FINAL DESIGN REPORT

Ka-Chow Trailer

ME 287

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Executive Summary:

Route 66 is a vital, although rough and uneven highway over which barrels of Filmore's Organic fuel must be transported. These 5.5lb barrels of oil must be balanced on the uppermost surface of a vehicle being towed along the highway.

Before starting the design process, detailed specifications were determined including size, weight, and budget constraints. The design meets all required specifications; however, it can sometimes slightly damage the roadway, see Design Testing for more details. Working with a $20 budget, a vehicle has been designed, tested, and iterated which can transport the payload successfully 90% of the time. It features compliant wheels inspired by wheels used on FIRST Robotics intake mechanisms, and a suspended plate to carry the payload.

Two main challenges were identified: the teeter-totter and the Death Bringers. (An offset pair of ramps.) The suspended platform serves two purposes, which are the general suspension of the payload and passive braking for the teeter-totter. By including tabs welded to the plate over the wheels, the weight of the payload pushes on the wheels, drastically increasing the force needed to turn them. This forces the trailer to be pulled down the teeter totter rather than coasting, preventing the otherwise inevitable failure due to rapid deceleration at the bottom. Efficiency is not an issue as large amounts of towing force are readily available. The compliant wheels are crucial to overcoming the Death Bringers, as they deform and allow the platform to remain level on drastically uneven terrain. Additionally, they help on all other parts of the highway, such as the rocks and tires.

Many prototypes were created, tested and discarded before reaching the current design. As described in Prototyping and Design Progression, the final design is the data-driven optimization of five prior failures and successes. The material cost of the final design is $12.50, just 62.5% of the budget.

Problem Statement:

The city of Radiator Springs has had an earthquake and needs a new device which can traverse the uneven, broken terrain of Route 66. The cargo transportation trailer currently in use is now incapable of hauling heavy barrels of Fillmore’s Organic Fuel across Route 66.

The new device will be towed along the highway and must balance a 5.5lb barrel of oil on its uppermost surface. The device itself may be up to 8 inches wide, 10 long and 12 high including the height of the payload and weigh no more than 8lbs. The city is not in dire need of a new transportation method, so they only allocated $20 for the project’s materials.

Stakeholder Analysis:

1. **Operators**
    1. Aspects that help
        1. Enables them to conduct their business on Route 66.
        2. Easy to tow
    2. Aspects that hinder
        1. Things could fall off
        2. The trailer could get stuck.
2. **Customers**
    1. Aspects that help
        1. Enables them to send goods on Route 66.
        2. Transportation speed
    2. Aspects that hinder
        1. Damage to goods
        2. Cost of sending goods
3. **Road maintenance crews**
    1. Aspects that help
        1. Continued employment
        2. Provide fuel to remote locations
    2. Aspects that hinder
        1. Fixing road damage
        2. Dealing with wrecked trailers
4. **Radiator Springs**
    1. Aspects that help
        1. Keeping the city running smoothly
        2. Economic benefits of a working highway
    2. Aspects that hinder
        1. Development cost
        2. Environmental impact of increased traffic

Benchmarking:

<table>
<tr><td>Sherp trailer by Sherp USA
https://sherpusadealer.com/argo-sherp-pro-xt-trailer/</td><td rowspan="2">Pros
Can float
Is designed to be towed and carry stuff
Can go over rough terrain</td><td rowspan="2">Cons
Doesn’t demonstrate the ability to balance the payload
Very boxy and heavy</td></tr>
<tr><td></td></tr>
<tr><td colspan="3">This is the trailer that is sold for SHERP vehicles which are renowned for their all-terrain abilities. It demonstrates how an amphibious trailer can conquer rough terrain. The load carried is enclosed which is in stark contrast to the needs of this project and reduces the relevance of this benchmark. This product suggests the possibility of using just two big wheels and relying on the tow rope to keep the trailer level.</td></tr>
<tr><td>Ball-n-Cone Isolator

The Bowls Project, Seismic Isolation Plinth

https://sherpusadealer.com/argo-sherp-pro-xt-trailer/</td><td rowspan="2">Pros
Self centers
Can support high loads
Passive</td><td rowspan="2">Cons
Doesn’t allow for large angular deflections of platform
Would not respond well to relatively drastic linear accelerations involved in being towed over rough terrain
Potentially heavy</td></tr>
<tr><td></td></tr>
</table>

This is an isolation concept for protecting buildings from earthquakes, while not directly applicable the concept could be used for keeping the payload level. This benchmark demonstrates four shallow bowls at the corners of a platform but the idea it inspires is that of one larger, more hemispherical bowl which holds the platform that supports the payload. When the outer hemisphere is disturbed, the angular deflections are dampened by gravity. In a video on the website the platform is shown coming back to rest after being disturbed from equilibrium over the course of a minute or so. Here are some images of a quick demo I made of this concept; however a real implementation would use bearings instead of water.

	Pros	Cons
Tank Treads on Ripsaw EV3-F4 https://gaadiwaadi.com/this-800-hp-ripsaw-ev3-f4-luxury-tank-is-a-mammoth-on-the-move/ 	• Great ground clearance • Ability to absorb bumps • Good traction • Durable	• Complicated • Could tip side to side a lot • May compel high CG

The Ripsaw EV3-F4 is a custom-built tank that showcases the possibility of using tank treads on high-performance off-road vehicles. Treads have been well tested, provide a lot of traction, and can traverse many terrains. The main aspect of this challenge is keeping the payload from falling off the vehicle, which usually means keeping the platform balanced. Treads can succeed at that, but they need deep suspension, which could be rather tall.

	Pros	Cons
Leaf Springs https://www.theengineerspost.com/leaf-spring-suspension/ 	• Cheap • Simple • Strong	• Heavy • Big

<table>
<tr><td colspan="3">Leaf Springs are an option for wheel suspension. They are often used on vehicles and provide a simple and relatively cheap solution. However, a custom leaf spring would need to be made because this project is much smaller than the typical scale which could drive up costs and/or complexity to the point of impracticability. Additionally, leaf springs are very stiff and could even be too stiff for this application.</td></tr>
<tr><td>Plastic Toboggan

https://www.walmart.com/ip/Slippery-Racer-Downhill-Thunder-Kids-Toddler-Plastic-Toboggan-Snow-Sled-Blue/187325697</td><td rowspan="2">Pros

• No moving parts
• Wide footprint</td><td rowspan="2">Cons

• Hard to control
• Doesn’t handle sharp bumps well</td></tr>
<tr><td></td></tr>
<tr><td colspan="3">A plastic toboggan demonstrates the concept of having a ramp at the front of the vehicle. Ramps are a simple way to get up and over and obstacle but are prone to getting stuck on things and flipping the vehicle around when they suddenly become unstuck. Having a wide ramp, however, can keep the vehicle stable by spanning rough terrain, or it could get stuck on things and bring about total failure.</td></tr>
<tr><td>Andy Mark Compliant Wheels

https://www.andymark.com/products/compliant-wheels</td><td rowspan="2">Pros

• Flexible
• Can be 3D printed from TPU
• Simple
• Light</td><td rowspan="2">Cons

• Limited “suspension” relative to diameter of wheel.
• Expensive as COTS part</td></tr>
<tr><td></td></tr>
<tr><td colspan="3">A compliant wheel is a useful tool especially in FIRST robotics where they are used extensively for acquiring game pieces from any orientation. A compliant wheel could help the vehicle traverse uneven terrain and the ones from andymark have a high coefficient of friction. Buying them will be quite expensive, but they can be printed from TPU. However, if they are printed, the durometer and grip</td></tr>
</table>

will be less ideal. Compliant wheels are also limited in the amount they comply, relative to their radius and may not be an ideal use of space, especially height.

Needs:

Need ID	Description of Need	Justification	Required?
1	Design can safely carry the payload along the highway.	It is the essence of the problem	Yes
2	Design must be able to be safely towed.	Operators need to be able to use the product.	Yes
3	Design must meet size and weight constraints.	Requested by Client	Yes
4	Design must be able to balance the payload on its topmost surface.	Requested by Client	Yes
5	Design must be cheap, at least under budget	The Client has a budget	Yes
6	Design must traverse uneven terrain	Requested by Client	Yes
7	Design should be fast	Benefits Customer.	No
8	Design does not damage roadway	Reduces work for maintenance crews	No
9	Design should be disposable or manageable at end of life. (i.e., not radioactive etc.)	Eases disposals by maintenance crews	No

Specifications:

Spec ID	Related Need ID	Specification	Justification and Reference	Req?
A	1,4	Design can hold at least 5.5lbs of cargo on its topmost surface	Customer requirement	Y
B	2	Design must have an attachment point capable of withstanding 30lbs of force along the direction of travel.	Customer requirement	Y
C	3	Design must be no larger than 8in W x 10 L x 12in H	Customer requirement	Y
D	3	Design must weigh no more than 8lbs	Customer requirement	Y
E1	1,4,6	Design must prevent tilting of the topmost surface such that the center of mass of the cargo stays above its base	Customer requirement	Y
E2	1,4,6	Design must prevent acceleration of the topmost surface such that the center of mass of the cargo stays above its base.	Customer requirement	Y
F	5	Design materials must not cost more than $20	Customer requirement	Y
G	9	Design must not be made of radioactive materials	Design must be disposable at end of life.	Y
H	7	Design should be capable of sustaining speeds of 1.25 in/s.	Customers would appreciate speedy delivery.	N
I	8	Roadway should have no distinguishable damage after the solution travels over it.	Maintenance crews don’t want to always be fixing the road.	N
J	9	Design should not be made of toxic materials	Design should be disposable at end of life.	N

Design Description:

As can be seen in figure 1, the final design is a wheeled trailer with a flat platform on top which holds the payload in the upright position. It is intentionally the maximum length and width and vertically as compact as possible to lessen tilting. The wheels are 3D printed from TPU and allow the design to smoothly traverse uneven terrain by bending and squishing. The wheels do not ride on bearings but are pressed onto a wooden axle. When built J-B weld was used to firmly attach the wheels as the quality of the press-fit degraded due to TPU expansion.

The payload rides on a plasma cut steel suspended plate which serves two purposes: reducing jostling of the payload and providing passive braking power to the wheels. When presented with a steep downward incline such as the teeter totter, the trailer cannot be allowed to coast down because it will come to a sudden stop at the bottom invariably resulting in the payload falling off. By including tabs on the sides of the suspension plate, the weight of the payload puts a bit of pressure on the wheels so they cannot spin easily. The full weight of the payload is not on the wheels because it is offset by the support of the springs. There are four posts at each corner of the suspension plate that the springs ride made of partially threaded bolts welded to the plate. This setup makes the trailer stop on the incline and allows the winch operator to pull the trailer <u>down</u> the ramp in a sudo-controlled fashion. There is a nut on the bottom of each bolt used to fine tune the height of the suspension plate while retaining a smooth shank that slides in the mount block.

As can be seen in figure 2 further braking power is supplied by the auxiliary braking system, composed of rubber bands attached to the axles, hindering the relative motion of the axles. The payload rests on a piece of sandpaper glued to the suspension plate which provides a very necessary increase in friction. The winch attaches to the hole in the front of the base plate.

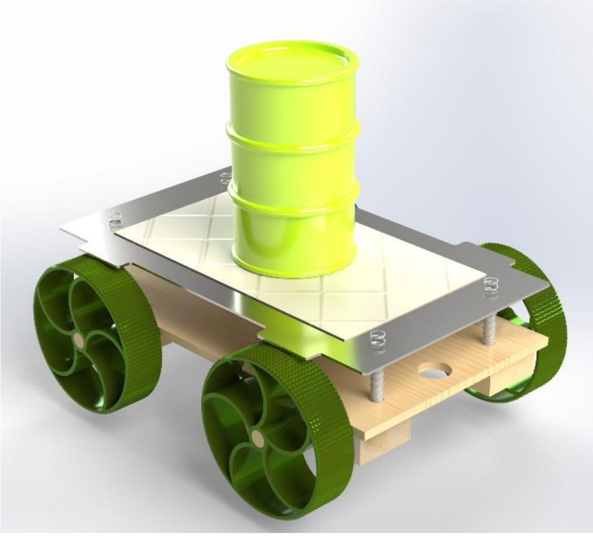

Figure 1: Overview of Design

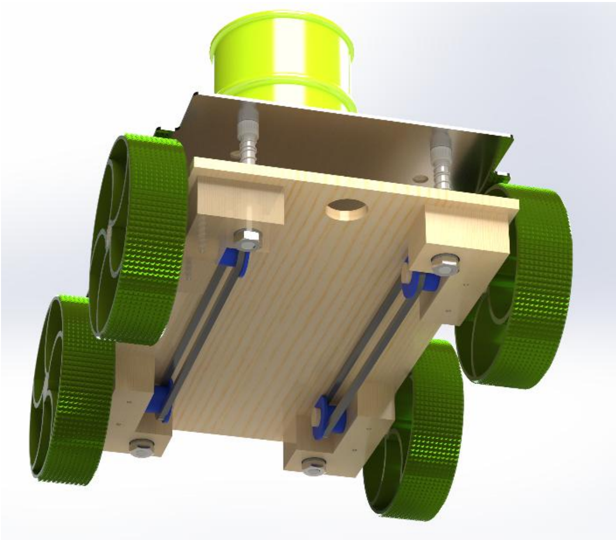

Figure 2: Underside of Design

Design Testing:

The primary method of testing the trailer is by running it on the course. This is accomplished by placing the vehicle on the course and towing it with the winch while carrying the payload. An operator does their best to vary the towing speed optimally, so some failures could possibly be attributed to operator error. If the speed is not changed, it is likely that all runs would fail. The final design testing was conducted by doing complete runs, however testing for prototypes was done by testing each obstacle individually and calculating the overall success rate. Below is a picture of the final trailer and its testing data:

Figure 3: Final design in real life.

Obstacle	Trials	# Pass	Success rate
Tires/Cone	10	10	100%
Teeter-Totter	10	10	100%
Ball pit/Rocks	10	10	100%
Death Bringers	10	9	90%
Overall	10	9	90%

Table 1 Final Design testing

This design has a 90% success rate which is quite impressive considering the difficulties of prior iterations. It has withstood many trials proving that not only can it succeed, but it is also robust. Given the 90% overall success rate, the final design passes specifications A, B, E1, E2, and G. It carried the payload, mostly did not drop it, got stuck several times and certainly had 30lbs of force on the attachment point. Spec C is met because it fits in the box. This design has not been weighed yet, but design iteration one weighed in at around 2lbs and the weight difference is not drastic, so if weighed, it would certainly meet spec D. With a total cost of $12.50, the materials meet specs F, G and J. See the Bill of Materials. The only spec it does not meet is the non-required spec I—the rocks get scratched, so the roadway sustains "distinguishable damage after the solution travels over it." The damage, however, is extremely minor and almost negligible.

Prototyping and Design Progression

Figure 4: Sled v1 (Prototype 1)

The final version of the design was heavily influenced by testing prior prototypes, which this section documents. The very first tests were of a sled shown in figure 4, which failed miserably, and for which no data is available. A variation of the initial sled with flippers, in the front also failed, as seen in figure 5, putting the nail in the coffin of a sled design. It is noteworthy that another student was able to see success with a significantly different type of sled. After this a third prototype was created which utilized the first iteration compliant wheels. (Figure 6)

Figure 5: Sled v2: (Prototype 2)

This prototype did very well and could have been the final design, except for the fact that the payload was held below the top of wheels, making it fail specification A. Referencing table 3, it had a success rate of 62.5% largely due to the large amount of wheel deformation and very low platform height. On the Death Bringers the wheels deformed a lot, allowing it to essentially remain level.

Obstacle	Trials	# Pass	Success rate
Tires/Cone	8	8	100%
Teeter-Totter	8	7	87.5%
Ball pit/Rocks	7	7	100%
Death Bringers	7	5	71.42%
Overall	8	5	62.5%

Table 2 Testing results for prototype v3

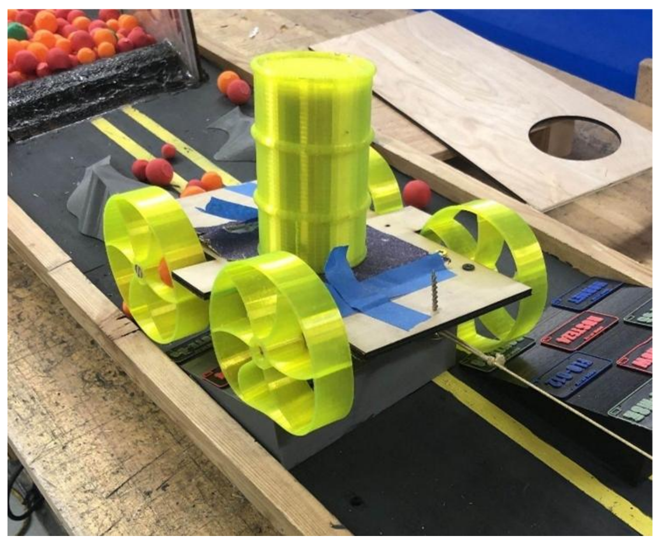

Figure 6: First compliant vehicle: Prototype 3

Figure 7: Design Iteration 1

To make the design pass specification A, the main attribute of the prototype's success had to be sacrificed, the height of the payload. To offset the height increase, the wheel size was reduced to 3.5 in. The suspension plate was introduced as the means of elevating the payload above the wheels. Due to fabricator skill concerns, it was decided to not weld the posts but use bolts, which necessitated a further height increase. The redesigned wheels were initially far too flexible and were reprinted before the official test. The resulting design, shown in figure 7, was the first official iteration which was far worse than prototype v3, but it at least passes the specifications. As can be seen from the test results in table 3, its success rate was 28.5%. It was too tall and went down the ramp too fast, but surprisingly did succeed during the official test.

After the official test, many ideas were thought of, and the trailer, shown in figures 8 and 9 was retrofitted with two of them and re-tested. The first idea was simple--just ditch the suspension plate and use a lower static block of wood. It was also noticed during the testing that the wheels would oftentimes randomly tilt and get slightly stuck under the suspension plate. In these scenarios it would slow the trailer on the teeter-totter and almost guarantee success for that obstacle. This observation prompted the idea of tabs on the plate, but as that was a more difficult modification the current auxiliary braking system was created.

Obstacle	Trials	# Pass	Success rate
Tires/Cone	2	2	100%
Teeter-Totter	7	4	57%
Ball pit/Rocks	4	4	100%
Death Bringers	4	2	50%
Overall	-	-	28.5%

Table 3 Design 1 Testing results.

As shown in table 4, when tested the changes did not measurably improve performance on the tetter totter, but they did help a bit with the Death Bringers. This yielded an overall success rate of 49.8%. Based on these results it was concluded that the suspension plate really did no harm but other changes were necessary. Considering that no contractor would be involved for the final iteration, the differences between the first official iteration and the final design were:

1. Welding the bolts to the plate to save height
2. Use five spokes instead of six to improve wheel deformation.
3. Add tabs to suspension plate to ensure braking power
4. Keep rubber-band brakes.

Figure 8: Iteration 1 Retrofitted, top

Table 4 Retrofitted Design Testing Results

Obstacle	Trials	# Pass	Success rate
Tires/Cone	0	0	100%
Teeter-Totter	10	6	60%
Ball pit/Rocks	6	6	100%
Death Bringers	6	5	86.3%
Overall	-	-	49.8%

Figure 9: Iteration 1 Retrotiffed, bottom

As was already shown in table 1, these changes were highly successful and were able to beat prototype 3 with a success rate of 90% in ten trials!

Bill of Material/Budget:

Table 4Bill of Materials.

Item	Qty	Name	Dimensions / Part Number	Manufacture r / Material	Cost
1	1	5mm underlayment	10” x 5.75”	Wood	$0.17
2	4	1/4"-20 Socket head 3"	91274A208	Alloy Steel	$0.84
3	4	¼’-20 Hex nut	95462A029	Allow Steel	$0.0895
4	4	1x2 board	1.5”x.75”	Wood	$0.12375
5	4	3/8 dowl	0.375”x2.5”	Wood dowl	$0.05625
6	4	Axle Stop	0.375” hub	TPU	$.03325
7	4	TPU Wheel	3.5 in	TPU	$0.771
8	4	TPU standoff	.281”	TPU	$0.01108
9	4	Spring	9657K286	Steel	$1.0108
10	1	Sandpaper	2x5 60 Grit	Sandpaper	$0.50
11	2	Rubber band	3 in loop	Rubber	$0.0425
				Total	**$12.50**