divided this by the gear ratio (12.7:1) of the gearbox used for the race.

Estimated top speed calculation:

v = (no-load speed)(1/$GR_{position\ 2}$)($R_{large\ wheel}$)

v =(1466.07657 rad/s)(1/12.7)(45 mm)(1 m/1000 mm) = 5.19 m/s

For the estimated pulling force, we decided to calculate two different estimates: the force due to the torque produced by the motor and the force of friction with the ground. We decided that friction was an important component of the pulling force of the car because if the tires begin to slip, the car cannot continue to pull effectively. For the first calculation, we multiplied the stall torque of the motor times the gear ratio (344.2:1) of the gearbox used for the pulling challenges, and divided this by the radius of the small wheels (used for the pulling challenges).

Estimated pulling force calculations:

F=(stall torque)($GR_{position\ 1}$)/$R_{small\ wheel}$

F=(0.01362 Nm)(344.2)(1/15.5 mm)(1000 mm/1 m) = 302.45 N

Estimated friction (using measured coefficient of friction above and mass of car = 0.495 kg):

F=(0.625)(0.495 kg)(9.81 m/s^2) = 3.035 N

Competition Results:

Overall, we believe that our car performed pretty well. We had a time of 4.51 seconds in the speed race, which put us around the middle, considering the potential random error as we were collecting time with a manual stopwatch. Our car shined during the pulling force test, coming in first place by normalized force, indicating good efficiency. We were 1-2 in the tug-of-war, where we were hoping to do better but were not totally dissatisfied.

Analysis of Competition Results:

For the average velocity calculation, the total displacement, 12 meters, will be divided by the total time. However, considering that our car was not going perfectly straight, it probably traversed a longer distance and had a higher speed.

$$v\ avg = \Delta s/\Delta t = 12\ m/4.51\ s = 2.66\ m/s$$

The error in our speed prediction (2.66 m/s actual (average) vs. 5.19 m/s predicted (max)) lies in the fact that we assumed zero inefficiencies. We assumed the motor turned freely at max velocity, meaning it applied zero force. Hence, since it applied zero force but velocity is constant, we also calculated the speed the car would go with zero friction. However, there is an inevitable friction that is caused by the interactions between ground and tires, axle and bushing, motor box and gears etc. We are also comparing average speed to maximum calculated speed. Because the car started from rest, we would of course expect the car to take some time to reach its maximum speed and therefore have a lower average speed than maximum speed.

We decided to also attempt to compare the maximum speed prediction to an estimation of our actual maximum speed, so that we could compare max speed to max speed rather than average speed to max speed. To find the max velocity, however, we need to do some calculus and make some assumptions. Primarily, we know that our car started from rest. Secondly, we will need to assume that the acceleration of the car is constant. This is so that we can use calculus to find an equation for velocity. Finally, we will assume that the car did not reach its maximum velocity until the very end. This is necessary because we do not have sufficient data for more detailed calculations. Of course, however, this will lead to some inaccuracies in our final answer.

$v = ds/dt = at$, where ds/dt is the first derivative of displacement, a is the constant acceleration (the car starts from rest).

$s(t) = \int at\, dt = (1/2)at^2 + C$

s(0) = 0

$s(t) = (1/2)at^2$

s(4.51 s) = 12 m

$12\, m = 1/2 \cdot a \cdot (4.51\, s)^2$

After rearranging,

$a = 1.17994\, m/s^2$

Substituting into v(t) and setting t as 4.51 s

$v(4.51\, s) = (1.17994\, m/s^2) * (4.51\, s) = 5.32\, m/s$

This value is slightly above the theoretical max. The primary reason for this are the assumptions. It is very likely that the car reached max velocity before it finished, which would mean that our value is inflated. Furthermore, although this is not as significant compared to the max speed assumption, the acceleration is probably not constant, which may have caused some random error. Additionally, since the time was measured with a manual stopwatch, it is likely that there is some uncertainty as the car was going quite fast.

Hence, one can conclude that our max speed was somewhere between the average speed and the estimation of the max speed, 2.66 m/s - 5.32 m/s. This likely puts the actual maximum speed below the predicted maximum speed of 5.19 m/s, which makes sense because our prediction assumed ideal properties such as no friction (as discussed above).

The electronic force meter already noted the max pull force our car demonstrated. It is titled as the peak force our car applied.

$Fmax = 1.82\, lbf\, (4.448\, N/lbf) = 8.10\, N$

For our pulling mechanism, our max force of 8.10 N is higher than the prediction of 3.035 N but much lower than the theoretical max of 302.45. During our theoretical max prediction, we assumed that the tires weren't spinning and the gearbox was idle. However, in the competition, we observed that the tires were spinning and slipping on the mat due to inadequate traction. This is the main reason our car had a much lower real pulling force. However, it was higher than the friction calculation. This could be because of the rubber wheels compressing when they are on the ground due to gravitational force. This event of compression/decompression also causes an extra energy loss, or friction. Meanwhile, our calculation of static friction only attends to the literal force between two non-compressed materials, which is likely how we got pull force larger than the friction force.

Final Results from Competition:

Challenge	Result 1	Result 2	Result 3 / Best of Results 1 & 2	Final Placement
Speed	DNF	4.51 s	Best: 4.51 s	8th
Pulling Force	Max: 1.78 lbf Avg: 1.40 lbf Normalized: 0.00283 lbf/g	Max: 1.82 lbf Avg: 1.31 lbf Normalized: 0.00265 lbf/g	Best Max: 1.82 lbf Best Avg: 1.40 lbf Best Normalized: 0.00283 lbf/g	1st
Tug-of-war	Loss (Match 8)	Win (Match B)	Loss (Match E)	Record: 1-2

Analysis of Performance:

Our car performed very well in the pulling force challenge, as we expected since we designed the car to be lightweight and produce significant torque as well as friction with the ground. We placed above average in the speed challenge, which is a result we were pleased with, as the car seemed to accelerate well and reach a high top speed relative to many of the other cars. Our lightweight design likely helped in this challenge as well. In our tug-of-war win, our car seemed to provide a very consistent pulling force, allowing our car to overpower our opponent.

A couple of things did not go as well as expected during the competition. Primarily, we expected to have more success in the tug-of-war challenge since our pulling force challenge went so well. However, our losses in this challenge were likely a result of our lightweight design reducing our friction with the ground and making it easier for our opponent to pull us. Also our matchups were difficult (one loss was against the runner-up, Procrastinators, and the other loss was against an honorable mention, The Rock).

Furthermore, we had a DNF for our first speed challenge trial due to our car's inability to go completely straight, causing it to crash into the wall on the first trial and preventing it from completing the 12-meter stretch. On the second run, we adjusted our starting position to better account for the tendency to turn, which allowed the car to finish the race without hitting the wall.

Future Design Improvements:

If our group was to remake or adjust our car we would probably want to laser cut the pieces for our car. We originally avoided laser cutting to save time and make the manufacturing process simpler, but more precise manufacturing would help our car to be more robust and successful. This would most significantly help us with our issue of misaligned axle positions and help our car go straighter. Moreover, we would also find ways to increase the weight of our car so in the tug-of-war challenge we would be able to compete better against the other cars. Since we were quite a ways ahead of other cars in the pulling force challenge, we could afford to increase the weight of our car a bit without sacrificing our success in the pulling force challenge. With these changes we would also want to make sure all of our wheels fit, as we originally planned to have 3 small wheels on each side in the torque position but could not fit this many wheels. With more wheels on our torque side we would increase the area of friction and therefore increase our chances in the tug-of-war and also further increase our pulling force.