EVALUATION OF TRENCH AND SLOTTED DRAIN MAINTENANCE AND CLEANING – PHASE 2

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Prepared for:

The Ohio Department of Transportation,
Office of Statewide Planning & Research

State Job Number 135521

November 2018

Final Report

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
FHWA/OH-2019-3</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2">4. Title and Subtitle
Evaluation of Trench and Slotted Drain Maintenance and Cleaning – Phase 2</td><td>5. Report Date
November 2018
6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s) (include 16 digit ORCID ID)
Hazem Elzarka (0000-0003-2845-4568), **Janet Dong, Adithya Kaushik, Ce Gao**</td><td>8. Performing Organization Report No.</td></tr>
<tr><td colspan="2">9. Performing Organization Name and Address
**University of Cincinnati
765 Baldwin Hall
2850 Campus Ways
Cincinnati, OH 45221-0071**</td><td>10. Work Unit No. (TRAIS)
11. Contract or Grant No.
SJN 135521</td></tr>
<tr><td colspan="2">12. Sponsoring Agency Name and Address
**Ohio Department of Transportation
1980 West Broad Street
Columbus, Ohio 43223**</td><td>13. Type of Report and Period Covered
Final Report
14. Sponsoring Agency Code</td></tr>
<tr><td colspan="3">15. Supplementary Notes</td></tr>
<tr><td colspan="3">16. Abstract
Trench and slotted drains are increasingly being used by ODOT to remove storm water from the roadways. These drains have to be properly cleaned and maintained to efficiently remove storm water from the roadway to prevent vehicles from hydroplaning, and to eliminate flooding. ODOT’s current procedure for cleaning/maintaining trench and slotted drains are not safe in many situations as they both require ODOT highway technicians to walk along the drain during cleaning and thus expose them to heavy traffic. The research evaluated ‘new’ methods for cleaning trench drains that are safer and more efficient and recommends using horizontal auger boring (HAB) equipment for cleaning drains. Other cleaning methods evaluated included the use of specialized sewer cleaning nozzles and the use of a drain cleaning robot developed as part of the project.</td></tr>
<tr><td colspan="2">17. Keywords
Trench drains, slotted drains, Horizontal Auger Boring, robotic cleaners, storm water system management</td><td>18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161</td></tr>
<tr><td>19. Security Classification (of this report)
Unclassified</td><td>20. Security Classification (of this page)
Unclassified</td><td>21. No. of Pages
117
22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) **Reproduction of completed pages authorized**

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and the U.S. Department of Transportation, Federal Highway Administration

Acknowledgments

This project was conducted in cooperation with ODOT and FHWA.

The authors would like to thank the ODOT Technical Liaisons and other key personnel providing assistance during this project:

- Mr. Dan Wise
- Mr. Shawn Rostorfer

We also want to thank Ms. Jill Martindale, Ms. Michelle Lucas, Ms. Cynthia Jones and Ms. Vicky Fout from ODOT's Office of Statewide Planning & Research for their time and assistance.

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Executive summary

Trench and slotted drains are commonly installed in roadway depressions along the shoulder or in gore areas. They are typically installed in these locations as a result of shallow pavement cross slopes that cannot be drained into a ditch or catch basin. Recently, the use of trench/slotted drains by ODOT in roadways has increased and is expected to continue to increase in the future which makes it necessary to develop methods for safely maintaining/cleaning trench and slotted drains. Without routine maintenance, the road grit accumulates in the bottom of the drain and quickly gets root bound by the noxious weeds and other vegetation. Once this happens, it becomes very labor intensive to clean and reestablish flow. Currently, ODOT clean trench drains manually or using a sewer cleaning truck. Both the manual process and the current ODOT procedure for using a sewer cleaning truck are not safe as they both require ODOT Highway technicians to walk along the drain during cleaning and thus expose them to heavy traffic. A safer process that is capable of cleaning the entire length of the drain from one location is needed. The goal of this research is to improve ODOT's current process of maintaining trench/slotted drains. To achieve this goal, the research team evaluated the current ODOT process for cleaning trench/slotted drains, developed a matrix of alternatives for cleaning trench/slotted drains that compares and contrast solutions that are available today and provided recommendations.

In Phase 1, the research team concluded that conventional methods used by ODOT and other DOTs to clean trench drains are not effective in many situations. Many trench/slotted drains failed because of inadequate or often no maintenance and had to be replaced at significant cost. One objective of phase 2 was to develop 'new' methods for cleaning trench drains that can be used safely in more situations. These new methods included employing horizontal auger boring (HAB) equipment, experimenting with specialized designs of sewer cleaning nozzles and developing a drain cleaning robot.

The process of cleaning trench drain with HAB equipment as developed by the research team is a new application for HAB machines. Continuous flights of augers are rotated and

simultaneously pushed by the HAB machine into the drain. As the length of auger is advanced into the drain, new auger sections are connected. As the augers continue to advance, the debris in the drain is loosened and the auger flights convey the material back to the cleanout location. The tube of a suction excavator is placed just above the augers in the cleanout location with the intent of sucking out the debris as it is being pulled back by the augers. The field tests have demonstrated that the use of a HAB machine in combination with a suction excavator is very effective in providing a safe and environmentally friendly process for cleaning trench drains.

Although the use of specialized hydro-jetting nozzles with a sewer truck reduces splashing, field tests have shown that when the drains are nearly full, this method still blows debris out of the drain creating a safety hazard. A cost analysis was performed and it was found that the use of a HAB unit in conjunction with a suction excavator provides the least cost alternative for cleaning trench drains at $2.37/lf of drain compared to $3.77/lf when a sewer cleaning truck is used and $9.50/lf when the drains are cleaned manually.

The drain cleaning robot prototype developed has demonstrated that the concept works. However, more work is needed to make the robot more powerful and heavy duty to enable it to move over different types of debris in the drain and to make it water proof.

Chapter 1- Introduction

1.1. Background

Trench and slotted drains are increasingly being used by ODOT to provide surface drainage in roadway depressions along the shoulder or in gore areas. Surface drainage is necessary to remove storm water from the roadway to prevent vehicles from hydroplaning and to prevent flooding. Trench and Slotted drains are very efficient systems for surface drainage. Their narrow continuous gutters adapt well to the surface conditions. They are commonly installed in roadway depressions along the shoulders or in gore areas. They are typically installed in these locations as a result of shallow pavement cross slopes that cannot be drained into a ditch or catch basin. Trench/slotted drains are able to take in large amount of water with great speed and are thus effective at removing storm water from the roadway and preventing vehicles from hydroplaning.

Trench/slotted drains require regular cleaning/maintenance because over a period of time they collect large amount of road grit and debris and start supporting vegetation growth. This interferes with the proper flow of water in the drains. With the increased use of trench/slotted drains on highway reconstruction projects and the reduction of available man hours necessary for maintenance, the drains are not being regularly maintained. When trench and slotted drains are not maintained they are unable to transmit the storm water runoff from the roadway. This can lead to safety concerns of water and/or ice on the roadway as well as premature roadway failure from saturated subsurface. Without routine maintenance the road grit accumulates in the bottom of the drain and quickly gets root bound by noxious weeds and other vegetation. Once this happens it becomes very difficult to clean the drains and reestablish flow. There are extreme situations where maintenance is impossible to perform due to the difficulty in accessing the drain with the sewer truck. In these situations, the drains had to be completely replaced at significant cost to ODOT. Even when annual maintenance is performed on the drains, it is labor intensive and inefficient. The purpose of this research is to improve the current ODOT process of maintaining trench and slotted drains.

1.2. Goals and Objectives

The overall goal of this project is to evaluate ODOT's current process for cleaning trench and slotted drains and develop alternative methods for cleaning those drains. The project was conducted in two phases. Phase I focused on establishing the current state of the practice for cleaning trench and slotted drains and preliminary evaluation of alternative cleaning methods. Phase II focused on developing 'new' methods for cleaning trench drains that are more efficient, environmentally friendly and can be used safely in more situations. These new methods included employing horizontal auger boring (HAB) equipment, experimenting with specialized designs of sewer cleaning nozzles and utilizing a drain cleaning robot developed as part of the research.

Phase 1 results are included as Chapters 2 and Chapters 3 of this final report. The objectives of Phase 1 were as follows:

1. Determine the state of current procedures and practices by Ohio DOT and other state DOTs for cleaning trench and slotted drains with a focus on production rates, costs, and best management practices.
2. Identify manufacturers of drain cleaning equipment, interview them to assess experiences and concerns, and recommend appropriate equipment for use in Ohio based on cost, effectiveness, safety, ease of use and production rates.

To achieve these objectives, the following tasks were completed as shown in Figure 1.1:

(1) Evaluate the current ODOT process for trench/slot drain cleaning/ maintenance.

(2) Develop a matrix of alternatives that will compare and contrast solutions that are available today and provide a recommendation on the most viable solution

(3) Provide an analysis of current equipment, materials and technology available for handling trench/slot drain maintenance.

(4) Provide an interim report detailing the findings from all the above steps. Recommend solutions for infield testing and analysis

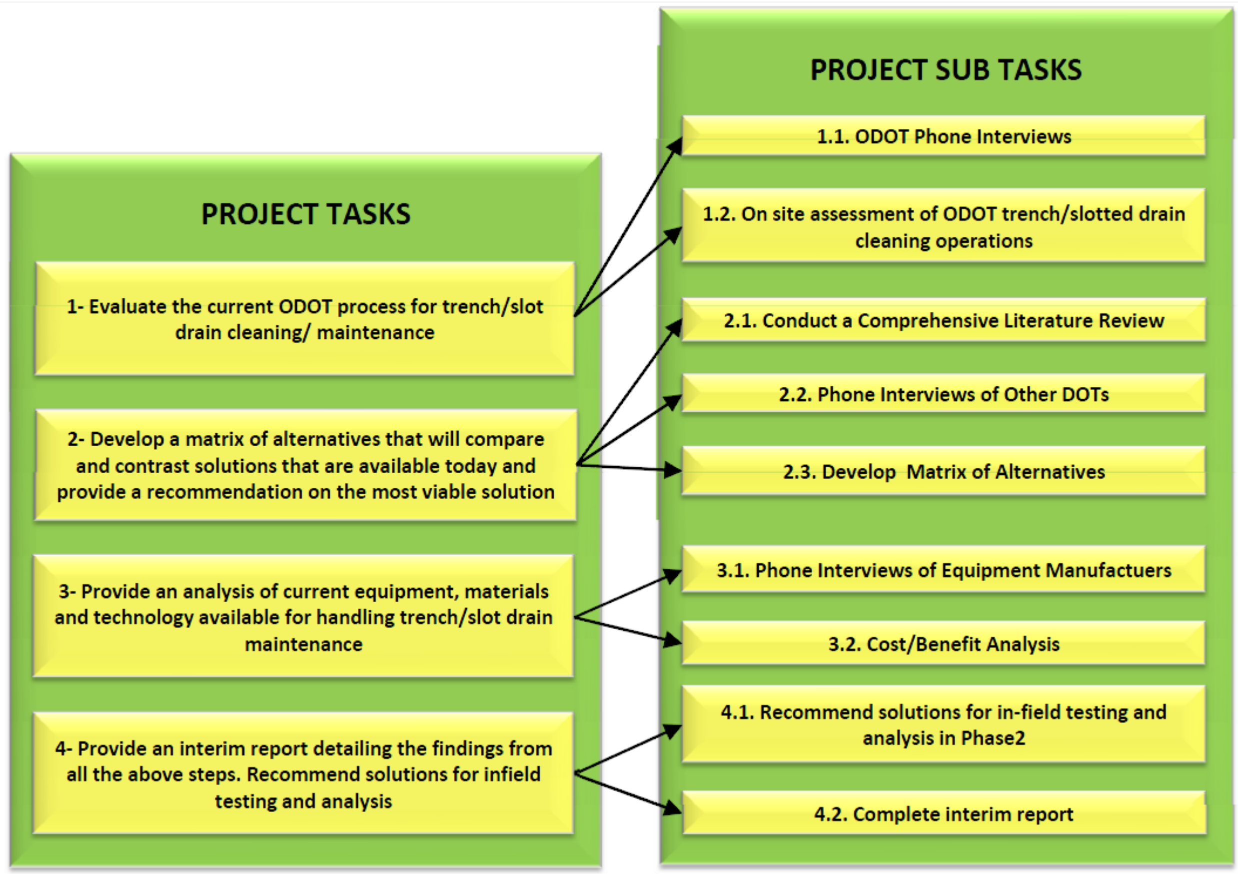


Figure 1.1. Summary of Tasks completed in Phase 1

Phase 2 was carried out after the decision was made to acquire a horizontal auger boring (HAB) machine to test and evaluate its effectiveness in cleaning trench drains and to develop a prototype robot and evaluate its potential use to remotely clean the drains. The objectives of Phase II were as follows:

1) Identify and procure special hydrojetting nozzles that improve the current ODOT process of cleaning drains with a Sewer Truck.
2) Identify and procure a suitable HAB machine for cleaning drains.
3) Design and build a prototype drain cleaning robot.

4) Perform in-field testing/analysis of newly developed technologies to evaluate their effectiveness in cleaning drains.
5) Identify site and drain conditions that effect the selection of the appropriate cleaning method.

1.3. Organization of this report

This report is divided into seven chapters. Chapter 1 introduces the research topic and includes a list of the research objectives. Chapter 2 presents background research into the current practice for trench/slotted drains cleaning, as well as field observations of current practices and information collected from ODOT, other transportation departments, and equipment manufacturers. A comparison of current practices and recommendations for field testing is presented in Chapter 3. Chapter 4 discusses the development of the drain cleaning robot and procurement of HAB equipment. Chapter 5 presents results of field tests conducted to evaluate the effectiveness of alternative methods of cleaning drains. Chapter 6 includes a cost analysis of the cleaning methods evaluated during the field tests. Based on earlier chapter analysis, as well as testing results, Chapter 7 discusses recommended methods for cleaning drains. Lastly, Chapter 8 summarizes the research conclusions and recommendations for ODOT continuing to move forward in their endeavor to cost-effectively maintain drains.

Chapter 2- Current Trench/Slotted Drain Cleaning Practices.

Background research into the current state of practice for cleaning trench and slotted drains are presented in this chapter. The research for this chapter was conducted in Fall 2016 and formed a foundation for the later chapters. This chapter is divided into two sections:

1. Evaluation of the current ODOT processes for cleaning trench and slotted drains.
2. Develop a matrix of alternatives that will compare and contrast solutions that are available today and provide a recommendation on the most viable solution

2.1. Evaluation of the current ODOT process for trench/slot drain cleaning/ maintenance.

This section includes results from two activities: (1) ODOT phone interviews, and (2) On site assessment of ODOT ditch cleaning operations.

2.1.1. ODOT Phone Interviews

Before conducting the phone interviews, the research team emailed all ODOT county managers and highway management administrators. A total of 104 emails were sent. The purpose of this short email was to find out which ODOT counties has either trench drains and/or slotted drains on its roads. 57 responses were received with a response rate ratio of 55%. Out of the 57 respondents, 14 have indicated that they have trench and/or slotted drains in their counties as listed in Table 2.1. All 14 respondents were contacted by phone. 7 returned the phone calls and were interviewed regarding cleaning equipment used, frequency of cleaning, crew size, factors affecting production rate, and safety concerns. The interviews were used to obtain an understanding of current ODOT processes for cleaning trench/slotted drains.

Table 2.1. List of ODOT Counties/Districts that indicated having trench and/or slotted drains in email response

#	County Name	Notes
1	Cuyahoga	Slotted drains on I271 between the express lane and the mainline
2	Highland	One Trench Drain and one Slotted Drain
3	Pike	Have both drains
4	Ross	On 23 South around the 0 - 5 mile markers, also on St Rt 104 near the Ross County Fairgrounds
5	Lawrence	Trench drains
6	Pickaway	One slotted
7	Auglaize	Slotted drains in the parking lot of the USR 33 Rest Areas (never been cleaned). Trench drains inside main facility. They get cleaned regularly
8	Fairfield	Some Slotted Drains on US 33 (never cleaned yet)
9	Summit	90' of slotted drain on I-271 Southbound at the Sr 8 split which is the 18.45 mile marker
10	Ashtabula	One trench drain which was just installed on project
11	Hamilton	Some slotted drains
12	District 2	Trench drains on a new ODOT project on I-75 and the gore area (no experience maintaining them)
13	Coshocton	Slotted drains on US 36 near Roscoe Village
14	Scioto	Have both styles

Below are the questions posed to county managers and transportation managers from the various ODOT county maintenance garages during the phone interviews.

District _____________ County _____________ Phone Number __________________________

Name of contact _________________________ Lane miles maintained ____________________

1. How many linear feet of trench and slotted do you maintain?
2. Do you have experience cleaning trench/slotted drains?
3. What is the typical length of a single installation?
4. What are the typical widths and depths of trench drains in inches?
5. Is it common to have vegetation in clogged drains?
6. How often do you clean trench drains you currently have?
7. What kind of methods you use for trench drain cleaning?
8. What is the production rate of each method (lf/hour)?
9. Where do you get rid of the waste from the cleaning operation?
10. How many people are typically involved in the cleaning operation?
11. Are all the equipment needed in the garage or at the district?
12. What are the limitations of current equipment used?

Interview Results

Table 2.2 summarizes results from the 7 phone interviews. As shown in Table 2.2, 2 of the interviewees (Ashtabula County and District 2) have just recently installed their first trench/slotted drain on their roadways and don't have experience yet maintaining the drains. The major findings from the interviews are further discussed in the following subsections. The subsections also include feedback received from Mr. Dan Wise and Mr. Shawn Rostorfer; members of the technical liaison team who were informally interviewed throughout the project.

Frequency of use

Recently, the use of trench/slotted drains by ODOT in roadways has increased. Data provided by Mr. Dan Wise has indicated that

- Since 2013, ODOT installed 33,578 LF of trench drains. Just in District 6 since 2013, ODOT installed 12,570 LF of trench drains.
- Since 2013, ODOT installed 8,236 LF of slotted drains.
- From Feb 2015 to June 2016 ODOT installed 11,510 LF of trench drains. Just in District 6 ODOT installed 9,356 LF.

The interview results have confirmed that the use of trench/slotted drains is going to continue to increase in the future which makes it necessary to develop standard procedures for effectively maintaining/cleaning trench and slotted drains.

Experience in and frequency of cleaning operations

Experience in cleaning trench/slotted drains is very limited in Ohio. Many counties have recently installed these drains for the first time and have not yet had to clean them. Counties that have had these drains for longer typically clean/inspect the drains every year. Without routine maintenance the road grit accumulates in the bottom of the drain and quickly gets root bound by noxious weeds and other vegetation which makes it very difficult to clean. In extremes cases, some slotted drains that were impossible to clean had to be completely replaced with significant cost to ODOT.

Equipment

As shown in Table 2, the predominant equipment used in Ohio for cleaning trench/slotted drains is a sewer cleaner (Vactor-Jet). The sewer cleaner is expensive, which prohibits purchase of a unit for each county. There is currently a relatively small number of sewer cleaners throughout the state and counties report sharing it amongst themselves. The need to share limits the use of the equipment.

Furthermore, the sewer cleaner such as a Vactor-Jet, is a large piece of equipment, and usually requires lane/shoulder closures to use. It typically cannot be driven off the pavement due to its weight. The sewer cleaner also requires the use of large volume of water which is mixed with the sediments built up in the drains and is carried to the stormwater system if not collected; this is not in compliance with current EPA standards particularly if the resulting water from the cleaning operation is drained to a stream or a wetland. Also the use of high pressure water from the sewer cleaner creates a large mess as the water and sediment escape through the holes in the grates.

Table 2.2. Survey Results for Equipment Usage

Questions	Answers						
County/District	Highland	Ross	Lawrence	Fairfield	Scioto	Ashtabula	District 2
How many linear feet of trench and slotted do you maintain?	Not Available	5 Miles	Not Available	200 feet	4,500 feet	Not Available	Not Available
Do you have experience cleaning trench/slotted drains?	Yes	Yes	Yes	Yes	Yes	No	No
What is the typical length of a single installation?	Not Available	55 feet	100 feet	Not Available	Not Available	Not Available	Not Available
Typical widths and depths of trench drains in inches?	W: 8-1/2 D: 18	W: 10 D: 12-16	W: 6-10 D: 6-8	Not Available	W: 4-5 D:8-10	Not Available	Not Available
Is it common to have vegetation in clogged drains?	Yes	Yes	No	Not Available	Yes	Not Available	Not Available
How often do you clean trench drains you currently have?	1/Year	1/Year	As needed or 1/year		Inspect 1/year		
What kind of methods you use for trench drain cleaning?	Vac-Con Air pressure	Vac-con	VAC-CON	VAC-CON	VAC-CON		
What is the production rate of each method (lf/hour)?	Not Available	Not Available	Not Available				
Where do you get rid of the waste from the cleaning operation	Landfill	Waste Site	Test and let other companies handle it	Approved site	Approved site		
How many people are typically involved in the cleaning operation	4-6	3-5	6-7		4-5		
Are all the equipment needed in garage or at district	Garage and District	District do Maintenance	Garage		District		
Limitation of current equipment	No	No	No		Slow, mess		

Standard Procedures

Currently there are no standard procedures for maintaining trench/slotted drains. Although most counties that provided feedback on equipment used have indicated the use of a sewer cleaner for cleaning, production rates are not known. Without knowing production rates, it is difficult to adequately plan for maintaining the drains with the available resources.

2.1.2 On site assessment of ODOT trench/slotted drain cleaning operations

In order to complement the information obtained from the phone interviews, the research team conducted 3 site visits to better understand challenges related to cleaning trench/slotted drains and to observe current cleaning operations in Ohio and to evaluate possible cleaning methods identified as a result of the literature review. The visits served to observe cleaning methods first hand, including crew composition, equipment usage and maintenance, and environmental measures taken. Table 2.3 provides more information about the date and location of the site visits.

Table 2.3. Summary of Site Visits and Demonstrations

Date	District	County	Description
9/16/2016	6	Franklin	• Tour of several ODOT installations of trench/slotted drains • Demonstration of various types of trench drains
10/12/2016	6	Franklin	• Observe ODOT`s current practices for cleaning trench/slotted drains • Evaluate possible cleaning methods identified as a result of the literature review
10/26/2016	6	Franklin	• Evaluate a Sewer Cleaner with a Water Recycling System • Evaluate different types of ENZ nozzles to clean trench drains

First site visit on 9/16/2016

The first site visit on 9/16/2016 consisted of a tour of several ODOT installations of trench/slotted drains in Franklin County, as well as a demonstration of the various types of trench drains and the ease of removing the grates from different types. Figure 2.1. shows several installations of drains around Franklin county. As shown in the figure, Trench and slotted drains are commonly installed in roadway depressions along the shoulder or in gore areas. They are typically installed in these locations as a result of shallow pavement cross slopes that cannot be drained into a ditch or catch basin. Many of the areas where trench/slotted drains are installed experience high traffic throughout the day and in many cases high speeds which present a challenge to safely clean the trenches.

Figure 2.1. Various installations of trench and slotted drains in Franklin County, Ohio

As shown in Figure 2.2, the drains over time collect different types of debris including grit and leaves. Drains that are not maintained on a regular basis become completely clogged and obstruct the necessary and designed flow of storm water from the roadway. That can lead to safety concerns of water and/or ice on the roadway as well as premature roadway failure from saturated subsurface. Furthermore, without routine maintenance the road grit accumulates in the bottom of the drain and quickly gets root bound by noxious weeds and other vegetation as shown in Figure 3. The presence of vegetation makes the drain harder to clean.

Figure 2.2. Debris and vegetation in trench drains

Figure 2.3. shows different styles for trench drains. Some trench drains are monolithic and have no removable grates. In another style of drains, the grates are screwed to the drain body. For this style, it is usually a painstaking job to unscrew and screw again grates; screws get rusty or lost and the job has to be performed on the knees which can cause workers getting hurt.

In a third style of drains as shown in Figure 2.3., locking rods are used to provide a firm linkage between the grates and the drain body. For this style, it is easier to remove and re-install the grates. A special tool as shown in Figure 2.4. permits easy locking of the drain cover and unlocking while the crew member is an upright position.

Monolithic drains **Screwed Grates** **Grates attached with locking rods**

Figure 2.3. Different style of drains

Figure 2.4. Tool to remove grates attached with locking rods

Second site visit on 10/12/2016

The purpose of the second visit on 10/12/2016 was to observe ODOT`s current practices for cleaning trench/slotted drains and to evaluate possible cleaning methods identified as a result of the literature review. Demonstrations of various cleaning operations were performed using a mechanical drain (plumber's snake), compressed air and a sewer cleaner (Vactor Jet). In addition a 30 ft section of the trench drain was cleaned manually to calculate the production rate of manual cleaning. Description and summary of cleaning methods observed are provided in the sections below.

Manual cleaning:

Three crew members participated in the manual cleaning process. As shown in Figure 2.5., the process consisted of unscrewing the grates, removing the debris and loading it in buckets, cleaning around the drain with a blower and re-installing the grates. The crew was able to clean 30 linear feet of drain in 1 hour. In other words, 3 man-hours were needed to clean 30 ft which amount to a production rate of 10ft/man-hour.

1-unscrewing grates 2-removing debris 3-loading debris in buckets 4-cleaning around drain with a blower 5- Installing grates

Figure 2.5. Manual cleaning of trench drains

Compressed air:

Compressed air was tested for cleaning a short section of trench drain. As shown in Figure 2.6., an ODOT personnel used compressed air to blow the debris out of the drain. The compressed air was not capable of completely removing the debris from the drain and as shown in Figure 2.6., debris from the drain scattered everywhere around the drain creating an unacceptable mess. Because of these limitations, it was concluded that compressed air is not a viable method for cleaning trench drains.

Figure 2.6. Use of compressed air in cleaning drains

Mechanical Drain (Plumber's snake):

As shown in Figure 2.7., a mechanical drain was tested for cleaning a short section of a trench drain to evaluate if it can loosen hard dirt accumulated in nearly fully clogged drains. However, because the drain was not completely full of debris, as the cable rotated, it rode on the top of the sediments and was unable to clear up clogging from inside the drain. Due to this observed limitation, it was concluded that the mechanical drain is not a viable method for cleaning trench drains.

Figure 2.7. Use of mechanical drain in cleaning trench drains

Sewer Cleaner:

A sewer cleaner was tested for cleaning a trench drain. As shown in Figure 2.8., the water jet nozzle was placed in the drain and the suction tube was placed behind it, also in the drain. Because the suction tube diameter is larger than the drain, a special extension hose was specially made to fit in the drain. Another option is to place the suction tube in the catch basin connected to the trench drain as will be demonstrated in a following section. The intent of placing the suction tube directly in the drain as opposed to placing it in the catch basin is to try to capture as much water used for cleaning the drain as possible. However, it was observed that a significant amount of water was not captured by the suction tube and was discharged to the catch basin.

It was observed that the sewer cleaner is capable of cleaning the trench drain. The nozzle used had a good propel thrust and was able to break down the hardened debris and clean the drain. However, as shown in Figure 2.8., the nozzle used splashed a significant amount of water and debris from the top holes in the grates. The large amount of splashed water can cause a safety hazard for drivers using the road and for ODOT crews. A wooden board was used to limit the amount of water splashed. The wooden board was effective in reducing splashed water in this case but may be difficult to use on other projects where traffic is heavier. Furthermore, a significant amount of debris cleaned from the drain escaped through the holes in the grates and ended up on the pavement next to the drain as shown in Figure 2.9. This debris will have to be removed either manually or using a street sweeper and disposed of safely. If left on the pavement, it will quickly move back and settle in the drain with any rain.

In summary, the sewer cleaner was shown to be a potential viable method for cleaning trench drains. However, there were several concerns with using the sewer cleaner that need to be addressed. These are:

- A large volume of water used for cleaning.
- Significant amount of splashing.
- Debris accumulating on the pavement next to the drain. This debris will have to be removed requiring additional resources and equipment.
- Inability to capture all the jetting water.

After contacting sewer cleaner manufacturers and nozzle manufacturers and discussing these concerns, the research team concluded that some of these concerns can potentially be improved using different types of nozzles and/or sewer cleaners. To evaluate the potential improvements, the research team scheduled a field test on 10/26/2016.

1-Placing Nozzle in Drain

2- Placing Suction tube in drain

Figure 2.8. Use of sewer cleaner in cleaning trench drains

Figure 2.9. Debris cleaned from the drain

Third visit on 10/26/2016

The purpose of this visit was to evaluate the capabilities of a Sewer Cleaner with a Water Recycling System and different types of ENZ nozzles to clean trench drains. The research team wanted to find out:

1. If the water recycling system can significantly reduce the volume of water used for cleaning.
2. If certain models of ENZ nozzles significantly reduce the amount of splashing and reduce the amount of debris accumulating on the pavement next to the drain after cleaning.

A water recycling system in a sewer cleaner reuses water for cleaning after filtering it. This reduces the amount of contaminated water that is discharged to the storm water network and also allows for uninterrupted line cleaning as it eliminates the need for periodically filling up the sewer cleaner with water. The Vactor 2100 Plus® Water Recycling System shown in Figure 2.10. was tested during this site visit.

Figure 2.10. Vactor 2100 Plus® Water Recycling System

Also during the site visit and as shown in Figure 2.11., two different water jet nozzles were tested: ENZ Flounder and ENZ Chisel Point. The ENZ flounder is suited to clean flat pipes and channels. The flat design combined with the rounded corners and edges provides the tool with good gliding properties. The ENZ chisel point, with its very strong concentrated forward jets and the sharp cutting edges, is capable of tearing through tough blockage.

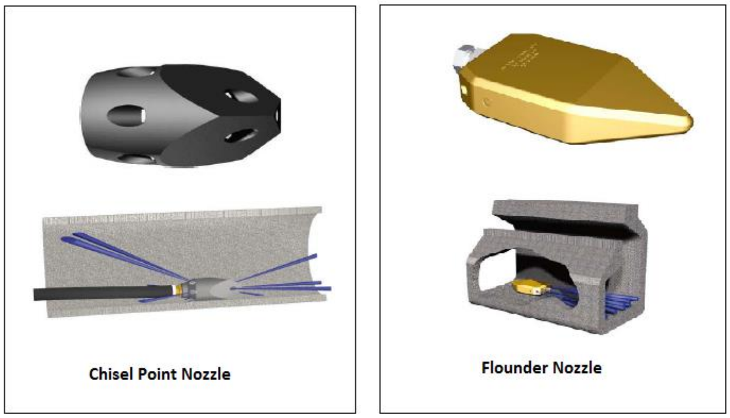


Figure 2.11. ENZ nozzles

A wooden board was used to control splashing. A string was attached to the board to allow a crew member to pull the board as the nozzle advanced inside the drain as shown in Figure 2.12.

Figure 2.12. Crew member pulling wooden board

When the Flounder nozzle was used, the splashing was significantly reduced as shown in Figure 2.13. The Flounder however was unable to tear through tough blockage because it didn't produce a concentrated forward jet. The Chisel Point nozzle was able to easily cut through all blockages but increased water splashing.

Figure 2.13. Reduced splashing when using Flounder nozzle

As shown in Figure 2.14., the suction tube was placed in the catch basin connected to the trench drain. The suction tube wasn't able to capture a lot of the water used for cleaning because the pipe connected to the trench drain was much higher than the other pipes connected to the catch basin. It is important to note that the fact the suction tube was not capable of capturing most of the cleaning water renders the water recycling capability of the sewer cleaner less useful without sand bags placed in front of outlet pipe. It was thus concluded that a water recycling system is not necessarily needed for trench drain cleaning.

Figure 2.14. Suction tube placed in catch basin

The cleaning was completed in one hour and used about 1000 gallons of water. 180 feet of trench drains were cleaned thoroughly. One additional half hour was needed for the crews to clean the debris blown out of the drain. This amounts to a production rate of 120 feet per hour and water consumption of 5.5 gallons per linear feet. Several stops occurred during work to change nozzles and when the crew member pulling the wooden board was unable to keep up with the nozzle moving up the drain. The field test has confirmed the viability of using the sewer cleaner for cleaning trench drains. The cleaning production rate achieved was 4 times faster than the manual cleaning rate. However, it is recommended that more research be conducted in phase 2 to further improve the process by designing a stepped cleaning process and identifying a suitable nozzle that eliminates the need for a crew person having to pull a wooden board. It is the research team's judgment that pulling a board to control splashing is not very safe particularly in high traffic areas. Nozzles' manufacturers such as ENZ can typically work with their customers to manufacture a suitable nozzle. It is recommended that in phase 2, the research team work with nozzle manufacturers to develop a nozzle whose spray pattern of the water jets prevent any water from splashing up directly eliminating water splashing and the need to clean up around work areas.

2.2. Develop a matrix of alternatives that will compare and contrast solutions that are available today and provide a recommendation on the most viable solution

This section includes results from two activities: (1) Literature review, (2) Phone interviews of other DOTs and (3) matrix of alternatives.

2.2.1. Literature Review

The literature review focused on trench/slotted drains' cleaning operations, factors affecting selection of cleaning method and best practices for cleaning trench/slotted drains.

<u>Trench/slotted drains' cleaning operations and procedures</u>

The literature review has identified potential methods of cleaning trench/slotted drains. Many of these methods were evaluated during the site visits as discussed in section 2.1.2. These cleaning methods are:

1. Manual cleaning
2. Flushing with water
3. Mechanical drain cleaning
4. Hydrojetting
5. Using a sewer cleaner

These methods are further discussed in the following subsections.

Manual Cleaning

When trench drains are cleaned manually as shown in Figure 2.15., most of the grates are first removed. Maintenance crews then remove debris from the drain manually with shovels or brushes. The size and shape of the shovel used will vary based on the drain's shape and size. The manual method is one of the methods recommended by the Tahoe Regional Planning Agency for cleaning trench drains with removable grates (TRPA BPM Handbook 2014).

Figure 2.15. Manual Cleaning of Trench drains

Although manual cleaning methods do not require expensive equipment, they are very labor intensive. Manual methods may also lead to possible injuries resulting from dropping grates on toes or back injuries resulting from improperly carrying heavy weight.

Flushing with water

This procedure is aligned with manufacturers' recommendations. One manufacturer, ACO, recommends in their site installation manual the following procedure:

1. Remove grates

2. Remove debris from channel
3. Flush channels with water or high pressure washer.
4. Repair damaged surfaces, if necessary, with an appropriate ACO repair kit.
5. Renew joint seals as required.
6. Empty rubbish baskets and clean out pipe connections.
7. Re-install rubbish baskets.
8. Re-install grates, ensuring they are locked in place.

As shown in Figure 2.16., flushing with water is labor intensive: first, maintenance crews have to manually remove the majority of the grates, and then they have to remove the debris from the channel, flush with water and re-install the grates. Depending on the trench drain types, the grates could be bolted on both sides and may have to be unscrewed for removal and screwed again for installation. The grates are heavy and have to be carefully handled by maintenance crews to avoid injuries such as injuries resulting from dropping grates on toes or back injuries resulting from improperly carrying heavy weight. Such injuries may results in workers' compensation claims and workdays' loss. Also the grates may have to be marked after removal to facilitate their installation in the correct position.

Figure 2.16. Cleaning Trench Drains by Flushing with Water

Mechanical drain cleaning

A mechanical drain cleaner is also called a plumber's auger, or drain snake. As shown in Figure 2.17., a mechanical drain cleaner uses an electric motor to twist a cable into the drain by mechanical force. As the cable rotates, it clears up clogging and removes debris from inside the drain. Special attachments for a mechanical drain cleaner can cut through tree roots and remove some types of foreign objects from a drain. The mechanical drain cleaning method is one of the methods recommended by California DOT for cleaning drains (CDOT 2014).

Figure 2.17. Cleaning a Trench Drain by a Mechanical Drain Cleaner

Hydrojetting

Hydrojetting or high pressure water jetting is an efficient and economical way to clean drain blockage. The typical composition of a hydro jetting unit (also called hydrojetter or jet rodder) includes a hose, nozzle, water pump and water tank. Using flexible hoses, water is propelled under varying pressures into the drain. As shown in Figure 2.18., forward and reverse jets direct powerful cleaning throughout the entire drain providing 360 degree coverage. The back-firing jets on a hydrojetter nozzle pull the jetter line into clogged drain. The high pressure water jetting penetrates and emulsifies grease, breaks up sludge and debris, pulverizes trees and shrubs, and flushes out the system, leaving the drains clean and free of obstruction.

Figure 2.18. Cleaning a Trench Drain by a hydrojetter

Hydrojetting is one of the methods recommended by California DOT for cleaning trench drains (CDOT 2014). Texas DOT also recommends hydrojetting for cleaning trench/slotted drains and have included in its “Standard Specifications for Construction and Maintenance of Highways, Streets and Bridges” specific requirements for using hydrojetting; Texas DOT require a self-contained, single-unit vehicle with a high-pressure water pump capable of pumping at least 60 gpm at 2,000 psi with at least 500 ft of hose and a water storage tank of at least 1,300 gallon capacity (TDOT, 2004).

Hydrojetting is capable of cleaning trench and slotted drains efficiently without removing the majority of the grates. Hydrojetting clean the drain more thoroughly and effectively than mechanical drain cleaning which only forms a hole in the clogged area as a temporarily solution but does not scour the perimeter of the drain. Since hydrojetting completely removes all obstructions from the drain, fewer cleaning is required. Furthermore, a hydrojetter can unclog a drain faster than when a mechanical drain is used. In addition, if blockage is caused by sludge buildup that has hardened, a mechanical drain cleaner may not be effective and a hydrojetter should be used. Hydrojetting costs more than a mechanical drain cleaner but depending on the situation can be more economical overall since cleaning intervals is typically increased. One drawback of hydrojetting is its inability to vacuum up the debris which leads to environmental concerns.

<u>Using a Sewer Cleaner</u>

A sewer cleaner, as shown in Figure 2.19., is a truck that combines high-pressure water jetting and a high-flow vacuum to break up blockages in drains, flush out debris and scour drains clean to restore and maintain normal flow. Using a sewer cleaner is one of the methods recommended by The Tahoe Regional Planning Agency for cleaning trench drains (TRPA BPM Handbook 2014). Using a sewer cleaner is expensive and sometimes it is difficult to get the cleaning process started if the drains are completely clogged.

Figure 2.19. Cleaning a Trench Drain by a Vactor-jet

Factors affecting selection of cleaning method

The literature review and the research team's previous experience with trench/slotted drains have identified several factors that need to be considered when deciding which drain cleaning method should be adopted for a particular project. The factors are listed and further discussed in the following subsections.

Degree of blockage

Some drains have accumulated an abundance of road grit because they have not been regularly maintained and as a result are completely blocked. For those drains, it may be necessary to vacuum the large amount of road grit as it rises up from the drain and a sewer cleaner may have to be used. For drains that are regularly inspected and maintained, a less expensive high pressure washer with high flow rates can potentially do the cleaning but may have negative environmental implications.

Location

The location of the trench/slotted drain will affect the type of debris accumulated in the drains. If the drain is installed near a forest, the debris collected in the drain will primarily be composed of falling leaves. Drains installed in cities will accumulate more dirt and grit. The type of debris and degree of blockage will impact the selection of the cleaning method as was discussed in the previous section. The impact on traffic will also be affected by the location of the drains.

Drains located in congested urban areas have to be cleaned in a speedy manner or at night to reduce impact on traffic. Furthermore, if the drains are located in high traffic areas (e.g. interstate), methods that require movement of crew members along the drain (i.e. manual methods) will not be adequate. In such cases, the cleaning method should enable the crew to clean the entire length of the drain from a starting point (e.g. catch basin) that is located away from the heavy traffic and bring all the debris back to the starting point.

Drain types

Some trench drains are monolithic and have no removable grates. For these drains, manual cleaning is not an option.

Drain length

Length of trench drain installations can vary from less than 20 ft to more than 20,000 lf. Shorter installations are typically used on exit ramps and across roads uphill of intersections. Long installations are used along highways constructed in flat areas. Shorter installations of trench/slotted drains can be more appropriately cleaned manually and may not justify the mobilization of large and expensive equipment. Long installations on the other hand should be cleaned with mechanical equipment to shorten the duration of the cleaning operation and to reduce the impact on traffic.

Best Practices for cleaning trench/slotted drains

The literature review has revealed several best practices including the following:

- The best way to know if trench drain systems are functioning properly is to observe and inspect them visually, especially during and immediately after rain or snowmelt events when higher flows put more stress on the drains. According to Washington State DOT, the entire drainage system should be generally inspected at least twice a year (WSDOT 2013). Inspections should cover: Grates and locking devices, Pits and rubbish baskets, adjacent paving.

- A trench maintenance plan should be adopted. A maintenance plan enables maintenance crews to periodically clean the drains cost-effectively before they become completely clogged in which case they require more expensive cleaning methods or in some cases total replacement. Although trench/slotted drain manufacturers understand the importance of a maintenance plan, they typically don't publish recommended maintenance schedules because the frequency of required maintenance will vary from one installation to another. New trench drains installations should initially be checked/cleaned twice per year and based on observation, the frequency of their cleaning can be properly determined.
- Planning the job should be done well in advance the drain cleaning operation to ensure that when equipment and workers arrive at the job site the drain can be cleaned correctly and efficiently. Planning should include visiting and inspecting the site to determine the correct type of equipment needed and the proper cleaning procedures (IRF 2010).
- Proper traffic control devices should be used to alert drivers that road maintenance is being performed and to help prevent traffic from interfering with the job (NYDOT 2009)

2.2.2. Phone Interviews of Other DOTs

The research team contacted various state DOTs and municipalities to request information about their trench/slotted cleaning procedures. Each DOT was asked about their drain cleaning process, and information was gathered about frequency of use of trench/slotted drains, equipment used, crew sizes and production rates. The sections below highlights information obtained from other DOTs.

<u>Florida</u>

- Florida has a significant amount of trench drains. It currently maintains more than 100 miles of those drains and plans to install more in the future.
- The drains get clogged and gets root bound by noxious weeds and other vegetation
- Trench drains get inspected every 2 years
- Equipment used include pressure washer, side blower and a Sewer Cleaner.

Pennsylvania

- Pennsylvania has only a limited amount of trench/slotted drain installations
- The drains are cleaned manually, or by a Sewer Cleaner.
- A subcontractor is usually hired to clean the drains and adequately dispose the waste.

Virginia

- Virginia has only a limited amount of trench/slotted drain installations
- The drains are cleaned by a sewer cleaner, pressure washer, or culvert cleaning equipment.
- A subcontractor is usually hired to clean the drains and adequately dispose the waste.

Massachusetts

- Massachusetts clean their trench/slotted drains every 2 years
- The drains are cleaned by a sewer cleaner.
- Cleaning of the drains is done in house.
- Debris removed from the drain is disposed of in approved decant facilities.
- A crew of 4 to 6 people performs the cleaning.

2.2.3 Develop Matrix of Alternatives

Information obtained as part of the previous research tasks was summarized in a matrix of alternatives for cleaning trench/slotted drains as shown in Figure 2.20. Only the cleaning methods that have potential have been listed in the matrix. Cleaning methods that were deemed inappropriate were excluded. The methods that were excluded are:

- Using compressed air: This method was excluded because of its limitations as observed during the second site visit that took place on 10/12/2016
- Using a mechanical drain (sewer snake): This method was excluded because of its limitations as observed during the second site visit that took place on 10/12/2016
- Flushing with water: This method was excluded because of its limitations as observed during the second site visit that took place on 10/12/2016
- Hydrojetting: Hydrojetting is very similar to using a sewer cleaner with the exception that the the hydrojectter doesn’t have suction capabilities that allow for the collection

of the water used in cleaning. This method was excluded after talking to the technical liaison team as they expressed concerns about the environment if the large volume of water used in Hydrojetting is not captured and is all allowed to be discharged in the stormwater drainage system.

As shown in Figure 2.20, the matrix of alternatives provides information on applicability, safety considerations, impact on the environment, and production rates if applicable. Two methods have been added to the matrix although they have not been field tested nor demonstrated during the site visits. These 2 methods are (1) Horizontal Directional Drill Technology and (2) Horizontal Auger Boring and are further explained below.

Horizontal Directional Drill (HDD) Technology

Horizontal directional drilling or HDD, is a trenchless method of installing underground pipe, conduit, or cable by using a surface-launched drilling rig as shown in Figure 2.21. Some companies have been using HDD to clean culvert and drains (Custome crews 2016, Harr Technologies 2016). These companies claim that they can effectively and efficiently clean clogged culverts and drains to like new condition at a fraction of the cost of other methods. The use of HDD technology offers many advantages including control of water injection/pressure as well as the ability to span any length of culvert simply by adding drill rods.

Method	Description	Applicability	Prodution Rate and Crew Requirement	Impact on Traffic	Environmental Impact	Safety/Health Concerns
Manual Cleaning	Manual cleaning operations consists of unscrewing bolts on and removing all grates, cleaning out dirt with shovel, re-installing all grates, screwing bolts and site cleaning.	It is applicable for all types of trench drains whose grates can be removed. Is feasible only if traffic conditions allows for crew members safely perform work along the entire length of drain. Not applicable for slotted drains and monolithic trench drains.	1 man hour to clean 10ft of trench drain (Observed). A 3 persons crew will clean 30 ft/hour	Requires closing of lane(s) adjacent to drains	Low environmental impact since no water is used.	Manual cleaning has to be performed on the knees which can cause back injuires. Other injuries may result from dropping grates on toes or back injuries resulting from improperly carrying heavy weight.
Sewer Cleaner	Using different types of nozzles as water jetting head to jet through the drain channel to have it thoroughly cleaned. Also, vaccum hose is used to collect the waste generated from cleaning.	Applicable for both trench drains and slotted drains.	180 ft / hour observed. Production rates can possibly by increased by further research in Phase 2.	Requires closing of lane(s) adjacent to drains. Large size of sewer cleaner causes a significant impact on traffic.	Large amount of water used in cleaning. Most of the water is not captured and flow into the storm water drainage network.	Safety rules and procedures for operating large equipment should be followed
Horizontal Directional Drills	Trenchless method of installing underground pipe, conduit, or cable by using a surface-launched drilling rig . Some companies have been using HDD to clean culvert and drains.	Applicable for both trench drains and slotted drains.	3-12 feet/minute (based on manufacturer information) depending on size/power of HDD rig and its ability to automatically load drilling rods.	Low impact on traffic since all cleaning will be performed from one cleaning location	Very little environmental impact, only a small amount of water may be needed.	Safety rules and procedures for operating large equipment should be followed
Horizontal Auger Boring	Continuous flights of augers are rotated and simultaneously pushed into the ground. As the length of auger is advanced into the hole, a new auger section is connected. As the bore progresses the ground is cut and the auger flights convey the material back to the starting point (cleanout location).	Applicable for both trench drains and slotted drains.	No production rate were available. Recommend field testing in Phase 2 to determine production rates	Low impact on traffic since all cleaning will be performed from one cleaning location	Very little environmental impact because it is a nearly dry operation.	Safety rules and procedures for operating large equipment should be followed

Figure 2.20. Matrix of Alternatives

Figure 2.21. Installing pipes using a HDD rig

If HDD is used successfully to clean drains there might be no need to close the lanes adjacent to the trench drains. The cleaning tools used with HDD technology are made of mild steel so that they won't damage the drains' bodies. One advantage of HDD compared to using a sewer cleaner is the significant reduction of water needed for cleaning. The volume of water that may be needed if HDD is used is a very small fraction (3-5%) of what is needed by the sewer cleaner. The HDD cleaning process can be completed in some cases completely dry without adding water. In other cases, a small volume of water can be added to loosen hard blockages. Also it has been reported that HDD can have a fast production rate (6 to 12 feet per minute) depending on the debris and the drill used (Harr Technologies 2016); a large drill such as a 10x15 Vermeer drill will be faster then a mini skid steer with a roto witch attachment.

Horizontal Auger Boring

Horizontal auger boring provides a safe method of boring a hole horizontally or cleaning a culvert. Continuous flights of augers as shown in Figure 2.22. are rotated and simultaneously pushed into the ground. As the length of auger is advanced into the hole, a new auger section is connected. As the bore progresses the ground is cut and the auger flights convey the material back to the starting point (cleanout location).

Figure 2.22. Horizontal Auger Boring

Chapter 3 – Comparison of Current Practices and Recommendations for field testing

A comparison of potential methods for cleaning trench/slotted drains are presented in this Chapter. Based on this comparison, several alternative cleaning methods were recommended for development and field testing. These included Horizontal Directional Drilling (HDD), specialized hydrojetting nozzles and robotic cleaners. This chapter is divided into three sections:

1. Interviews of equipment manufacturers
2. Preliminary cost/benefit analysis
3. Recommended solutions for infield testing and analysis

3.1 Interviews of Equipment Manufacturers

The research team assembled a list of 4 manufacturers that design and produce equipment that the previous project's tasks have shown their potential for effectively cleaning trench slotted drains. Each manufacturer was phone-interviewed regarding their various models. The interview addressed maximum length of drain that can be cleaned, speed of cleaning/drilling, equipment cost and required training. Summary of the results of the phone interviews are included in Table 3.1. More information about the 4 manufacturers is provided in the following sections.

Harr Technologies

Harr Technologies has developed a method for cleaning and restoring clogged and damaged culverts using HDD technology. Harr has developed a set of tools and attachments for a horizontal directional drill (HDD). The tools as shown in Figure 3.1. come in several sizes to accommodate for different diameter culvers and include:

- A box pull bucket. The operator drills a pilot hole through a clogged culvert, connects a pull bucket to the drill pipe on the other end, and pulls back unwanted debris.
- A round pull bucket designed for round culverts. It works in a similar manner as the box pull bucket. An operator drills a pilot hole through a clogged culvert, connects a pull bucket to the drill pipe on the other end, and pulls back unwanted debris.

- A push bucket designed to push material out the far end of the culvert. Unlike pull bucket, a push bucket is connected to the drill stem at the beginning and it is pushed down a culvert, consequently forcing debris and material out of a culvert. It can also function as a scoop removing material bucket full at a time.
- A barrel Reamer: Barrel reamer is designed to loosen and remove heavy material located in the culvert. By utilizing rotational force and push force of horizontal directional drill, a barrel reamer is pushed through a culvert while rotating. This allows to loosen compressed debris and forces it out of a culvert.
- A brush designed to fine clean a culvert.
- A forward articulating reaming tool which uses an internal coil to draw debris into a holding cylinder so it can be removed from the drainage structure. The tool is attached and rotated by an HDD drill. As the drill moves forward with the tool rotating, debris is loaded inside the cylinder. Once the cylinder is loaded, the HDD drill backs up until the tool exits the structure; then reverses rotation to remove the debris.

Figure 3.1. Harr Technologies tools (Source: http://www.harrtech.com/)

Table 3.1. Summary of results of manufacturers' phone interviews

	Harr Technologies	Porta Mole	little beaver	ENZ
Type of Equipment	Culvert tools used for Horizontal Boring	Horizontal Boring	Horizontal Boring	Nozzle
Is it a completed system for boring	No-requires HDD drill (i.e. vermeer or ditch witch)	Yes	Yes	No-nozzles used with Sewer Cleaner
Has product been previously used for trench drain or culvert cleaning?	Yes	Yes	No	Yes
Recommended products for applications	Different tools including barrel reamer, push bucket, pull bucket & Forward arituculating reamer tool	TM9 , TM11	MDL-5H	Flounder
Type of drain product is suitable for	All types	Round – anywhere from ¾ " to 24"	Not for drains	All types
How long (in linear feet) can the equipment reach	Depends on type of HDD drill used in the cleaning	good to 150 ft	N/A	Depends on hose length on Sewer Cleaner
What is the typical speed of drilling	6-12 feet per minute depending on HDD drill used	3-5 feet per minute with light resistance or 1 - 2 feet per minute with hard resistance	Varies	
How much does the product cost	Culvert cleaning tools cost $300-1000 each. Cost of HDD extra	$7500.00 to $20,000.00	$2,700.00 - $5,000.00	Nozzles cost $500-1000 each. Cost of Sewer cleaner extra
How much training is needed for crew members	Simple tool / training can be provided over the phone	4-6 hours recommended	Very little	Very little

Little Beaver

The Little Beaver is a small boring unit that is used to make small straight horizontal bores. As shown in Figure 3.2, the Little Beaver offers two types of boring attachments: the dry-type horizontal boring attachment uses a 5 foot long by 3 inch diameter auger to drill under sidewalks for conduit water pipe or irrigation installation.

The little beaver wet type horizontal boring attachment uses standard schedule 80 three-quarter inch water pipe, a special swivel adapter and a drill bit to bore horizontal holes up to 50 feet in length. The special water drill bit is screwed on the leading end of the water pipe. As many sections of water pipes to complete the hole may be assembled. As the drill bit loosen soil the stream of water coming out of the bit carries spoil from the hole keeping the hole flushed and open.

The little beaver has not been previously used to clean culvert/drains and has a limited reach (50 feet). It has been excluded from further analysis.

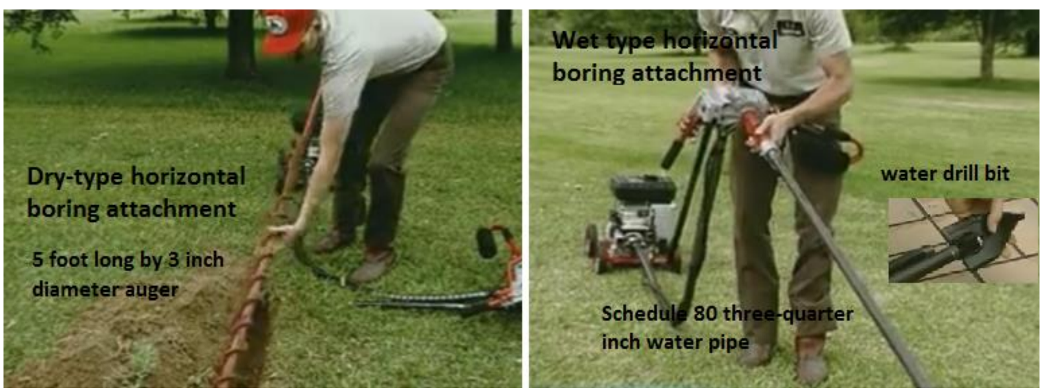


Figure 3.2. Little Beaver boring attachments (Source: http://www.littlebeaver.com/)

ENZ

ENZ offers a large range of high quality pipe cleaning tools that are used in conjunction with Hydrojetting equipment. The research team has already tested two different ENZ nozzles during the third site visit as discussed in section 1.2. The ENZ representative has indicated that the company can customize their existing nozzles to meet their customers' needs. For example, he noted during the third site visit that the Flounder nozzle can be modified by adding a high pressure forward jet that is capable of tearing through tough blockage while keeping the water splashing to a minimum.

3.2. Recommend solutions for infield testing and analysis

In Phase 2 of the project, the research team recommends using a horizontal auger boring (HAB) machine to clean trench and slotted drains. It should be noted that there is a large number of HAB machines in the market with varying power and initial costs ($30,000 to $150,000) and more research should be performed in Phase 2 to determine which HAB machine is more appropriate for cleaning drains.

The research team also recommends improving the process of cleaning trench/slotted drains with a sewer truck by identifying a suitable nozzle that eliminates the need for a crew person having to pull a wooden board. It is the research team's judgment that pulling a board to control water splashing is not very safe particularly in high traffic areas. It is recommended that in phase 2, the research team evaluates nozzles whose spray pattern of the water jets prevent any water from splashing up directly which would eliminate the need for using a wooden board to cover the top holes of the grates and the need to clean up around work areas.

The research team also conducted a preliminary evaluation of using cleaning robots to clean trench drains. Cleaning robots such as the one shown in Figure 3.7 are successfully being used to clean and suck settled material in large sewage pipelines (larger than 30" in diameter), manifolds and tunnels. They are remotely controlled from outside, and are equipped with a drilling head and a suction tube that is connected to either a suction excavator or a vacuum truck (Sewer Cleaner). Some models are equipped with water blast nozzles and various auger attachments that break up hard soil for easier suction/removal.

Since no cleaning robot that is small enough to fit in the trench drain exists in the market, a preliminary cost analysis for this technology could not be performed. However, the research team recommended developing a prototype robot for cleaning drains.

Figure 3.3. Prototype robot to clean drains (Source: http://www. suction-excavator.com)

Chapter 4 – Development of Prototype Robot and Procurement of Equipment

This chapter discusses the development of the drain cleaning robot and procurement of new equipment. It is divided into two sections:

1. Development of drain cleaning robot
2. Procurement of HAB equipment

4.1. Development of drain cleaning robot

the University of Cincinnati research team has developed a remote controlled four-wheel drive robot designed to fit into a trench drain and clean it from inside without interfering with the surrounding traffic. The robot as shown in Figure 4.1. moves inside the drain on rubber wheels and has a cutting assembly that loosens the debris inside the drain for easier removal and is equipped with a suction tube that can be connected to a suction excavator (vacuum).

The robot is designed to suck settled material inside the drains and is intended to carry the material directly into the container of the suction excavator. The robot was custom designed by the University of Cincinnati research team with the intent of eliminating the need for ODOT personnel to expose themselves to dangerous conditions by manually removing the grates of the drains in the middle of the roads as shown in Figure 2.5 and eliminating water consumption and splashing caused by using a sewer truck to clean the drain as shown in Figure 2.9. Features of the UC robot include a customized modular design that can be fitted with different size cutting assemblies. The cutting assembly breaks up hard debris and removes vegetation inside the drain to facilitate suction by the vacuum. The remote control which controls both the cutting assembly and drive system allows for simultaneous cleaning and vacuuming.

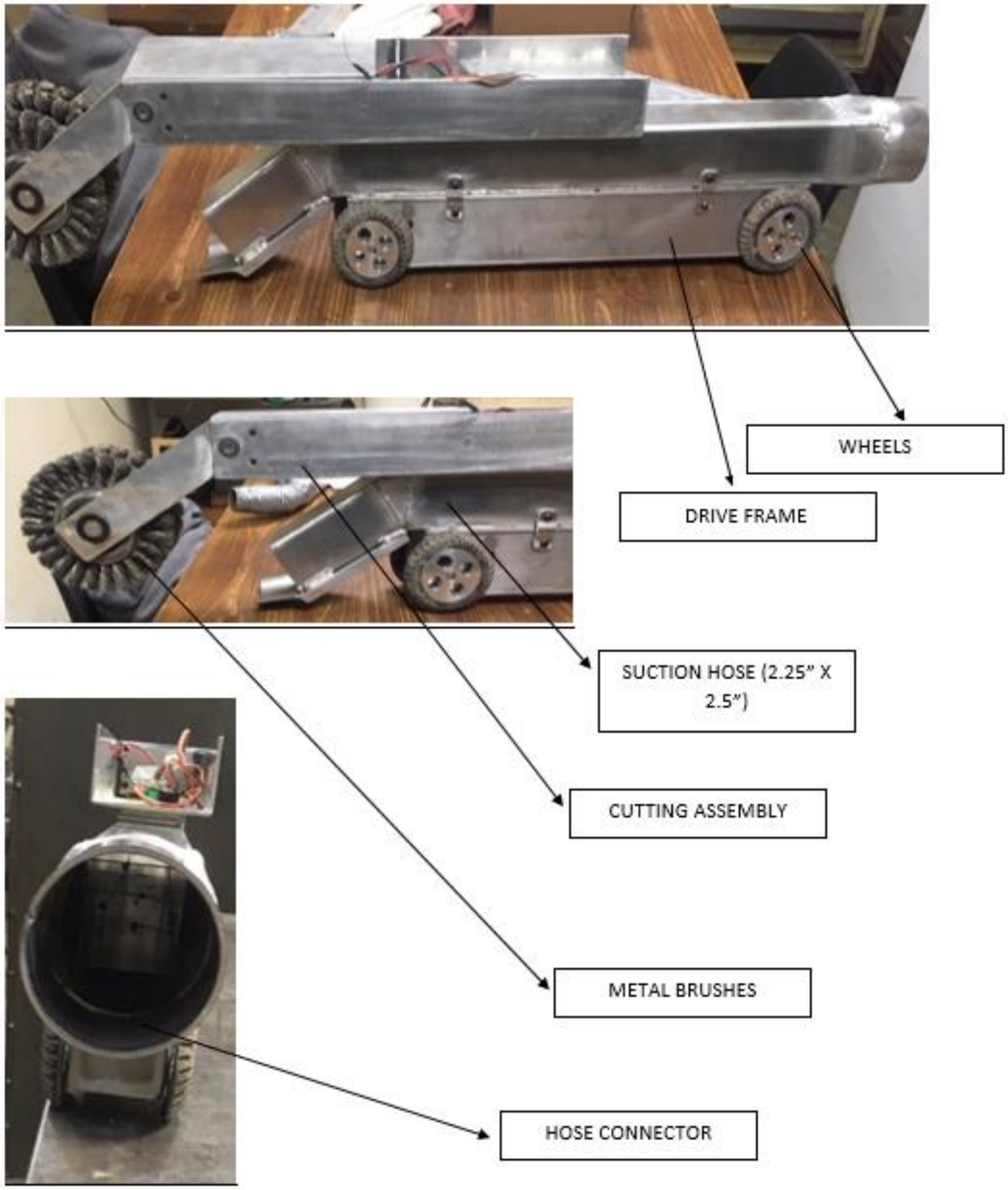


Figure 4.1. Remote controlled cleaning robot developed by the UC research team

Design Objectives

A main objective of the design was for the robot to be operated from a single cleanout location in order to reduce impact on traffic and increase safety of ODOT technicians involved in the drain cleaning operation. Other design objectives included:

1. Robot is capable of breaking up hard debris and removing vegetation inside the drain

2. Robot is capable of transporting the loosened debris from the drain to an attached suction excavator (vacuum) located at the cleanout location.
3. Robot is capable of moving freely forward and backward inside the drain while carrying all of its modules and pulling behind a suction hose that connects it to the suction excavator.

Design Challenge

Although cleaning robots have been successfully used to clean and suck settled material in sewage pipelines for a long time, those robots have only been used on larger pipelines (larger than 30" in diameter). The small size of the trench drain in which the robot needed to operate presented the biggest design challenge. The design team had to ensure that all the required components (motors, batteries, remote control receivers, shafts, bearings, gears, sprockets, etc.) could be assembled inside a robot frame that can move easily in the small drain section shown in Figure 4.2. The small drain size presented a particular challenge when selecting the motors for the robot's drive system. The design called for powerful motors to be able to meet the design objectives discussed above, yet the size of powerful motors would not fit inside the drain. A tradeoff between motor's power and size had to be done and two prototypes were developed. The second and final prototype is described in more details in Appendix A. The first prototype is described in Appendix B in order to highlight the lessons learned.

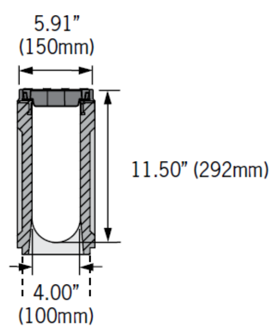


Figure 4.2. Dimensions of Trench Drain

4.2. Procurement of HAB equipment

In phase 1 of the project as described in Chapters 2 and 3, the research team evaluated the current ODOT process for cleaning trench drains, and developed a matrix of alternatives that compares and contrasts available solutions and recommended testing horizontal directional drilling (HAB) technology for potential use in Ohio for cleaning trench drains.

The process of cleaning trench drain with a HAB drill is a new application for HAB technology. The research team wanted to test this process because other methods currently used were not effective in cleaning trench drains in many situations as discussed in Chapter 2. As stated in Chapter 2, clogged drains were a problem nationwide. This problem was attributed to inadequate or often no maintenance. One of the main reasons DOTs have not maintained their trench drains is due to the lack of efficient and effective drain cleaning methods. Manual removal of the grates and cleaning, and utilizing sewer trucks are methods that have been used to clean drains in the past. These methods however are not effective in many situations particularly when the debris blockage in the drains is significant and when the drains are located in heavily travelled areas. In such situations, when all cleaning methods failed, DOTs had to tear down the drains and completely replace them with significant cost.

One objective of the research was to develop a method of employing horizontal directional drilling (HAB) equipment for accessing and cleaning drains. The use of HAB technology for cleaning drains was envisioned to offer many advantages including elimination of water usage and the ability to span any length of drains simply by adding drill rods or augers.

A main objective of the research team when designing the process of using HAB technology for cleaning trench drains was the ability to complete the cleaning process from a single cleanout location to which all the debris is brought back. This was important in order to reduce impact on traffic and increase safety of ODOT technicians involved in the drain cleaning operation. To achieve this objective, the research team considered two methods in which the HAB machine can be used to clean the drains.

1. In the first method, continuous flights of augers are rotated and simultaneously pushed by the HAB machine into the drain. As the length of auger is advanced into the drain, a new auger section is connected. As the augers continue to advance, the debris in the drain is loosened and the auger flights convey the debris back to the cleanout location (starting point). More augers are added until they span the entire length of the drain.

2. In the second method, a cutting carbide head (or similar tools as those developed by Harr technologies as discussed in Chapter 3) is attached to drill rods which are rotated and pushed by the HAB machine into the drains. This loosens the hardened debris in the drain. When the drill rods reach the end of the drain, the grate of the last section of the drain is manually removed and the carbide head is replaced with a pull bucket that is attached to the drill rods. As the drill rods are pulled back to the entry/starting point (cleanout location) by the HAB machine, the loosened debris is also pulled back by the pull bucket to the starting point.

After consultation with the technical liaison team, it was decided that the first method be used and that augers instead of drill rods be purchased. The following were the reasons behind this decision.

1. The first method uses a single step process where the augers simultaneously loosen the debris and bring it back to the cleanout position. The second method utilizes a two-step process where the cutting head first loosens the debris and then the pull bucket brings the debris back to the cleanout position.
2. Although the use of drilling rods as described in the second method has been successful in cleaning out culverts, there was a concern that if this method is used for cleaning trench drains, the pull bucket may push the debris outside the openings of the grates instead of pulling it all the way back to the starting point. This is not an issue when cleaning culverts since the culverts don’t have any openings through which the debris can escape.

3. When trench drains are installed in highway gore areas such as shown in Figure 4.12, the second method requires that the grates at the end of the drains be manually removed to replace the cutting head with a pull bucket. This would significantly impact traffic and expose ODOT technicians to safety hazards because the end of the drain is typically in an area with heavy traffic.

Figure 4.3. Use of trench drains in highway gore areas

Selection of HAB machine

There is a large number of HAB machines in the market with varying power and initial costs ($30,000 to $150,000). The research team considered the following factors in the selection process:

1. Initial cost of equipment
2. Is the equipment light-weight and portable?
3. Is the equipment easy to maintain?
4. Is the price of the equipment justifiable even if not used often?

Based on the above factors, a Bobcat MT55 Mini Track Loader with a boring unit attachment as shown in Figure 4.4. was selected. The Bobcat MT55 is small enough to allow the cleaning of the drain without a significant disturbance to traffic. The small size of the MT55 allows it to get into tighter spaces, without destroying landscape. It can easily fit in the back of a pickup truck or 6x8 trailer and takes one to two people to operate. Another advantage of the MT55 is that it can be used by ODOT crews for other maintenance activities such as culvert cleaning and repair. The MT55 will also fit into ODOT's equipment maintenance schedule better than any other make and model due to ODOT already owning the Bobcat brand and being familiar with PM schedules. The specifications of the MT55 is included in Appendix C and the specifications of the boring unit attachment is included in Appendix D.

Figure 4.4. MT55 Mini Track Loader with a boring unit attachment

Chapter 5 –Field Tests

Different methods for cleaning trench drains were tested and are presented in this Chapter. These included Horizontal Auger Boring (HAB), special hydrojetting nozzles, drain cleaning robot and vacuum cleaners (suction excavators). The objective of the field tests was to determine the suitability and effectiveness of the various methods under different project conditions. Table 5.1 provides more information about the date and location of the field tests.

Table 5.1. Summary of trench drains cleaning field tests

Date	Location	Cleaning Methods Tested
09/08/2017	Columbus	HAB
3/2/2018	Columbus	HAB, Robot, Nozzle
3/23/2018	Columbus	Nozzles
4/25/2018	Youngstown	Robot, Vacuum
5/2/2018	Columbus	Vacuum
7/26/2018	Columbus	HAB and Vacuum

Field Test on 09/08/2017

The purpose of the field test conducted on 09/08/2017 was to evaluate the potential use of Horizontal Auger Boring (HAB) to clean trench drains. The research team wanted to:

1. Develop procedures for cleaning the trench drain with a HAB machine.
2. Evaluate the effectiveness of the HAB cleaning process.

Develop procedures for use of HAB technology in cleaning trench drains

The following procedure as illustrated in Figures 5.1., 5.2., and 5.3. has been developed to clean trench drains with HAB:

1. Locate a suitable cleanout location and move HAB machine next to it.
2. Remove grates from some drain's sections and manually clean them.
3. Insert first auger section into drain.
4. Advance auger section forward with boring machine.

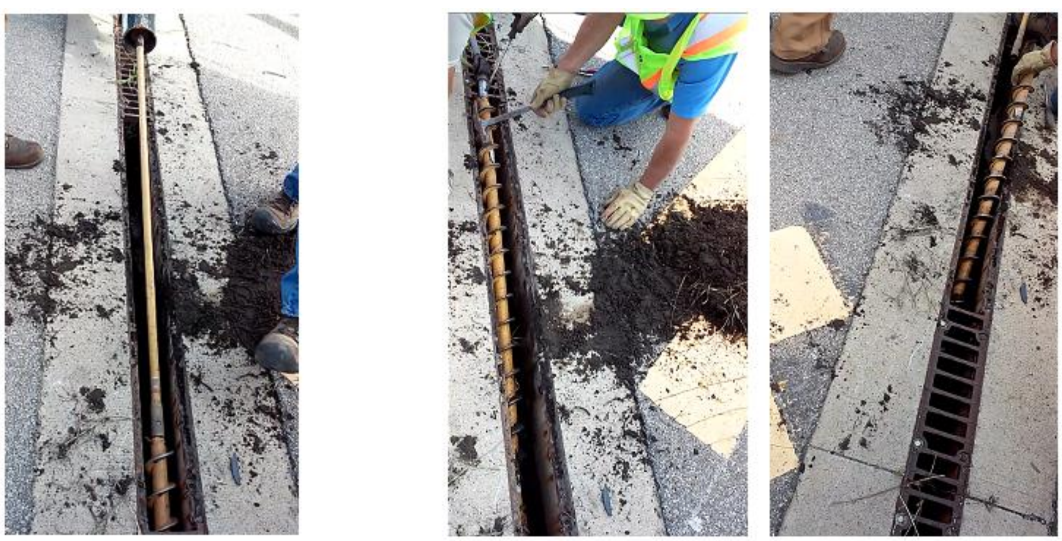
5. Disconnect auger section from boring machine and back up machine to create room to slide another auger section to be connected.
6. Connect another auger section to previous section and to boring machine.
7. Repeat steps 4 to 7 to keep adding more auger sections in to span entire length of drain to be cleaned.
8. Auger flights convey the material back to the cleanout location.
9. Remove collected debris from cleanout position, load it away from site, and re-install the grates

1-Locate a suitable cleanout position

2-Remove grates from some drain's sections

3-Insert first auger section into drain

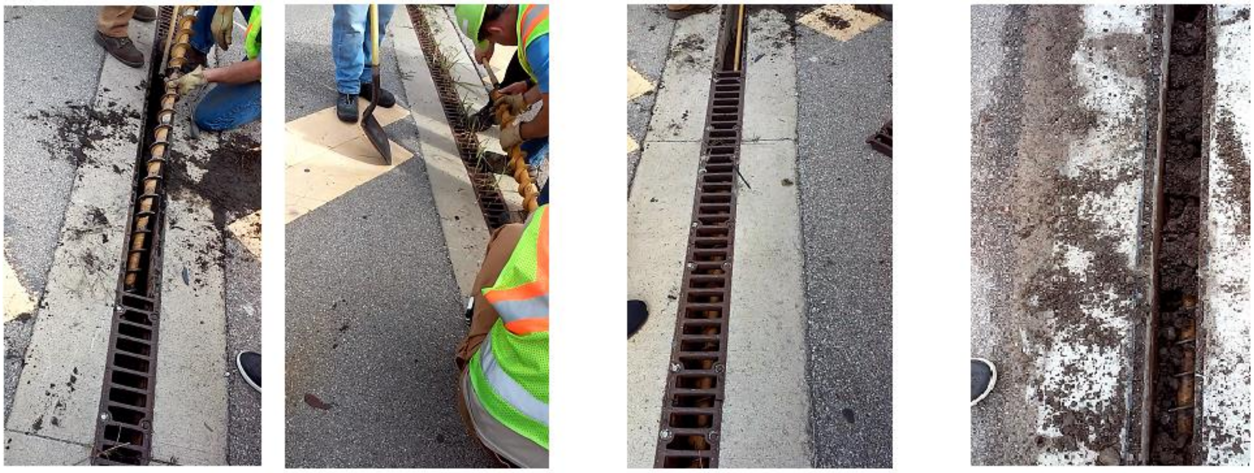
Figure 5.1. Procedures for cleaning trench drains with HAB (1/3)



4-Push auger section forward with drill

5- Disconnect auger section from drill

Figure 5.2. Procedures for cleaning trench drains with HAB (2/3)



6-Connect another auger section to previous section and to drill

7-Repeat steps 4 to 7 until you connect all auger sections to cover entire length of drain to be cleaned.

8-Auger flights convey the material back to the cleanout location

Figure 5.3. Procedures for cleaning trench drains with HAB (3/3)

Evaluate effectiveness of proposed technology

The process of cleaning trench drain with a HAB machine as described above is a new application for HAB machines. Continuous flights of augers are rotated and simultaneously pushed by the HAB machine into the drain. As the length of auger is advanced into the drain, a new auger section is connected. As the augers continue to advance the debris in the drain is loosened and the auger flights convey the material back to the starting point (cleanout location).

There exists a variety of different size augers and accessories that can be used with the HAB machine. The augers used in this test as shown in Figure 5.4. were 2.5 in. diameter.

Figure 5.4. 2.5 in. auger sections used in the field test

The test showed that the proposed process does work as is illustrated in the “before” and “after” cleaning pictures shown in Figure 5.5. Although the augers didn’t remove all the debris from the drain, they were able to remove the roots, vegetation and mud in the drains.

Before Cleaning with HDD　　　　After Cleaning with HDD

Figure 5.5. Results of cleaning drain using proposed HAB process

However, it was observed during the test that because the debris in the drain was wet and sticky, the augers were pushing some of the debris up the walls of the drains as shown in Figure 5.5. Since the size of augers was 2.5 inches and the width of the drain was 4 inches, there was too big of gap that prevented the augers from getting a good hold of some of the debris and carrying it back. As a result, the augers pushed some of the debris to the side instead of pulling it back. In addition, it was observed that as the HAB machine advanced the augers, the front digger was riding on the top of the debris instead of digging into it as shown in Figure 5.6.

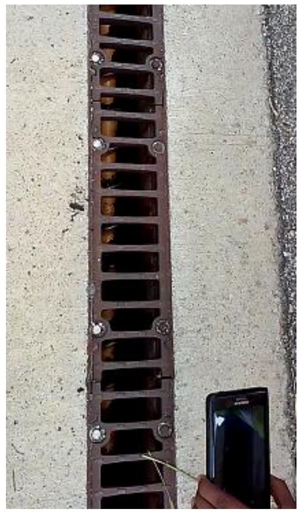


Figure 5.6. Front digger riding on top of the debris

Based on the results of this test, it was decided that another test be performed using different size augers that are closer to the size of the drain (e.g. 4”) and that different methods of attaching the augers to the HAB machine be explored to move the augers lower and closer to the bottom of the drains in order to reduce the likelihood of them riding on top of the debris.

Field Test on 3/2/2018

This test was conducted on 3/2/2018 in the parking lot of ODOT District 6 office. The purpose of the test was to evaluate the potential use of HAB equipment, UC developed robot, and hydro jetting nozzle to clean trench drains. Description and summary of cleaning methods observed are provided in the sections below.

HAB

As mentioned above, a variety of different size augers and accessories are available for use with the HAB machine. In the previous field test, only one size of augers was used and because it was much smaller than the size of the drain, the augers were not carrying all the debris back to the cleanout position. Furthermore, it was observed that as the HAB drill advanced the augers, the front digger was riding on the top of the debris instead of digging into it.

Therefore, this field test was designed to evaluate the performance of augers whose size were closer to the width of the drain (4 in.). Two different sizes were evaluated (4 in. and 3 ¼ in. augers). Furthermore, in order to reduce the likelihood of the augers riding on top of the debris, different methods of attaching the augers to the HAB equipment using different numbers of universal joints were tested as shown in Figure 5.7. Also different test runs were conducted with and without the front digger shown in Figure 5.8. Table 5.2. summarizes the various tests conducted and Figure 5.9. shows equipment for testing setup #3.

Figure 5.7. Different methods of attaching augers to HAB equipment

Figure 5.8. Front Digger

Table 5.2. Summary of set-ups for HAB tests

Set-up #	Auger Size	# of Universal Joints used	Front Digger	Observations
#1	4	2	Yes	Auger was too big for the drain
#2	3 1/4	2	Yes	Augers were wobbling too much
#3	3 1/4	0	Yes	Augers advanced but front digger rode on top occasionally
#4	3 1/4	1	No	Seemed to work best

Figure 5.9. Testing set-up #3: no universal joint, 3 ¼ in. augers and front digger

Following are more details about each testing set-up and resulting performance.

Set up #1:

In this set-up 4 in. diameter augers were used. The connection of the HAB machine to the augers was made using two universal joints in an attempt to achieve a more favorable augers' entry angle into the drain. Because the width of the drain was 4 in., the 4 in. diameter augers used in set-up #1 were touching the walls of the drain and couldn`t reach the bottom of the drain. When the augers were rotated with the HAB machine, they were tearing up the walls of the drain and the test was stopped. It was concluded that the size of augers used should be slightly smaller than the drains.

Set up #2:

In this set-up, 3 ¼ in. diameter augers were used as well as two universal joints and a front digger. The use of two universal joints caused the augers' connection to the HAB machine to wobble too much creating a safety hazard.

Set up #3

In this set-up, as shown in Figure 5.9., 3 ¼ in. diameter augers were used as well as a front digger. No universal joint was used. The wobbling stopped but the tilted auger's entry angle into the drain and the use of the relatively light front digger caused the augers to ride on the debris occasionally instead of digging into it and carrying it back to the cleanout location.

Set up #4

In this set-up, 3 ¼ in. diameter augers were used as well as 1 universal joint. The front digger was removed in this setup. The use of one universal joint enabled the augers to be relatively horizontal at the drain's entry and close to the drain's bottoms as shown in Figure 5.7. This and the fact that the lighter front digger was not attached to the front of the augers reduced the frequency of the augers riding on top. This set-up seemed to be the most effective one as shown in the before and after conditions illustrated in Figure 5.10. In terms of speed, it cleaned 6 sections of drains (18 ft) within 3 minutes and the estimated production rate is 6 ft/min. It should be noted that this time didn`t include the time spent to connect the augers. For connecting augers, it took 30 seconds to 2 minutes for each connection.

Figure 5.10. Results of cleaning trench drain with HAB and augers

The results of this test showed that with the correct set-up, the use of HAB equipment with augers has the potential to provide a safe, effective and environmentally friendly process for cleaning trench drains particularly if the drains have a high degree of blockage. In such cases of high blockage, the traditional method of cleaning drains with a sewer truck and a hydrojetting nozzle consumes a large volume of water and causes a lot of water/debris splash that create unsafe condition for both ODOT crews and road users. In this test, however only a limited number of augers were available and tested. As such it was decided that more auger sections should be procured and that another test be performed using more augers connected together to evaluate the impact of the length of the drain on the effectiveness of this method and its production rate. It should also be noted that as shown in Figure 5.11. the debris carried by the augers and piled up near the cleanout position has to be collected and loaded away from site. If the debris is left on the pavement, it will quickly move back and settle in the drain with any rain. Removing the debris can be accomplished manually in cases were the amount of debris is not significant as shown in Figure 5.11. However, if long drains are cleaned and large amounts of debris are piled near the cleanout position, other methods of collecting and loading the debris (e.g. vacuum systems) should be explored. As such, the research team decided to investigate the possible use of different vacuum systems to remove and load large amount of collected debris.

Figure 5.11. Debris collected near cleanout position

Robot

As discussed in section 4, the University of Cincinnati research team has developed a remote controlled robot which fits into the drain and cleans it without needing to interfere with the surrounding traffic. The robot moves inside the drain on rubber wheels and has a cutting assembly that loosens the debris inside the drain for easier removal and is equipped with a suction tube connected to a suction excavator (vacuum).

To test the robot, it was connected to a vacuum cleaner as shown in Figure 5.12. When the robot was placed inside the trench drain as shown in Figure 5.13., it fit well in the drain and moved freely using the remote control in the forward and backward directions. The cutting assembly also worked well using the remote control and loosened the debris. However, the vacuum system that the robot was connected to was not strong enough to suck the debris loosened by the cutting assembly.

Figure 5.12. UC robot connected to a vacuum system

Figure 5.13. UC robot inside the trench drain

Based on the results of this test, it was decided that other more powerful vacuum systems be used with the robot.

Nozzle

As discussed in Chapters 2 and 3, a sewer truck is one of the traditional methods used by ODOT to clean trench drains. However, this method has some issues as it causes significant amount of water splashing and leaves a significant amount of debris on the pavement next to the drain as shown in Figure 5.14. The splashed water and accumulated debris creates a safety hazards to ODOT crews and the travelling public.

Figure 5.14. Water splash caused when a sewer truck is used for cleaning the drain

The objective of this test was to evaluate the use of a drainage channel nozzle that was specially created by ENZ to clean channel drains. The drainage channel nozzle as shown in Figures 5.15 and 5.16. is suited for cleaning channels with gutters, and flushing out of debris, gravel, leaves, and straw. This nozzle had a concentrated forward jet and 8 backward (thrust) jets. The spray pattern of the backward jets prevents any water from splashing up directly, reducing safety concerns and virtually eliminating need for clean-up work around the drains.

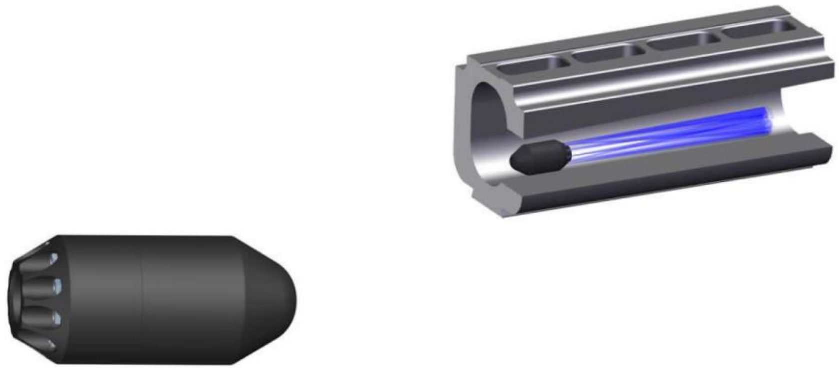


Figure 5.15. Drainage channel nozzle

Figure 5.16. Drainage channel nozzle inside trench drain

When the Drainage Channel nozzle was used, the splashing was eliminated. The Drainage Channel nozzle however was slow in advancing forward in the drain because the angle of its backward jets was zero degree (horizontal) and the size of the backward jets was small. This has significantly reduced the cleaning speed particularly in areas of the drain that experienced a high degree of blockage. The research team decided to invite a representative of the nozzle manufacturer to adjust the size of the backward jets of the Drainage Channel nozzle and re-test it.

Field Test on 3/23/2018

The purpose of the field test conducted on 3/23/2018 was to evaluate improvement in the performance of the Drainage Channel nozzle after adjusting the size of the backward jets. The ENZ representative attended the field test and has modified the nozzle with back jets that are 2mm larger than the original to increase the water flow rate and propelling force. Figure 5.17. shows the modified nozzle. To have a better evaluation of the nozzle`s cutting ability inside the drain, the following two conditions were tested:

1. Drain was half full with loose debris.
2. Drain was completely full with compacted debris.

Figure 5.17. Modified Drainage Channel Nozzle

Enlarging the size of the back jets significantly increased the speed of the nozzle and enabled it to easily cut through both types of debris. However, when the drain was completely full with compacted debris the water and debris splashing increased significantly. The reasons behind this were:

1. The surface of the debris was so close to the openings of the grates and even though the angle of the backward jets of the nozzle was zero degree (horizontal), the debris and the water still escaped through the opening.
2. An aggressive cleaning process was attempted where the entire length of the drain was cleaned right away.

One way to reduce the splashing is to use a stepped cleaning process where the nozzle is propelled forward only 20 ft at a time and brought backward to bring back the debris. The results of this test showed that the process of cleaning the drains with a sewer truck has its challenges. It works well when the drain is 30% or less full and the right hydrojetting nozzle is used. However, in cases where the drain is completely blocked with debris, the water and debris splashing resulting from the cleaning process creates a safety hazard to ODOT crews and the travelling public. Thus, cleaning trench drains with sewer trucks can only be a viable safe option if a maintenance plan for trench drains is adopted by ODOT. A maintenance plan enables maintenance crews to periodically clean the drains effectively with the sewer truck before they become completely clogged in which case they require more expensive cleaning methods or in some cases total replacement with significant cost to ODOT.

Field Test on 4/25/2018

It was observed in prior field tests that the performance of the UC trench drain cleaning robot is significantly affected by the suction power of the vacuum system to which it is connected. Thus the field test on 4/25/2018 was conducted in Youngstown, Ohio at the site of a distributor of industrial vacuum systems to evaluate improvement in performance of the cleaning robot if a powerful vacuum is used. The vacuum used in this test was the Hurricane 500 system manufactured by the Industrial Vacuum company as shown in Figure 5.18. The Hurricane 500 is typically used by roofing contractors to vacuum loose roof ballast through up to 1000 ft. of vacuum hose. Its vacuum air flow is 2350 CFM and pulling capacity can be up to 27 inches of mercury. The specifications of the Hurricane 500 system are included in Appendix E.

Figure 5.18. Hurricane 500 vacuuming system

To have a better evaluation of the Hurricane 500 system, the following test configurations were used:

1. Vacuum and robot without cutter assembly: In this test, the vacuum hose was connected to the robot while the cutting assembly was not attached to the robot.
2. Vacuum and robot with cutter assembly: In this test, the fully assembled robot was connected to the Hurricane 500 suction excavator and tested.
3. Vacuum alone: In this test, the vacuum hose connected to the Hurricane 500 was used alone to clean the drain.

Figures 5.19., 5.20. and 5.21. show the three test configurations as described above. It should be noted that the vacuum hose through which the debris was carried to the collection tank of the Hurricane 500 was 100 ft. in length and 3 in. in diameter. It should also be noted that the debris used in the tests was loose top soil.

Figure 5.19. Test of UC cleaning robot without cutter assembly connected to Hurricane 500

Figure 5.20. Test of UC cleaning robot with cutter assembly connected to Hurricane 500

Figure 5.21. Test of Hurricane 500 suction excavator alone

The tests showed that the Hurricane 500 vacuum unit when operated at about 2,200 RPM, provided enough suction force to easily pick up and transport the loose debris inside the trench drain through a 100 ft. long hose to its collection tank as is illustrated in the “before” and “after” cleaning pictures shown in Figure 5.22.

Before Cleaning with Hurricane 500

After Cleaning with Hurricane 500

Figure 5.22. Comparison of drain channel before and after cleaning with Hurricane 500 suction excavator

Although the Hurricane 500 worked well, the research team was concerned because of its size. As shown in Appendix E, the Hurricane 500 is a large machine that weighs 9,500 lbs. Because of this concern, the research team decided to test an additional suction excavator which is smaller in size. The small size of the suction excavator is important to ODOT because they prefer to do the cleaning of the drain without a significant disturbance to traffic. ODOT prefers equipment that can easily fit in the back of a pickup truck or 6x8 trailer and that does not require too many people to operate.

Field Test on 5/2/2018

Although it was observed in prior field tests that the Hurricane 500 suction excavator had enough suction power to clean trench drains when the debris is in loose state, the research team wanted to test a smaller suction excavator to evaluate its effectiveness in cleaning trench drains. This field test was conducted on 5/2/2018 in Columbus, Ohio. The vacuum used in this test is the trailer mounted FX 20 system manufactured by Ditch Witch as shown in Figure 5.23. Its vacuum air flow is 540 CFM and pulling capacity can be up to 15 inches of mercury. The specifications of the FX 20 system are included in Appendix F.

Figure 5.23. Ditch Witch FX30 Trailer Mounted Vacuum Unit

When the Ditch Witch vacuum unit was tried on loose debris in the drain, it had enough suction force to remove the debris from the drain when the suction hose length was 50 ft. However, when the length of the hose was extended to 100 ft., there was significant reduction in suction power. Furthermore, the Ditch Witch unit was not able to easily remove compacted debris. It was thus concluded that the suction excavator would only work if the debris is loose. In case of hardened debris, the suction excavator should be used in conjunction with other methods that break up the hardened debris.

Field Test on 7/26/2018

This test was conducted on 7/26/2018 in the parking lot of ODOT District 6 office. Previous field tests have illustrated the potential of using HAB equipment with augers to provide a safe, effective and environmentally friendly process for cleaning trench drains. Previous tests also indicated the need for collecting the debris carried by the augers and piled up near the cleanout position and loading it away off site. If the debris is left on the pavement, it will quickly move back and settle in the drain with any rain. The objectives of the test were to:

1. Evaluate the potential use of HAB equipment in conjunction with a suction excavator to simultaneously clean the drains and collect the spoil.
2. Continue improving the proposed process of using HAB technology for cleaning the drains by preventing the augers from riding on the top of the debris instead of digging into it.
3. Evaluate the use of pins as a quicker way to connect the augers instead of snap-on connections.
4. Evaluate the performance of poly augers.

Figure 5.24 shows the equipment used for this field test which consisted of:

- Bobcat MT55 Mini Track Loader with a boring unit attachment
- Ditch Witch FX25 Trailer Mounted suction excavator (vacuum) Unit

Bobcat MT55 Mini Track Loader with a boring unit attachment

Ditch Witch FX25 Trailer Mounted Vacuum Unit

Figure 5.24. Equipment used for field test on 7/26/2018

In this test, it was found that using a drill rod guide such as that shown in Figure 5.25. is very effective in ensuring that the augers continue to dig the debris and don't ride on the top as they advance in the drains. The purpose of the drill rod guide is to stabilize the lead drill rod just behind the augers. By manually applying pressure on the drill rod guide, the HAB unit operator's assistant can change the direction of the drill rods and augers to force them into the bottom of the trench drains. The drill rod guide allows the operator's assistant to safely perform this task while standing outside and to the side of the drain. **It should be noted that the use of hands, feet or tools other than the drill rod guide to align the rods and augers can result in serious bodily injury.**

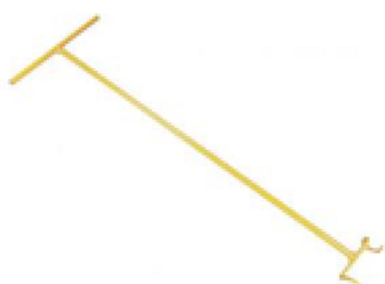


Figure 5.25. Use of drill rod guide

Also in this test, a new arrangement for connecting the augers to the HAB unit was utilized as shown in Figure 5.26. Two drill rods were connected to the boring unit and the augers were then connected to the drill rods. The suction tube of the Ditch Witch FX25 was placed just above the augers in the cleanout location with the intent of vacuuming the debris as it is being pulled back by the augers. A drill rod guide was used to safely push the augers to the bottom of the drain by manually applying pressure as discussed above and as shown in Figure 5.27.

Figure 5.26. Use of HAB machine in conjunction with suction excavator

Figure 5.27. Manually applying pressure on drill rods to push augers to the bottom of the drain

With the set-up used in this test as described above, the augers did an outstanding job cleaning the drain which was full of debris as illustrated in the before and after conditions shown in Figure 5.28. In terms of speed, it cleaned 10 sections of drains (30 ft) within 10 minutes and the estimated production rate is 3 ft/min. It should be noted that this time didn`t include the time spent to connect the augers. For connecting augers, it took 30 seconds to 2 minutes for each connection. It is expected that the time to connect/disconnect augers will reduce as ODOT technicians become more familiar with the process.

Figure 5.28. Results of cleaning trench drain with HB unit, augers and vacuum

The pressure that was applied on the drill rods using the drill rod guide was effective in making the augers scrape the bottom of the drain. Before using the drill rod guide as described in previous field tests, the augers had a tendency to ride on the top of the debris and didn't bring all the debris back. Furthermore, the operator of the HAB machine indicated that as he was advancing the augers into the drain, he was slightly moving the rods/augers in the horizontal direction (from left to right and from right to left) to ensure that the augers covered the complete width of the drain and cleaned it in its entirety. Before doing that as described in previous field tests, the 3.25" augers which are smaller than the 4" drain would only clean one side of the drain and push some of the debris to the other side and not bring all the debris back. In this test, however, as shown in Figure 5.28., all the debris was brought back.

Placing the suction tube of the suction excavator just above where the drill rods connected to the augers was very effective in sucking out the debris as it is being pulled back by the augers. This significantly improved the efficiency of the cleaning process as it virtually eliminated any required later cleanup work around the cleanout location and also eliminated the possibility of the collected debris to move back to the drain as more auger sections are added.

It should be noted that the debris that was pulled back was greatly agitated by the augers and was easily sucked by the vacuum without any need for adding water. Even though the Ditch Witch FX25 vacuum system used has the capability of adding water to loosen hard blockages in order to facilitate the suction, water was not needed because as stated above the debris was greatly agitated by the augers. Not adding water and making the cleaning process dry was very important to ODOT as it wanted to reduce the environmental impact of its maintenance operations. In summary, this field test has demonstrated that the use of a HAB machine in combination with a suction excavator is very effective in providing a safe and environmentally friendly process for cleaning trench drains.

This field test also evaluated the use of pins as a quicker way to connect the augers instead of Snap-On connections which were used in previous field tests. Figure 5.29 compares pinned connections vs. Snap-On connections. The pin connections were much faster to connect and release, however, their durability was a concern as one of them failed during the test. Although not tested as part of the project, it is suggested that coarse thread grade 8 bolt be used to make the augers' connections more durable.

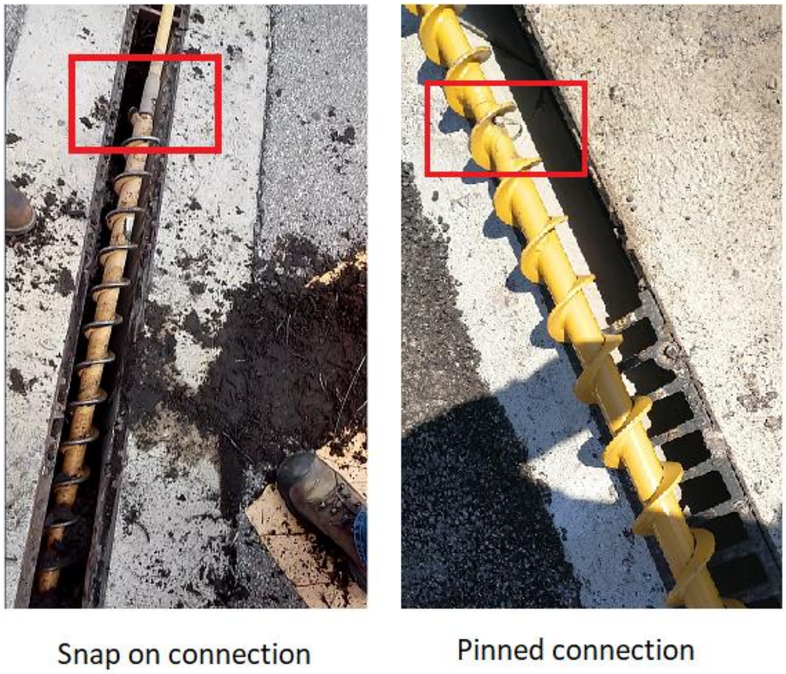


Figure 5.29. Pinned vs. Snap-On augers' connections

In addition, the field test also evaluated the use of poly augers made from High Density Polyethylene (HDPE) as shown in Figure 5.30. The research team wanted to test the lightweight poly augers to see if they are capable of bringing back the debris while reducing the power requirements of the HAB unit. However, it was observed that the poly augers have to be connected in a certain order as indicated by the manufacturer which significantly increased the connection time and slowed down the cleaning process. Furthermore, the light weight of the poly augers caused them to ride on top of the debris instead of digging into it and cleaning the drain thoroughly.

Figure 5.30. Poly Augers

Chapter 6 – Cost Analysis

The preliminary cost benefit analysis conducted as part of Phase 1 was revised to reflect findings from the field tests described in Chapter 5. The cost analysis was performed on the following trench drain cleaning methods that were evaluated during the field tests:

- Manual cleaning
- Using a sewer truck
- Using a Horizontal Auger Boring (HAB) machine
- Using a HAB machine and a suction excavator

Since as previously discussed in Chapter 2 both the manual cleaning and the sewer truck methods require ODOT Highway technicians to walk along the drain during cleaning, a maintenance of traffic (MOT) procedure involving lane closures is needed to ensure the safety of the workers. The MOT procedure requires the use of flaggers, arrow boards and a crash attenuator. On the other hand, the two methods utilizing the HAB machine can complete the cleaning process from a single cleanout location to which all the debris is brought back. These two methods do not require lane closures. The resources required for each method and their hourly costs are provided in Tables 6.1 to 6.4. The hourly rates of equipment used and crew wages were obtained from ODOT.

Table 6.1. Resources required and their hourly cost for manual cleaning of drains

Manual Cleaning with MOT				
		Quantity	Unit Price ($/hour)	Hourly cost ($/hour)
Labor				
	Flaggers	2	34	68
	Highway tech	3	34	102
Equipment				
	Dump truck to pull crash attenuator	1	71.03	71.03
	Pickup truck / cone trailer	2	16.87	33.74
	Arrow boards	2	2.38	4.76
	Crash attenuator	1	5.5	5.5
			Total Hourly Cost ($/hour)	**$ 285.03**

Table 6.2. Resources required and their hourly cost for cleaning drains with a sewer truck

Sewer Truck with MOT				
		Quantity	Unit Price ($/hour)	Hourly cost ($/hour)
Labor				
	Flaggers	2	34	68
	Highway tech	4	34	136
Equipment				
	Sewer Truck	1	133.62	133.62
	Dump truck to pull crash attenuator	1	71.03	71.03
	Crash attenuator	1	5.5	5.5
	Pickup truck / cone trailer	2	16.87	33.74
	Arrow boards	2	2.38	4.76
			Total Hourly Cost ($/hour)	**$ 452.65**

Table 6.3. Resources required and their hourly cost for cleaning drains with a HAB machine

Horizontal Auger Boring unit only (no MOT needed)				
		Quantity	Unit Price ($/hour)	Hourly cost ($/hour)
Labor				
	Highway tech	3	34	102
Equipment				
	Pickup truck / trailer	1	16.87	16.87
	Boring Unit	1	16.24	16.24
	Dump truck to pull crash attenuator	1	71.03	71.03
	Crash attenuator	1	5.5	5.5
			Total Hourly Cost ($/hour)	**$ 211.64**

Table 6.4. Resources required and their hourly cost for cleaning drains with a HAB machine and a suction excavator

HAB unit and Suction Excavator (no MOT needed)				
		Quantity	Unit Price ($/hour)	Hourly cost ($/hour)
Labor				
	Highway tech	3	34	102
Equipment				
	Pickup truck /trailer	2	16.87	33.74
	Boring Unit	1	16.24	16.24
	Dump truck to pull crash attenuator	1	71.03	71.03
	Crash attenuator	1	5.5	5.5
	Suction Excavator	1	15.57	15.57
			Total Hourly Cost ($/hour)	**$ 244.08**

Once the hourly costs of each cleaning method are calculated, a comparative cost analysis can be performed by knowing the production rate of each method. For the two methods employing the HAB unit, the production rate was calculated by first determining the total time (in minutes) needed to clean an auger length (4ft) of the drain. This total cleaning time consists of the following two components:

1. Time (in minutes) to connect the 4ft auger.
2. Time (in minutes) to advance the 4ft auger inside the drain and bring back the debris to the cleanout position.

Once the total cleaning time (in minutes) is calculated the production rate is calculated as (4ft/total cleaning time in minutes). Table 6.5 provides the cleaning production rates and supporting data for the two methods employing the HAB unit.

Table 6.5. Cleaning production rates and supporting data for the two methods employing the HAB unit

Cleaning Production Rate of HAB unit (with and without suction excavator)				
Cleaning Method	Time (min) to advance auger	Time (min) to connect auger	Total cleaning time (min) for 4 feet	Cleaning production rate (feet/min)
Boring unit only	1.33	2.00	3.33	1.20
Boring unit and suction excavator	1.33	1.00	2.33	1.71

As shown in Table 6.5. The difference in cleaning time for the two methods results from the time required to connect the auger. The use of a suction excavator reduces the time to connect augers. If a suction excavator is not used, 1 additional minute is needed to clean debris under the auger manually before making the connection to prevent the augers from riding on top. The use of the suction excavator improves the efficiency of the cleaning process as it virtually eliminates any required later cleanup work around the cleanout location and also eliminates the possibility of the collected debris to move back to the drain as more auger sections are added.

The production rates for removing the debris from the drains for both the manual cleaning and the sewer truck methods were calculated in Phase I of the project. The production rate of the sewer truck method was updated to account for the extra time needed to clean the debris left on the road after removing it from the drains. As was illustrated in Figure 2.9, when a sewer truck is used for cleaning the drains, a significant amount of debris escapes through the holes in the grates and ends up on the pavement next to the drain. This debris has to be removed either manually or using a street sweeper and disposed of safely. If left on the pavement, it will quickly move back and settle in the drain with any rain.

Table 6.6. provides the production rates for all the drain cleaning methods evaluated, their hourly costs ($) as well their unit costs ($/ft). It should be noted that the provided unit costs in Table 6.5 do not include the additional cost of water needed when the sewer truck is used nor

the additional "road user" cost resulting from the larger traffic disruption caused when either the manual or sewer truck methods are used. It should also be noted that the production rate of the method utilizing the sewer truck was obtained when the drain was only partly full with debris. In cases where the drain is completely blocked with debris the production rate will be lower and in extreme cases where the debris is very compacted, cleaning trench drains with sewer trucks may not be even viable. Finally, the small sizes of the suction excavator and HAB machine as compared to the sewer truck offers an important advantage to ODOT as they cause less disturbance to traffic and do not require too many people to operate.

Table 6.6. Cleaning production rates and unit costs for the evaluated cleaning methods

Unit Cost of various drain cleaning methods				
Cleaning Method	Hourly cost ($/hour)	Production Rate (feet/min)	Unit Cost of cleaning Drain ($/feet)	Length of drain cleaned per hour (ft)
Manual Cleaning with MOT	$ 285.03	0.50	**$ 9.50**	30.00
HAB unit only (no MOT needed)	$ 211.64	1.20	**$ 2.94**	72.00
HAB unit and suction excavator (no MOT needed)	$ 244.08	1.71	**$ 2.37**	102.86
Sewer Truck with MOT (not including cost of water and dumping collected waste water)	$ 452.65	2.00	**$ 3.77**	120.00

As shown in Table 6.6., the use of a HAB unit in conjunction with a suction excavator provides the least cost alternative for cleaning trench drains as measured during the field tests. From the data in Table 6.6, it was easy to calculate the length of the trench drains that need to be cleaned to pay for the equipment needed for each method as shown in the table below.

Pay back of various drain cleaning methods			
Cleaning Method	Unit Cost ($/feet)	Cost of Equipment	Payback period (length of drain cleaned in lf)
HAB unit only (no MOT needed)	$ 2.94	$ 24,106.99	3673.97
HAB unit and suction excavator (no MOT needed)	$ 2.37	$ 46,777.40	6562.49

Chapter 7 – Recommendations for Cleaning Drains

Different methods for cleaning trench drains were field tested as part of this research. The field tests have concluded that although the different cleaning methods tested are applicable in different situations, the use of HAB technology in combination with a suction excavator offer several advantages over the other methods as further detailed in this Chapter. Another conclusion from the field tests was that the degree of blockage in the drain has a strong impact on the applicability of the various cleaning methods. In this Chapter, the applicability of the various drain cleaning methods is discussed.

HAB machine

The process of cleaning trench drain with a HAB machine as described in this report is a new application of HAB machines. Continuous flights of augers are rotated and simultaneously pushed by the HAB machine into the drain. As the length of auger is advanced into the drain, a new auger section is connected. As the augers continue to advance the debris in the drain is loosened and the auger flights convey the material back to the starting point (cleanout location). The field tests have shown that this method is effective. The augers are able to remove the roots, vegetation and mud in the drains.

The biggest advantage of using HAB technology as proposed in this research for cleaning trench drains is the ability to complete the cleaning process from a single cleanout location to which all the debris is brought back. This is important in order to reduce impact on traffic and increase safety of ODOT technicians involved in the drain cleaning operation. Another advantage of this method is the elimination of water usage and the ability to span any length of drains simply by adding augers. Furthermore, the fact that the HAB equipment used in this research is small in size offers additional advantages as it can get into tighter spaces, can easily fit in the back of a pickup truck or 6x8 trailer and takes one to two people to operate.

One disadvantage of using HAB equipment for cleaning drains is that connecting and disconnecting auger sections is labor intensive and consumes time. Although this reduce the speed of cleaning, the safety gains obtained from eliminating the water/debris splash caused by using a sewer truck outweigh the reduced production rate. Furthermore, it is expected that the time to connect/disconnect augers will reduce as ODOT technicians become more familiar with the process.

It should also be noted that the debris carried by the augers and piled up near the cleanout position has to be collected and loaded away from site. If the debris is left on the pavement, it will quickly move back and settle in the drain with any rain. Removing the debris can be accomplished manually in cases were the amount of debris is not significant. Using a suction excavator in conjunction with the HAB machine is very effective in sucking out the debris as it is being pulled back by the augers. This significantly improves the efficiency of the cleaning process as it virtually eliminates any required later cleanup work around the cleanout location and also eliminates the possibility of the collected debris moving back to the drain as more auger sections are added.

Sewer truck with specialized Drainage Channel Nozzle

The Drainage Channel nozzle has a concentrated forward jet and 8 backward (thrust) jets. The spray pattern of the backward jets prevents any water from splashing up directly, reducing safety concerns and virtually eliminating need for clean-up work around the drains. The field tests have shown that this method is only applicable when the debris blockage in the drain is not significant (less than 30%). The biggest advantage of this method is that water and debris splashing are essentially eliminated if a stepped cleaning process is used. In a stepped cleaning process, the hydrojetting nozzle is propelled forward only 20 ft. at a time and brought backward to bring back the debris. Another advantage of this method is that it completely cleans the drain and removes all debris.

One disadvantage of using the Drainage Channel Nozzle is that the nozzle is slow in advancing forward in the drain because the angle of its backward jets is zero degree (horizontal) and the size of the backward jets is small. Another disadvantage of using this method is that it uses large volume of water for cleaning and if a stepped cleaning process is used, the cleaning production rate is reduced.

It should be noted that even when the Drainage Channel nozzle is used and in cases where the drain is completely blocked with debris, the water and debris splashing resulting from the cleaning process creates a safety hazard to ODOT crews and the travelling public. Thus, cleaning trench drains with sewer trucks and specialized drainage channel nozzle can only be a viable safe option if a maintenance plan for trench drains is adopted by ODOT. A maintenance plan enables maintenance crews to periodically clean the drains effectively before they become completely clogged in which case they require more expensive cleaning methods or in some cases total replacement at significant cost to ODOT.

Drain cleaning robot

the University of Cincinnati research team has developed a remote controlled four-wheel drive robot which fits into a trench drain and cleans it from inside without interfering with the surrounding traffic. The robot moves inside the drain on rubber wheels and has a cutting assembly that loosens the debris inside the drain for easier removal and is equipped with a suction tube connected to a suction excavator (vacuum). The robot has three main systems: a driving system, a cutting system and a vacuum system. To clean the drain channel, all three systems of the robot need to work properly. Although the field tests have demonstrated that the robot prototype's driving and cutting system work as intended, more work still need to be done on the robot to ensure that the loosened dirt is efficiently sucked by the vacuum system as the current prototype is unable to pull a long suction hose behind it. Also additional work is needed to make the robot more heavy duty to enable the robot to move over different types of debris and to make it water proof.

Recommended Drain Cleaning Procedure

Based on the field tests, it is recommended to use a HAB machine in conjunction with a suction excavator to clean trench drains. The recommended cleaning procedure is:

1. Locate a suitable cleanout location and move HAB machine next to it.

2. Remove grates from some drain’s sections and manually clean them.
3. Insert first auger section into drain.
4. Advance auger section forward with boring machine.
5. Place suction tube of the suction excavator just above the augers in the cleanout location with the intent of vacuuming the debris as it is being pulled back by the augers.
6. Disconnect auger section from boring machine and back up machine to create room to slide another auger section to be connected.
7. Connect another auger section to previous section and to boring machine.
8. Repeat steps 4 to 8 to keep adding more auger sections in to span entire length of drain to be cleaned.
9. Auger flights convey the material back to the cleanout location.
10. Remove collected debris from cleanout position, load it away from site, and re-install the grates

Chapter 8 – Conclusions and Future Work

Recently, the use of trench/slotted drains by ODOT in roadways has increased and is expected to continue to increase in the future which makes it necessary to develop procedures for safely maintaining/cleaning trench and slotted drains. Phone interviews conducted as part of the research has concluded that clogged drains were a problem nationwide. This problem was attributed to inadequate or often no maintenance. One of the main reasons DOTs have not maintained their trench drains is due to the lack of safe, efficient and effective drain cleaning methods. Manual removal of the grates and cleaning, and utilizing sewer trucks are methods that have been used to clean drains in the past. These methods however are not safe in many situations particularly when the debris blockage in the drains is significant and when the drains are located in heavily travelled areas. In such situations, when all cleaning methods failed, DOTs had to tear down the drains and completely replace them at significant cost.

The goal of this research is to improve ODOT's current process of maintaining drains. To achieve this goal, the research team first evaluated the conventional methods that ODOT currently utilizes for drain cleaning. One conventional method which utilizes a Sewer truck was found to have the following difficulties:

1. Large volume of water is used in cleaning and most of the water is not captured and flows into the storm water drainage network.
2. Significant amounts of water and debris are splashed from the openings of the drains' grates creating unsafe condition for both ODOT crews and road users.

To reduce the difficulties associated with current ODOT drain cleaning procedures discussed above, the research team developed a matrix of alternatives that compared and contrasted solutions that are available today and provided the following recommendations for phase 2:

1. Evaluating the potential use of HAB Horizontal Auger Boring (HAB) technology for cleaning drains.

2. Evaluating the potential use of specialized hydrojetting nozzles for cleaning drains in order to reduce the volume of water splashing during the cleaning process, reduce the amount of debris accumulating on the pavement next to the drain after cleaning and eliminate the possibility of flying debris hitting vehicles.
3. Evaluating the potential use of a custom designed and fabricated robot for cleaning drains.

The process of cleaning trench drain with HAB Horizontal Auger Boring (HAB) equipment as described in this report is a new application for HAB. Continuous flights of augers are rotated and simultaneously pushed by the HAB machine into the drain. As the length of auger is advanced into the drain, a new auger section is connected. As the augers continue to advance the debris in the drain is loosened and the auger flights convey the material back to the starting point (cleanout location). The results of field tests showed that with the correct set-up, the use of HAB equipment in conjunction with a suction excavator provides a safe and environmentally friendly process for cleaning trench drains.

Although the use of specialized hydrojetting nozzles with a sewer truck reduces splashing, this method of cleaning is only applicable when the debris blockage in the drain is not significant (less than 30%) and when a stepped cleaning process is used. When the drain is full with debris, the surface of the debris is close to the openings of the grates and the splashing increases which produces a large mess on the pavement next to the drains and creates a safety hazard to ODOT crews and the travelling public. Moreover, this method utilizes a significant amount of water. Therefore, the use of HAB technology in conjunction with a suction excavator is a better option for cleaning trench drains.

The robot prototype developed by the University of Cincinnati research team to clean the drains has demonstrated that the concept works. However, more work is still needed on the robot to ensure that the loosened dirt is efficiently sucked by the vacuum system as the current prototype is unable to pull a long suction hose behind it. Also additional work is needed to make the robot more heavy duty to enable it to move over different types of debris and to make it water proof.

Future work

One of the main conclusions from the field tests was that the degree of blockage in the drain has a very strong impact on the applicability of the various cleaning methods. It is suggested that the drains be added to ODOT asset management database and that a blockage rating be developed to help select which cleaning method is more suitable.

It is also suggested that more work be done to further develop the drain cleaning robot. As discussed above, although the developed prototype has shown good potential, it still needs further development. One of the current concerns with the robot is that the power provided by the drive motors could be insufficient for pulling a long suction hose behind the robot. To overcome this, other types of drive motors could be looked into. These motors would provide higher torque and speed for about the same size when compared to the drive motors currently used. One of the constraints that limited the use of more powerful motors in the robot is space availability since all the required components (motors, batteries, remote control receivers, etc.) had be assembled inside a robot frame that can move easily in the small drain section. One way of reducing the space constraints is that instead of placing the batteries in the robot frame to power the motors, provide the power through a supply cable that the robot drag through the drain. This would open up more space in the robot frame for using larger and more powerful motors.

Additionally, the robot can be further automated through actuators and sensors in order to reduce manual involvement. For instance, a sensor could be used to decide the drive velocity of the robot by sensing the level of debris present in front of the robot. By adjusting the speed based on the amount of debris continuously, the robot can control its drive speed on its own. Furthermore, artificial intelligence could be used to make the robot more autonomous.

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Appendix A- Second and Final Prototype of UC Robot

The second and final prototype of UC's robot is shown in Figure A.1. To ensure that all the robot's components would fit inside the drain, a computer-based 3D model of the robot was developed as shown in Figure A.2.

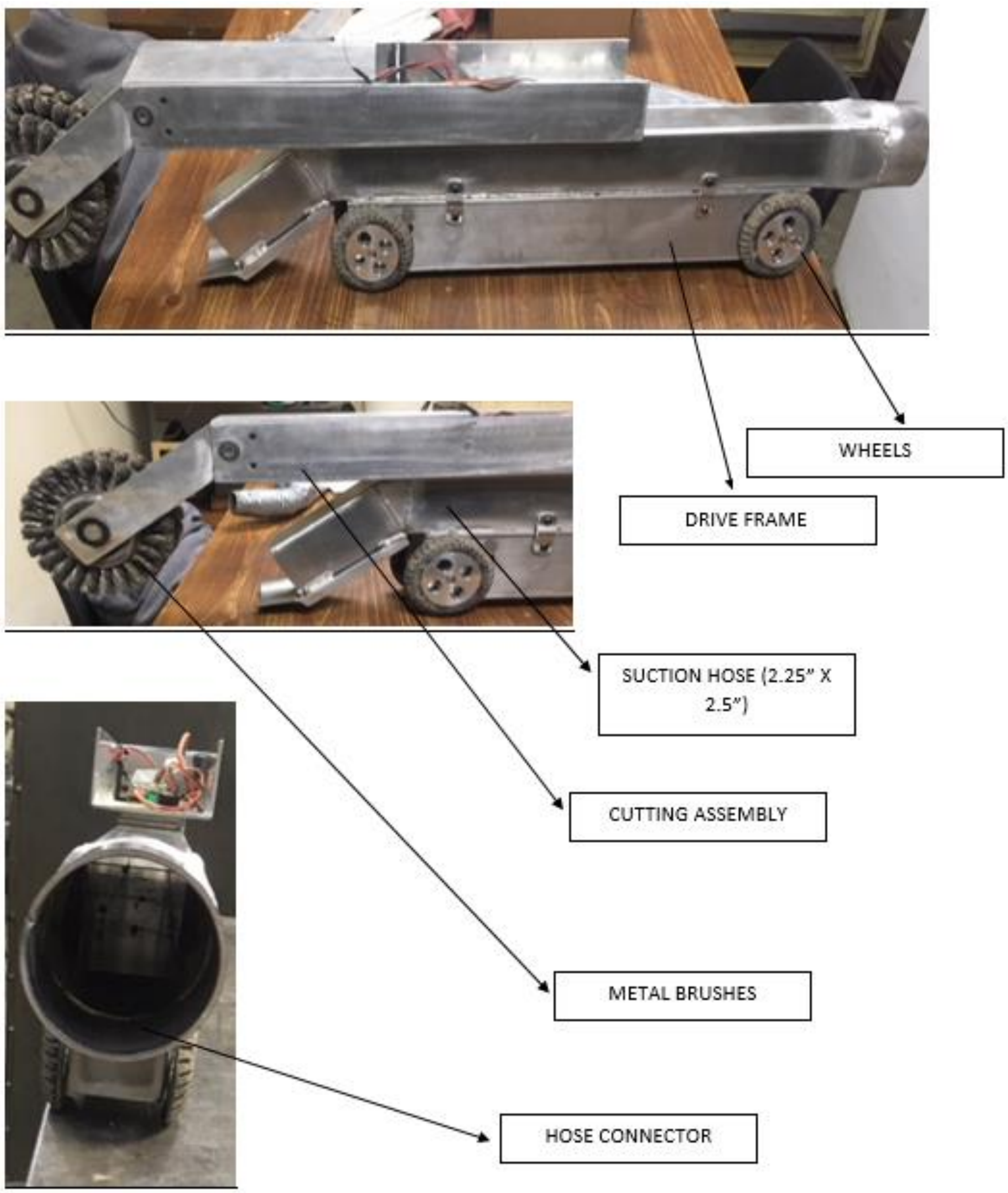
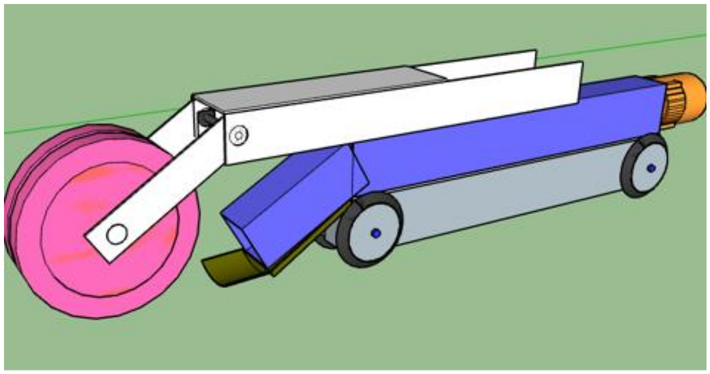
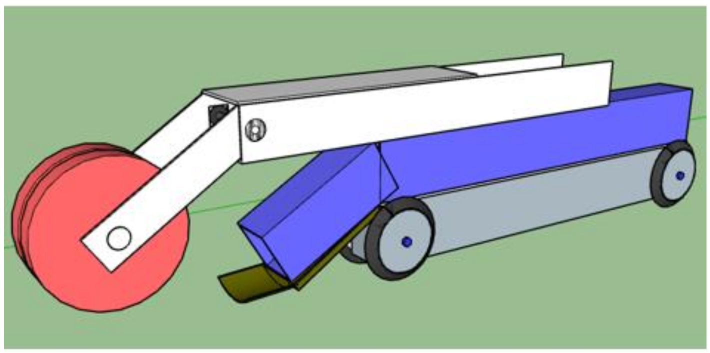


Figure A.1. Second and final remote controlled cleaning robot



Second Model complete assembly with 8 inch metal brushes



Second Model complete assembly with 6 inch metal brushes

Figure A.2. Computer-based 3D models of the robot

Robot Modules

The cleaning robot has three main modules which are listed below and further described in the following sections:

1. A drive system
2. A suction tube assembly
3. A cutting assembly

Drive System:

The robot's drive system as shown in Figures A.3. and A.4. consists of a drive frame that houses two dual shaft motors, a motor driver, a receiver to receive the RC signal and a set of batteries to provide power to the motors. The robot moves as a four-wheel drive where a dual shaft motor is attached to each set of wheels. There are four wheels attached to the frame. Each wheel is 4 inches in diameter and 0.4 inches wide. The wheels are curved to increase their contact areas with the drain's bottom surface and improve traction.

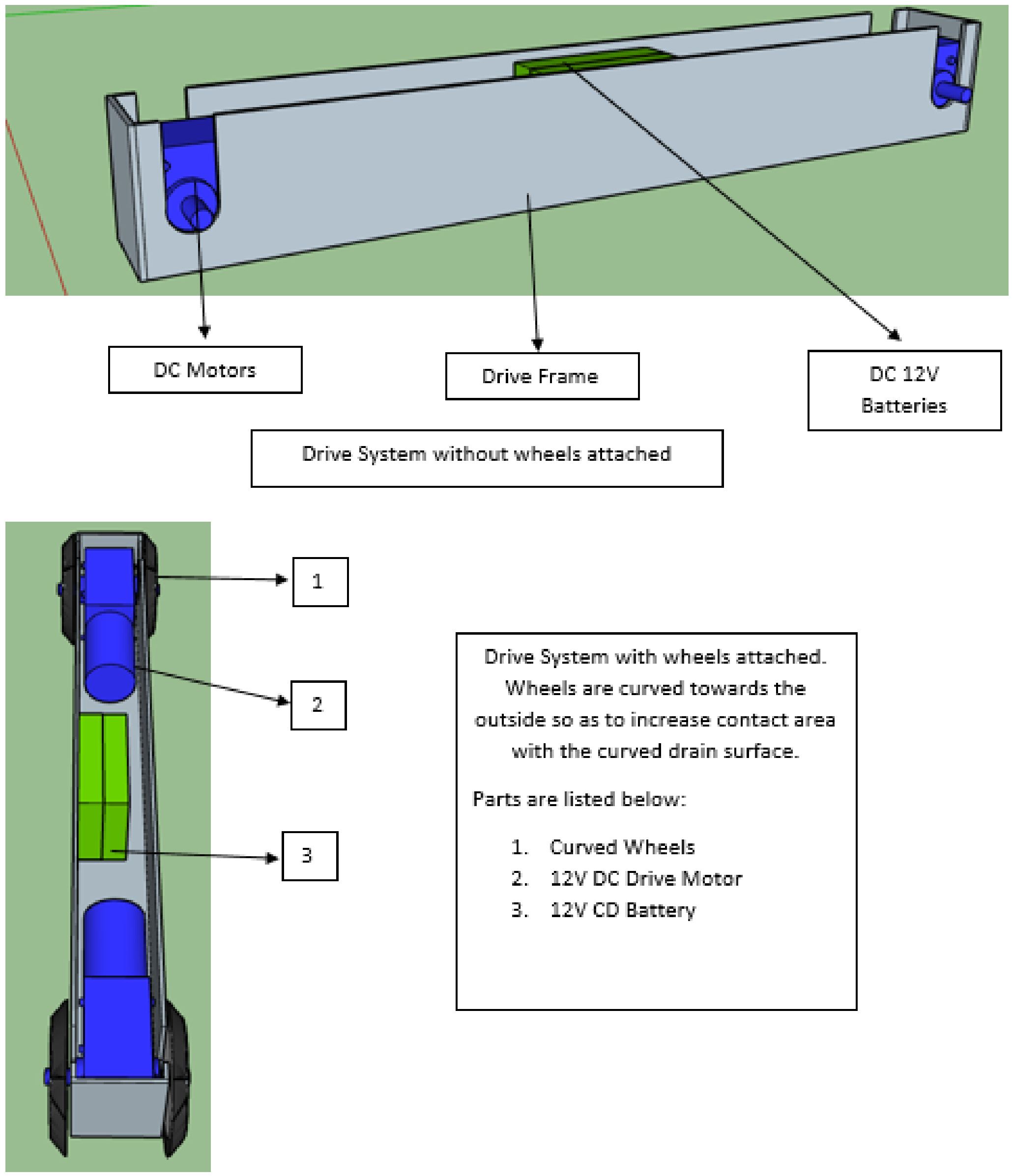


Figure A.3. 3D model of the robot's drive system

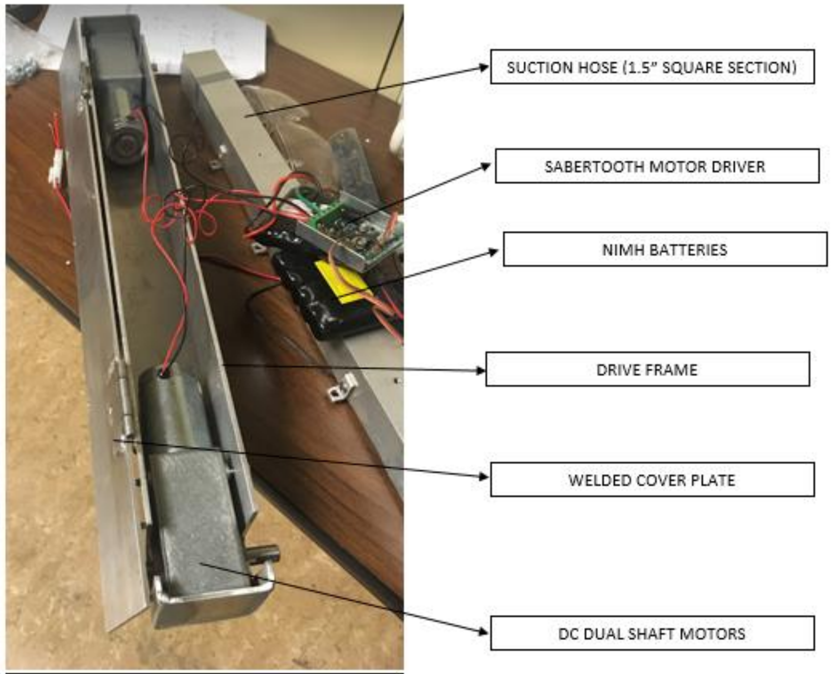


Figure A.4. Drive system of UC's drain cleaning robot

Suction tube assembly:

The suction tube assembly as shown in Figures A.5. and A.6. is designed to enable the loosened debris to be transported from the drain to the suction hose of a suction excavator (vacuum) located at the cleanout location. It consists of a square horizontal suction tube and bent extension, a shovel, and a hose connector. The curved shovel is used for scooping dirt from the drain. The bent square tube extension at the front is the part through which the debris first gets sucked in and then passes to the horizontal suction tube. The hose connector connects the square suction tube to a 3" round hose of a suction excavator.

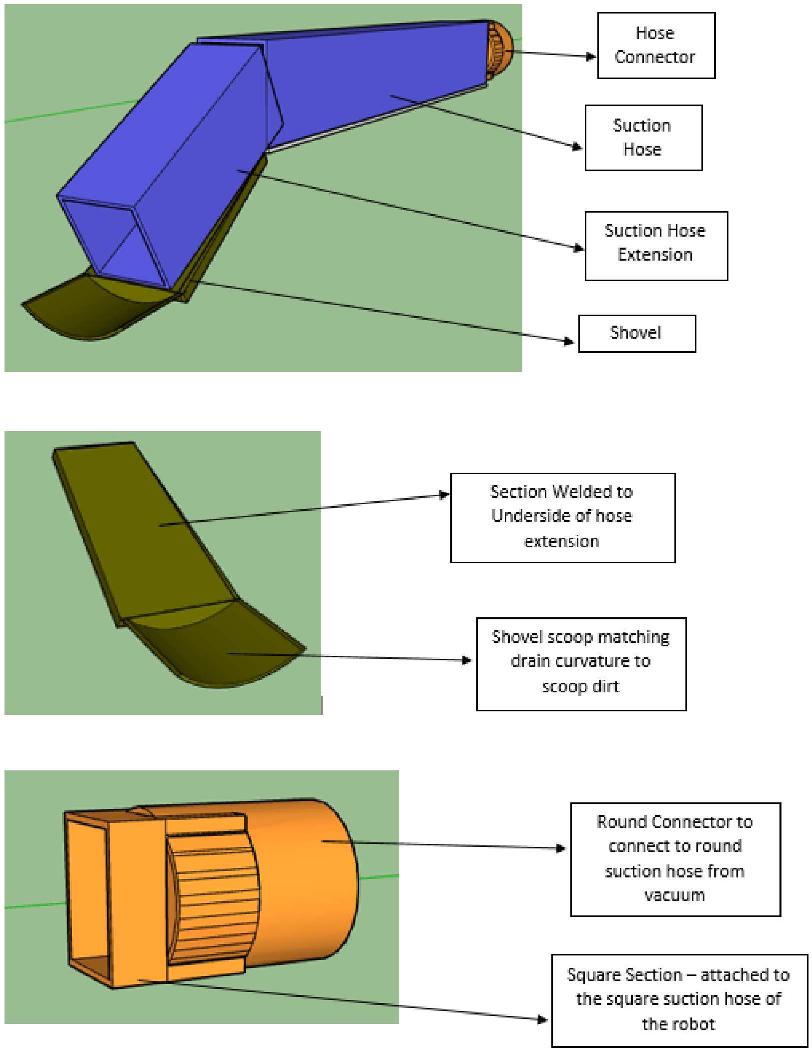
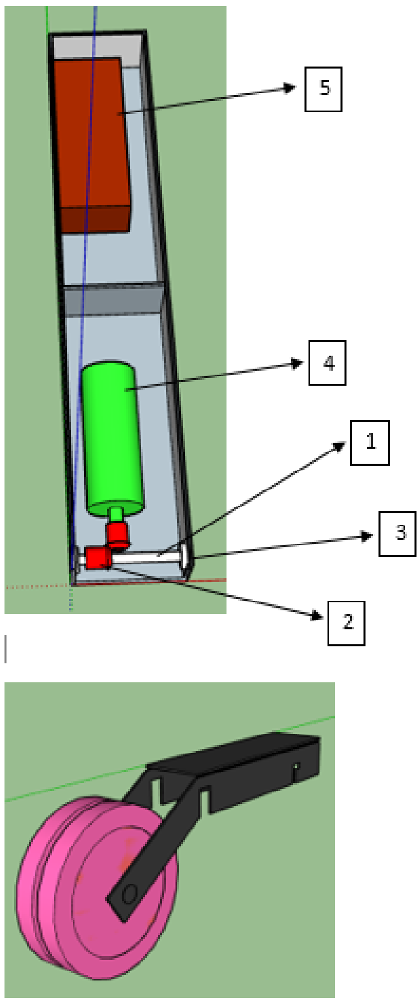


Figure A.5. 3D model of the robot's suction tube assembly

Figure A.6. Drive System and suction tube assembly of final model

Cutting Assembly:

The function of the cutting assembly is to break up the hardened debris in the drain using rotating metal brushes. Once the debris is loosened, it falls down to the bottom of the drain where it is sucked by the suction tube which is connected to the suction excavator (vacuum). The cutting assembly as shown in Figures A.7. and A.8. consists of a cutting frame and a cutting arm.



Cutting Frame containing:

1- Shafts
2- Bevel Gears
3- Bearings
4- DC Motor
5- Battery

Cutting Arm with metal brushes.

Figure A.7. 3D model of the robot's cutting assembly

Figure A.8. Robot's cutting assembly

The cutting arm has a shaft that contains a sprocket and a number of metal brushes. The cutting frame houses a 24V DC motor powered by a 24V, 5Ah battery. The motor is attached to a coupler and a bevel gear. When the motor is switched on, the bevel gear engages with the gear on a shaft. This engagement of the gears makes a sprocket on the shaft rotate. This sprocket is further engaged with a second sprocket on the shaft of the cutting arm to which the metal brushes are attached. The engagement is done through a chain. When the motor is rotating, the bevel gears engage and drive the first sprocket which in turn drives the metal brushes through engagement with the second sprocket.

As shown in Figures A.7. and A.8., the cutting frame is designed in such a way that the battery, motor driver and the receiver are in a separate compartment behind the motor. This protects the electronic components in the system from dirt and debris which is acted upon by the cutter in the front. As shown in Figure A.9., the robot has been designed in a way that creates enough clearance between the metal brushes and the shovel to provide some time for the dirt to accumulate before being sucked by the suction excavator.

Figure A.9. Drive System and suction tube assembly of final model

Two sets of cutting arms have been manufactured for the robot as shown in Figure A.2. The first set uses 6 inches' metal brushes and should be selected if the drain is not completely blocked with debris. The second set uses 8 inches' metal brushes and should be selected if the drain is fully blocked.

Remote Controller

The Remote Controller controls the robot motion through a transmitter and 2 receivers attached to both the drive and cutting systems. The transmitter as shown in Figure A.10.

controls the speed and direction of both the cutting mechanism and the drive system. The transmitter transmits an RF signal to the receivers.

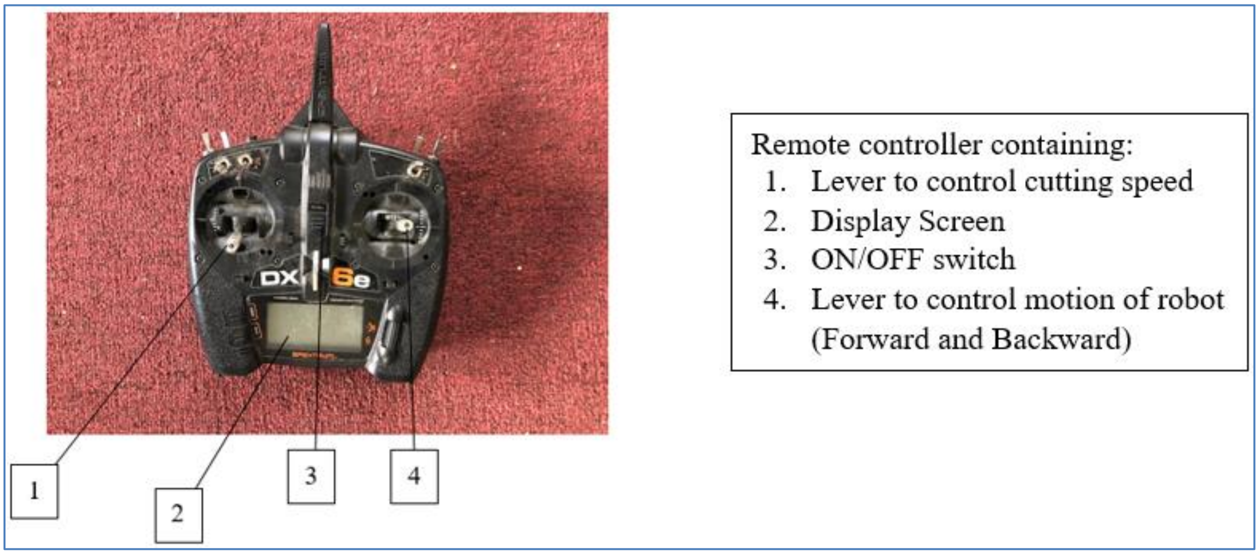


Figure A.10. Robot’s remote controller

Appendix B- First Prototype of UC Robot

The first prototype of UC's robot is shown in Figures B.1. and B.2. Testing of the first prototype has revealed some issues/concerns that necessitated a development of the second prototype which was discussed in detail in Appendix A. Those issues/concerns which are discussed below to document the lessons learned included:

1. The first prototype was 3.9" wide. Although it was a bit narrower than the 4" wide trench drain, the imperfections of the manufacturing and installation processes of the drains prevented the robot from freely moving particularly at the intersections of the drains' sections. From this lesson-learned, the width of the second prototype was limited to 3.75". We didn't reduce the width of the second prototype less than 3.75" in order to prevent the robot from wobbling inside the drain.
2. The wheels used in the first prototype were flat. During testing, the research team observed that the wheels, because of their flatness, did not have enough contact with the drain's bottom which is curved. This resulted in little traction that prevented the robot from moving freely inside the drain.
    - From this lesson- learned, the wheels of the second prototype were custom made to be curved in order to increase their contact areas with the drain's bottom surface and improve traction.
3. The design of the first prototype's drive was completely different from the second prototype. As shown in Figure B.3., the motor of the drive system of the first prototype is attached to a coupler and a bevel gear such that when the motor is switched on, the bevel gear engages with the gear on the wheel shaft. This engagement of the gears makes the front wheels rotate. Since the motor only acts on the front wheels, the first prototype is a front wheels drive vehicle.
    - Such a design proved to be problematic. During testing, when the robot moved and encountered large resistance, the bevel gears disengaged frequently.
    - From this lesson- learned, the second prototype was designed as a four-wheels drive vehicle; it utilizes two DC Dual Shaft Motors attached to both sets of

wheels. The dual shaft motors come with a gear box and don't require additional gears to transmit the motion to the wheels thus eliminating the gears' disengagement problem.

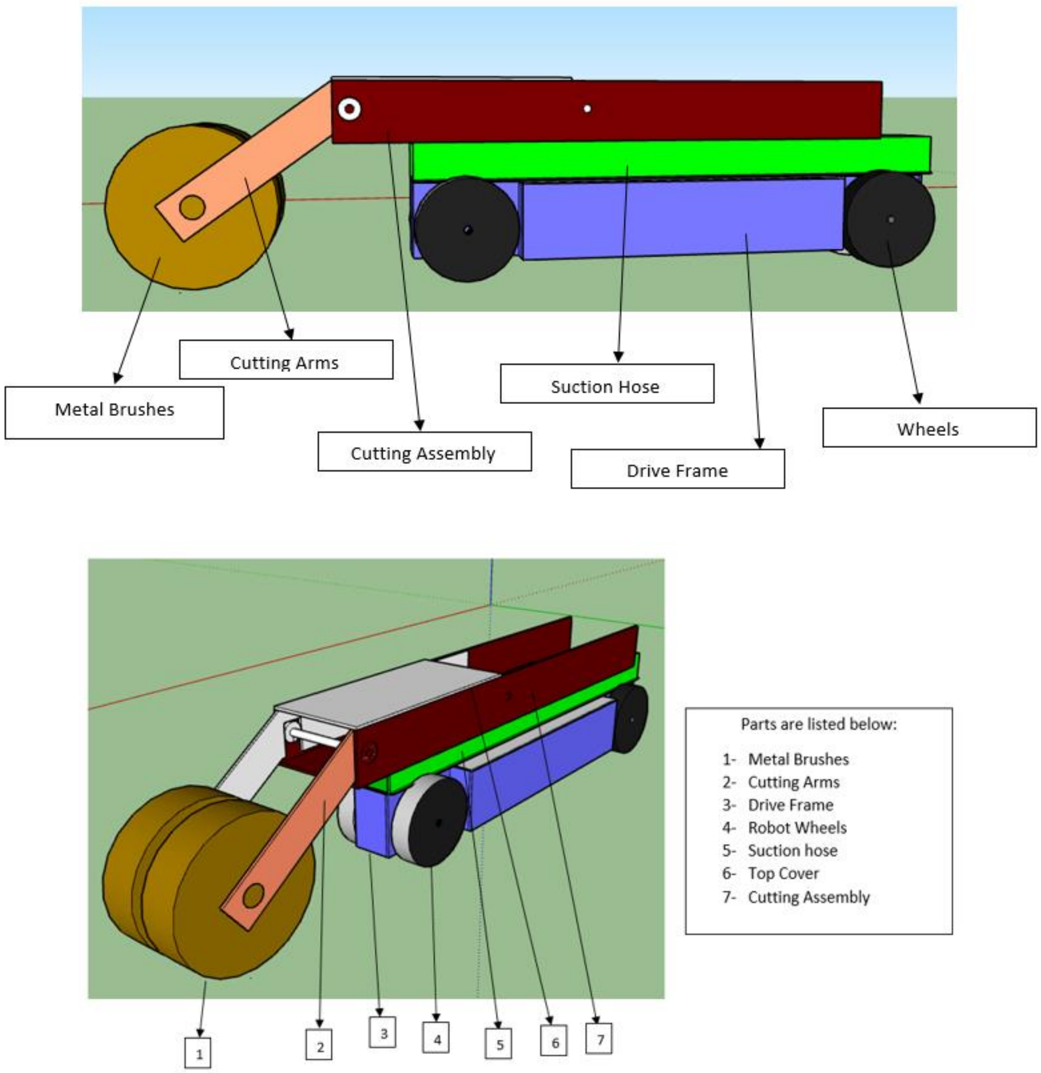


Figure B.1. 3D model of the first prototype of UC's drain cleaning robot

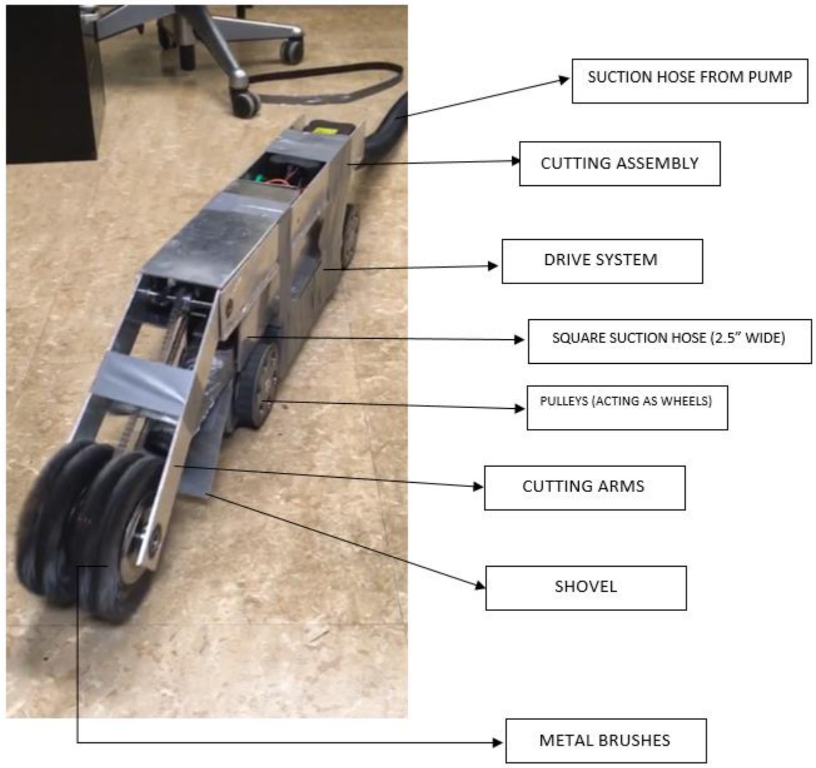
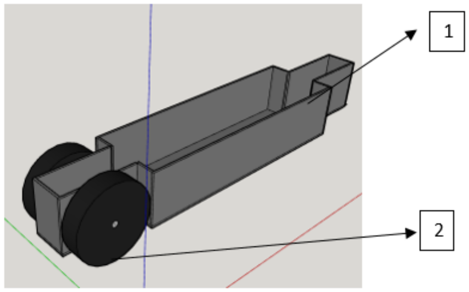


Figure B.2. First prototype of UC's drain cleaning robot

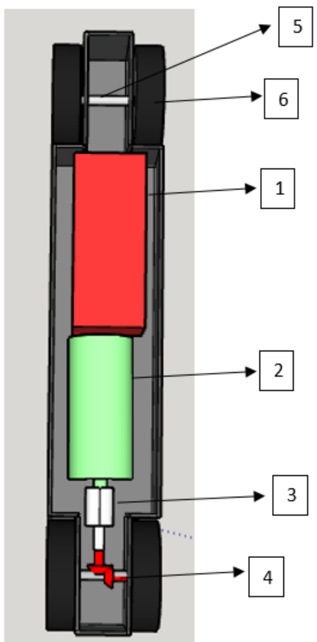
Drive System:



Drive Frame for housing drive components with wheels.

1 – Drive Frame

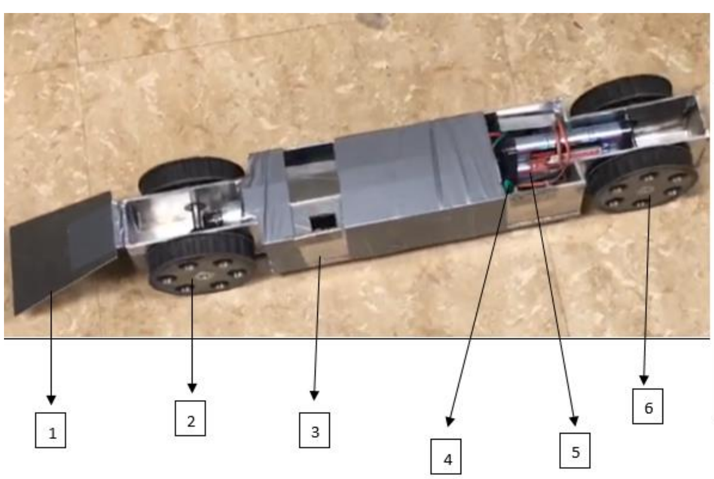
2 – Robot Wheels



Drive System top view showing all the components. These are mentioned below:

1- 12V Batteries
2- DC 12V Motor
3- Shaft Coupler
4- Bevel Gears
5- Shafts
6- Wheels

Figure B.3. 3D model of the first prototype of UC robot's drive system



Parts shown in image above are listed below:

1 – Shovel

2 – Robot Wheels

3 – Drive Frame

4 – Circuit Switch

5 – DC 12V Batteries

6 – Shafts for Robot Wheels

Figure B.4. Drive system of first prototype of UC robot's

Appendix C- Specifications of Bobcat MT55 Mini Track Loader

Mini Track Loaders / MT55 Mini Track Loader

Specifications & Options

Engine

Emissions Tier (EPA)	Tier 4
Engine Cooling	Liquid
Engine Fuel	Diesel
Displacement	55 in³
Number of Cylinders	3
Horsepower	24.8 hp

Performance

Rated Operating Capacity (SAE)	550 lb
Tipping Load	1610 lb
Operating Weight	2610 lb
Ground Pressure (Rubber)	4.9 psi
Travel Speed	3.5 mph
Travel Speed - Reverse	1.4 mph

Capacities

Fuel Tank	7 gal

Hydraulic System

Pump Capacity	12 gal/min
System Relief @ Quick Couplers	2,900 psi
Auxiliary Std Flow	n/a

Dimension

Length	93.1 in
Width	35.6 in
Height	49.1 in
Height to Bucket Hinge Pin	71.2 in
Length of track on ground	34 in
Reach @ Maximum Height	18.2 in

Appendix D- Specifications of Boring Unit Attachment

Attachments / Boring Unit

Specifications

⊖ General

Operating Weight	130 lb
Length	26.8 in
Width	36 in
Height	17.5 in
Maximum recommended boring distance	30 ft

⊖ Compatible Carriers

Skid-Steer Loaders	
Bobcat S70	■

Mini Track Loaders	
Bobcat MT55	■
Bobcat MT85	■

Appendix E- Specifications of Hurricane 500 Vacuum System

HURRICANE 500

SPECIFICATIONS

Dimensional drawing on other side

•TRAILER MOUNTED Chassis - tandem 7,000# axles, 4"x 6" rectangular tube frame, with four 8-lug ST235/85/R16 ten ply radials. DOT lighting with electric brakes.

•POWER SOURCE John Deere or Cummins turbo-charged diesel engine, 6 cylinder, 170 HP @ 2,400 RPM

•P.T.O. (clutch) Heavy duty NACD 11.5" clutch

•VACUUM AIR FLOW (blower) Positive displacement, 2350 CFM capable of 27" Hg, 5 belt driven with guard. (Roots 616 DVJ or equal)

•FILTRATION SYSTEM (3-Stage)
Stage 1: Cyclonic separation
Stage 2: Baghouse/37 Teflon coated, quick change filter bags with air cannon providing reverse pulse filter cleaning
Stage 3: Horizontal mounted high efficiency blower safety filter

•HYDRAULICS 4.5 GPM, 2200 PSI, direct drive

•ENCLOSURE Lockable steel shroud over engine

•INSTRUMENT PANEL (fully enclosed) 12 volt key start, Murphy safety system (low oil pressure/high water temperature auto shutdown) Gauges: oil pressure, water temperature, ammeter, tachometer with hour meter, filter cleaning on/off switch, material vacuum & dump time controls

•AIR COMPRESSOR Direct drive Bendix twin cylinder; water cooled & oil pressure fed. Haldex air dryer with electronic heater. AMSE certified air tank mounted on vibration isolators (provides air to pneumatic controls and self cleaning filter sytem)

STANDARD EQUIPMENT

- Paint - one color (custom lettering available)
- Wet or dry operation
- Tool box
- Automatic cone vibrator
- 100 gallon fuel tank
- Adjustable pintle hook
- Emergency stop button
- 10" inspection door (hopper)
- Hydraulic lift leg to level trailer
- Spare tire & carrier
- Tool-less flip top lid on baghouse

OPTIONS

- Cold weather package
- HEPA filtration
- Slide gate discharge
- Auxiliary 50 gallon fuel tank
- 16" manhole on baghouse
- Asbestos/hazardous waste package
- Parking brake
- Auger in cone
- Auxiliary air hose 120 PSI
- Skid mount
- 150 HP electric motor
- 4 point certified lifting cage
- High reach package

SAFETY FEATURES

- OSHA approved belt guard
- Remote emergency stop button
- Safety struts for baghouse
- Emergency breakaway chain
- Wheel chocks
- Optional HEPA filtration
- Electric brakes
- Low oil or high temp engine shutdown

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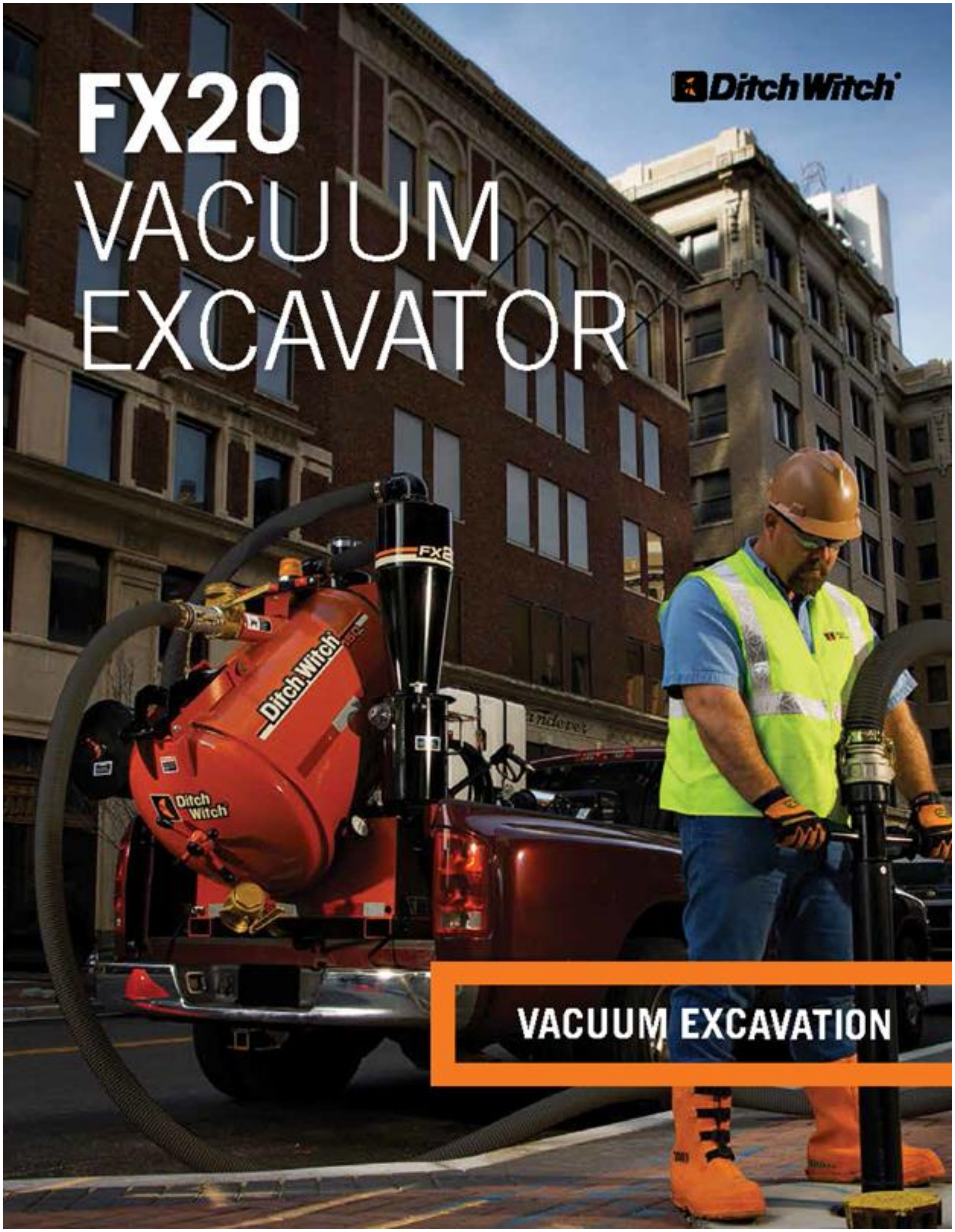
INDUSTRIAL
VACUUM
HURRICANE
HURRICANE
500
DIMENSIONS
WIDTH 99"
WEIGHT 9,500 lbs
Length when Raised 284"
Raised Height 220"
Discharge Height 101"
Lowered Height 133"
Hitch to Ground 31.5"
*High reach option
up to 132" available
Length when Lowered 204"

Appendix F- Specifications of Ditch Witch Fx-20 Vacuum System




FX20 VACUUM EXCAVATOR
1
150-gallon (568-L) vac tank is mounted permanently at a 45-degree angle, making the dumping cycle quick and easy.
2
Curbside operator's console is designed to make controls easily accessible; console can be positioned on either side of the unit.
6
Cyclone separator cleans the air before it ever reaches the filter, minimizing maintenance.
5
Outstanding suction power of 540 cfm (15.3 m³/min) in a compact, extremely durable package; belt-driven blower is reliable and easy to maintain.
4
Skid-mounted FX20 can fit in the back of a pickup truck, on a flatbed trailer or a specially designed Ditch Witch trailer.
3
27-hp (20.1-kW) Kohler® gas engine is renowned for its reliability and ease of maintenance.
Ditch Witch

FX20 VACUUM EXCAVATOR SPECIFICATIONS

	U.S.	METRIC
DIMENSIONS		
TRAILER		
Length	174 in	4.42 m
Width	86 in	2.18 m
Height	93 in	2.36 m
Weight, empty	2,576 lb	1168 kg
Trailer GVWR	4,500 lb	2041 kg
Axle rating	4,500 lb	2041 kg
SKID		
Length	109 in	2.77 m
Width	63 in	1.6 m
Height	74 in	1.88 m
Weight, empty	1,594 lb	723 kg
POWER		
Engine	Kohler® CH740S	
Fuel	Gasoline	
Cooling medium	Air	
Injection	Carburetor	
Aspiration	Natural	
Number of cylinders	2	
Displacement	44 in³	725 ml
Bore	3.27 in	83 mm
Stroke	2.64 in	67 mm
Manufacturer's gross power rating (SAE J1940)	27 hp	20.1 kW
Rated speed	3,600 rpm	
Fuel tank capacity	10 gal	38 L

	U.S.	METRIC
VACUUM SYSTEM		
Blower displacement	540 cfm	15.3 m³/min
Drive type	Belt	
Vacuum, max	15 in Hg	381 mm Hg
Hose	3 in	76 mm
Vacuum tank capacity	150 gal	568 L
Outlet valve size	4 in	102 mm
Tank inlet valve size	4 in	102 mm
Tank dump angle, max/fixed	45°	
Filter type	Washable polyester	
Filter area	74 ft²	6.9 m²
Water trap capacity	4.5 gal	17 L
WATER SYSTEM		
Water tank capacity	80 gal	303 L
Water pump flow	2.6 gpm	9.8 l/min
Water pump pressure, max	3,000 psi	207 bar
Clutch type	Electric w/auto de-clutch and low water shut down feature	
Hose reel (locking)	50 ft	15.3 m
BATTERY		
Group	12V	
SAE reserve capacity rating	41 min	
SAE cold crank rating @ 0°F (-18°C)	340 amps	
NOISE LEVEL		
Sound power	110 dBA	
Sound pressure per ISO	84 dBA	

Specifications are general and subject to change without notice. If exact measurements are required, equipment should be weighed and measured. Due to selected options, delivered equipment may not necessarily match that shown.