MINNESOTA DEPARTMENT OF TRANSPORTATION

RESEARCH

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Development of a Trash Harvester for MnDOT-- Phase II

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16. Abstract (Limit: 200 words)

Trash collection along a roadside is usually done by hand which requires a lot of workers and time. There are machines available to remove trash on smooth surfaces such as concrete, but none of them are able to pick-up litter on grassy areas.

The objective of this project is to design and build a machine to collect trash and litter lying on grassy areas alongside a road. A "trash harvester" would make the process easier, safer, faster, and more economical. The trash harvester was initially designed with a shredding attachment; however this has been superseded with a conveyor design.

The trash harvesting principle has been proven in field trials and the machine will collect 100% of paper, bottles, and soda cans. The machine will also lift 2 x 4s up to 15” in length.

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Development of a Trash Harvester for MnDOT– Phase II

Final Report

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Executive Summary

Trash collection along a roadside is usually done by hand which requires a lot of workers and time. There are machines available to remove trash on smooth surfaces such as concrete, but none of them are able to pick-up litter on grassy areas.

The objective of this project is to design and build a machine to collect trash and litter lying on grassy areas alongside a road. A "trash harvester" would make the process easier, safer, faster, and more economical. The trash harvester was initially designed with a shredding attachment; however this has been superseded with a conveyor design.

The trash harvesting principle has been proven in field trials and the machine will collect 100% of paper, bottles, and soda cans. The machine will also lift 2 x 4s up to 15” in length.

1. Problem Statement

The collection of trash in the metro area costs $2M per year. The cost is largely due to the labor required to gather trash along the sides of the Minnesota Department of Transportation (MnDOT) right of way. The tidiness of the metro area is a matter of civic pride. What visitors see influences their opinion of the city.

The purpose of this project is to mechanize the trash collection process. The objective of this study is to design and build a machine to collect trash and litter (such as paper, plastic bags, bottles, aluminum cans, etc) lying on grassy areas alongside a road. Such a machine would make the process easier, safer, faster, and more economical.

Figure 1: Need for a trash harvesting machine

2. MnDOT Proposal

The trash harvesting machine is designed to collect trash lying on grass along roads and highways. An initial set of machine specifications was developed in consultation with Bob Wryk and his colleagues from the Minnesota Department of Transportation in February 2005. The following is a list of the pertinent specifications:

- Transport width below 8 feet
- Working width below 20 feet
- Transport speed around 15 mph
- Operational speed around 2 mph
- Stable on 4 to 1 slopes
- Shall minimize the amount of grass harvested
- Minimize traffic disturbance

The trash collection machine will become an integral part of a right-of-way maintenance regimen. Thus, the benefits of developing the trash harvesting platform are many folds. First the road right-of-way will be free of trash and debris. Second the platform could be used to perform other tasks simultaneously. The machine could be used to aerate the soil, apply fertilizer, seed where needed or could be adapted to mow grass.

We also defined and ranked what constituted a typical sample of trash. The materials are listed below according to decreasing volume:

- Paper
- Cans/plastic bottles
- Plastic-tarps-retreads
- Mufflers-hub caps
- Sheetrock-wood-carpet
- Clothing-diapers
- Dead animals
- Wheels-tires
- Nails
- Glass bottles

We came to an agreement that the machine should be able to harvest the top four categories of trash. The machine will not be able to pick-up very small objects like metal nails or big objects like rubber tires or dead animals. The maximum volume of trash to be "harvested" is 10 cubic yards per mile. The volume of trash carried by the trash harvesting machine will be limited by the size of the collection bin and/or the stability constraints.

There has been very little research conducted on this type of machine. Most machinery that we have been able to identify is designed to clean the hard shoulder or the road surface. The specialty machine that Department of Transportation is looking for is intended for use on the off-road, sloping right-of-way.

To the best of our knowledge there has been no attempt to develop an off-road trash harvesting machine as described in MnDOT proposal. Caltrans, the Californian Department of Transportation, has developed their own machines to collect trash along roads but those machines designed to pin point rather big pieces of litter on hard surfaces are not suitable for our application that requires a machine that would be able to sweep large grassy areas and pick up smaller litter.

Figure 2: Caltrans trash collection solutions

3. Trash Harvesting Process

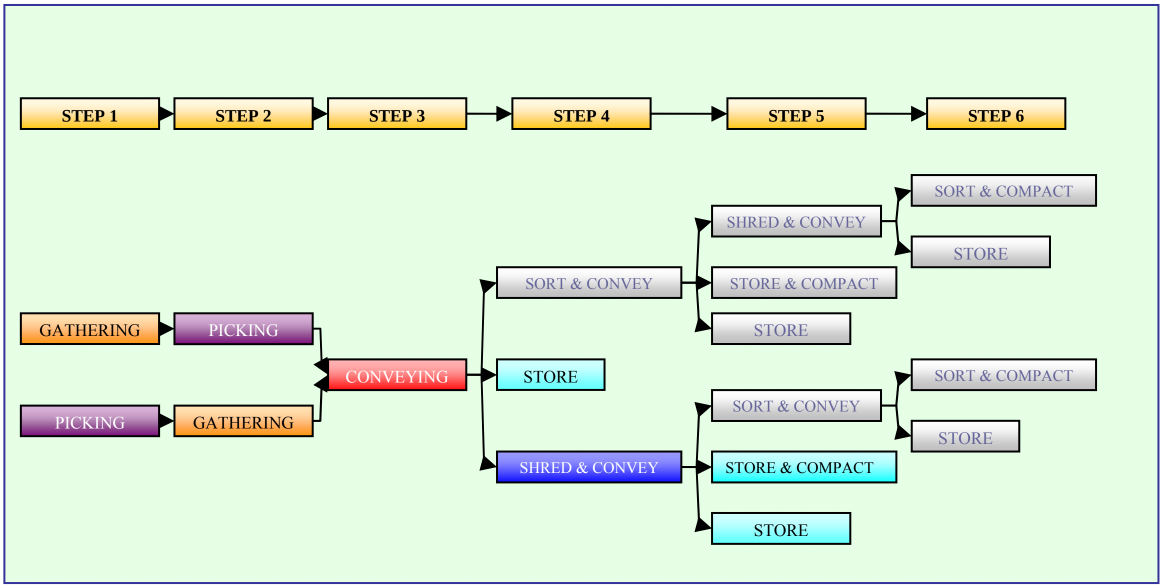


Figure 3: Trash harvesting process

The first step in the design process of the trash harvester is a clear definition of what the trash harvesting process is. How can we break this process down into simple steps and what is the sequence of these steps?

The first two steps in the trash harvesting process are gathering and picking. These first steps are perceived as the most difficult steps in the trash harvesting process. By gathering we mean collecting the trash to a specific area/location. By picking, we mean lifting the litter off the ground and placing it on the machine. We can gather first and then pick the trash up. Alternatively, it is possible to pick up the trash first and then gather it. It may seem equivalent but as we will see later, the sequence of these first two steps calls out for very different technological solutions.

The third step is conveying. Conveying means that we move the trash from one location to another location on the machine. This step is similar to gathering except that gathering can also mean moving the trash from one place to another while the material is still on the ground.

We rapidly decided that sorting the trash would be too complex such off-highway mobile equipment. The machine will be designed to minimize the amount of grass collected from the first place instead of sorting out the trash from grass afterward.

Prior to storing the material, the trash harvesting process can include shredding and/or compacting. Shredding the trash has several advantages. First, once the trash is shredded, it is easier to convey it from one place to another one and greatly simplifies the conveying process in comparison of having to move raw and bulky material. It also allows us to increase the autonomy of the trash harvesting machine by reducing the number of stops to unload thus boosting productivity.

4. Concept Generation

The next step in the design process is ideation through brainstorming and other techniques. We came up with several concepts based on what we believe are the two most technologies for trash picking: the tine technology and the vacuum technology.

The tine technology means using spring tines, brushes, rakes, etc… to pick up and/or gather the trash. By vacuum technology, we mean using a vacuum to pull the trash out of the grass and convey it to the machine.

Our initial idea was to have the trash harvesting machine driving on the shoulder of the road. The machine would use either the tine or the vacuum technology to perform the picking and gathering functions. The picking/gathering boom would extend several feet on the right side of the machine. Several arrangements are possible depending on the technology used (tine or vacuum) and the sequence of trash harvesting process (picking first or gathering first).

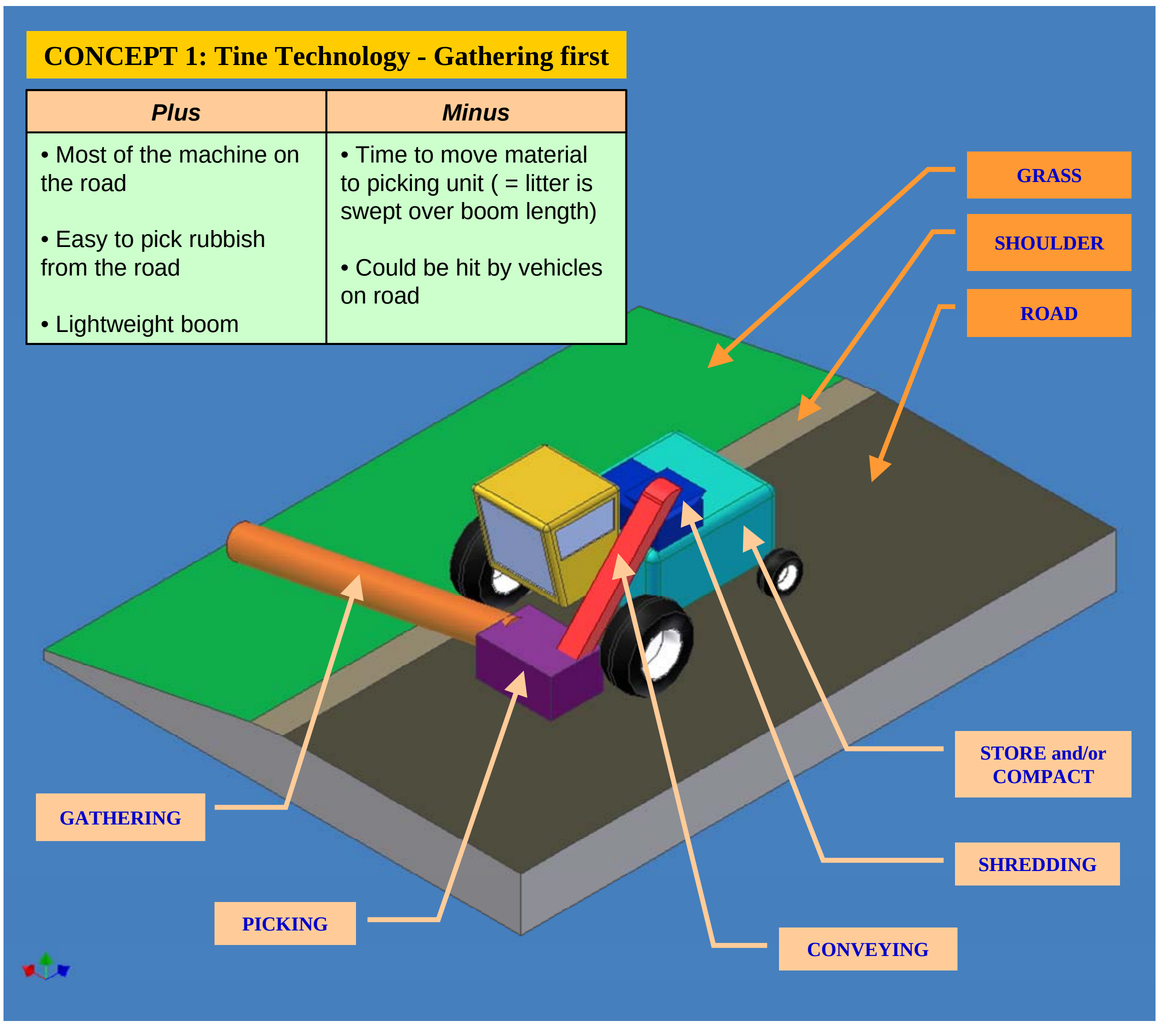


Figure 4: Tine technology – Gathering first

This first concept illustrates the "gathering first" process combined with the tine technology for the gathering and picking steps. The gathering first process makes the second step, the picking step, easier since it is much simpler to pick-up litter on a hard surface like the shoulder rather than on a rough grassy terrain. Many technologies already exist to pick up trash on a hard surface. The main drawback with gathering first is that a significant quantity of dry grass, stones and other undesired material might be gathered as well since the ground would be swept over a long distance.

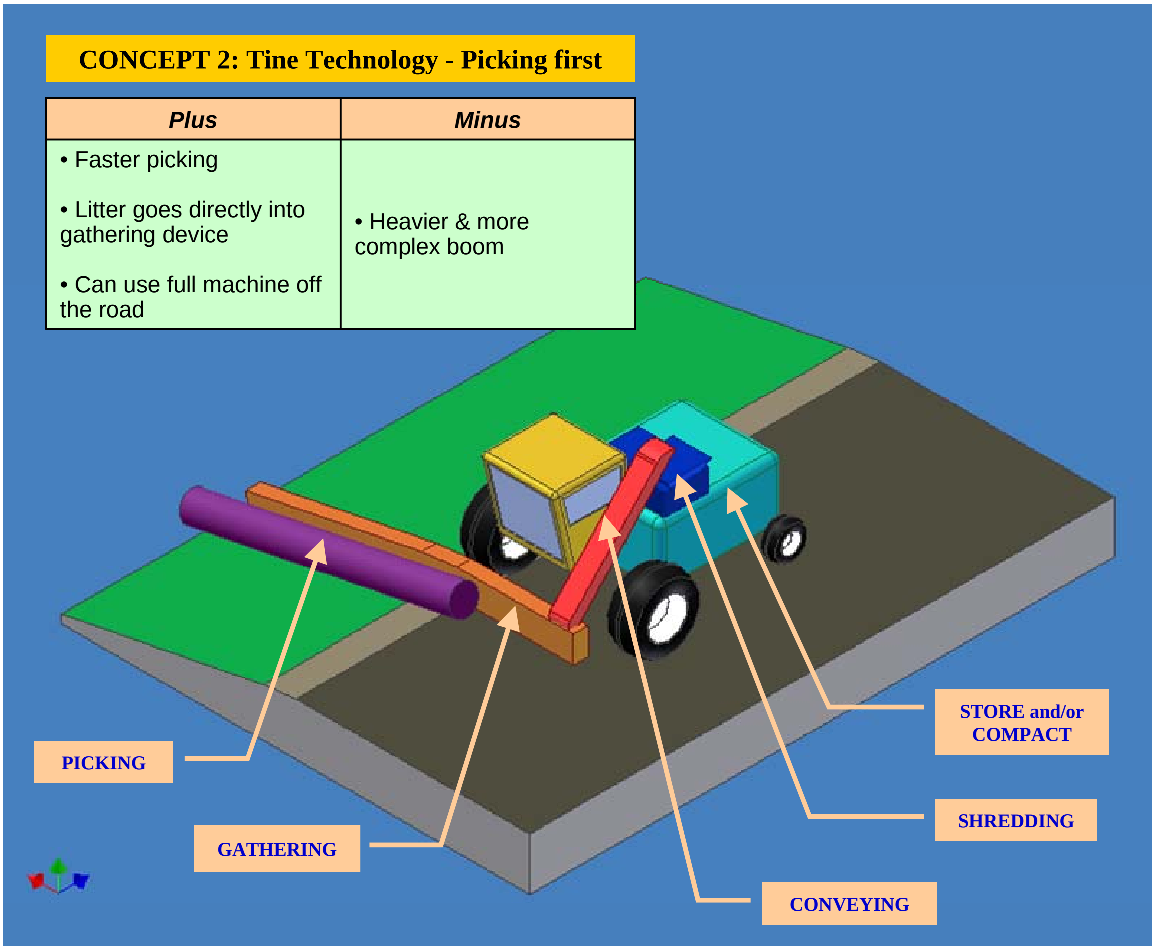


Figure 5: Tine technology – Picking first

This second picture illustrates the "picking first" concept associated with the tine technology. In this concept, the picking step is more delicate than in the "gathering first" concept since there is no existing technology to pick up trash from grassy areas. Unlike gathering first, picking first has the potential to minimize the amount of undesired material like dry grass, stones collected. The drawback of such a concept is a heavier boom since both picking and gathering functions are spread over the width of the boom.

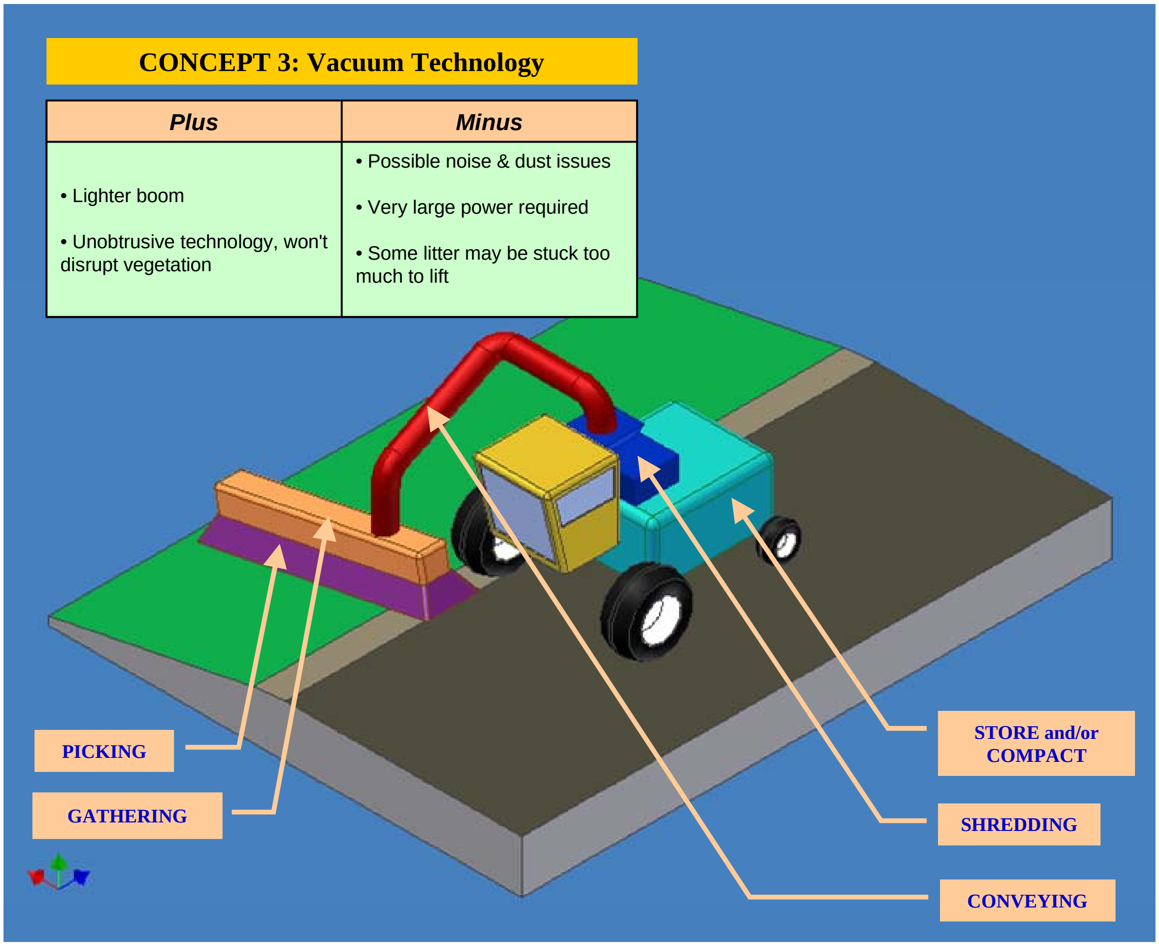


Figure 6: Vacuum technology

This third concept illustrates the vacuum technology. With this technology, the gathering, picking and conveying are all performed at once by the same system. The main issues with the vacuum technology are dust formation and noise level as well as power requirement: Dust and noise are potential hazards for road users. To be able to pull the trash out of the grass over such a large collection area, a very large vacuum and thus, a very powerful machine is required.

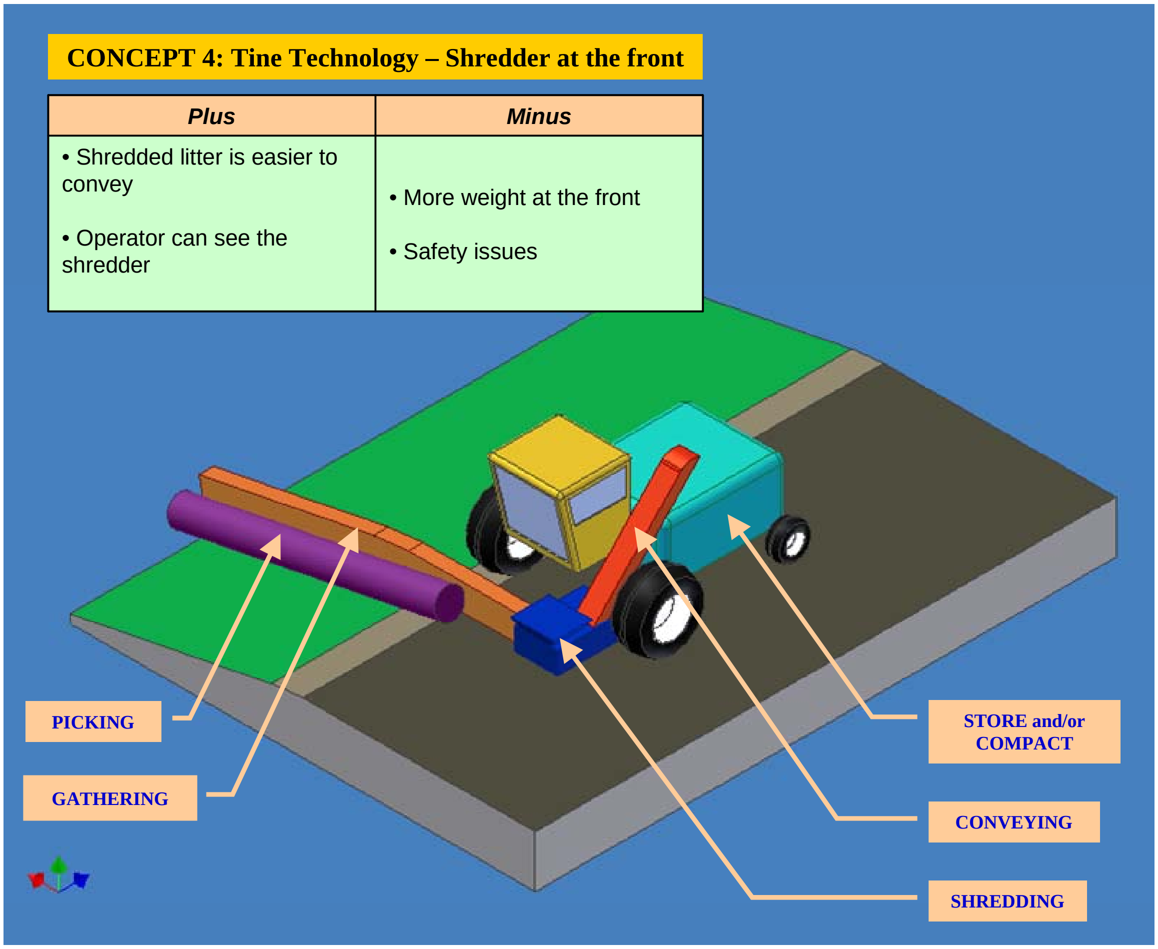


Figure 7: Tine technology – Shredder at the front

This last concept illustrates an interesting variation of concept 2 with the shredder located at the front of the machine after the gathering step and before conveying the trash to the storage area. By reducing the size of the trash, it greatly simplifies the conveying step. On the other hand, safety is a major when using shredders. This concept also brings more weight to the front of the machine.

5. Technologies for Trash Harvesting

In the first part of this chapter, we will further refine the concepts previously introduced by reviewing the different technologies that would enable us to achieve the different tasks of the trash harvesting process. The goal here is to evaluate the feasibility of the different concepts.

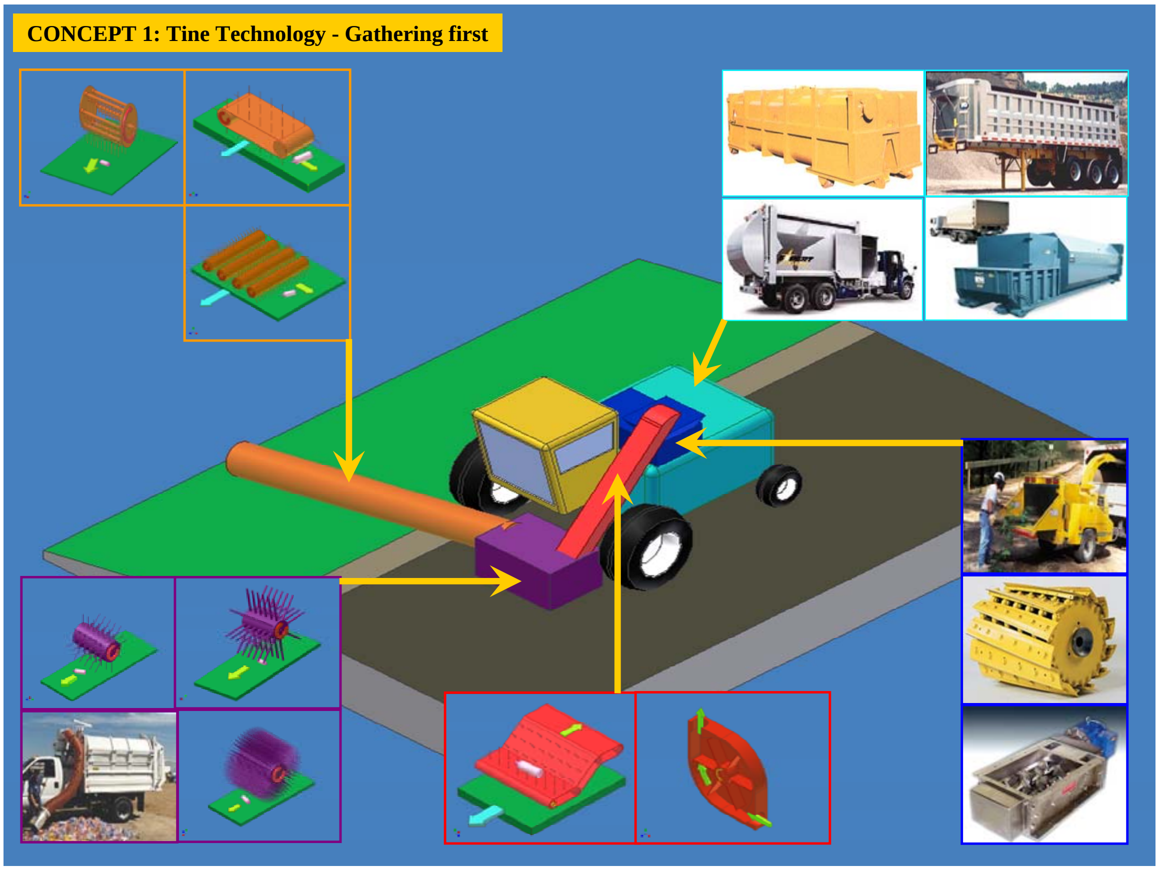


Figure 8: Technologies for gathering first

With concept 1, the gathering step could be achieved by using an existing technology like a hay rake. Spring tines mounted on a belt or a series of rolls could also be used for this first task.
For the picking step, we could use brushes, spring tines or rigid rods mounted on a rotating cylinder that would push the trash to the conveying system. A vacuum could also be use to perform that task. In this particular case, there is no need for a conveyor since the vacuum would act as both a picking and a conveying system.

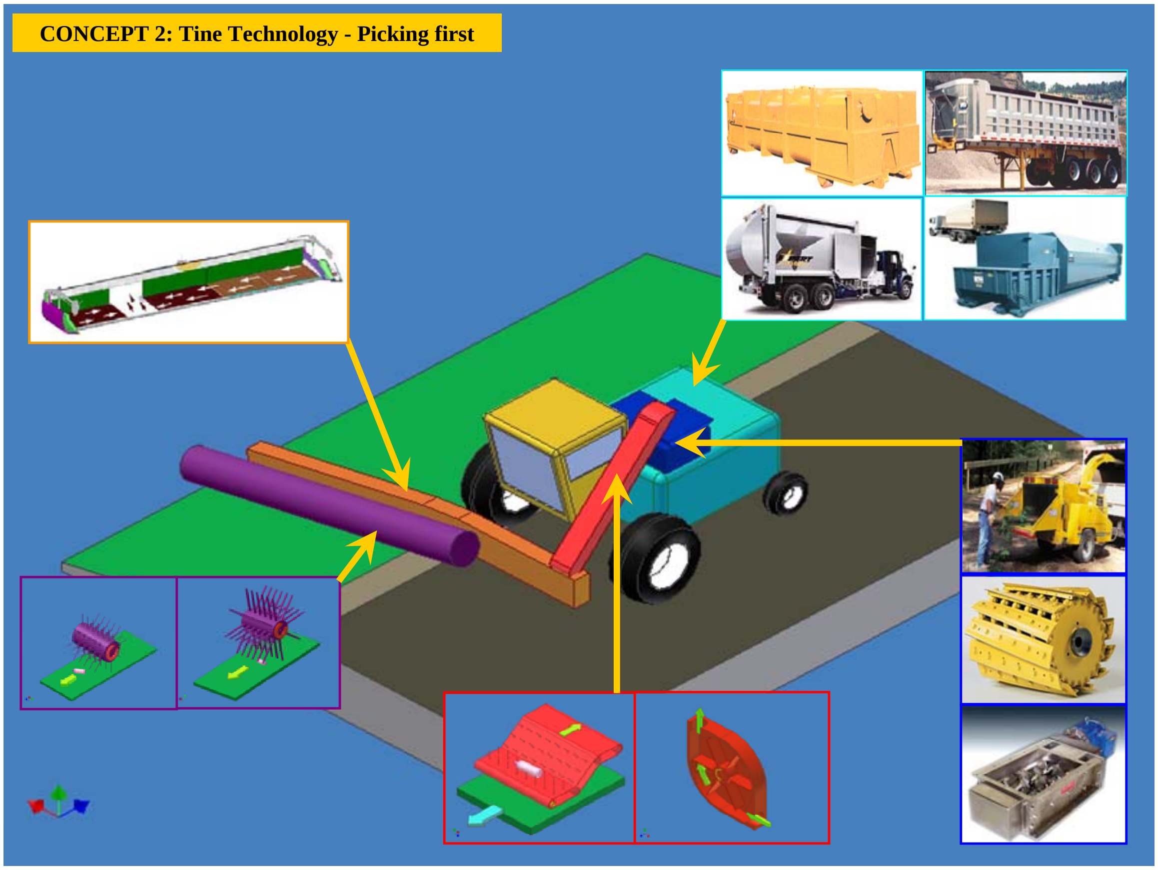


Figure 9: Technologies for picking first

With the second concept, the picking step would also make use of spring tines or brushes attached to a rotating reel. Unlike the concept 1 where the picking step happens on a hard and flat surface, the design of the tine/cylinder system would have to accommodate for rough grassy terrains.

In all the concepts presented, we can either use a belt of a fan type of conveyor to move the trash from the front of the machine to the storage area.

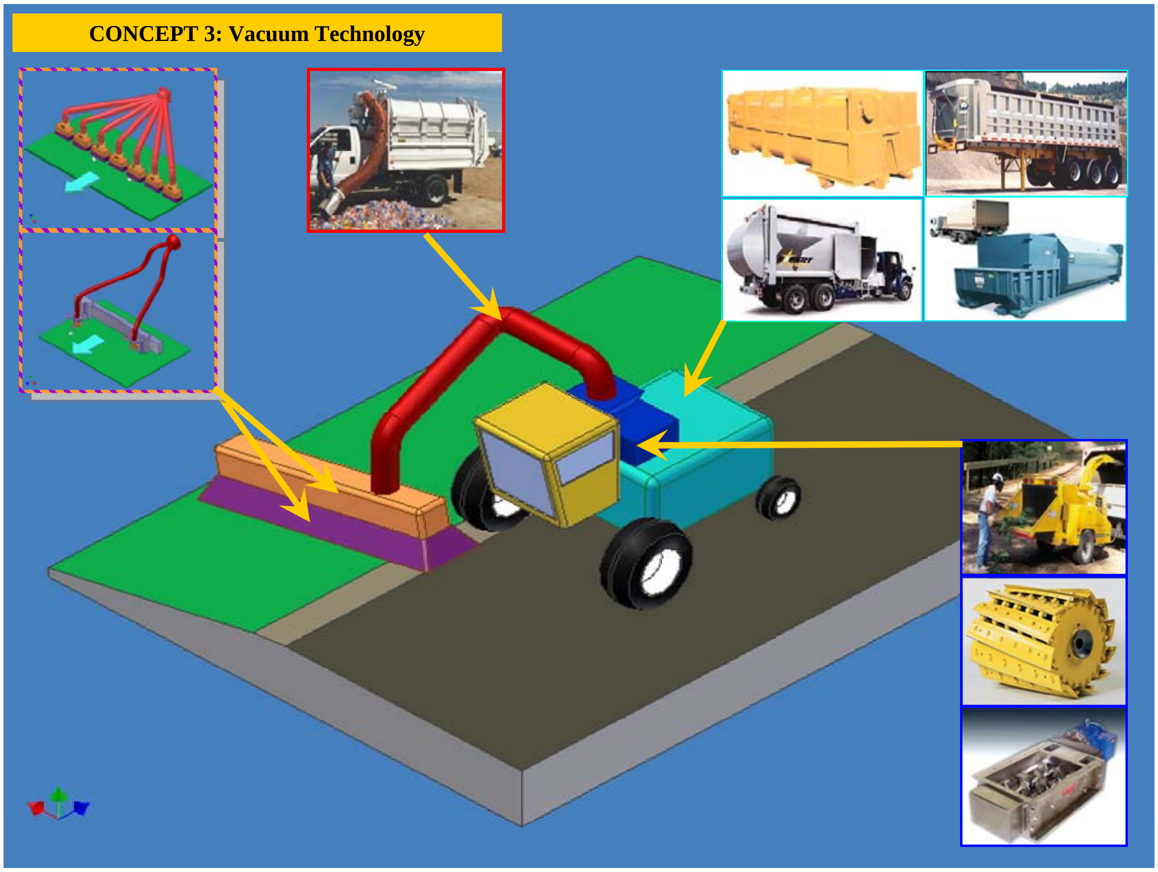


Figure 10: Technologies for the vacuum concept

With the vacuum technology, the picking, gathering and conveying step are all performed simultaneously by a large vacuum location at the back of the machine. Different concepts are available for the picking/gathering systems as shown in the illustration above. This concept is based on the machine developed by CALTRANS but adapted to the conditions in Minnesota (Flat large grassy areas versus bushes found by the Californian right of ways).

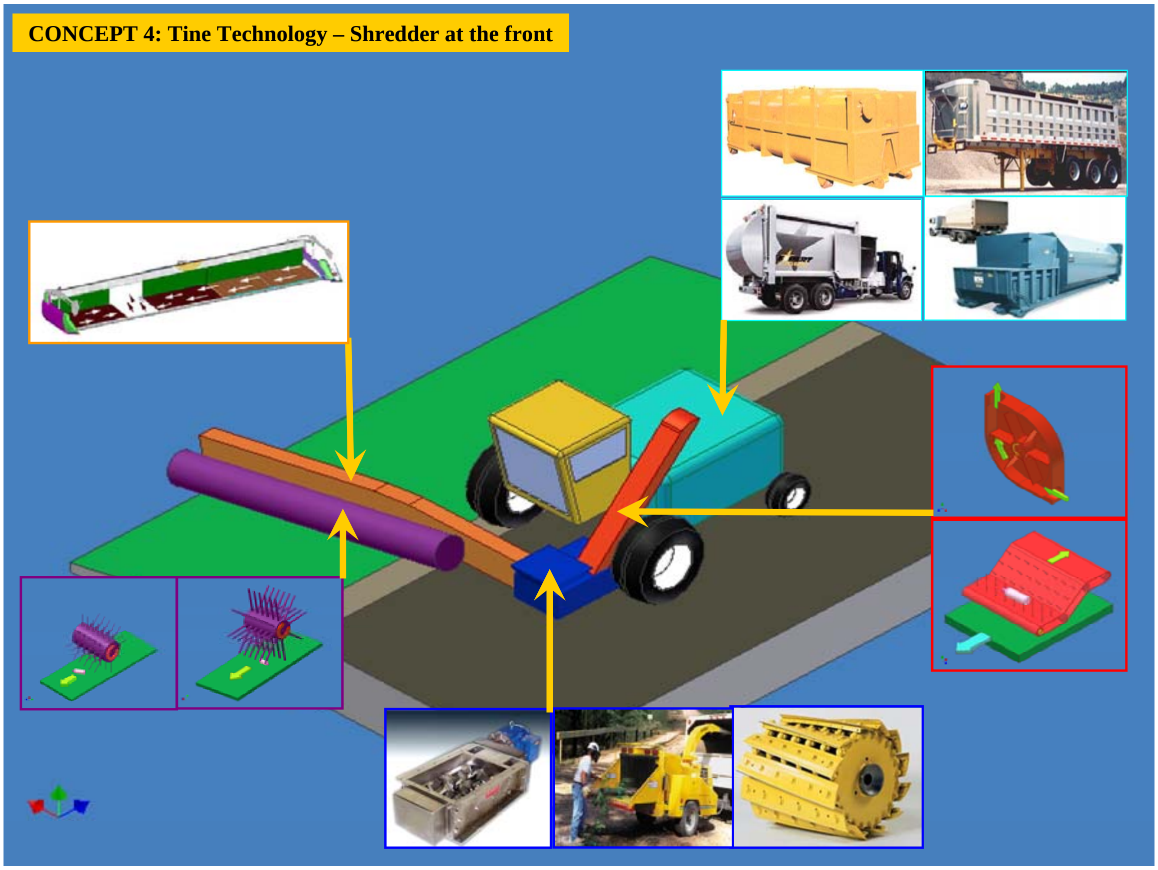


Figure 11: Technologies for shredder at the front

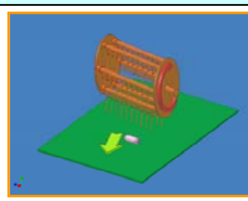
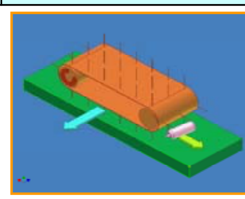
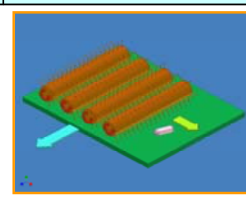
This concept is identical to concept 2 except that the shredder is located at the front of the machine instead of at the back, behind the operator. There are several existing technologies that could be use to shred litter: wood chippers, industrial crushers and forage choppers are among them. The gathering task, like concept 2, can be done using a belt conveyor, technology found on draper header on combine harvesters.

In all concepts, the storage unit can either be a semi trailer or a roll over dump box, a compactor unit, etc… depending on the size of the machine.

In this second part of the chapter, we will review a qualitative comparison of the technologies available for each step of the trash harvesting process using a matrix approach.

Table 1: Technology comparison - Gathering

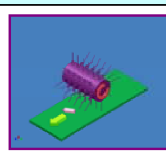
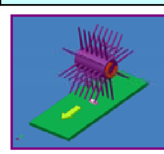
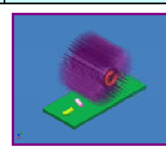
STEP	CONCEPT / CRITERIA	TINE TECHNOLOGY		
		HAY RAKE: ROLABAR	TINES ON BELTS/CHAINS	ROTARY TINES
GATHERING	EFFICIENCY IN TALL GRASS	+	-	-
	EFFICIENCY IN SHORT GRASS			
	SMALLER LITTER			
	BIGGER LITTER	+	-	-
	LITTERS WITHOUT DRY GRASS			
	STEEP INCLINES	-	+	+
	ABILITY TO FOLLOW THE GROUND	-	-	+
	MOVING PARTS			
	MAINTENANCE	-	+	-
	RELIABILITY			
	COST	+	+	-
	OTHER CRITERIA			

We believe that the hay rake type of equipment is the best option for gathering larger pieces of litter in tall grass because of the open space in front of the tines. On the other hand, the other two systems (the tines on belt and the rotary tines) can present some advantages in steep inclines. The rotary tine system has the ability to follow the terrain unlike the other systems. But this advantage comes with a higher cost and maintenance.

Table 2: Technology comparison – Picking

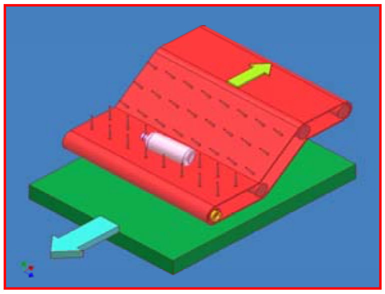
STEP	CONCEPTS / CRITERIA	TINE TECHNOLOGY			VACUUM TECHNOLOGY
		SPRING TINES	RIGID TINES	BROOM	
PICKING	EFFICIENCY IN TALL GRASS	+	-	-	-
	EFFICIENCY IN SHORT GRASS				
	EFFICIENCY ON CONCRETE	-	-	+	+
	SMALLER LITTER	-	-	+	+
	BIGGER LITTER	+	+	-	-
	LITTERS WITHOUT DRY GRASS	-	+	-	+
	MOVING PARTS			-	+
	MAINTENANCE				
	RELIABILITY			+	-
	COST			+	-
	OTHER CRITERIA				

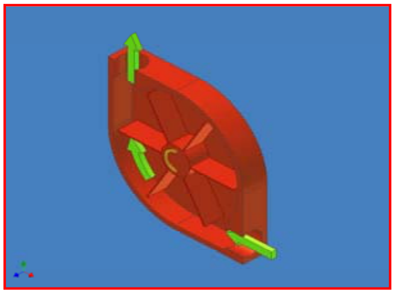





For the picking task, the vacuum technology is good alternative to brooms/brushes when picking up smaller trash on hard surfaces like concrete or asphalt. We believe that spring/rigid tines are the optimum solution for tall grass/rough terrain type of conditions. Unlike the vacuum technology, the tine technology would be able to handle large detritus with a minimal power requirement. Regarding reliability and cost, the advantage also goes to the tine technology.

Table 3: Technology comparison – Conveying

STEP	CONCEPTS / CRITERIA	BELTS/CHAINS	FAN/BLOWER
CONVEYING	SMALLER LITTER	-	+
	BIGGER LITTER	+	-
	RELIABILITY	+	-
	MOVING PARTS	-	+
	MAINTENANCE	-	+
	COST	-	+
	OTHER CRITERIA		

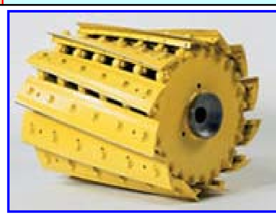




For the conveying system, two options are available: a belt/chain or a fan type of conveyor. If the trash is shredded (meaning the trash is small enough), the fan conveyor is probably the best options. For larger pieces of litter and superior reliability, the belt conveyor would be the best choice.

Table 4: Technology comparison – Shredding

STEP	CONCEPTS / CRITERIA	AGRI SHREDDERS	WASTE SHREDDERS	WOOD CHIPPERS
SHREDDING	PAPER	+	-	+
	PLASTIC	+	+	+
	RUBBER	-	+	-
	METAL	-	+	-
	CAPACITY			
	POWER REQUIRED	-	+	+
	MOVING PARTS	+	-	-
	MAINTENANCE			
	RELIABILITY	-	+	-
	COST			
	OTHER CRITERIA			



Different types of shredder are already available for different industries and could be suitable to shred the trash found on the grassy ditches by the road. Based on the comparison matrix above, the industrial crusher (middle column) seems to be the best alternative for our application. Unlike the other system, it can shred metal. A low power requirement and a high reliability are definitely strong advantages for our application.

Table 5: Technology comparison – Storing

STEP	CONCEPTS / CRITERIA	SEMI-TRAILER	ROLL-OFF CONTAINER	SIDE LOADER CONTAINER	COMPACTOR CONTAINER
	VOLUME	+	-	-	+
	MANEUVRABILITY	-	+	+	+
	RELIABILITY				
STORAGE	MOVING PARTS	+	+	-	-
	MAINTENANCE	-	+	+	-
	COST	-	+	+	-
	OTHER CRITERIA				




The choice of the storage unit depends largely on the maximum allowable size and weight for the trash harvesting machine. A semi-trailer would obviously require a very powerful machine. A side loader/compactor container is most likely too heavy for a mobile machine that will evolve on grassy terrain. A small/medium size dumpster may be the best option for our specific application.

6. Concept Selection

The next phase in the design process after ideation is concept selection. Which concept do we choose for the trash harvesting machine? How do we know which one is best for our application?

The qualitative comparison between the different concepts we just did indicates that the tine technology (concepts 1, 2 and 4) might be the preferred choice for our machine versus the vacuum technology (concept 3). We believe that the vacuum technology, suitable for picking small littler on hard flat surfaces like asphalt, is not suitable for larger pieces of litter on rough tall grass terrains. We also believe that some technologies used on farm machinery like crop lifters and draper headers on combine harvesters and spring tines on hay equipment will allow us to build a machine that will be able to pick up trash in the conditions mentioned previously. To further reinforce our convictions, we decided to put the tine technology to the test by performing simple experiments.

Figure 12: Preliminary field tests

We decided to test if a regular, unmodified hay rake would be able to move trash through grass. We first wanted to evaluate how the hay rake could handle large trash. We placed a heavy piece of metal similar to a car muffler on a short grass area and slowly drove the hay rake through the terrain. Surprisingly, the rake performed very well and was able to move the "muffler" from one side of the machine to the other side which is approximately 10 feet.

Figure 13: Hay rake & muffler

A second test was conducted to evaluate how the tine technology performs in tall grass. We randomly place various types of trash (aluminum cans, cardboard, plastic bags, PVC pipes, paper, etc…) on a tall grass area and drove the hay rake through the area. Again the performance of the hay rake surpassed our expectations and successfully pulled most of the trash out of the grass.

Figure 14: Hay rake & tall grass

After these tests, we are confident the trash harvester should be based on the tine technology. We consider that the picking first concept provide more advantages in terms of minimizing the amount of dry grass mixed with the trash collected: With the gathering first concept, the wider the boom, the more likely dry grass, stones and other detritus are likely to be gathered as well. Despite obvious safety issues, we also consider that the trash harvester should be equipped with a shredder unit placed after the gathering step and before the conveying in order to:

- Simplify the conveying step: Conveying shredded material is a lot easier than conveying big bulky material.
- Reduce the size of the trash: Since we can put more trash in a given volume, there is no need for trash compaction.

We selected concept #2 as the foundation for developing the trash harvesting machine. The trash harvesting process sequence will be: picking-gathering-shredding-conveying-storing.

7. Final Concept

The design process is an iterative process. Thanks to the input from different meetings with MnDOT personnel, we have been able to further refine the specifications and requirements.

Every design is a compromise and technical choices must be made to find the best fit for the application without jeopardizing the target cost and performance. Here is a list of the features we think are both feasible and reasonably satisfying for this application:

- 100% “off-the-road” machine with excellent hillside capabilities
- Based on a small, highly maneuverable agricultural tractor chassis
- Narrower working width…but faster working speed
- Any design will pick up some grass, we will minimize it.
- Will unload into a bigger unit remaining on the shoulder
- Moved from site to site using a trailer pulled by the bigger unit

In our finalized concept, we have a smaller, more maneuverable, zero traffic disturbance, and 100% off-the-road machine built around an agricultural tractor chassis having excellent hillside capabilities. A pick-up unit at the front of the machine lifts and collects the material using a combination of tines and a rotary broom. The trash lifted by the tines is pushed on a conveyor belt by brush/tines mounted on a reel. A blower/shredder on the side of the pick-up frame cuts the material into small pieces and sends it to the storage unit at the back of the machine.

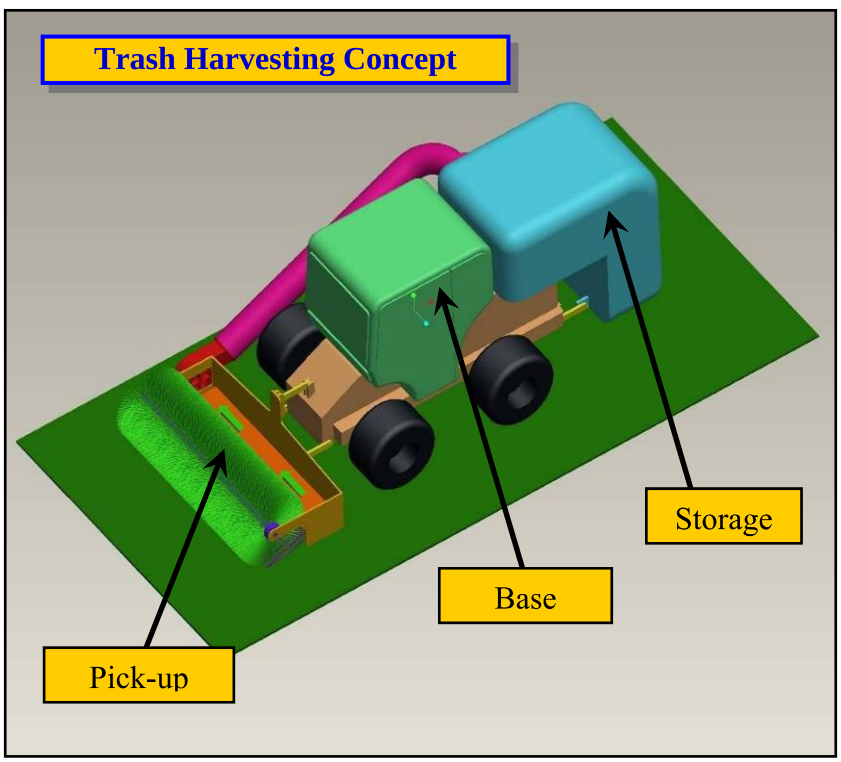


Figure 15: Trash harvesting concept

Once full, the hopper is unloaded into a truck remaining on the shoulder. The unit is moved from site to site using a low-trailer at the back of that truck. To do so the width of the trash harvesting unit has to be relatively small (around 8 feet) so the operator does not need to disconnect the pick-up every time one moves from site to site.

We will dedicate our resources in the design and manufacturing of the pick-up unit which will accomplish the picking, gathering and shredding functions described earlier. The pick-up unit is the most critical system in the trash harvesting process and will decide whether the project is a success or not. Thus, the pick-up unit design requires all our attention and efforts. On the other hand, the base machine, as well as the storage unit, can be purchased from existing manufacturers.

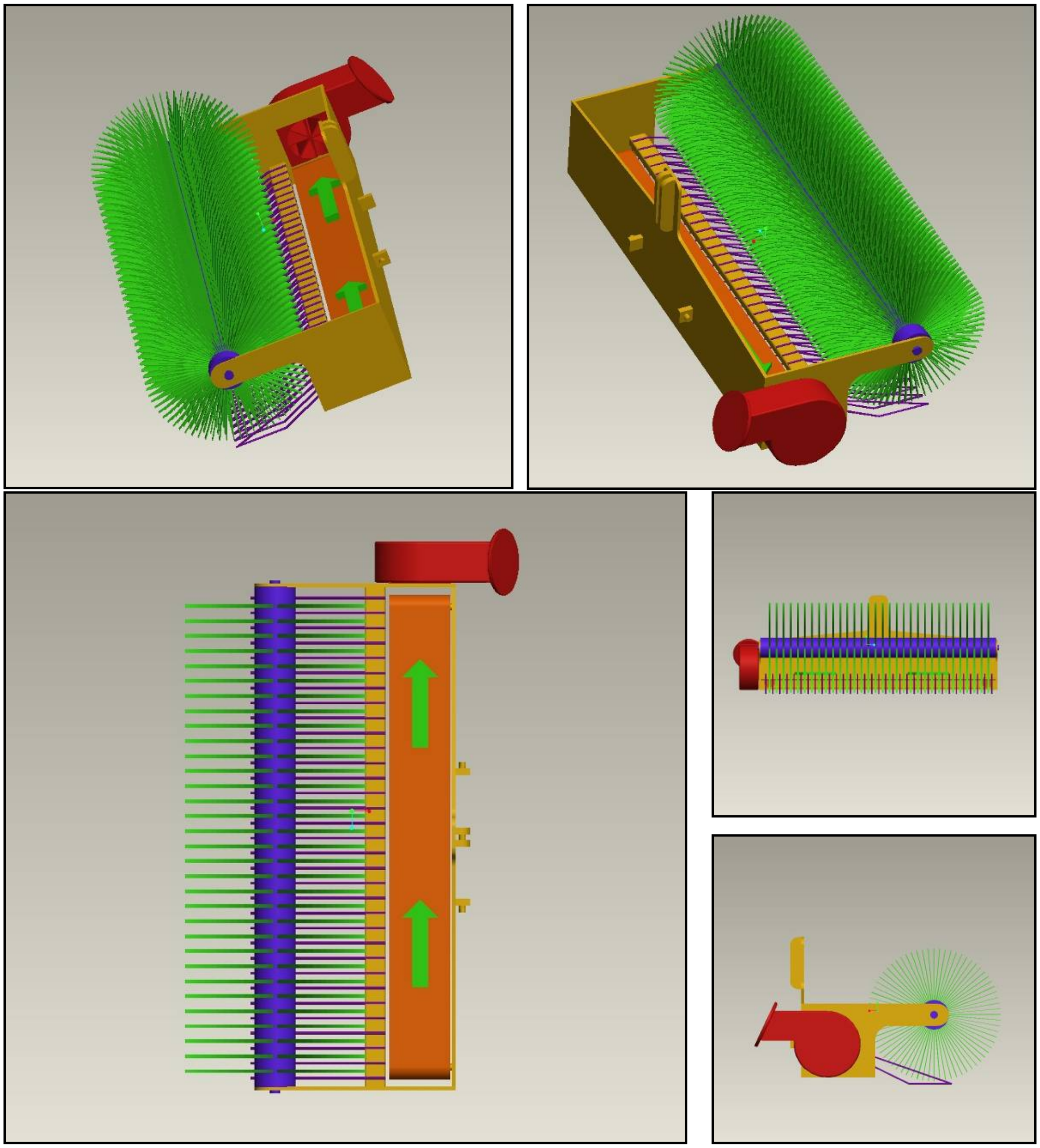


Figure 16: Trash pick-up concept

The choice of a base machine for the trash harvester is broad and goes from conventional agricultural tractors to highly specialized self-propelled equipment used for various types of work. Now we will review the pros and cons of these different machines and choose the one that best fits our requirements.

- The conventional agricultural tractor: John Deere 5000 series

Figure 17: John Deere tractor

The John Deere 5000 series is a typical small/medium size agricultural tractor. This is a reliable affordable machine with a proven customer service and support. On the down side, this machine has limited hillside capabilities, no reverse operator station and no hydrostatic transmission. Our application requires a great visibility over the pick-up unit and a fine control of the speed of the machine. These requirements cannot be achieve with a traditional cad arrangement and a mechanical transmission.

- The utility work tool carrier: Bobcat Toolcat

Figure 18: Bobcat tool carrier

The Bobcat Toolcat is a light, compact, highly maneuverable machine that provides a good visibility over the front implement. The 2-speed infinitely variable type of transmission is suitable for our application. On the downside, this machine has very limited hillside capabilities and load carrying capacity.

- The specialized agricultural tractor: Carraro TRH series

Figure 19: Carraro specialized tractor

The Carraro TRH series is a specialty agricultural tractor often used in orchards and vineyards in California. Its reversible operator station and hydrostatic transmission are well suited for our application. On the downside, the Carraro TRH is an expensive machine with very limited hydraulic system used to power implements. We envision that the pick-up unit will be using mainly hydraulic as power source versus power take off.

- The hillside tool carrier: Aebi Terratrac series

Figure 20: Aebi hillside tool carrier

The Aebi Terratrac series is a tool carrier designed for extreme hillside applications. Duals are available all around for increased stability. Its hydrostatic transmission and front 3-point hitch is perfect for our application. Like the Carraro tractor, the Aebi Terratrac is an expensive machine with limited hydraulic capabilities. There is also limited room at the back of the machine for the storage unit. Another concern is the proximity of the dealership and the availability of service part.

- The compact articulated tool carrier: Holder C9.74

Figure 21: Holder articulated tool carrier

The Holder is a compact articulated tool carrier mainly used for snow blowing sidewalks. The position of the cab relative to the front hitch provides excellent visibility over the implement. The robust articulated frame gives the Holder a very tight turning radius. Like the other specialized machines, the Holder is an expensive machine but unlike the Carraro and Aebi, the Holder has plenty of hydraulic power and a flat bed at the back that is the ideal location for a storage unit.

Unlike the Carraro and Aebi, maintenance and service is not an issue with the Holder: Custom Motor Co located in Minneapolis has a long experience of Holder tractor and will undoubtedly provide professional support and assistance to the MnDOT personnel.

We chose the Holder C4.74 as the base machine for our project because of its great hillside capabilities, unsurpassed control, visibility and maneuverability, robust articulated frame and sophisticated front hitch, ample hydraulic power and large flat bed.

Performance analysis

We estimate a working speed of 5 mph (= fast walking pace). The width of the picking unit would be around 8 feet. Thus, we can determine the field capacity of the machine using the following formula:

$$Efficiency = \frac{S \times w \times e}{8.25}$$

- Efficiency is the field efficiency in acres per hour
- S is the ground speed in miles per hour
- w is the working width of the pick-up unit in foot
- e is the ratio working time/total time

If we assume e = 0.75 (meaning that 75% of the time the machine is picking trash, the remaining time account for unloading and pauses), we thus have an efficiency of 3.4 acres per hour. The field capacity of the machine is in the range 3-3.5 acres per hour. The storage unit will be the large vacuum unit purchased from Holder for their tractors when used as street sweepers. The vacuum unit installed on the flat bed of the tractor features a large hopper to accommodate the shredded trash.

- Safety analysis

In our application, safety is a critical issue not only for the operator of the machine but also for the people driving on the road while the trash harvesting machine is working. The base machine has a very low center of gravity for excellent hillside capabilities. Spacers between the wheel hubs and the rims can be added to provide extra stability when working on very steep slopes. The standard ROPS (Rollover Protective Structure) cab with air conditioning provides a quiet and comfortable working environment for the operator. The great visibility on the pick-up unit and the hydrostatic transmission give the operator a total control of the machine for increased productivity and safety. By avoiding chain and belt drives and using direct hydraulic drives, we dramatically reduce potential safety hazards for the operator. We will make sure all the rotating components will be properly shielded. Also, when using hydraulic drives, the relief pressure can be adjust to minimize hazards in case of malfunction or plugging of the conveyor and shredder. The trash harvesting machine will always remain on the grassy area. The machine will unload into a truck remaining on the shoulder and having all the safety warnings and following the current MnDOT safety procedures (Mars lights, etc...).

- Cost analysis

The Holder C4.74 has a tag price around $80,000. For the prototype, we found a demo unit having a couple hundred hours, full options for half the price of a brand new machine. We estimate the total cost for designing and manufacturing the pick-up around $40,000 (material and man hours). Thus, the total cost of the project is around $80,000.

8. Working Prototype

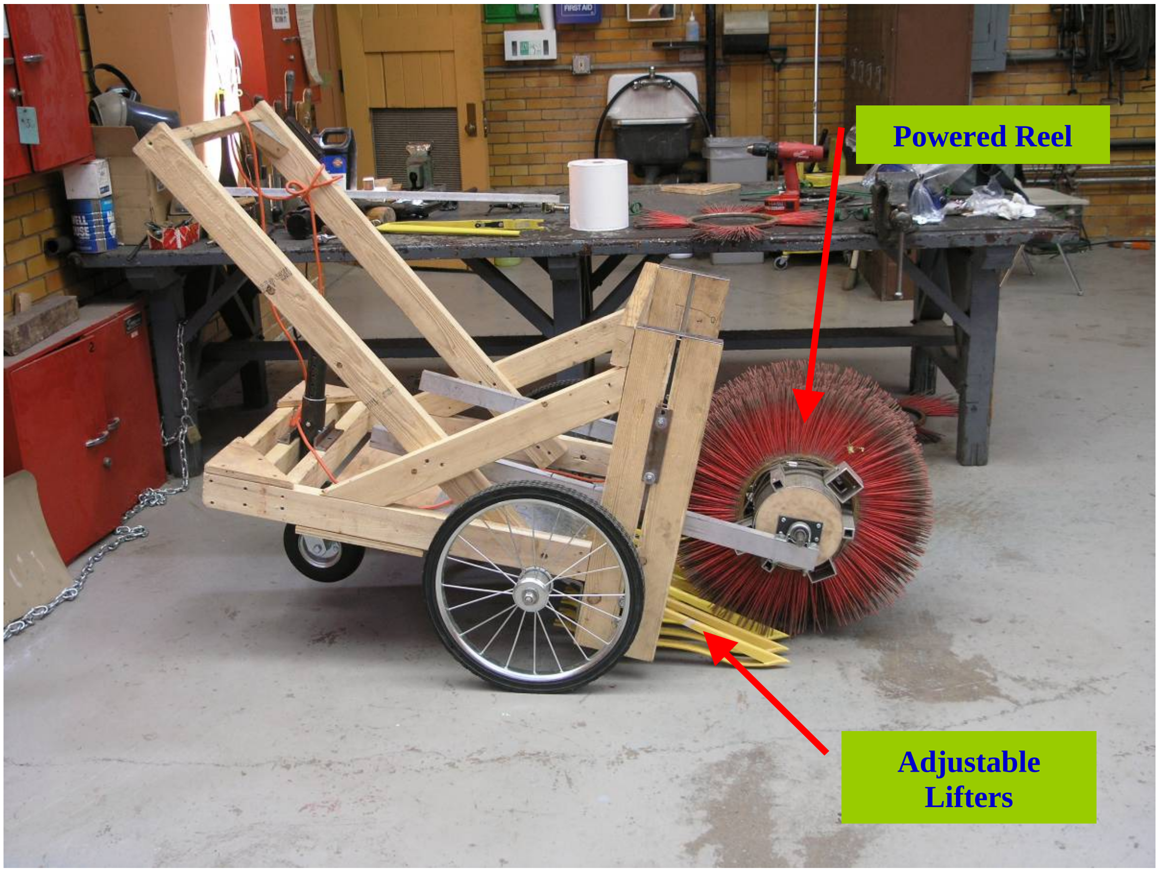


Figure 22: Working prototype

We built a prototype in order to perform a qualitative evaluation of our concept. Our requirements for the first prototype are the following:

- Experimental push cart type
- Modular conception, easily adjustable to various field conditions
- Working prototype designed to evaluate the pick-up/gathering unit only

The cart prototype is 3 foot wide and made of light materials so it can be pushed by hand. At the front of the machine, a rotary reel operates above a series of lift tines, described in the Final Design report. Both the reel and the lifters can be easily adjusted upward and downward to accommodate field conditions, especially different lengths of grass. The can be adjusted forward and backward. On the prototype, the reel is powered by a 90VDC electric gear motor. Mounted on the handle of the prototype, a controller enables us to modulate the speed of the reel from 0 to a maximum speed of 60 rpm. The power is provided by a portable generator that can be installed on the machine. Of course, the actual trash harvester will use hydraulic as a source of power and a more robust design. The following pictures illustrate the details and possible configurations of the first working prototype: crop lifters / custom made tines, brushes / spring tines, etc…

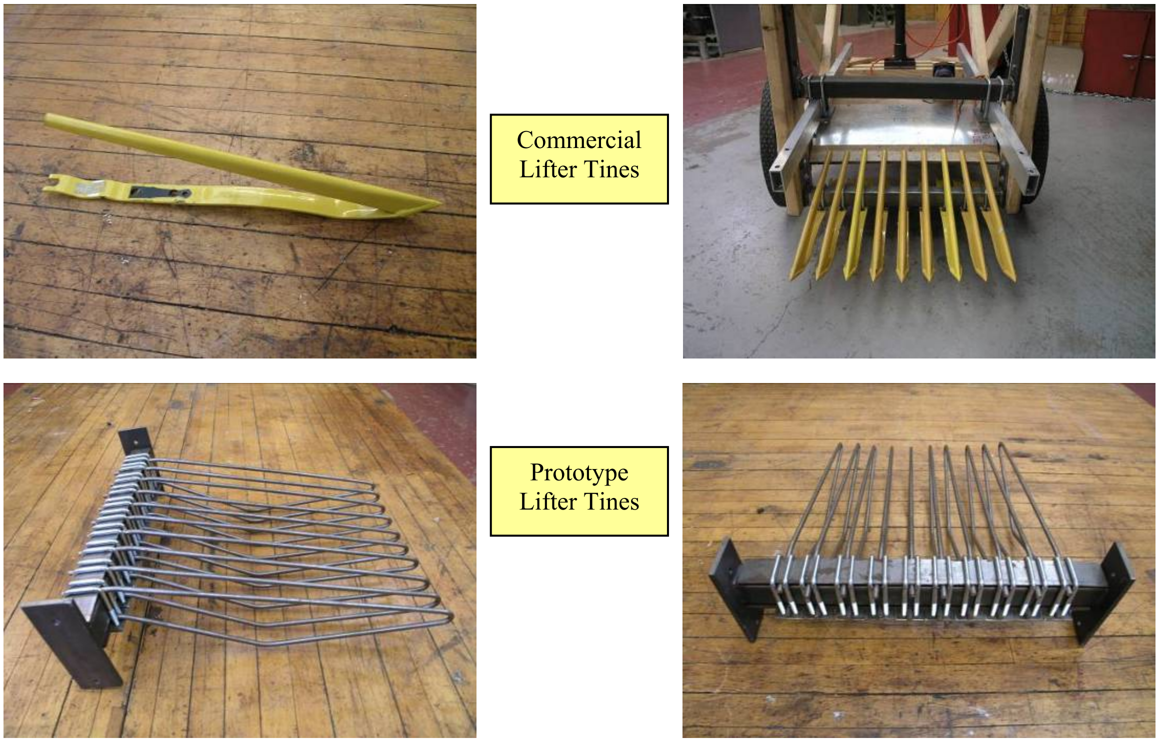


Figure 23: Working prototype – Lifting tines details

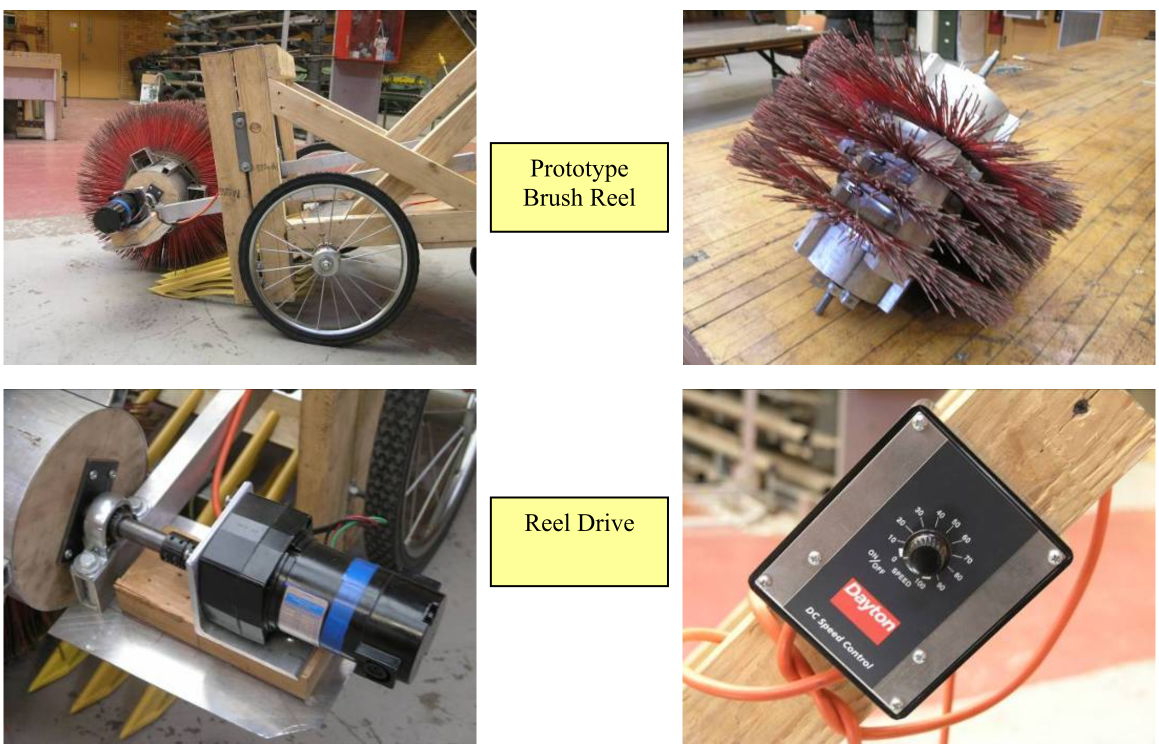


Figure 24: Working prototype – Reel drive and control details

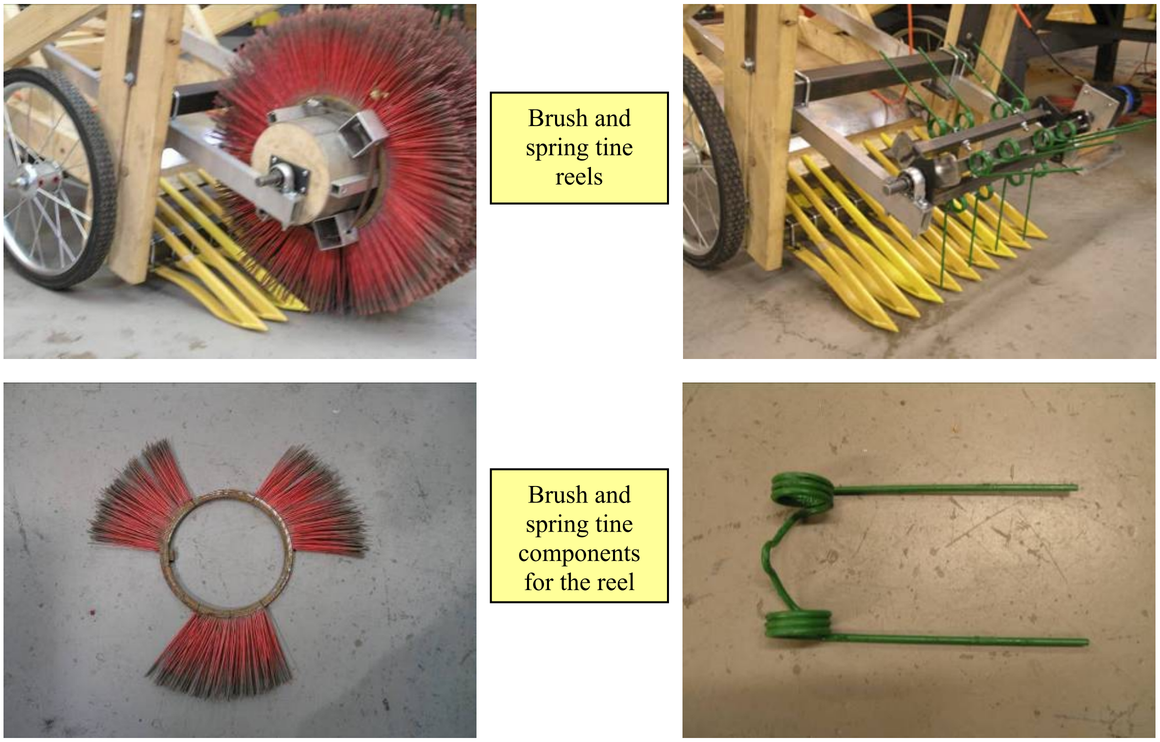


Figure 25: Working prototype – Reel details

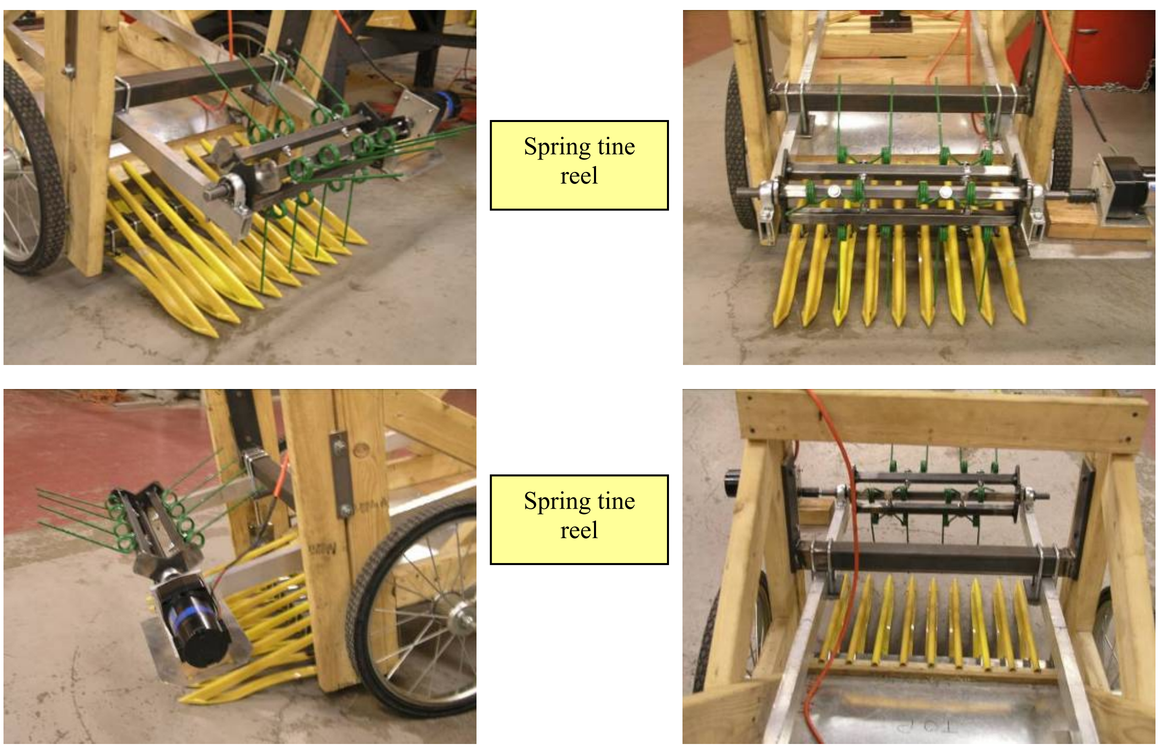


Figure 26: Working prototype – Pick-up details

The first field tests revealed that the lifters concept worked well fine in both short and tall grass. The key in the lifters design is that the tines have to be “slim” enough so they can get through the grass without tearing it. The space between the lifters is also a critical parameter: It has to be less than the dimensions of the smallest objects we want to pick up, for instance the diameter of a pop can.

Different types of reel were tested in both short and tall grass. Different designs have different efficiency depending on the field conditions which the length of the grass is the most critical parameter. The reel equipped with a brush works perfectly is short grass conditions when the one equipped with spring tines works better in longer grass.
A crucial point is that the reel has to be adjustable in both up-down and forward-backward directions in order to accommodate the various grass lengths along MnDOT right of way: From very short by the shoulder to very tall along the fence. We are confident that the reel will work in both short and long grass with all types of trash. Of course, the more use of the reel, the more grass will be collected with the trash. During the tests we noticed that, on shorter grass, once the lifters and the reel are set properly, the picking unit is more efficient at higher speed. This prevents the trash from “rolling” in front of the lifters.

Figure 27: Working prototype – Field tests

9. Key Design Features

A CAD model of the full scale pick-up was developed in order to optimize each of its components. In this chapter, we will review the key features of the trash harvester pick-up, explain our design intent and justify our choices.

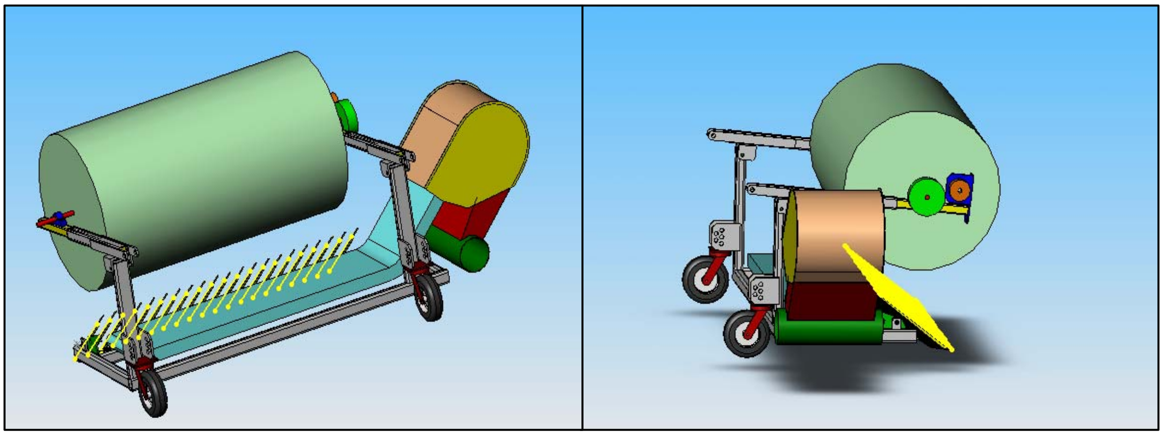


Figure 28: Pick-up – CAD model

- Lifting Bar

The lifting bar mechanism is critical in the ability of picking up the trash efficiently. As we noticed during the field tests with the prototype, having a floating lifting bar can dramatically increase the trash picking efficiency. Ideally the lifting bar would have a wide magnitude of rotation in order to be able to follow rough terrain. Practically, the range of motion will have to be limited in the upper position in order to avoid interference between the lifting bar and the conveyor. In fact, the spring tines have to go over and overlap with the conveyor so that the litter can be placed on the conveyor.
The position of the bar will be determined according to what we believe is a good working position. The first guess of the ideal position of the lifting bar is critical in order to avoid redesigning and remanufacturing the mounting frame plate and lifting bar. Holes adjacent to the pivot of the lifting beam can be used to lock the beam in position.

- Reel Frame

The beam supporting the broom/reel will receive cross members in order to increase the torsional strength of the frame. The cross members have to be placed on the frame so it doesn't interfere with the broom/reel when retracted to its closest position. Attention should also be paid to the visibility from the operator cab. The ideal solution is a 2x2 beam welded at the end of the two pivoting arms attached to the main frame. If necessary, another 2x2 beam across the frame could be welded at the back of the pivoting arms where the cylinders are attached. But for visibility and safety issues (pinch point), this solution will be used only if the extra strength given by the addition of the first 2x2 remains too low.

For the tractor attachments, a heavy beam will have to be welded across the two pillars. Then another shorter beam will have to will have to join this upper beam with the existing bottom beam. This shorter beam will be ideally placed at the same location as the median plane of the tractor.

- Height Gauge Wheels

The same way that a floating feature is essential in the good performance of the lifting bar, guiding wheels similar to draper pick-up are essential in the ability of the pick-up to follow the terrain and thus its overall performance will increase. We chose swiveling wheels over fixed wheels for ease of turning. This is especially important with an articulated tractor, not to mention the fact that safe work in slopes starts a total control of the machine: The guiding wheel will support most of the weight of the pick-up making the whole machine easier to drive and steer in those extreme conditions.

The ideal position for the guiding wheels would be at the front of the pick-up frame, as close to the lifting bar as possible. Since the wheels can rotate, the mounting position of the wheels has to be relatively far from both the frame and the lifting bar in order for the wheels to rotate freely. In this configuration, it requires a complex frame that would be an add-on to the existing frame, which increase even more the already heavy frame. Every design involved trade-offs: A less ideal position from a function/efficiency point of a view is to put the wheels at the back of the frame where the cylinders are located. With minimal weight increase, solid mounting supports for the wheels are possible. Even though this location for the guiding wheels is not as ideal as the front position, I still believe that a reasonable level of pick-up position control can be achieved in that position.

- Shredder

The shredder concept consists of an 8 inch diameter pipe having the same length as the conveyor belt in order to provide a smooth, unobstructed flow of trash and minimize plugging. A rotating shaft with rigid knives comb the trash through fixed counter blades spaced every one inch. The way of rotation of the shaft can influence greatly the efficiency of the shredding action. We can foresee that as more aggressive shredding is achieved if the trash is pushed through the bottom side of the counter blades (clockwise when facing the vacuum side of the shredder) which provides more room for the rotating blades to “grab” the litter, especially plastic bottles or aluminum cans.

A variation of this design would have the blades and counter blades at a certain angle. An increase in shredder efficiency could be achieved with this solution: the blades would push the trash in a direction opposite to the vacuum side. Only the trash small enough would be pulled on the other side and sucked by the vacuum. The remaining litter would still be pushed in the opposite direction and shredded until being small enough to be sucked by the vacuum. Another variation would have a shredding unit similar to a rotary combine threshing unit where the clearance between the blades and counter blades would decrease when going from the drive side to the vacuum side. With this configuration, the trash would be shred finer and finer as it would move along in the shredder unit.

- Shielding and Safety

Shielding is important in the trash collection process: A good shielding will provide a material flow as smooth as possible throughout the whole machine in order to prevent clogging which means increase safety issues and reduced productivity as well. A rule of thumb is that a shield must always be attached to only one structural member over a short length in order to prevent shearing when the whole structure is under constraint. In order to maintain a great visibility on the implement, we will use thick crystal clear, impact resistant polycarbonate to shield completely the pick-up frame. A frame for shields will be built and bolt onto the reel. Galvanized metal sheets and Plexiglas will be used to full enclose the reel. Also, a complete shield removable for maintenance, made out of thick metal sheets will wrap both the end of the conveyor and the feed area of the shredder in order to prevent the operator to reach the shredder blades with its hands. Permanent magnets installed above the conveyor will remove the pieces of metal that are big enough to damage the shredder

When traveling on highways, the trash harvester (base tractor and pick up unit) should be equipped with the SMV symbol at the rear and extremity light on the sides of the picking unit. Also, the shielding on the trash harvesting machine has been designed to meet many of the guidelines given in the ANSI/ASAE Standard ANSI/ASAE S493.1 JUL 03 "Guarding for Agricultural Equipment".

<u>Extract from ANSI/ASAE S493.1 JUL 03:</u>

"4.1 Components which must be exposed for proper function, drainage or cleaning shall be guarded to the maximum extent that is <u>practicable</u> and reasonable as permitted by the intended operation or use."

We applied the guideline described in paragraph 4.1 - guarding requirements when designing the complete shield around the reel. Also, revolving shafts and other revolving parts were guarded as mentioned in paragraph 4.2. Safety signs were provided stating that guards must be kept in place and/or the machine should not be operated with guards removed as advised in paragraph 4.5.

The material used for shielding was galvanized steel and clear polycarbonate with no openings. The guards are rigidly fixed, have no sharp edges, and are weather resistant according to paragraph 5.4 – Guarding construction. Also, guards are attached to the machine such that they cannot be removed without the use of a tool. They may be openable (shredder and reel drive shield) but remains attached to the machine by means of hinges.

10. Pick-up Realization

The design and fabrication of the pick-up unit are key elements in the success and efficiency of the trash harvesting machine. When designing the pick-up, we kept in mind our manufacturing capabilities and human resources when making make-or-buy decisions.

Obviously, we will have to build a custom frame for the pick-up and buy the hydraulic components to power it: cylinders, motors and hoses. We also decided that it was easier to buy a belt conveyor rather than making one in the shop. We will also buy a standard rotary broom used on street sweeper as our reel for short grass conditions and making a custom reel for tall grass conditions. As confirmed by earlier tests, we will use John Deere crop lifters as a way to lift the trash off the ground. The long grass reel will be spring tines from the hay equipment manufacturer Kuhn to push the trash onto the conveyor belt. We looked at shredders available on the market but none were suitable for our application: Most of them were too heavy and pricey for small mobile equipment like the trash harvesting machine.

The steel tubes and metal sheets used to build the pick-up frame were purchased from Discount Steel for the frame and shields. We bought a conveyor from Dorner. Polycarbonate sheets for shielding were purchased from Plastics International. Hydraulics motors are Eaton motors from Motion Industries. The cylinder are made by Prince and the hydraulic plumbing (hoses and fittings) was done by Pirtek. Other components like ball bearing, caster wheels, draw pins, drill bits, grinding discs, safety labels, hose clamps, hardware, etc… necessary to the fabrication of the unit were purchased from McMaster-Carr.

Figure 29: Pick-up – Frame

We used regular carbon steel tubes for the frame of the pick-up unit (blue parts) with different sections and wall thicknesses in order to minimize the weight of the frame without compromising its structural integrity. Where needed, we added cross braces and thicker material to further improve the rigidity and integrity of the frame.

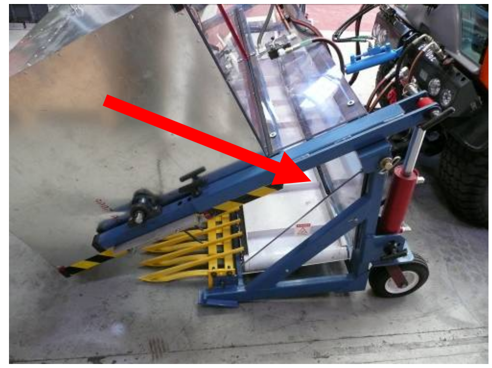


Figure 30: Pick-up – Reinforcements

The pick-up frame is built around an 8 feet long / 8 inch wide conveyor with a two feet incline with a cleated belt so the trash can be discharge in the shredder located on the right side of the conveyor.

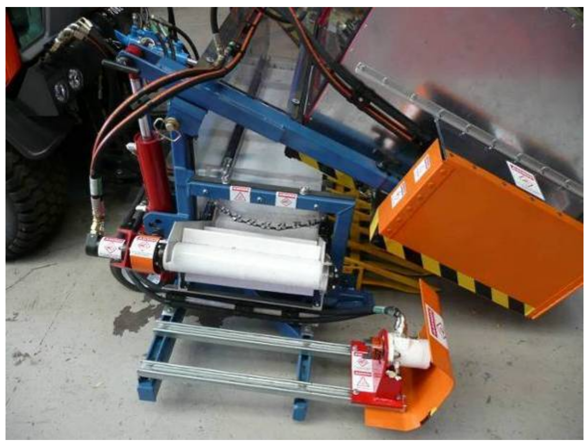


Figure 31: Conveyor discharge

The crop lifters tines are bolted on two Unistrut channels so the space between the tines can be adjusted. Also adjustable is the position of the lifting bar on the frame. When removed, the two top bolts on each side of the frame allow the lifting bar to float.

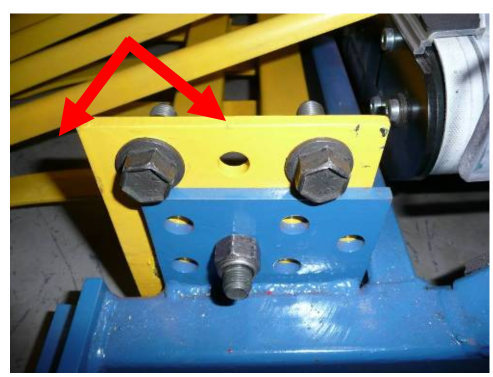


Figure 32: Trash lifting bar

The gauge wheel mounted at the rear associated with skid plate at the front of the frame allows the pick-up to follow the ground closely.

Figure 33: Supporting wheels and skid plates

When developing the trash harvester pick-up, we made sure we had the built-in adjustability we need for fields tests in various conditions: Both the lifting cylinder and the reel can be adjusted to match the conditions in the fields: short grass/tall grass, etc…

Figure 34: Reel adjustments

Another key element in the adaptability of the pick-up unit to various conditions is the hydraulic top link. With such a feature, the operator can adjust on the fly the height of the lifting tines relative to the ground.

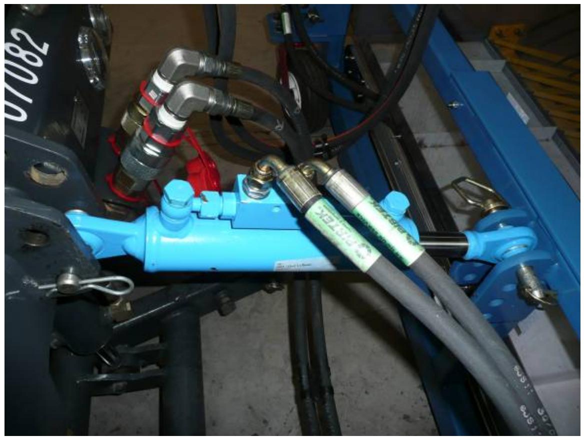


Figure 35: Hydraulic Top Link

The conveyor, reel and shredder are driven by hydraulic motors using the Holder tractor as a source for hydraulic power. Both the conveyor and the shredder are direct driven. Because of the low speed requirement, the reel is belt driven. The motor supports have been designed for easy service: For instance, the shredder can be removed without removing the hydraulic motor from the support.

Figure 36: Hydraulic motors

Strong magnets located above the conveyor will prevent large ferrous material from entering the shredding unit.

Figure 37: Magnets

A combination of clear polycarbonate, galvanized steel and aluminum sheets has been used to provide a complete shield of the reel as well as the drives of the hydraulic motors.

Figure 38: Shielding

In addition to provide complete shielding, we made extensive use of safety labels and warnings.

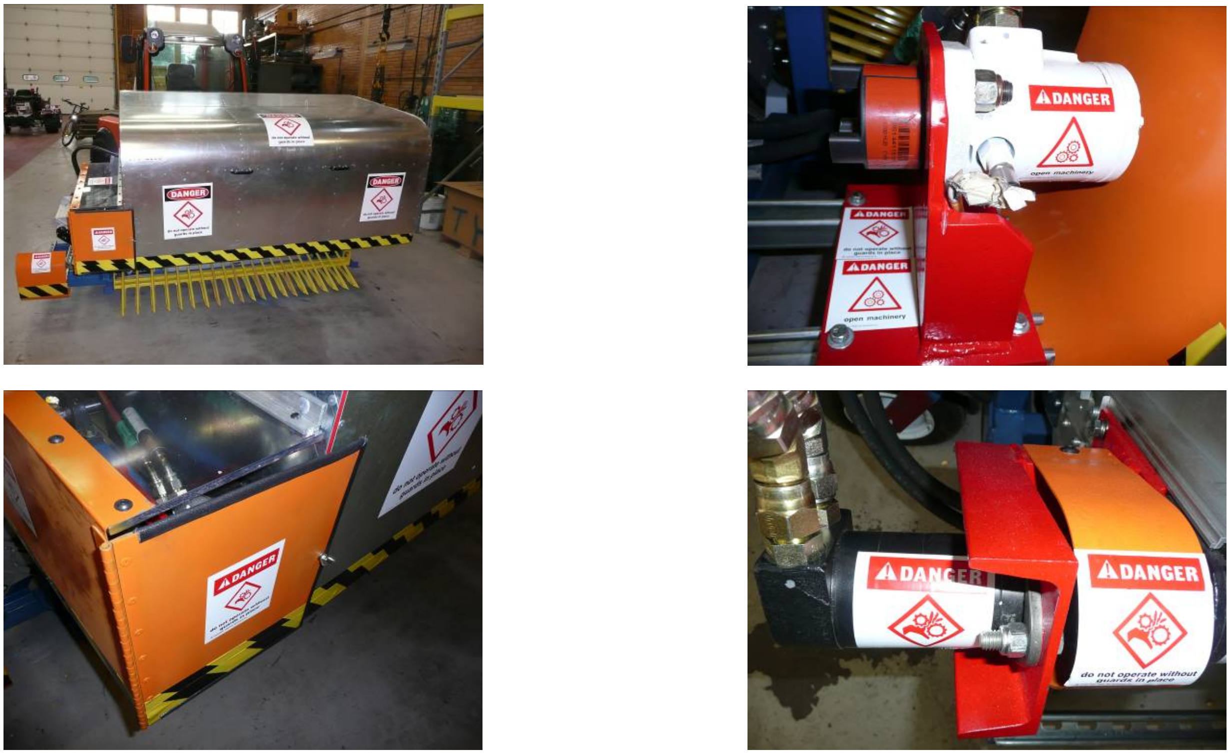


Figure 39: Safety labels

The hydraulic plumbing was done by a professional from Pirtek.

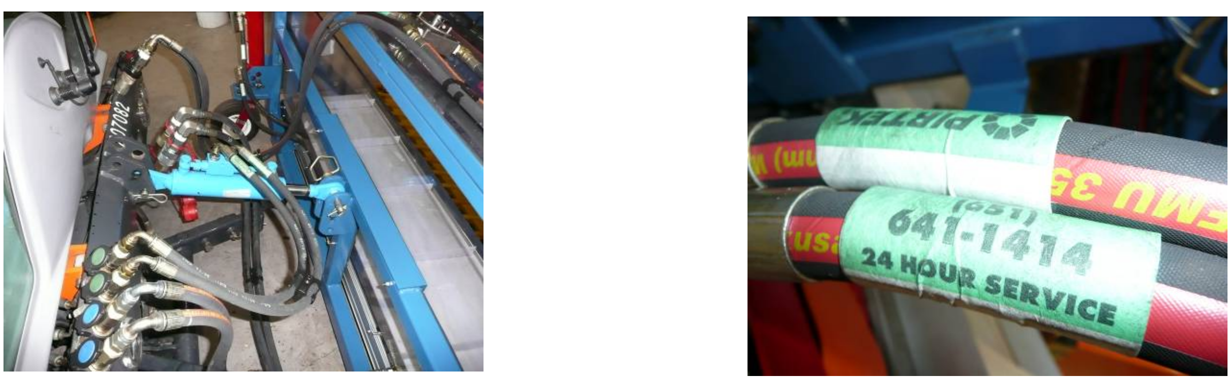


Figure 40: Hydraulic plumbing

A lot of attention has been paid to the routing and clamping of the hoses for extended service life and reduced maintenance costs.

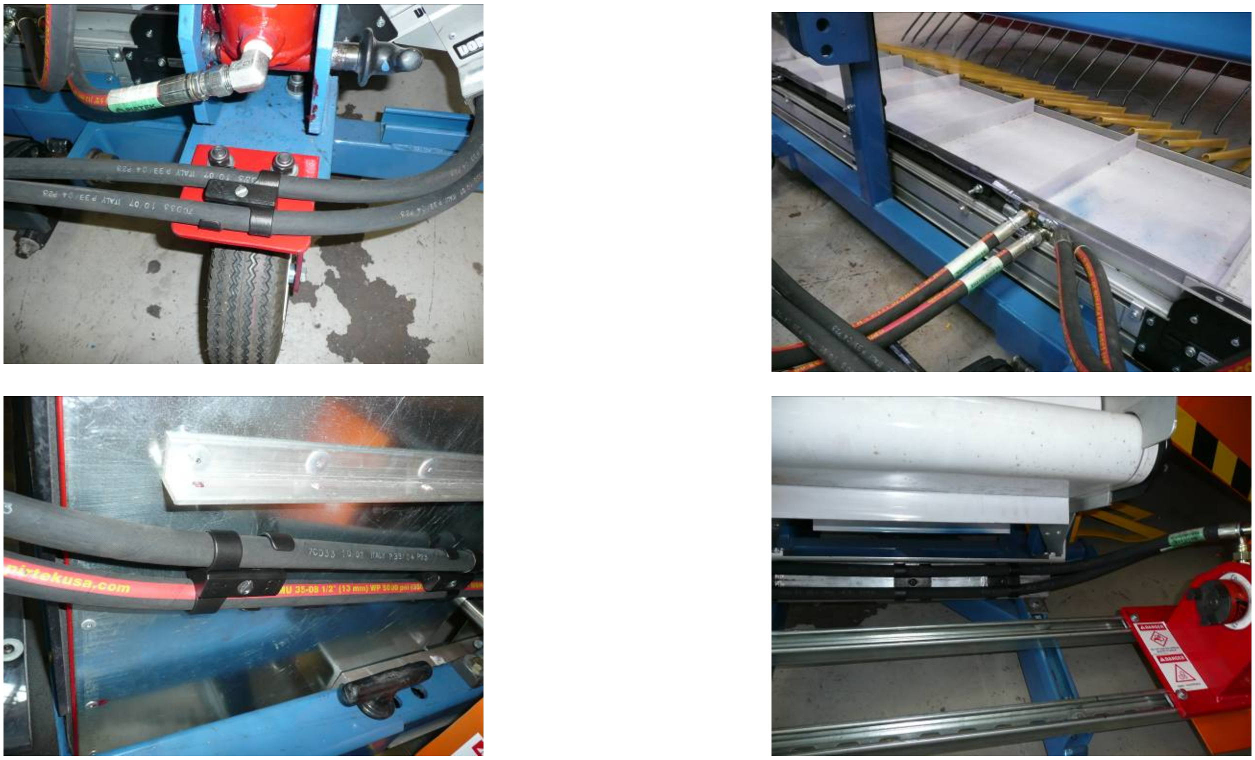


Figure 41: Hoses routing

An adjustable flow divider distributes the flow to both the reel and the conveyor. A label in the cab indicates the different hydraulic functions and their controls.

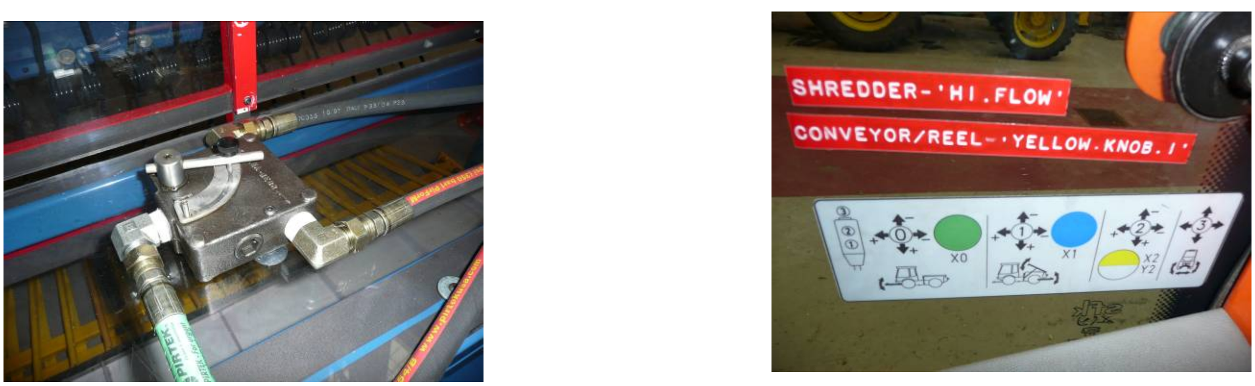


Figure 42: Hydraulic details

Throughout the fabrication, we paid a lot of attention to the “details”: large washers, rubber bands to isolate the plastic shields from the frame, lock nuts, caps on beam ends, hose clamps, etc…

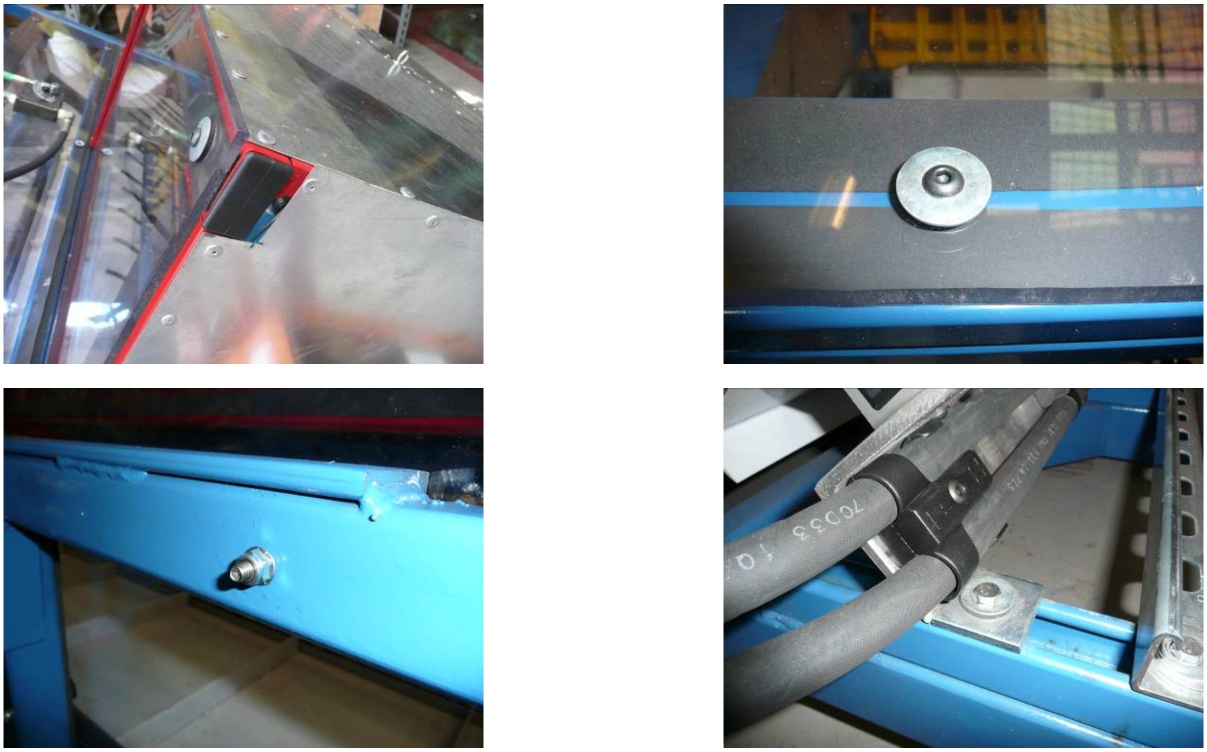


Figure 43: Fit and finish

Another “detail”: When we designed the three point hitch of the pick-up unit, we made sure to keep an optimum visibility over the implement. The position of the lower draw pins are such as the two supporting pillars on the side of the pick-up frame are aligned with the cab posts. So when the operator sits in the cab, he has an unobstructed forward and lateral visibility over the pick-up unit.

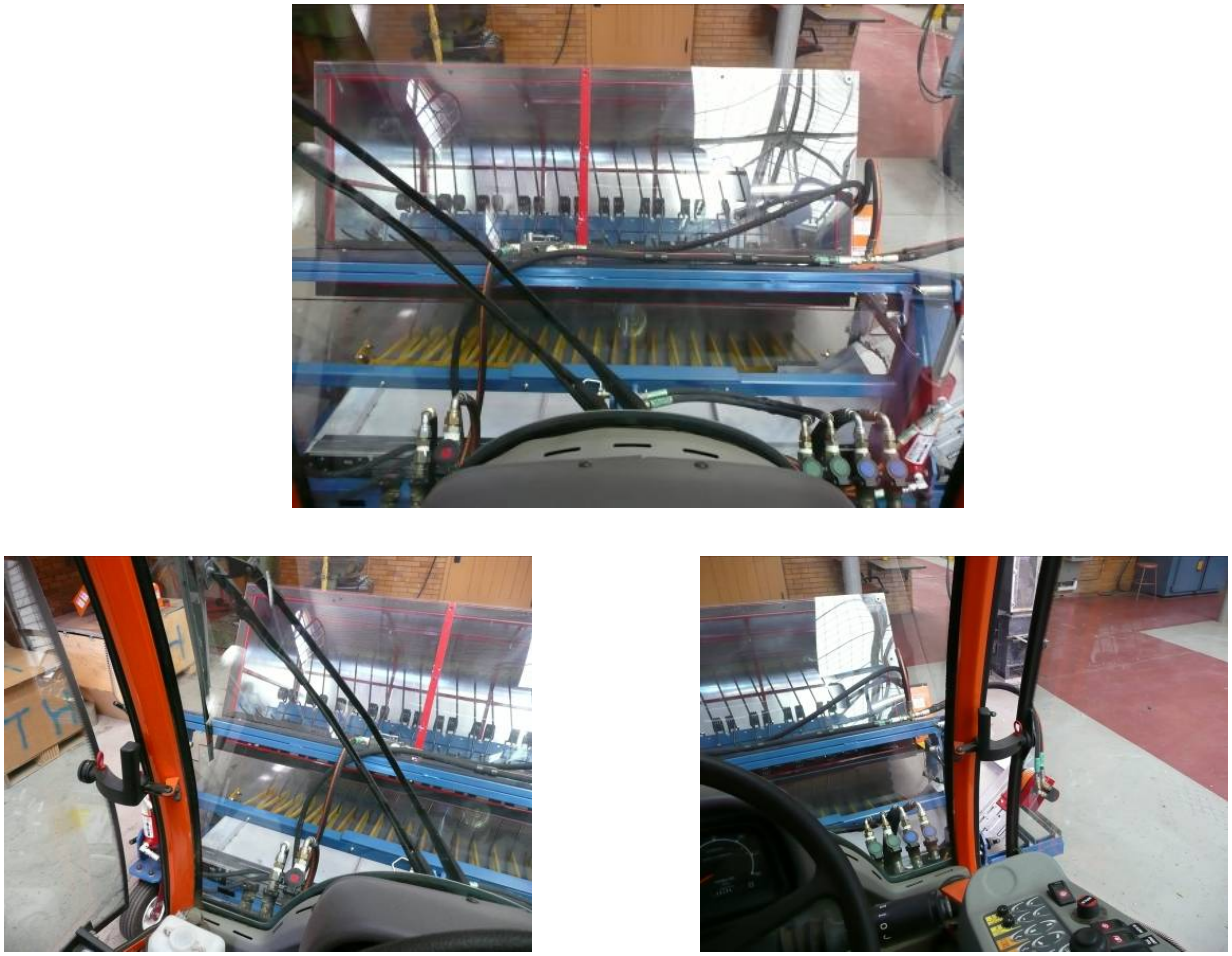


Figure 44: Visibility from the cab

For short grass conditions, a rotary brush can be used as an alternative to the spring tine reel.

Figure 45: Brush reel

Below are some pictures of the completed pick-up unit attached to the holder tractor:

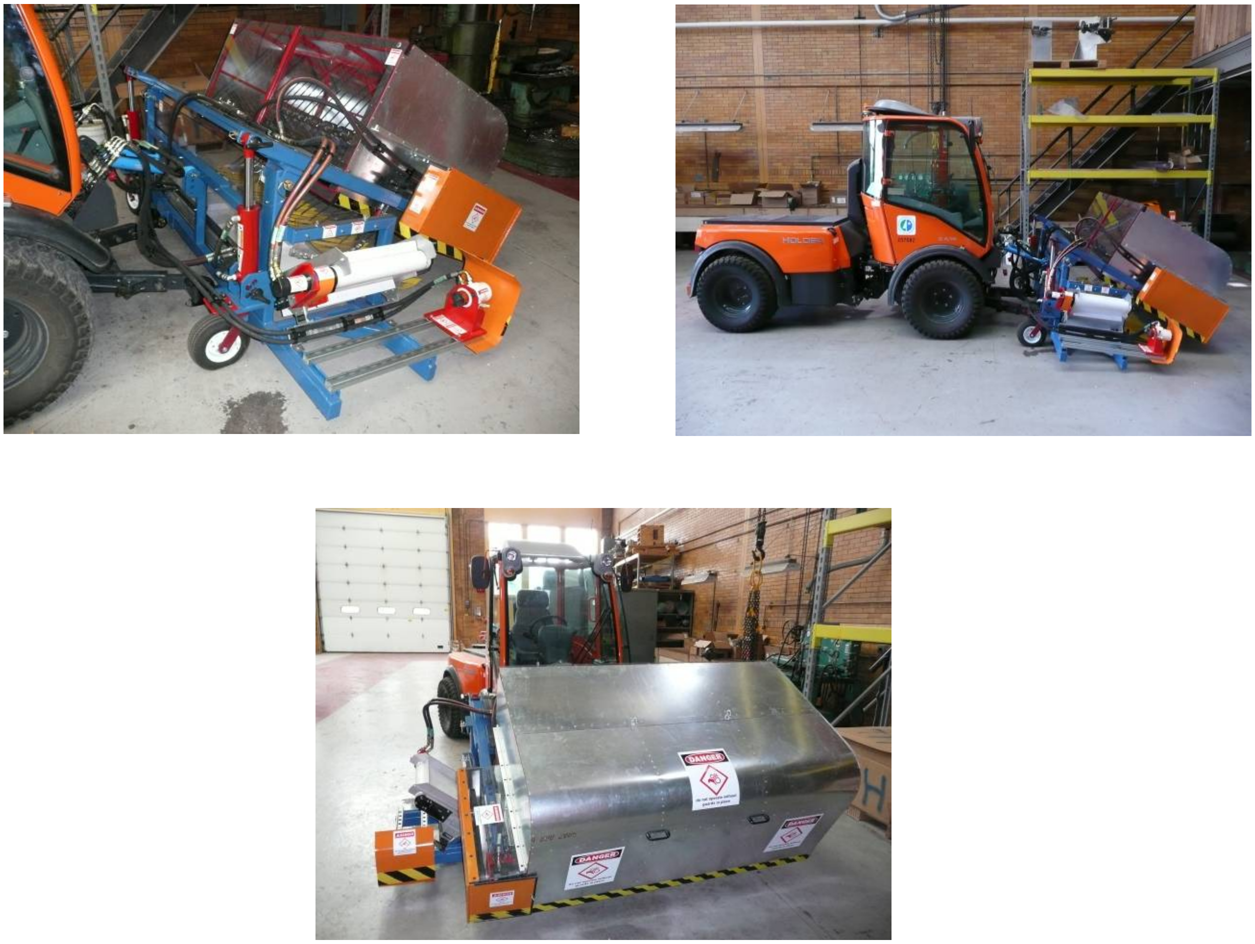


Figure 46: Trash harvesting machine

11. Structural Analysis

For safety reasons, we will perform a structural analysis of the cross brace beam member. A failure of this beam while driving by the side of the road could have dramatic consequences for the operator and the machine.

Figure 47: Cross brace

- Force Calculations

The total weight of the pick-up including its supporting frame is 1050 lbs with a repartition Front/Rear of 30/70. The weight was measured at the locations of the wheels of the frame supporting the pick-up unit. The dimensions of the rectangular supporting frame are 78 inches by 42. Knowing the weight repartition and the dimension of the frame, we can determine the forward location X of center of gravity of the pick-up unit: X = 0.30 x 42 inches. Thus, X equals 12.5 inches.

If we estimate a distance between the hitch pin and the supporting frame of 3 to 4 inches, we will have a forward distance between the center of gravity and the hitch mounts of roughly 16 inches. The distance between the top link and the lift arms is approximately 18 inches. We assume that the top link is close to horizontal position.

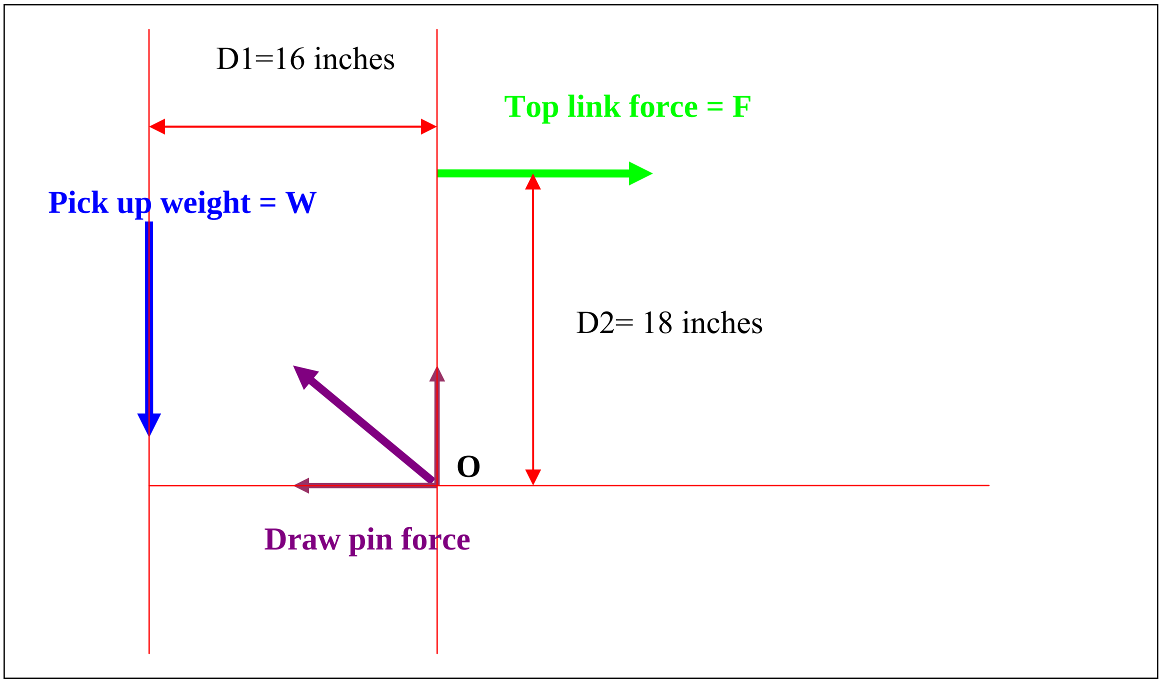


Figure 48: Cross brace - Force calculations

We are interested in knowing the force applied to the cross brace by the top link. Looking at the momentums around the point O, we have at equilibrium: W x D1 = F x D2. Thus, F = W x (D1/D2) which gives: F = 940 lbs. If the top link force F is not horizontal but makes an angle α with the horizontal, the distance D2 becomes D2' = D2 x cosα. Thus, F = W x (D1/D2 x cosα). For α varying in a +/- 35 degree interval, F varies between 940 lbs and 1140 lbs.

In its working position, the pick-up unit is most likely to be slightly tilted forward. This tilt angle β increases the distance D1 (D1'=D1/cosβ) and decreases the distance D2 (D2'=D2 x cosβ). Eventually, the top link force is increased by $(\cos\beta)^2$. For an acceptable tilt angle of 25 degrees, F max would be around 1500 lbs.

- Stress Calculations

The cross brace is 70 inch long and we assume that the load is applied in the middle of the beam. That is not quite the case since the hitch location is a bit offset (location along the beam is 30 inches instead of 70/2=35 inches) but this assumption, in addition of being more conservative, simplifies the calculations. As for the boundary conditions, the beam is fixed at its both ends. A spreadsheet based was created in order to easily try different load conditions/material properties.

With the following parameters:

- Load = 1500 lbs
- Young modulus = 3x10^7 PSI
- Shear strength = 200 MPa

The safety factor is the ratio of the maximum stress over the shear strength. The results are shown in the following table for different loads and wall thicknesses.

Table 6: Safety factors for different loads and wall thicknesses

Safety Factor for a cross brace beam: 2x2 square tube		
Load in pounds (top link)	3/8 inch wall thickness	1/2 inch wall thickness
1500	2.5	2.75
1750	2.1	2.3
2000	1.8	2
2500	1.5	1.6

Through this simple calculation, we verified the structural integrity of the pick-up frame. Since we used a 3/8 inch wall thickness, we have a safety factor of 2.5 which is well above the accepted minimum value of 1.5.

However, the pick-up frame is likely encounter shock loads while the trash harvesting machine is going through rough and bumpy terrains. In these conditions, it is good practice to have a coefficient well above the minimum value of 1.5. That is why a thick piece of L angle beam has been welded to the cross brace beam in the hitch/top link region in order to reinforce it.

12. Shredder Tests

- Technology

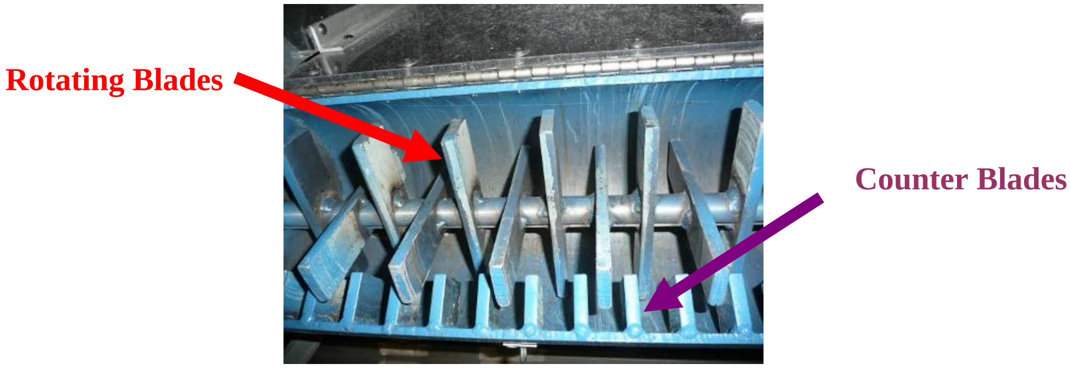


Figure 49: Shredder details

The shredder developed for the trash harvesting machine consists of a series of blades welded on a shaft rotation inside an 8 inch diameter cylinder cut in half. Stationary blades are welded on the inside wall of the cylinder. The rotating blades force the material to go through the stationary blades resulting in the shredding process.

- Purpose and Methodology

A test bench was built to measure the performance of the shredder unit with the most frequent trash that would be picked up by the trash harvester machine as indicated by MnDOT. This series of tests will measure the qualitative performance of the shredder with litter such as such as aluminum cans, papers, plastic bags and bottles. We will observe how the shredder performs for each category of trash, notice what works, what doesn't work and make recommendations for future improvements.
When looking from the outlet side of the shredding unit, the shredder rotor should rotate clockwise for maximum efficiency. However, tests will also be performed with the rotor rotating anti-clockwise.

- Test bench characteristics

  - Electrical motor nominal speed = 1750 rpm
  - Electrical motor power: =1 hp
  - Speed reduction = 4:1
  - Shredder rotor nominal speed =400 rpm

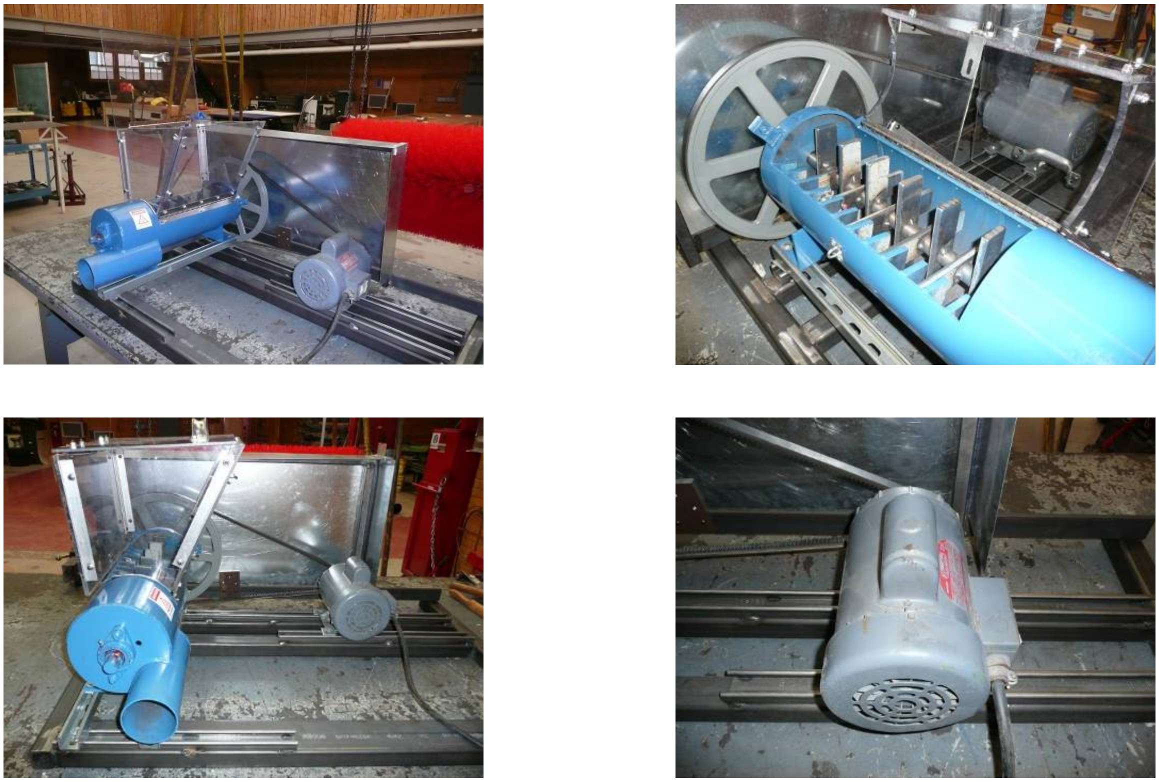


Figure 50: Shredder test bench

- Paper

We noticed that the paper is easily and quickly shredded. Paper is unlikely to plug the shredder and could be shredded even finer if sharp knives were installed either on the rotating blades or the stationary blades.

Figure 51: Shredder - Paper

- Plastic Bag

Like paper, plastic bag is unlikely to plug the shredder but tends to wrap around the rotor.

Figure 52: Shredder – Plastic bag

- Aluminum Can

Aluminum cans were found easy to shear. Like plastics, aluminum will not plug the shredder but tends to get stuck between the stationary blades. A smaller clearance between the rotor and the stationary blades could avoid this and would increase efficiency as well.

Figure 53: Shredder - Aluminum

- Plastic Bottle

Plastic used for plastic bottle is a material very easy to cut with a sharp knife but quite difficult to shear by having a round piece of metal going through the material like it is the case with the trash harvester shredder. Plastic bottles tend to get stuck between the counter blades and the rotating blades and are likely to plug the shredder. Again, sharp knives installed on the rotor would prevent the plastics to plug the shredder.

Figure 54: Shredder – plastic bottle

- Anti-clockwise Rotation

The shredder is designed to rotate clockwise under normal operating conditions so the rotor pushes the trash through the stationary blades from the bottom. The trash naturally falls into the space opposite the stationary blades. Pushed by the rotor, the trash has no other choice than going through the stationary knives. When the shredder rotates anti-clockwise, the trash tends to bounce back against the rotating blades. This problem could be alleviated by reducing the speed of the rotor which would allow the blades to grab the trash and push it through the stationary knives. However, slowing down the rotor would decrease the efficiency of the rotor by reducing its impact force.

- Future improvements

The shredder gives acceptable results with materials easy to tear like aluminum cans or papers but hard plastic is likely to plug the rotor. The first improvement would be to installed sharp knives (stationary, on the rotor or both) so the shredder would cut the material instead of tearing it apart. Along with a tighter clearance between the rotating blades and the stationary counter blades, this would not only prevent plugging and shred the trash finer but would also reduce dramatically the amount of power needed for the shredder. The second improvement would be to have the rotating blades follow a helicoidal path so the trash would not only shredded but also pushed by the rotor toward the outlet of the shredder. This configuration would reduce the vacuum power required to pull the trash out of the shredder and prevent plugging as well.

13. Operating Instructions when Equipped with Shredder

1. Switch on the main switch for the work hydraulic and raise the reel to provide visibility on the yellow lifting tines

Figure 55: Operating instructions – Step 1

2. Lower the 3-point hitch in order to put the pick-up on the ground

Figure 56: Operating instructions – Step 2

3. Activate the float position of both the 3-point hitch and the tilt function

Figure 57: Operating instructions – Step 3

4. Adjust the top link to the desired position: the tip of the yellow tines should be a between 1 and 2 inches off the ground

Figure 58: Operating instructions – Step 4

5. Lower the reel to the desired position depending on the conditions

Figure 59: Operating instructions – Step 5

6. Rev up the engine using the hand throttle to the desired rpm

Figure 60: Operating instructions – Step 6

7. Engage and adjust the hydraulic function for the shredder

Figure 61: Operating instructions – Step 7

8. Engage adjust the hydraulic function for the reel/conveyor

Figure 62: Operating instructions – Step 8

9. With the speed knob on 0, set the speed mode switch to 3 or 4

Figure 63: Operating instructions – Step 9

10. Engage the left-hand reverser in forward

Figure 64: Operating instructions – Step 10

11. Adjusting the ground speed with the speed knob

Figure 65: Operating instructions – Step 11

14. Field Tests

We first tested the trash harvesting machine in June 2007 on both short grass and tall grass/rough terrain conditions.

Figure 66: Short grass conditions

Figure 67: Tall grass conditions

On short grass, the trash harvesting machine was able to pick up more than 95% of the trash at a fast walking pace. In tall grass/rough terrain conditions, we were able to pick-up most of the trash lying on the ground after an adjustment of the inclination of the pick-up using the hydraulic top link.

Figure 68: Stuck pop cans

These first field tests were very promising and revealed opportunities for further improvements of the trash harvesting machine. We first noticed that quite a bit of trash, especially pop cans, was stuck between the lifting tines. This issue can be solved by reducing the distance between the lifting tines. The tests were done with the lifting bar in the locked position. We believe that a floating mode can improve the picking efficiency. Also, the performance of the pick-up strongly depends on the experience and skills of the operator. It certainly takes time, for both the operator but also for the designer, to understand the behavior of a new machine and get the most performance and productivity out of it.

15. Final Design and Testing

Based on recommendations from the TAP we decided to remove the shredder and fit a "more passive" conveyor to lift the trash from the gathering unit into a collection bin. This was done as it was thought that the probable frequency of shredder malfunctions would present an unacceptable hazard to the operator while unplugging the machine. The redesign was not an easy task due to the complexity of having an articulating vehicle as the test platform. In this situation articulated steering results in the rear section of the vehicle rotating with respect to the front of the vehicle, about the steering pivot. Ideally the conveyor would be situated on the central axis of the tractor, lifting the trash up and over the cab and into a bin on the rear of the machine. This would further limit the field of view from the cab to the gathering elements of the machine. A compromise was made in adding the conveyor on the right hand side of the machine as shown in Figures 69 and 70. In this position the trash can be loaded into the bin when driving straight ahead, in right had turns and moderate left hand turns, however trash cannot be loaded in severe left hand turns as the harvested trash will be deposited onto the ground.

Figure 69: Trash Harvester Final Configuration

Figure 70: Side View of Harvester

Motion of the gathering unit with respect to the vehicle during lifting and tilting operations was accommodated by pivoting the lower end of the lift conveyor and allowing the upper end to slide on its support rail. This is a complex mechanism. The lower end of the conveyor is cantilevered over the support shaft. This did lead to some fittings loosening during transport and may present a future maintenance problem.

A hoop and net wind shield has been constructed to cover the conveyor. This prevents trash from being blown off the conveyor in windy conditions, and also prevents material being picked off the conveyor by bystanders. The netting is secured on one side by zip ties and the other side is of the netting is drawn tight and a series of latches secure it to the conveyor. A small hydraulic motor drives the conveyor See Figure 71.

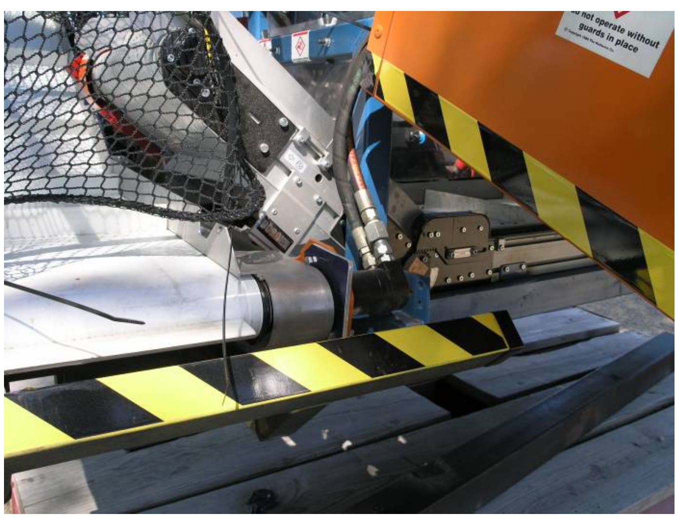


Figure 71: Conveyor Drive Motor

16. Operational Aspects of Machine Performance

The machine was field tested on sloping meadow grass on a farm near Millville, Minnesota. Trials were set up by placing ten pieces of a single type of trash (cans, bottles, or paper) in the un-mown grass. The harvester was then adjusted by the operator and a pass made over the trail site. Adjustments were made to improve the trash collection rate. The following observations were made:

- When operating in log grass it is very difficult to gauge the height of the lifting tines above toe soil surface.

- The height of the lifting tines greatly influences the gathering performance of the harvester.

The machine performed best when the gathering unit was lowered onto the gauge wheels (at the rear of the header) and the height of the lifting tines was modulated using the hydraulically adjustable top link. When operating in this mode it was possible to collect 95-100% of all trashed placed in front of the machine.

17. Machine Improvements

The harvester could be improved by adding automatic header height control. The hydraulic system on the Holder tractor allows the header to be rotated laterally, pitched forwards, and lifted up and down, This adjustability id very good for fine adjustments of the mechanism, however it id difficult to use "on-the-fly". An automated control system would be beneficial for adjusting the height of the lifters.

The forward visibility of the operator is restricted by the shield around the rotating tines. Shielding is necessary to prevent a bystander from becoming entangled in the gathering unit. A smaller reel would allow better visibility forward of the machine. Visibility of the functional components is excellent.

The size of the dump bin on the back of the tractor was limited by the position of the conveyor. This constraint is difficult to remove unless the shredder is replaced.

18. Conclusions

A fully functioning trash harvester has been designed, fabricated and tested within the limits of this project. The machine will collect 100% of commonly found trash categories (cans, bottles, and paper) when adjusted so that the tines are below the trash in the vegetation canopy. The machine has a multi axis three point hitch which is probable more complex than needed on this machine however it will allow fine adjustments to be made to the lifting mechanism. Main improvements which should be addressed before production are; forward visibility, header height control, and dump box capacity. Overall the machine functions beyond expectations.