EVALUATION OF THE OHIO DEPARTMENT OF TRANSPORTATION'S CURRENT STORM SEWER CLEANING OPERATIONS

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16. Abstract

The Ohio Department of Transportation (ODOT) is in charge of constructing, maintaining and ensuring the safety of roads within its control. Proper maintenance procedures are critical in reducing the amount of funding required to sustain long lasting and safe roads. One maintenance responsibility of ODOT is to inspect and clean the storm sewer infrastructure along its roadways. If not properly maintained, storm sewers may become full of debris and flood the road with storm water, creating a safety hazard for the traveling public and negatively impacting the pavement condition.

This study will provide ODOT, contractors and other state DOT's a review of an alternative equipment option that is now available. The Recycler is a piece of equipment that is similar in functionality to a Vacuum Jet Truck (VJT), but with the addition of a water recycling system used to filter the wastewater removed from sewers. The filtered wastewater may then be reused for jetting purposes, removing the need to make long refill and decanting trips.

Field data were obtained by observing the VJT and Recycler operations over the course of a summer maintenance season. The data were used to model the production rates and economics associated with both the VJT and Recycler equipment options. An overall cost-benefit analysis was completed as well as an implementation plan for different types of structures, operator training and environmental settings. The team found that the Recycler studied is a viable and economically feasible option to incorporate into a DOT or contractor equipment fleet as it is 52% more productive than the VJT.

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Prepared in cooperation with the Ohio Department of Transportation
and the U.S. Department of Transportation, Federal Highway Administration

EXECUTIVE SUMMARY

The Ohio Department of Transportation (ODOT) is in charge of constructing, maintaining and ensuring the safety of roads within its control. Proper maintenance procedures are critical in reducing the amount of funding required to sustain long lasting and safe roads. One maintenance responsibility of ODOT is to inspect and clean the storm sewer infrastructure along its roadways. If not properly maintained, storm sewers may become full of debris and flood the road with storm water, creating a safety hazard for the traveling public and negatively impacting the pavement condition.

This study will provide ODOT, contractors and other state DOT's a review of an alternative equipment option that is now available. The Recycler is a piece of equipment that is similar in functionality to a Vacuum Jet Truck (VJT), but with the addition of a water recycling system used to filter the wastewater removed from sewers. The filtered wastewater may then be reused for jetting purposes, removing the need to make long refill and decanting trips.

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Additional analysis of the equipment economics suggested that a required ownership time of 4.35 years was required to break-even on the costs. The expected lifespan of the Recycler is approximately 10 years, resulting in five to six years of operating in profit. The team also found that the Recycler's unique pump system is able to clean difficult hydrodynamic separator structures 3.73 times as fast as the current VJT system.

This study provides ODOT, as well as other state DOT's and contractors, an alternative equipment option that may increase the storm sewer cleaning production rate. This increase in production also results in reduced maintenance costs associated with cleaning storm sewers. As DOT budgets continue to be exhausted, reducing costs is a high priority. While cost savings are important, the safety considerations are also significant as a more productive cleaning regimen means that fewer storm sewer may become clogged and flood the road surface. Overall, the Recycler is a viable option that any equipment manager should consider incorporating into their fleet.

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- Mr. Dan Wise, ODOT,
- Mr. Jonathan Prier, ODOT, and
- Mr. Mark Edwards, ODOT.

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Customary Unit	SI Unit	Factor	SI Unit	Customary Unit	Factor
Length			Length		
inches	millimeters	25.4	millimeters	inches	0.039
inches	centimeters	2.54	centimeters	inches	0.394
feet	meters	0.305	meters	feet	3.281
yards	meters	0.914	meters	yards	1.094
miles	kilometers	1.61	kilometers	miles	0.621
Area			Area		
square inches	square millimeters	645.1	square millimeters	square inches	0.00155
square feet	square meters	0.093	square meters	square feet	10.764
square yards	square meters	0.836	square meters	square yards	1.196
acres	hectares	0.405	hectares	acres	2.471
square miles	square kilometers	2.59	square kilometers	square miles	0.386
Volume			Volume		
gallons	liters	3.785	liters	gallons	0.264
cubic feet	cubic meters	0.028	cubic meters	cubic feet	35.314
cubic yards	cubic meters	0.765	cubic meters	cubic yards	1.308
Mass			Mass		
ounces	grams	28.35	grams	ounces	0.035
pounds	kilograms	0.454	kilograms	pounds	2.205
short tons	mega grams	0.907	mega grams	short tons	1.102

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LIST OF ACRONYMS

CAN – Controller Area Network

DOT – Department of Transportation

EPA – Environmental Protection Agency

GIS – Geographic Information System

gpm – Gallons per minute

hr - Hours

mi – Miles

MS4 – Municipal Separate Storm Sewer Systems

ODNR – Ohio Department of Natural Resources

ODOT – Ohio Department of Transportation

OEPA – Ohio Environmental Protection Agency

PD – Positive Displacement

PE – Professional Engineer

PI – Principal Investigator

PPE – Personal Protective Equipment

Recycler – A VJT with the ability to recycler the wastewater on-board

RFP – Request for Proposal

ROW – Right of Way

SOP – Standard Operating Procedure

SWMP – Storm Water Management Plan

SWMPPP – Storm Water Management Pollution Prevention Plan

TIMS – Transportation Information Management System

TMDL – Total Maximum Daily Load

UARF – University of Akron Research Foundation

US – United States

USEPA – United States Environmental Protection Agency

VaDOT – Virginia Department of Transportation

VJT – Vacuum Jet Truck

CHAPTER I – INTRODUCTION

The Ohio Department of Transportation (ODOT) is in charge of constructing, maintaining and ensuring the safety of roads within its control. ODOT is responsible for over 43,000 lane miles of roadway in Ohio. ODOT District 6, located in central Ohio, includes the city of Columbus and is accountable for 4,921 lane miles of roadway across eight counties. In fiscal year 2018, ODOT spent $2.3 billion on construction projects including $132.3 million on roadway maintenance and $20.4 million on culvert preservation projects. In addition, ODOT spent $581.7 million on pavement projects, some of which was caused by the impact water has on the pavement conditions (ODOT, 2018). Proper maintenance procedures are critical in reducing the amount of funding required to sustain long lasting and safe roads in Ohio.

One responsibility of ODOT is to maintain the storm sewer infrastructure along its roadways. If not properly maintained, storm sewers may become full of debris and flood the road with storm water, creating a safety hazard for the traveling public as well as negatively impacting the pavement condition. Standing water on the road surface reduces the visibility of lane striping, creates hydroplaning possibilities, and has the potential to cause lasting damage to the pavement. This damage may include cracks, potholes and washout, which may reduce the pavement lifespan (Thodesen & Hoff, 2010). For these reasons, effectively and efficiently removing debris from storm sewers is an essential part of any DOT maintenance plan. The purpose of this research is to determine if ODOT may improve their storm sewer cleaning operations through the use of better equipment.

1.1 Purpose and Objectives

This research team proposes that five objectives must be met in order to ensure that this project is considered a success. These five objectives include:

- Objective 1 – Complete a literature review and series of surveys, at both national and local levels, to help determine the state of practice in regards to the maintenance of storm sewers,
- Objective 2 – Review current ODOT operations using historical and current field data to create a current state of practice within ODOT,
- Objective 3 – Test and collect data on alternate equipment options available to ODOT,
- Objective 4 – Evaluate the differences in equipment operations including the cleaning effectiveness, production rate and associated costs, and
- Objective 5 – Develop a list of recommendations on equipment selection dependent on environmental, structural and operational factors.

The research team believes that meeting these objectives will result in a successful project.

1.2 Benefits from this Research

The research team believes that this study will result in benefits such as; greater storm sewer cleaning efficiency as well as the reduction in operational costs attributed to maintaining storm sewers. The increased cleaning efficiency is expected to increase the number of storm sewers that ODOT is able to maintain throughout the year. As a result, a decrease in road surface flooding may occur which would benefit the traveling public as safety and pavement conditions increase.

1.3 Organization of this Report

This report is divided into six chapters. Chapter I introduces the topic and includes a list of the research objectives. Chapter II presents the alternative equipment selection process. Chapter III explains the current state of practice. Chapter IV presents the historical and in-field data collected during this study. Chapter V presents a cost-benefit analysis of the production rate and economics of each piece of equipment. Chapter VI presents a series of case studies that the research team reviewed, including training and environmental setting implementation. In addition, Appendices at the end of the report include survey and testing data as well as testing photos.

1.4 Key Terminology

This section will provide definitions for key terminology that will be used throughout this report. The key terminologies are as follows:

- Storm sewer – The term "storm sewer" is used to describe any storm water drainage infrastructure evaluated in this study. Storm sewer structures include; catch basins, manhole vaults, plated drains, hydrodynamic separators and lateral lines,
- Vacuum jet truck (VJT) – The term vacuum jet truck (VJT) is used to describe the equipment that District 6 currently uses. The VJT is commonly referred to as a combination truck or vactor. The team notes that VACTOR is a brand name that has become synonymous with VJTs. Pictures of the VJT may be found in Figure 1, and
- Recycler – The term "Recycler" describes a piece of equipment that has VJT technology as well as the added capability of recycling wastewater and reusing it for jetting purposes. There are numerous Recycler manufacturers and models; however, the research team focused on the BUCHER RECycler 315 in this report. The Phase I report of this project *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* explains the decision to choose this piece of equipment. A full description of the Recycler may be found in Chapter III.

CHAPTER II – EQUIPMENT SELECTION

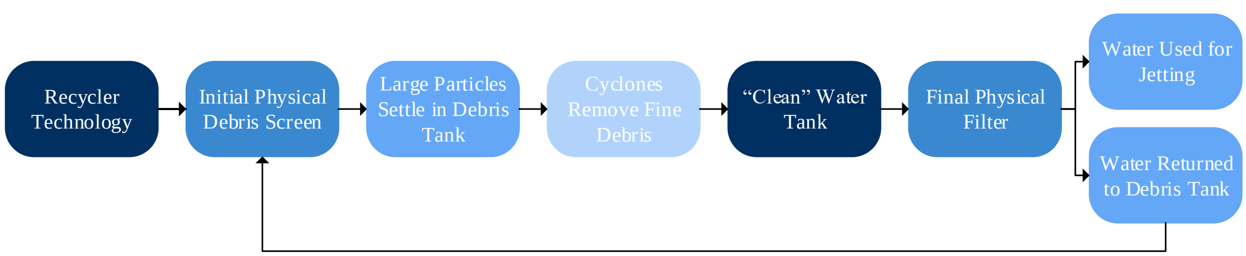
The research team completed a full equipment review in Phase I of this project *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* (Schneider et al., 2018) to determine which piece of alternative equipment to purchase. The team studied a series of equipment options that may be implemented to improve storm sewer cleaning operations in ODOT District 6. The options studied included; pump systems, runner trucks, water trucks, dewatering trucks and the Recycler. This chapter broken into four sections, as follows:

- <u>Section One</u> – Recycler overview,
- <u>Section Two</u> – Recycler options,
- <u>Section Three</u> – Recycler capital cost, and
- <u>Section Four</u> – Customer survey.

After reviewing all available options and the associated environmental regulations that may govern each, the team determined that the Recycler was the best option for District 6 to implement. In Phase I of this project, the research team completed demonstrations of the GapVax Recycler, BUCHER RECycler 315, Camel 1200 Recycler and Vactor 2100 Plus Recycler. After reviewing the Recycler options, the team chose to study the BUCHER RECycler 315 on a Kenworth T880 chassis further in Phase II of this project. Refer to the full Phase I report of this project: *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* (Schneider et al., 2018) for more information.

2.1 Recycler Overview

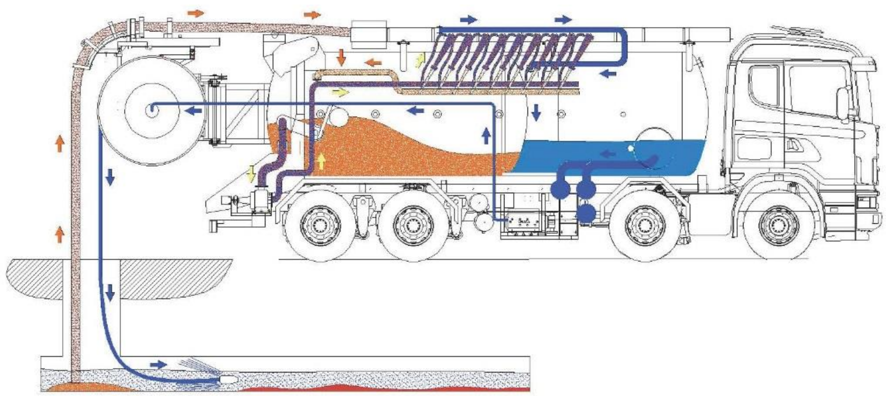
The Recycler is a new equipment technology that is similar in functionality to a VJT, but with a water recycling system built into the truck. The recycling system is used to filter the water removed from the storm sewer so that it may sufficiently be pumped and reused for jetting purposes. A visual representation of the treatment steps used by the recycling system may be found in Figure 2.1.



Note: The process shown is representative of the BUCHER RECycler 315.

Figure 2.1: Recycling Technology Process

The process described in this section is specific for the BUCHER RECycler 315; however, the principals are similar for most Recyclers. The system operates by first vacuuming debris/wastewater from the storm sewer where it enters the debris body after passing through a coarse filter that removes contaminants down to ¾" in diameter. The contaminants in the debris/wastewater then settle to the bottom of the debris tank while the top of the water column is transferred to the "clean" water tank through a series of nine cyclones. These cyclones operate without a filter by spinning the water to create a centrifugal force which is used to separate the solids from liquid. Figure 2.2 shows an illustration of the path of debris/wastewater as it travels through the BUCHER RECycler 315.



Note: Illustration obtained from BUCHER RECycler Brochure (JHL RECycler, 2017).

Figure 2.2: BUCHER RECycler 315 Illustration

The heavier solids travel downward and are transferred to the debris tank while the water, which may also contain particles with a density lighter than or close to the density of water, exits the top of the system and is transferred to the "clean" water tank. The final step of the recycling system sends the water through a final physical filter which is used to protect the pumps if any debris happened to make its way through the system. The water is then ready to be used for jetting or be recirculated into the debris tank where it re-enters the recycling system (Schneider et al., 2018).

2.2 Recycler Options

The team worked with the ODOT technical liaisons and BUCHER Municipal representatives to determine which feature would be best suited for the environmental setting in District 6. Optional features were based on the environment that the equipment would be operating in and the types of structures that it was expected to encounter. Table 2.1 lists the optional features that the technical liaisons chose to purchase with the Recycler to improve its operations specific to District 6.

Table 2.1: BUCHER RECycler 315 Optional Feature Selection

Item	Description
Air Compressor	Onboard air compressor used to pump air to end of vacuum hose to allow for deeper suction.
Snorkel Hose	Attachment to vacuum hose that allows compressed air to be pumped to bottom of structure at end of vacuum hose to allow for deeper suction.
Nozzle Set	Two 1/2" jet nozzles, two 3/4" jet nozzles and four 5/4" jet nozzles.
Jet Handle	Custom made jetting handle for 1/2" jet hose.

Note: The custom jet handle was fabricated by the research team and ODOT personnel.

As seen in Table 2.1, the Recycler purchased added a few optional features. The base model of the BUCHER RECycler 315 comes with most of the necessary features. In addition, the optional "winter package" was not purchased as the summer weather variant is able to operate in temperature as low as 35 degrees Fahrenheit.

2.3 Recycler Capital Cost

The research team purchased the Recycler at the start of the project in April 2018. The cost breakdown of the equipment and optional features is listed in Table 2.2.

Table 2.2: BUCHER RECycler 315 Capital Cost Summary

Item	Cost
RECycler 315	$575,000
Air Compressor	$10,000
Base Warranty	$2,600
Engine Warranty	$600
Aftertreatment Warranty	$1,905
Total	**$590,105**

Note: Recycler was purchased in April, 2018.

As seen in Table 2.2, the final cost of the Recycler was $590,105. This price included the optional air compressor and extended warranties. In addition to the cost of the Recycler, the research team and ODOT spent an additional $100 in parts to fabricate a custom jetting handle.

2.4 Customer Survey

The research team completed a customer survey of DOTs, contractors and other agencies that have purchased a BUCHER Recycler. The purpose of the survey was to determine how other customers implemented the Recycler into their existing fleet. Similarly, the team wanted to determine if there were any unique ways, settings or structures that the equipment may be implemented on. In addition, the team wanted to see if the production rate estimates produced by the model was similar to other customer experience. Many of BUCHER's current customers are located in Europe where the Recycler technology started. The team made their best effort to survey customers whose environment, regulations and economic factors were similar to the United States and Ohio specifically. Table 2.3 shows a summary of the results of the customer survey.

Table 2.3: Customer Survey Key Findings

Customer Survey		
Reason Selected		
	Recycling Option	75% of Customers
	Vacuum Power	25% of Customers
Production Rate Increase		
	25% Increase	25% of Customers
	60-70% Increase	25% of Customers
	Unsure/No Response	50% of Customers
Standard of Cleanliness Compared to Traditional VJT		
	Similar Standard	75% of Customers
	No Response	25% of Customers
Year Purchased		
	2015	25% of Customers
	2017	25% of Customers
	2018	50% of Customers
Additional Options Purchased		
	Additional Nozzles	25% of Customers
	None	75% of Customers
Structures Cleaned		
	Sanitary Sewers	43% of Customers
	Storm Sewers	57% of Customers
Problem Debris		
	Rags	25% of Customers
	Fine Silt	25% of Customers
	No Response	50% of Customers
Number of Operators		
	1	25% of Customers
	No Response	75% of Customers
Flood Event Prevention		
	Equipment has Prevented Flood Events	50% of Customers
	Equipment has not Prevented Flood Events	50% of Customers
Maintenance Cost Comparison		
	Higher than Standard VJT	75% of Customers
	Unsure	25% of Customers
Operating Cost Comparison		
	Same as Standard VJT	25% of Customers
	Unsure	50% of Customers
	No Response	25% of Customers
Current and Expected Savings		
	25% Savings in Labor	25% of Customers
	Unsure	75% of Customers

Note: The research team successfully surveyed four customers. Survey was conducted in the fall of 2018.

As seen in Table 2.3, the customers surveyed had overall positive comments on the Recycler. All customers said that they saw some form of production improvement, although some did not have specific numbers reported. Half of the customers surveyed used the equipment on similar structures to ODOT, such as storm sewers. Of the customers that responded, all said that they saw a savings in labor but increase in maintenance costs.

The purpose of this report, and the following chapters, is to verify through field testing that the Recycler is a viable option for ODOT District 6 to implement in its equipment fleet. Due to the increased capital cost of the Recycler over traditional equipment, an increase in the production rate is required to offset the initial capital costs. In addition, the team used customer survey information to better implement the Recycler in ODOT's existing fleet and learn from their mistakes. Appendix A includes a summary of additional Recycler options available.

CHAPTER III – STATE OF PRACTICE

The goal of this chapter is to present an overview of the current practices implemented by ODOT District 6, national DOTs outside of District 6 and other ODOT Districts. The team developed the current state of practice by conducting phone surveys and discussions with District 6 personnel. This chapter is broken into three sections, which include:

- Section One – District 6 operations,
- Section Two – National DOT survey, and
- Section Three – ODOT District survey.

In this chapter the research team first established a baseline of traditional methods that District 6 implements to maintain storm sewers. The team then conducted a national DOT and ODOT District phone survey to compare District 6 operations to.

3.1 District 6 Operations

The research team began by reviewing the first phase of this project, *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* (Schneider et al., 2018). The team completed a full review of ODOT's current state of practice over a six-month timeline during Phase I. Key ODOT personnel were interviewed and the equipment was shadowed to observe operations. The team found that ODOT District 6 currently uses two VJT's to clean storm sewers. The VJT is able to both vacuum debris from the structure and jet the lateral lines that branch from the access point. Figure 3.1 shows the current VJT systems used in District 6.

(a) (b)

Note: Pictures taken in summer 2018 by the research team in ODOT District 6.

Figure 3.1: Current VJTs. (a) Vac-Con VJT, (b) Vactor 2100 VJT.

The VJT operates by combining the use of the vacuum and jetting system to remove and loosen debris that has filled the storm sewer structure. The VJT starts by vacuuming the debris/wastewater from the top of the water column if present. The operator typically would vacuum the structure until they were able to reach the bottom of the structure where they would access the lateral lines that branch off of the main structure. Next, the operator uses high pressure water jetting system to loosen any remaining debris. If there is no standing water or debris present, the operator may then start by jetting the lateral lines immediately. While the structure is being cleaned, the vacuum system remains engaged so that any water jetted may be collected and stored in the debris tank onboard the truck so that it may be disposed of at an approved facility. The two most important characteristics of the VJT are the debris and water capacity, summarized in Table 3.1.

Table 3.1: Current VJT Specifications

Description	Description	Specifications
Debris Capacity (cy)	Vac-Con	9
	Vactor	15
Water Capacity (gal)	Vac-Con	1,500
	Vactor	1,500

Note: Information gathered in Summer 2017 during demonstration setup by ODOT District 6.

Even though the VJT is the industry standard, there are numerous disadvantages when it comes to using it to clean storm sewers. The VJT has a limited water capacity that may be used for jetting, which sometimes requires the VJT to make numerous trips to refill water in a single shift. In addition, the VJT may quickly fill its debris tank with debris/wastewater and need to make a trip to an approved facility to dump the tank which may take over two hours.

The time associated with tasks not related to cleaning storm sewers, such as refilling water and dumping debris/wastewater, reduces the amount of productive time cleaning storm sewers. Table 3.2 summarizes the key advantages and disadvantages of the VJT, determined through field observations and discussions with the technical liaisons.

Table 3.2: Advantages and Disadvantages of Vacuum Jet Truck

Advantages	Disadvantages
Industry leader in storm sewer maintenance	Low water capacity requires trips to refill water
Years of field use to improve technology	Low debris/wastewater capacity requires trips to approved dump facility
Operator friendly and well known throughout almost every DOT in the nation	Large, rigid vacuum hose limits accessibility in certain structures
Common replacement parts and known maintenance solutions	Vacuum unable to pull from bottom of water column
Relatively low capital costs	Relatively high operational costs

Note: Some advantages and disadvantages are specific to ODOT District 6 and may not apply in all cases.

As seen in Table 3.2, the VJT has the advantage of being an industry standard piece of equipment. However, its disadvantages have historically limited its effective use in District 6.

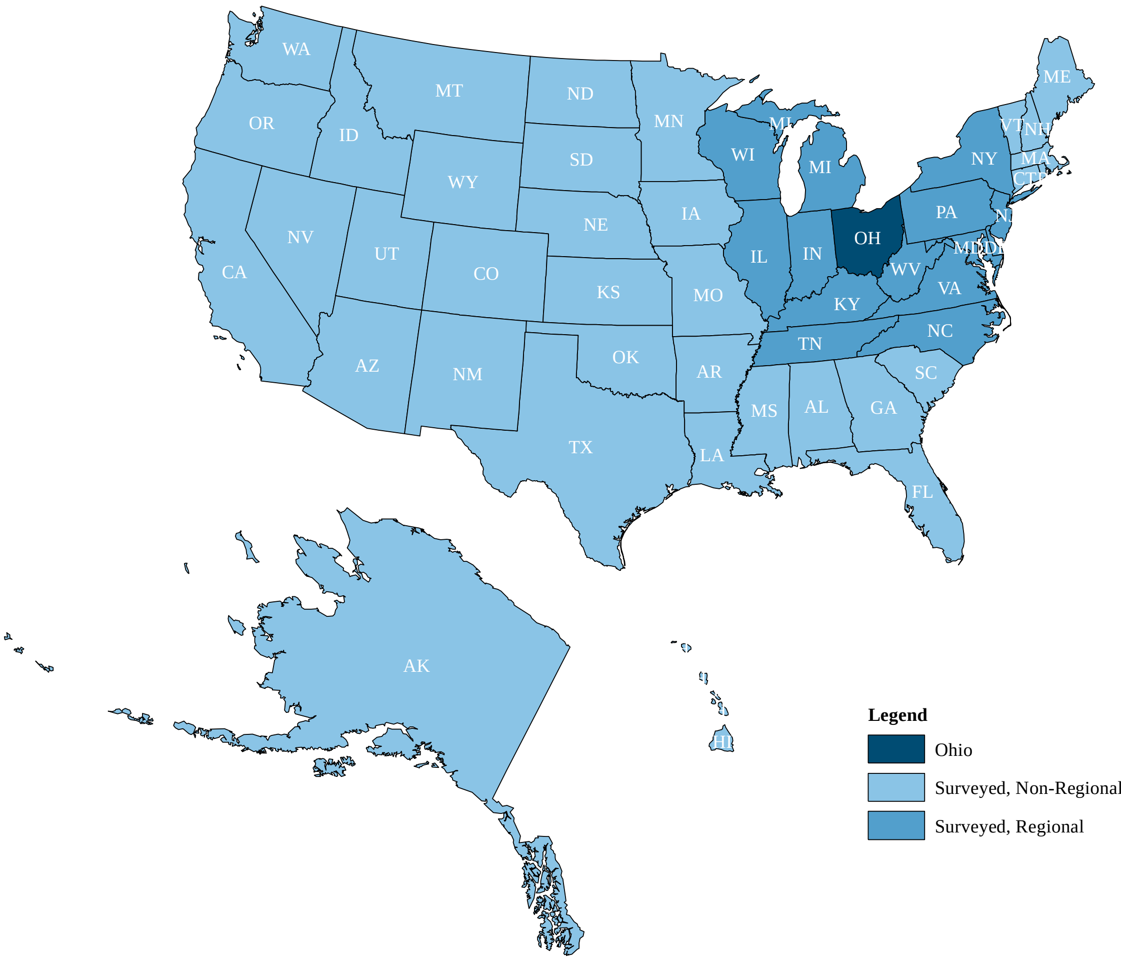
The information gathered in the state of practice was used to help develop the economic and production rate models used in this study. This information also helped the team develop a list of questions to ask in the national and ODODT District surveys. Surveys were completed in order to ensure that the practices used in ODOT District 6 are similar to those elsewhere in ODOT and the nation. These surveys are important in determining if the results of this study are applicable to other state DOTs and contractors.

3.2 National Survey

The national survey was conducted with the intention of establishing a baseline set of data in which the BUCHER RECycler 315 may be compared against. The goal of the survey was to obtain nationwide information on topics such as:

- Equipment used,
- Cleaning effectiveness,
- Cleaning production rates,
- Maintenance costs, and
- Operational costs.

This information allowed the research team to determine if the results of this study are applicable outside of ODOT District 6. Figure 3.2 presents the states in which the research team received responses.



Note: Surveyed completed in the summer of 2018. Map generated in ArcGIS.

Figure 3.2: States Surveyed in National Survey

As presented in Figure 3.2, the research team successfully surveyed all 49 states outside of the state of Ohio. The team received two responses from Indiana, Massachusetts, Pennsylvania and Virginia and four responses from Oregon, for a total of 56 responses. The team received multiple responses from some states as some survey respondents returned calls after another state representative completed the survey. In order to not selectively remove responses, the team included all responses received. Table 3.3 shows a summary of the responses received from the national survey.

Table 3.3: National Survey Key Findings

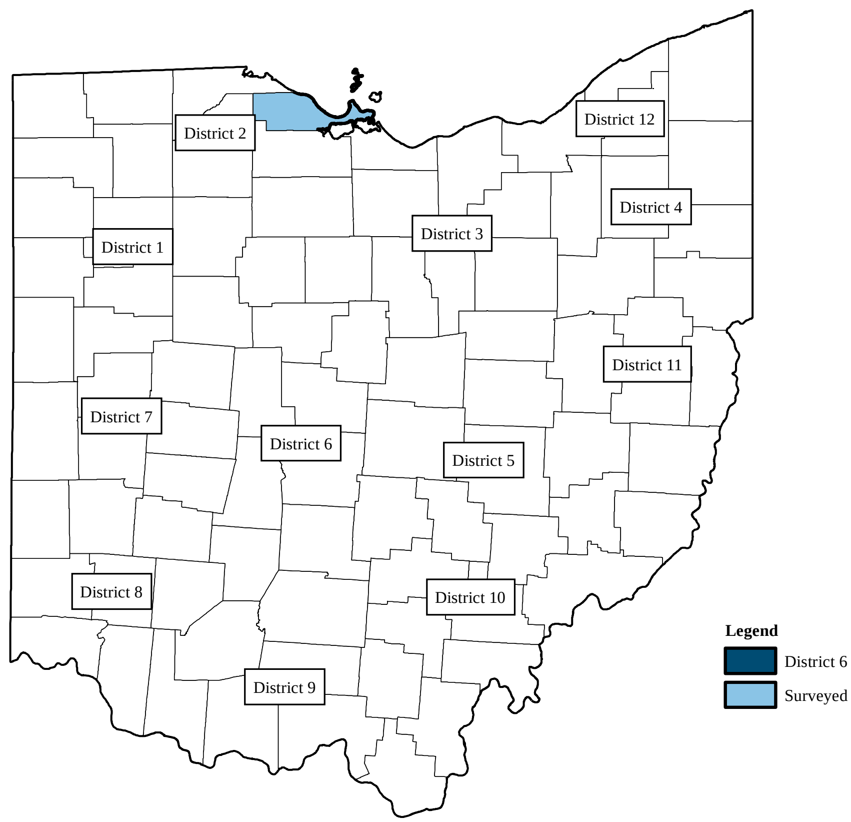
National Survey		
Equipment Utilized		
	Vacuum Jet Truck	57% of DOTs
	Recycler	3% of DOTs
	Other / Unsure	40% of DOTs
Cleaning Production Rate		
	< 5 Structures	14% of DOTs
	5-10 Structures	13% of DOTs
	> 10 Structures	27% of DOTs
	Other / Unsure	46% of DOTs
Equipment Age		
	< 10 Years	25% of DOTs
	> 10 Years	16% of DOTs
	Other / Unsure	59% of DOTs
Number of Operators		
	1-2 Operators	34% of DOTs
	3-4 Operators	30% of DOTs
	> 4 Operators	20% of DOTs
	Other / Unsure	16% of DOTs
Frequency of Site Departures		
	< 1 / shift	32% of DOTs
	1-2 / shift	18% of DOTs
	> 2 / shift	13% of DOTs
	Other / Unsure	38% of DOTs
Maintenance Schedule		
	Daily / Weekly	24% of DOTs
	Monthly	9% of DOTs
	Annually / Need Based	41% of DOTs
	Other / Unsure	27% of DOTs
Current / Expected Maintenance Costs		
	< $10,000 / year	11% of DOTs
	$10,001-$50,000 / year	5% of DOTs
	> $50,000 / year	2% of DOTs
	Other / Unsure	82% of DOTs

Note: The research team surveyed all 49 states outside of Ohio. Full state responses may be found in Appendix E. The research team spoke with state DOT district and regional equipment managers. Multiple responses recorded refers to survey respondents having multiple responses for a single question (i.e. district/garage owns two different pieces of equipment, multiple sized structures are cleaned, etc.).

As seen in Table 3.3, the majority of national DOT's implement the use of a VJT to clean storm sewers with limited use of the Recycler technology. Most DOT VJT's are under ten years old and use between one and two operators. VJT maintenance typically costs under $10,000 per VJT per year nationwide. These results are important as they verify that the field data collected and used in the production rate and economic models is comparable to other DOT operations.

3.3 ODOT District Survey

The research team used the same questions asked during the national survey when interviewing ODOT District personnel. The goal of the ODOT District survey was to determine if there were similar practices to District 6 used elsewhere or if operations may be improved. The team added some additional questions to the ODOT District survey that would capture data relevant to District 6 operations due to their close geographic locations. The survey successfully captured 16 responses from Districts outside of District 6. The Districts surveyed may be found in Figure 3.3.



Note: Surveyed completed in the summer of 2018. Map generated in ArcGIS.

Figure 3.3: Districts Surveyed in ODOT Survey

As seen in Figure 3.3, the research team successfully surveyed all 11 ODOT Districts outside of District 6. The team received four responses from District 4 and two each from District's 5 and 7. Similar to the national survey, some Districts have multiple responses due to representatives returning responses after another representative had already completed the survey. The key findings associated with the ODOT District survey may be found in Table 3.4.

Table 3.4: ODOT District Survey Key Findings

ODOT Survey		
Equipment Utilized		
	Vacuum Jet Truck	89% of Districts
	Other / Unsure	11% of Districts
Cleaning Production Rate		
	< 5 Structures	25% of Districts
	5-10 Structures	31% of Districts
	> 10 Structures	19% of Districts
	Other / Unsure	25% of Districts
Equipment Age		
	< 10 Years	56% of Districts
	> 10 Years	19% of Districts
	No Response	25% of Districts
Number of Operators		
	1-2 Operators	44% of Districts
	3-4 Operators	19% of Districts
	> 4 Operators	13% of Districts
	Other / Unsure	24% of Districts
Frequency of Site Departures		
	Seldom	56% of Districts
	Often	19% of Districts
	Other / Unsure	25% of Districts
Maintenance Schedule (Multiple Responses Recorded)		
	Monthly	5% of Districts
	Annually / Need Based	68% of Districts
	Other / Unsure	27% of Districts
Current / Expected Maintenance Costs		
	Less than $10,000 / year	6% of Districts
	$10,001-$50,000 / year	31% of Districts
	Greater than $50,000 / year	6% of Districts
	Other / Unsure	57% of Districts

Note: The research team surveyed all 11 districts outside of District 6. Full district responses may be found in Appendix E. The research team spoke with district and regional equipment managers. Multiple responses recorded refers to survey respondents having multiple responses for a single question (i.e. district/garage owns two different pieces of equipment, multiple sized structures are cleaned, etc.).

As seen in Table 3.4, almost every ODOT District responded that they use a VJT to clean storm sewers. The majority of ODOT Districts clean between five and ten structures per shift. As mentioned in section 3.2, most ODOT VJT's are less than ten years old and use between one and two operators. VJT maintenance regionally, is typically addressed as needed at a cost of $10,000 to $50,000 per year per VJT. The majority of Districts stated that the annual operational costs were less than $20,000 per year per VJT. This information will be used in conjunction with the national survey results to verify the field data used in the production rate and economic models is comparable to other Districts.

CHAPTER IV – DATA COLLECTION

The purpose of this chapter is to outline the types of data that were collected throughout this study and present the field data. This chapter is broken into three main sections, including information for both the VJT and Recycler. The sections are defined as follows:

- Section One – Testing methodology,
- Section Two – Equipment testing, and
- Section Three – Operator feedback.

The team completed data collection in the summer and fall of 2018. In addition, the research team obtained historical data on the VJT operations from the ODOT technical liaisons.

4.1 Testing Methodology

The research team began by developing a testing protocol that may be used to ensure valid data are collected across all equipment, environment and structure types. The team worked with the ODOT technical liaisons to develop the testing schedule and referenced outside studies and research for verified techniques. The research team began by reviewing literature that conducted testing on similar structures, equipment and/or environments. The goal of this portion of the literature review was to confirm that the methodology the team developed was comparable to previous studies methodology. Table 4.1 outlines the key findings of the testing methodology literature review.

Table 4.1: Testing Methodology Literature Review Key Findings

Material Evaluated	Evaluation Application	Findings	Reference
Evaluation of New Technology in Culvert Cleaning	Tunnel mucker system demonstrated a 79% reduction in costs when compared to the use of typical vacuum truck systems.	Caltrans evaluated the tunnel mucker system with production data collected over 599 days compared to baseline data collected from VJT operations.	Clark, 2012
Evaluation and Development of High Flow Vacuum Systems for Roadway and Roadside Litter Collection	Caltrans evaluated a tele-robotic system that allows VJT operators to control the nozzle from within the truck cab.	Caltrans compared the cleaning effectiveness and accuracy of the robotic system with baseline data collected from standard VJT operations.	Clark, 2014
Catch Basin Inlet Cleaning Pilot Study: Final Report	The city of San Diego compared manual and VJT cleaning methods of catch basins to evaluate cleaning method's effect on pollutant concentration	The city of San Diego cleaned structures both manually and with a VJT and recommended the VJT for dealing with standing water in basins.	Tetra Tech, 2012

Material Evaluated	Evaluation Application	Findings	Reference
Analysis of the Environmental Advantages of the Bluewater Recycler Truck	The CO_2 emissions of the Bluewater Recycler were estimated from travel logs and compared to standard VJTs.	Detailed travel and activity logs for the Recycler illustrated an increase in productivity compared to standard VJTs.	Douglas, 2008
Effective and Efficient Roadside Ditch Cleaning	Field testing of the Ditchmaster 800 in ODOT demonstrated higher production rates and less environmental drawbacks than conventional methods.	Field data collected included crew size, test location, weather conditions, structure dimensions, time logs, and reasons for stopping and measured productivity in structures/time.	Elzarka, 2017

Note: Limited research on the Recycler itself is available due to the new nature of the technology.

As seen in Table 4.1, the team found research that studied similar structures cleaning operations with different equipment. These studies were used to evaluate the methodology developed for this report. The research team also reviewed previous research that relates to the maintenance of storm sewers, culverts, pipes and underdrains in order to determine an acceptable number of data points to collect to assess equipment and operational performance. A table of key findings was developed and may be found in Table 4.2.

Table 4.2: Field Data Sample Size Literature Review Key Findings

Material Evaluated	Evaluation Application	Findings	Reference
Evaluation of New Technology in Culvert Cleaning	Tunnel mucker system demonstrated a 79% reduction in costs compared to the use of VJT systems.	Caltrans selected the tunnel mucking system based on 41 cleanings during a 599 day period.	Clark, 2012
Risk Assessment and Update of Inspection Procedures for Culverts	ODOT created a culvert inspection rating system in 2003 in its Culvert Inspection Manual.	ODOT created its culvert rating system based on inspections of 60 culverts across 8 of 12 ODOT districts.	Mitchell, 2005
Evaluation of Box Culvert Maintenance Methods	The MT 3234 tunnel mucker was evaluated by cleaning seven culverts in Mahoning and Columbiana Counties.	The study identified an inventory of culverts accessible to the MT 3234 based on certain physical properties and the ODOT TIMS database.	Miller, 2015
Drain Inlet Cleaning Efficacy Study	An evaluation of the Caltrans drainage cleaning program.	Caltrans recorded cleaning data from 54 drain inlets during the 2000-2001 cleaning season.	Caltrans, 2003
Evaluation of Modified Cleaning System for Pipes and Underdrains	A custom “Modified Cleaning System” was developed to increase cleaning production rate of pipes and underdrains.	The study found that a custom made “Modified Cleaning System” may be more cost beneficial than a VJT after testing 60 of 76 structures.	Schneider, 2018

Note: This literature review focused on similar studies that were approximately the same duration to compare to, a single cleaning season.

As seen in Table 4.2, the research team reviewed five reports that related to the maintenance of similar structures that were tested in this report. The team found that for studies that were conducted over a single cleaning season, the number of data points ranged from seven to 60. Table 4.3 summarizes the findings.

Table 4.3: Summary of Culverts Evaluated in Previous Research

Study	Reference	Count
Evaluation of New Technology in Culvert Cleaning	Clark, 2012	41
Risk Assessment and Update of Inspection Procedures for Culverts	Mitchell, 2005	60
Drain Inlet Cleaning Efficacy Study	Caltrans, 2003	54
Evaluation of Box Culvert Maintenance Methods	Miller, 2015	7
Effective and Economical Cleaning of Pipes and Underdrains	Schneider, 2018	60
Average		**44**
Evaluation of ODOT's Current Storm Sewer Cleaning Operations		**72**

Note: Count refers to the number of structures that were evaluated in each study.

As seen in Table 4.3, the five reports that studied a similar problem averaged just over 44 structures evaluated. The team successfully observed 72 structures during this study, 28 more than similar studies on average. During equipment testing, the team collected data such as locations, timing of operations and environmental factors. Table 4.4 lists a summary of the data collected during field testing.

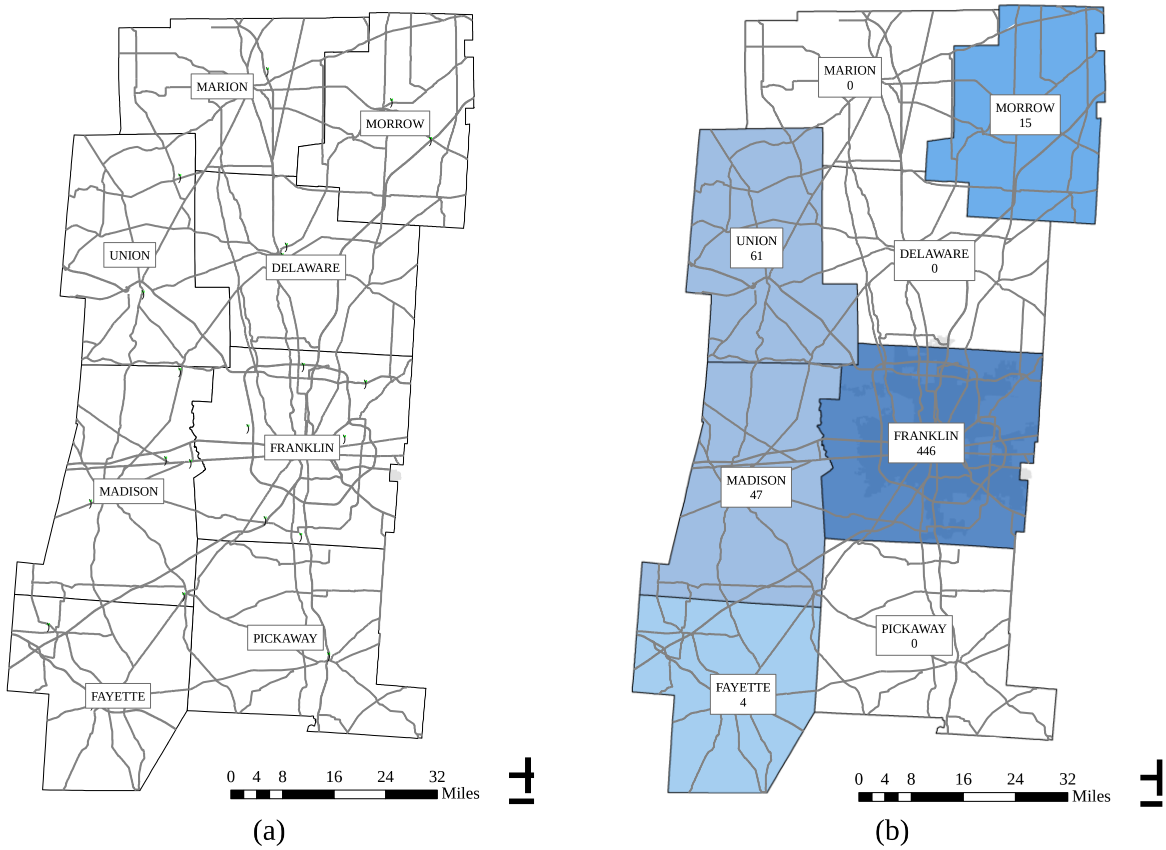
Table 4.4: Field Data Collection Summary

Category	Item	Notes
Location Information	County	County structure is located in
	Road	Road structure is located on
	Mile marker	State and county mile marker structure is located nearest
	Coordinates	Latitude and longitude of structure
Environmental Information	Precipitation	Sunny, cloudy, light rain, heavy rain or snow
	Visibility	Excellent, satisfactory or poor
	Road Type	Highway, arterial or residential
	Surrounding Environment	High or low density of structures
Timing Information	Arrival, Start, End, Departure and Task Time	Time and description of maintenance steps
Structure Information	Blockage Type	Grease, sand/dirt/clay, roots, large debris or other
	Structure Type / Size	Type of structure and opening size
	Water / Debris Use	Amount of water and debris used
	Recycling Use	Recycling system was used
	Reason to Leave	Water trip, decant trip, finish cleaning, etc.

Note: See Appendix D for more information on field data collection sheet.

As seen in Table 4.4, the team collected data on a total of 14 items across four categories. The majority of data collection occurred in the timing information category. The timing data collected is what the team used to calculate the average times of certain tasks for each piece of equipment. The timing information is the main variable in which the model uses to estimate the production rates and the economic analysis as seen in Equations 5.1 through 5.9.

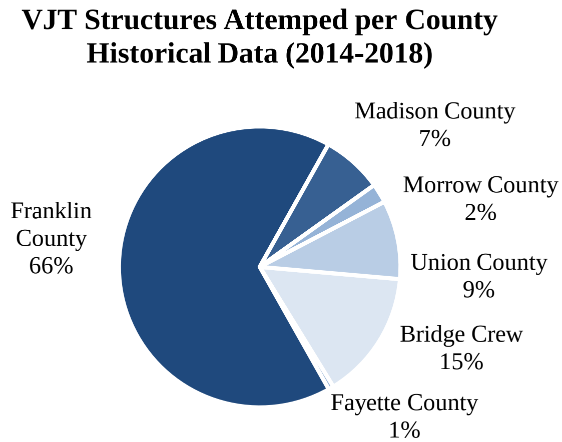
The ODOT technical liaisons provided the research team with five years of historical data dating to 2014. The data were obtained using the Enterprise Information Management System (EIMS) to find Work Orders (WO) by day. Figure 4.1 shows the District 6 facilities and historical VJT operational locations by count.

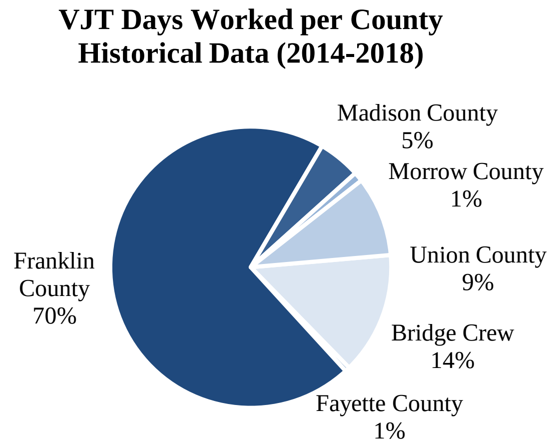


Note: Historical data from 2014-2018 (as of 06/27/2018). Map generated in ArcGIS.

Figure 4.1: Testing Locations (a) ODOT facility locations represented as green squares, (b) Historical VJT use locations

As seen in Figure 4.1, the large majority of VJT operations occurred inside Franklin County since 2014. Figure 4.2 presents a summary of the number of times the VJT operated in each county since 2014.





Site	Structures Attempted	Days Worked	Average Structures/Day
Bridge Crew	100	26	4
Fayette County	4	1	4
Franklin County	446	130	3
Madison County	47	9	5
Morrow County	15	2	8
Union County	61	17	4
Total	**673**	**185**	**4**

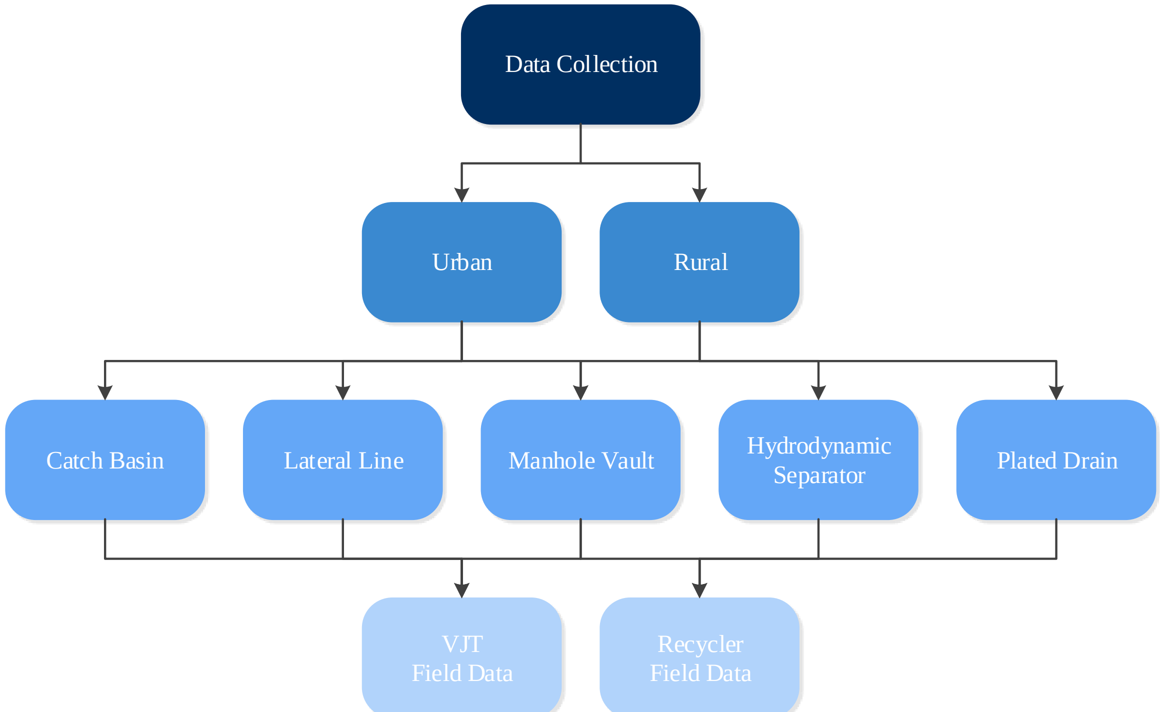
Note: Data obtained from ODOT. Includes data from 2014-2018 (as of 06/27/2018). Grove City, Hilliard and Westerville Outposts were assumed to operate in Franklin County. Mount Sterling Outpost was assumed to operate in Madison County.

Figure 4.2: Historical Structures Attempted per County (2014-2018)

As seen in Figure 4.2, the majority of VJT use occurred in Franklin County due to the VJT being stored there. The Bridge Crew, Fayette, Madison, Morrow and Union Counties make up a small portion of the VJT use that accounts for roughly 30-34% of the structures attempted and/or days worked. The historical information may be used to validate that the testing locations used in this study are comparable to where the VJT traditionally operates. In addition, the team may also confirm that the field data values are similar to previous years and that the model generates an estimate that is similar to the historical production rate.

Franklin County saw the most VJT instances due to the high concentration of storm sewers in along the Interstates surrounding the city of Columbus. The other two counties that saw a relatively larger portion of the VJT operations were in low density settings in Union and Madison Counties. These results informed the research team on where the appropriate testing locations should occur based on historical data.

The research team used the literature review and historical data to develop a testing methodology that determined where to clean structures. The team determined that the field testing should have a similar location makeup as the historical data. This means that the majority of testing occurs in Franklin County with additional testing occurring in both Madison and Union Counties. In addition, the type of structure should be similar to what is represented through each county. Additionally this also means that Franklin County would primarily clean catch basins while Madison and Union Counties would clean heavily lateral lines. The team determined that testing approximately equal between the VJT and Recycler would allow for a fair comparison. Figure 4.3 shows the breakdown in equipment testing.



Note: See following sections for information on environmental setting and structure type.

Figure 4.3: Data Collection Technique

As seen in Figure 4.3, the data is first split between high and low density settings. Next, the type of structure is taken into consideration based on the type of setting. Finally, the equipment used to test that setting and structure is determined.

The team notes that the largest factor in determining the testing schedule was ODOT's schedule. The team had to work with the technical liaisons to schedule the operators and equipment to match the methodology as closely as possible. In some instances, due to scheduling conflicts, equipment availability and/or emergency operations, the team had to collect data that did not match historical records exactly. Each of the layers in Figure 4.3 represent the following three sections.

4.1.1 *Setting Type*

The research team completed data collection for a total of 72 structures, split between the Vac-Con, Vactor 2100 and BUCHER RECycler 315. In addition to the 72 structures that data was collected for, an additional 47 structures were inspected but determined to not need cleaned. In total the research team was present for 119 structure inspections. Table 4.5 shows a summary of the testing dates, locations and equipment tested.

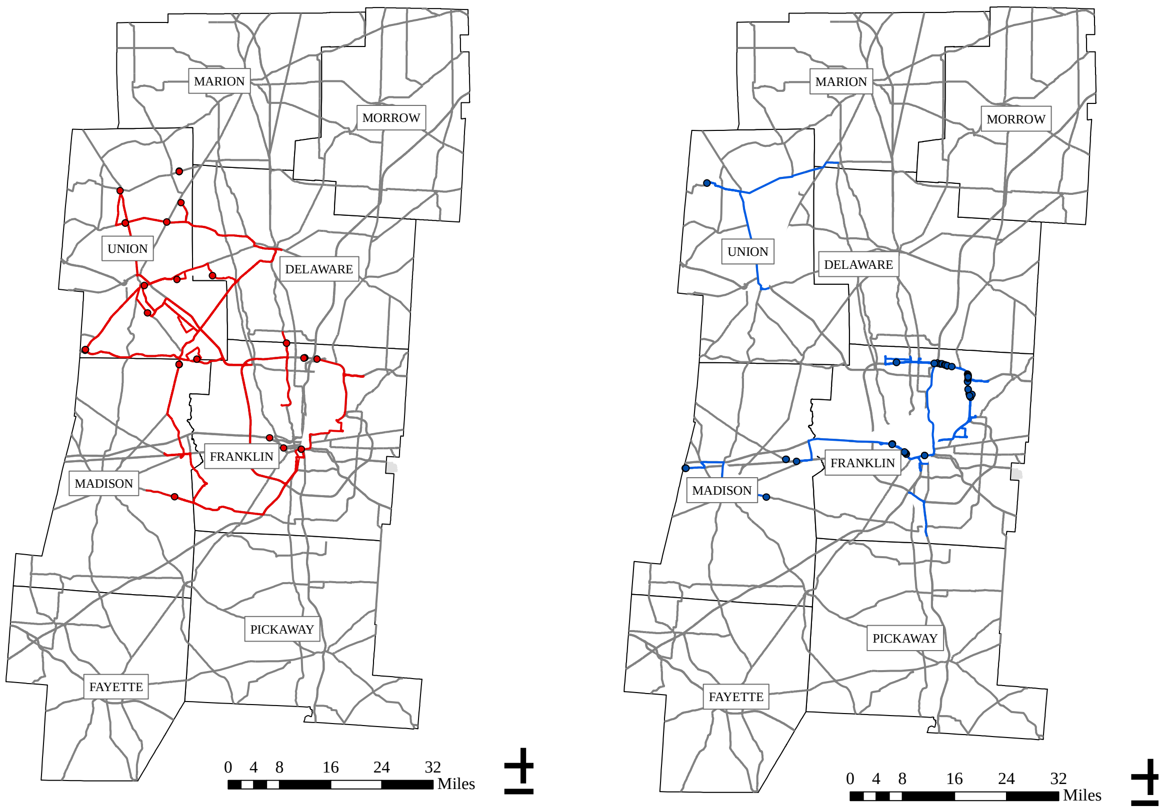
Table 4.5: Testing Location Summary

Date	Location	Task	Testing Samples
06/25/2018	Union County	VJT Testing	3
	Franklin County	VJT Testing	1
06/26/2018	Madison County	VJT Testing	4
06/27/2018	Union County	VJT Testing	5
06/28/2018	Madison County	VJT Testing	2
	Union County	VJT Testing	4
06/29/2018	Union County	VJT Testing	4
07/03/2018	Union County	VJT Testing	2
07/09/2018	Franklin County	Recycler Training	N/A[1]
07/10/2018	Franklin County	Recycler Training	N/A[1]
07/11/2018	Franklin County	Recycler Training	N/A[1]
07/16/2018	Franklin County	Recycler Testing	5
07/17/2018	Franklin County	VJT Testing	1
		Recycler Testing	1
07/18/2018	Franklin County	Recycler Testing	1
07/19/2018	Franklin County	VJT Testing	2
		Recycler Testing	2
08/22/2018	Franklin County	Recycler Testing	1
08/28/2018	Franklin County	Recycler Testing	1
08/30/2018	Madison County	Recycler Testing	2
09/25/2018	Union County	Recycler Testing	1
09/26/2018	Franklin County	Recycler Testing	3
09/27/2018	Madison County	Recycler Testing	1
10/02/2018	Franklin County	VJT Testing	1
		Recycler Testing	2
10/03/2018	Franklin County	VJT Testing	2
		Recycler Testing	1
10/04/2018	Franklin County	Recycler Testing	5
10/06/2018	Franklin County	VJT Testing	1
		Recycler Testing	4
10/09/2018	Franklin County	Recycler Testing	7
10/11/2018	Madison County	Recycler Testing	3

Note: (1) Testing sample is not applicable due to operator training. See Appendix C for detailed list of data collection.

As seen in Table 4.5, the team conducted 25 days of testing and site visits during the summer and fall of 2018. All testing occurred in Franklin, Madison and Union counties which is similar to the historical data.

These 25 days did not include the days spent training or days in which testing was canceled due to emergency maintenance work elsewhere in the District. The research team had to work within District 6's existing schedule while not interrupting operations. Refer to Appendix C for more information on the field testing data. Figure 4.4 shows the testing locations for each category of equipment.

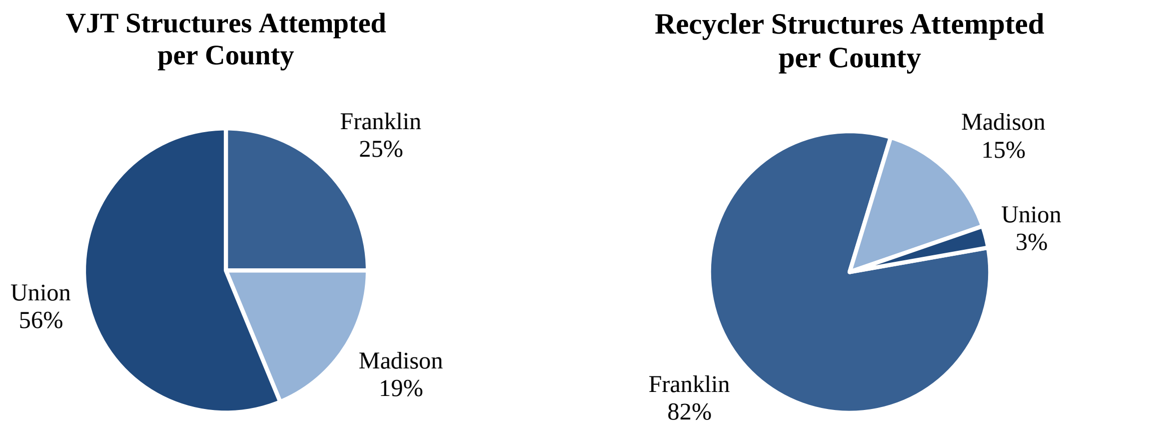


(a) (b)

Note: Testing was conducted Summer and Fall of 2018. Map generated in ArcGIS.

Figure 4.4: Testing Locations (a) VJT test locations, (b) Recycler test locations

As seen in Figure 4.4, the project setting, located in ODOT District 6, comprised of eight counties; Delaware, Fayette, Franklin, Madison, Marion, Morrow, Pickaway and Union. This research focused on Franklin, Madison and Union Counties specifically as discussed in the historical data section previously. Figure 4.5 breaks down the testing locations by county.



County	Structures Inspected	Structures Attempted	Structures Trained
Franklin	76	41	4
VJT	14	8	0
Recycler	62	33	4
Madison	21	12	0
VJT	6	6	0
Recycler	15	6	0
Union	22	19	0
VJT	21	18	0
Recycler	1	1	0
Total	**119**	**72**	**4**

Note: Structures inspected refers to structures that were evaluated for cleaning but were already clean

Figure 4.5: Structures Attempted per County

As seen in Figure 4.5, the majority of testing for the VJT occurred in Union County with the remaining testing split between Franklin and Madison Counties. The majority of testing for the Recycler occurred in Franklin County with some occurring in Madison and Union Counties. Due to operator training requirements, District 6 based the truck out of the Franklin County Westerville garage. This allowed for ODOT to only train two operators. For this reason, more Recycler testing occurred in Franklin County than for the VJT. Overall, the testing locations occurred where ODOT scheduled based on reported blockages, emergency flooding and operator scheduling; however, the testing locations are consistent with where the VJT operated traditionally based on historical data.

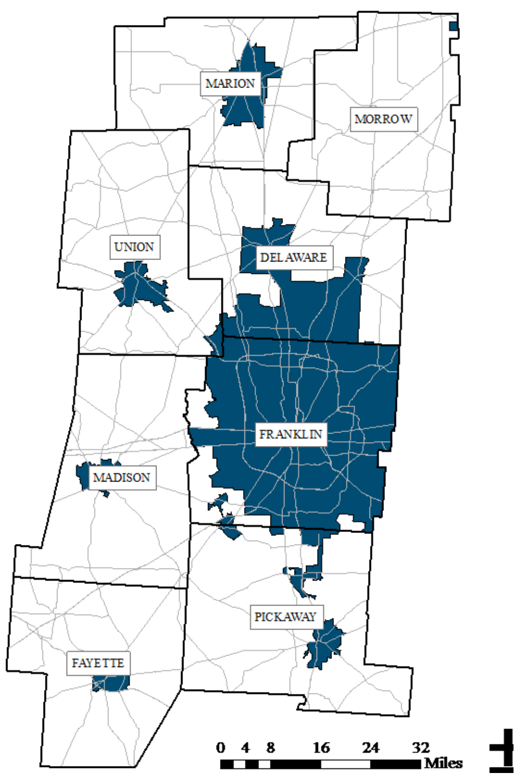
The type of setting in which the equipment was observed correlates closely to the counties in which they were tested. The majority of counties in District 6 are low density in nature, including; Fayette, Madison, Marion, Morrow, Pickaway and Union. Inversely, Delaware and Franklin Counties are more high density settings with Franklin County being the location of the city of Columbus. Examples of the different types of setting classifications may be found in Figure 4.6, as defined by the research team.

(a) (b)

Note: Pictures taken by research team in the summer and fall of 2018.

Figure 4.6: Setting Type Classifications (a) Low density setting (b) High density setting

As seen in Figure 4.6, the two classifications of setting types were in stark contrast to one another. The low density setting included sparsely located storm sewers-often with severe clogs-and long trips to refill and decant. The high density setting had closely located structures with long lateral lines and narrow work zones; however, limited access roads sometimes lengthened refill and decant trip times as well. Figure 4.7 shows the defined urban outlines of the high density areas in District 6.

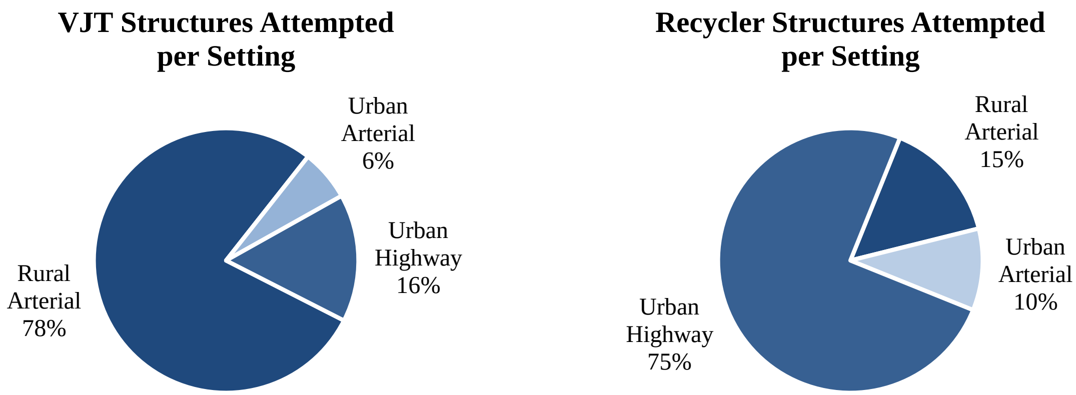


(a) (b)

Note: Testing was conducted the summer and fall of 2018. Map generated in ArcGIS.

Figure 4.7: District 6 Urban Outline

As seen in Figure 4.7, the majority of the high density areas in District 6 occur in Franklin County. The city of Columbus is located in Franklin County which is the largest city in Ohio. The remaining counties in District 6 are relatively low density in nature. The breakdown of testing locations based on setting type may be found in Figure 4.8.



Environment	Road Type	Equipment	Structures Attempted
Low Density	Arterial	VJT	25
		Recycler	6
	Highway	VJT	0
		Recycler	0
High Density	Arterial	VJT	2
		Recycler	4
	Highway	VJT	5
		Recycler	30
Total			**72**

Note: Environmental settings were judged at the discretion of the observer.

Figure 4.8: Structure Attempted per Setting

As seen in Figure 4.8, the low and high density environments were broken down further into road types. The road types included arterials and highways. This information allowed the team to see if there was any difference between low and high volume roads.

4.1.2 Structure Type

The type of structure that was cleaned during each test event was also collected. Each structure was identified as either a lateral line, catch basin, manhole vault, hydrodynamic separator or plated drain. Examples of each type of structure may be found in Figure 4.9.


(a)

(b)

(c)

(d)

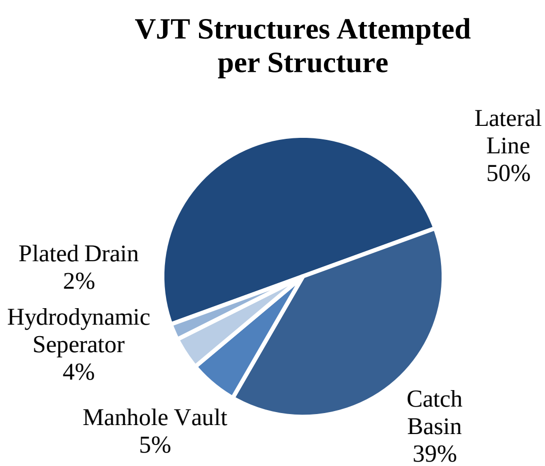
(e)

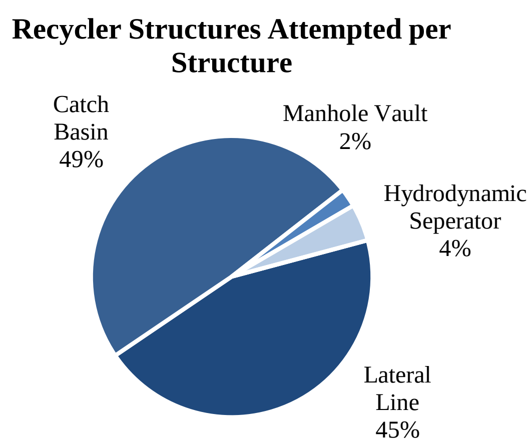
(f)

Note: Pictures taken by the research team in the summer of 2018.

Figure 4.9: Structure Type Classifications (a) Lateral line inside of catch basin, (b) Lateral line emptying, into catch basin, (c) Catch basin, (d) Manhole vault, (e) Hydrodynamic separator, and (f) Plated drain.

As seen in Figure 4.9, structures such as the catch basin and manhole vault are similar in depth and shape. Likewise, structures such as the hydrodynamic separator are much deeper and wider than normal and the plated drain has a narrower opening than other structures. Figure 4.10 shows the breakdown of structure types that were tested.





Structure	Primary Structure[1]	Secondary Structure[2]	Total Structure
Lateral Line	4	57	61
VJT	3	24	27
Recycler	1	33	34
Catch Basin	59	0	59
VJT	23	0	23

Structure	Primary Structure[1]	Secondary Structure[2]	Total Structure
Recycler	36	0	36
Manhole Vault	4	0	4
VJT	3	0	3
Recycler	1	0	1
Hydrodynamic Separator	4	0	4
VJT	2	0	2
Recycler	2	0	2
Plated Drain	1	0	1
VJT	1	0	1
Recycler	0	0	0
Total	**72**	**57**	**129**

Note: (1) Primary structure refers to the first structure cleaned at that site. (2) At many sites a secondary structure was also present, typically a lateral line that branched from the primary structure

Figure 4.10: Structures Attempted per Structure Type

As seen in Figure 4.10, the breakdown for both equipment categories was similar. Catch basins and lateral lines made up the majority of structures cleaned with a small sample of manhole vaults, plated drains and hydrodynamic separators incorporated in each.

4.1.3 Equipment Type

District 6 currently operates two different VJTs, a Vac-Con and Vactor 2100, that were tested. The sole Recycler option that was tested was the BUCHER RECycler 315 that was purchased for this study. Figure 4.11 presents the three equipment options studied by the research team.

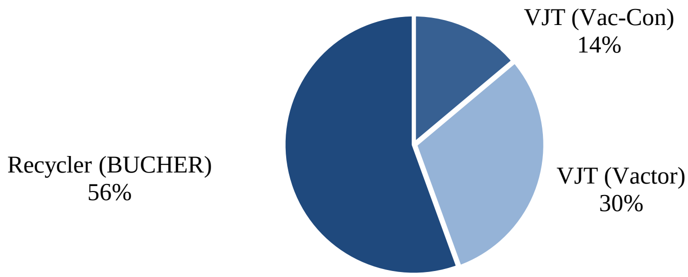
(a) (b) (c)

Note: Pictures taken by research team in the summer and fall of 2018.

Figure 4.11: Equipment Type Classifications (a) Vac-Con VJT (b) Vactor VJT (c) BUCHER Recycler

As seen in Figure 4.11, all three pieces of equipment are similar. The largest differences, excluding the recycling system, is that the operating position is on the rear of the vehicle for the Recycler instead of at the front as in the VJT. Figure 4.12 shows the breakdown in testing for each piece of equipment.

Structures Attempted per Equipment



Equipment	Structures Inspected	Structures Attempted	Structures Trained
VJT	41	32	0
Vac-Con	20	10	0
Vactor 2100	21	22	0
Recycler	78	40	4
BUCHER RECycler 315	78	40	4
Total	**119**	**72**	**4**

Note: Structure inspected refers to structures determined to be clean and not need maintenance work.

Figure 4.12: Structures Attempted per Equipment

As seen in Figure 4.12, the field data was split roughly equally between the Recycler and VJT. In addition, the VJT was split between the Vac-Con and Vactor, with the Vactor having approximately twice as many observations as the Vac-Con due to ODOT's operational schedule. Based on the testing methodology, 72 structures observed is comparable to similar research conducted during a single cleaning season.

4.2 Equipment Testing

This section outlines the results of the equipment field testing. The research team conducted field data collection on the VJT system while waiting on the Recycler to be delivered. Approximately five months of testing was conducted between the two equipment systems.

4.2.1 VJT Testing

The team completed equipment testing with the traditional VJT equipment by observing operations for approximately one month. Overall, the research team collected 32 field data points and 673 historical data points. The team collected a total of 705 data points for the traditional VJT equipment. In addition, the team notes that nine additional structures were inspected but determined to not need maintenance performed.

The research team conducted field observations of the VJT over the summer and fall of 2018. The team followed both the Vac-Con and Vactor VJTs that District 6 operates to clean storm sewers. Table 4.6 summarizes the field data results for the VJT observations across 32 structures.

Table 4.6: VJT Field Data Summary

Task	Average (min)	Standard Deviation
Shift Length	330	30
Travel Time	30	10
Clean Structure	45	15
Refill Water	80	20
Decant Debris/Wastewater	60	15
Filter Clean	N/A	N/A
Structures Inspected[1]	**41**	**-**
Structures Cleaned[2]	**32**	**-**

Note: (1) Structures inspected refers to the total structures visited, including structures that were determined to not need to be maintained. (2) Structures cleaned refers to the structures that were attempted to be cleaned and which operational data was collected for. This quantity is the sample size for the data.

As seen in Table 4.6, the research team averaged the shift length, travel time, time to clean structure, time to refill water, time to decant debris/wastewater and time to clean filters. For the VJT, the time to clean filters is not applicable since there is not a recycling system onboard which may reduce the overall time to clean the structure.

4.2.2 Recycler Testing

Once the Recycler was delivered, manufacturer representatives conducted a two week long training session with the ODOT District 6 operators. During the first week of training, the team did not record data on operations since manufacturer representatives were operating the equipment with the ODOT operators shadowing. The team collected data during the second week of training once the ODOT operators were running the equipment.

The team completed a preliminary review of the data to determine if the second week of training should be included in the production rate and equipment cost calculations. The decision to include the data was made based on its similarities to the post-training data. In addition, the second week of training included some data types that were not collected for the remainder of the observation period that the research team wanted to capture. A more extensive analysis of the training compared to post-training data may be found in the following chapters.

The research team completed a total of 40 observations of attempted storm sewer cleaning with the Recycler. In addition, the team notes that 38 additional structures were inspected but determined to not need maintenance performed. Table 4.7 summarizes the field data results for the 40 Recycler observations.

Table 4.7: Recycler Field Data Summary

Task	Average (min)	Standard Deviation
Shift Length	330	30
Travel Time	30	10
Clean Structure	45	15
Refill Water	0	0
Decant Debris/Wastewater	60	15
Filter Clean	2	6
Structures Inspected[1]	**78**	-
Structures Cleaned[2]	**40**	-

Note: (1) Structures inspected refers to the total structures visited, including structures that were determined to not need to be maintained. (2) Structures cleaned refers to the structures that were attempted to be cleaned and which operational data was collected for. This quantity is the sample size for the data.

As seen in Table 4.7, the additional filter clean step is a process that occurs if the Recycler is operated in conditions such as oil, grease and/or leaves which tend to clog the filter system. This process may happen automatically or at the discretion of the operator. During field testing, the filter clean step occurred seven out of 40 times (15%). The team notes that out of these seven times, six of them occurred on back to back days. After consulting with the manufacturer, it was recognized that a full system washout was needed to remove built up debris. The full system washout only required approximately fifteen more minutes of maintenance work than the average daily maintenance and prevented the need to perform filter cleaning during operations.

4.2.3 Testing Summary

The research team evaluated the field data testing results and compared the two systems against each other. The team found that, on average, many of the times between the VJT and Recycler were similar. A summary of the parameter differences may be found in Table 4.8.

Table 4.8: Equipment Parameter Differences

Task	Difference
Shift Length	0
Travel Time	0
Clean Structure	0
Refill Water	80
Decant Debris/Wastewater	0
Filter Clean	2

Note: Refer to Tables 13 and 14 for the actual data for each piece of equipment.

As seen in Table 4.8, the majority of the average values for the field data were similar. The largest difference was the 80 minutes it took for the VJT to make a water trip that the Recycler did not. The frequency of these water trips caused the largest difference in the production rate estimate shown in the following chapters. In addition, the Recycler sometimes required a filter cleaning on-site that required two minutes. The time spent cleaning filters added additional time to clean the storm sewer and reduced the production rate. The team notes that while the VJT did not have to clean filters, the 80 minutes spent on a water refill trip decreased the production rate further than the filter clean.

4.3 Operator Feedback

The research team conducted interviews with the two operators that were responsible for running both the VJT and the Recycler for the majority of the field testing. The team believed that the operators were the best source of knowledge and opinion when it came to judging the day to day operations of the Recycler. These employees know both pieces of equipment the best and have the closest knowledge of the intricacies of each. The responses in Table 4.9 are a summary of the interviews held with each operator.

Table 4.9: Operator Feedback Key Findings

Question	Operator 1	Operator 2
Does the Recycler improve the cleaning production rate over the VJT?	Yes	Yes
Does the Recycler clean storm sewers as effectively as the VJT?	Yes	Yes
Does the Recycler require more daily maintenance than the VJT?	No	Yes
Does the Recycler require more training overall than the VJT?	Yes	Yes
Are the controls on the Recycler understandable and intuitive?	Yes[1]	Yes
Is the Recycler vacuum hose safer, more efficient and easier to use than the VJT?	Yes	Yes
When operating the Recycler, is the noise environment at a lower level than when operating the VJT?	Yes[2]	Yes
As you become more familiar and comfortable with operating the Recycler, would you consider the Recycler to be a safer option for the operator with regards to noise level, back strain, pinch points and overall safety?	Yes	Yes
Is the Recycler more effective in cleaning a typical storm sewer than the VJT?	Yes	Yes
Is the Recycler more effective in cleaning a typical hydrodynamic separator than the VJT?	Yes[3]	Yes
What is the most beneficial feature of the Recycler over the VJT?	Recycling[4]	Recycling[4]
Would you recommend/prefer the Recycler over the VJT?	**Yes[5]**	**Yes[6]**

Notes: Interviews were conducted in the fall 2018 after testing was completed, (1) Operator 1 reported controls are slightly more complicated than VJT but still understandable, (2) Operator 1 reported that noise levels were much lower on the Recycler than the VJT, (3) Operator 1 reported that the Recycler was much more effective at cleaning the hydrodynamic separator than the VJT, (4) Both Operator 1 and 2 reported that water recycling allowed them to avoid water refill trips, Operator 2 also commented that decanting trips may also be avoided due to the Recycling, (5) Operator 1 noted that if possible, having both pieces of equipment may be beneficial as the VJT may be used in tasks not related to storm sewer cleaning, (6) Operator 2 noted that proper training is critical in ensuring the Recycler is the preferred option.

As seen in Table 4.9, both operators have a positive opinion on the Recycler overall. In their experience, the Recycler is easier to use, more operator friendly and more productive than the VJT. However, they did comment that the training on the Recycler required more time and the computer system was more difficult to learn.

The field data collected during the equipment testing will be used in the model simulations to determine the production rates and economics of each piece of equipment. In addition, the historical data may be used to verify that the data collected during this study is comparable to previous years and that the model is accurate. Similarly, operator feedback provides an insight to the opinions of the employees who use the equipment on a daily basis, a factor that is sometimes missed in quantitative analysis.

CHAPTER V – COST-BENEFIT ANALYSIS

Chapter Five presents an economic analysis of both pieces of equipment that were studied throughout this research. It also presents the operational advantages and disadvantages that each option presents. In order to justify any alternative piece of equipment, such as the Recycler, an economic analysis must show that the new option presents a cost savings compared to the traditional equipment. Due to the higher capital cost associated with the Recycler compared to the VJT, any increase in capital cost must be offset by an operational cost savings. This chapter is organized in the following sections:

- Section One – Introduction to cost-benefit analysis,
- Section Two – Production rate comparison,
- Section Three – Annualized cost comparison,
- Section Four – Outcome stability, and
- Section Five – Break-Even Analysis.

In reviewing the costs associated with both pieces of equipment, a few factors had to be determined. Using Phase I of this project *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* as a starting point, the research team modified the existing assumptions made. Table 5.1 shows a sample cost matrix of the VJT and Recycler options available to District 6.

Table 5.1: Cost Matrix for Options Available

Equipment	Capital Cost	Maintenance Cost	Labor Cost	Water Cost	Fuel Cost
VJT	Low-Medium	Medium	High	High	High
Recycler	Medium-High	High	Low	Low	Medium

Note: District 6 currently is not charged disposal fees for decanting material. Low, medium and high refers to the relative difference between the VJT and Recycler in cost for each category.

As seen in Table 5.1, the team used the field data, along with survey data, to estimate the total cost of significant categories. The capital cost of the Recycler is significantly higher than that of the VJT. The maintenance costs of the Recycler are also expected to be higher than the VJT, although little data has been collected on the maintenance due to it being a new technology. While the capital and maintenance costs are expected to be lower in the VJT, the labor, water, and fuel costs are all expected to be lower in the Recycler.

5.1 Introduction to Cost-Benefit Analysis

The research team completed a literature review on studies that compared large scale DOT equipment assets. The goal of this review was to confirm that the models used to compare the VJT to the Recycler were similar to previously developed models that compared expensive assets. Table 5.2 summarizes the key findings of the equipment evaluation literature review.

Table 5.2: Cost-Benefit Analysis Literature Review Key Findings

Material Evaluated	Evaluation Application	Findings	Reference
Evaluation of Box Culvert Maintenance Methods	The study identified an inventory of culverts accessible to the MT 3234 based on certain physical properties and the ODOT TIMS database.	No cost-benefit compared to the VJT was conducted for the MT 3234.	Miller, 2015
Major Equipment Life-Cycle Cost Analysis	Life-cycle cost analysis allowed the Minnesota Public Works Fleet Services Division to identify critical inputs to determine the life expectancy of equipment.	The Minnesota Public Works Fleet Services Division listed substantial data and methods for determining equipment operating, ownership, and maintenance costs.	Gransberg, 2015
Fleet Equipment Asset Management Performance Measure	A Caltrans survey of six DOTs determined that utilization rates, preventative maintenance costs, replacement life cycle, and downtime are the four most used performance metrics	PennDOT provided detailed information on cost vs usage statistics for their rolling fleet, including fuel usage and age factors.	Caltrans, 2012
The Replace/Repair Decision for Heavy Equipment	VDOT developed a system of determining cost forecasting with a relatively small set of cost data for specialized equipment	VDOT determined that a ratio of cost per year to date over cost per life to date allows operators to determine an estimated unit cost for the next fiscal year.	Gillespie, 2004
Optimizing the Life Cycle of PennDOT Equipment	PennDOT developed a tool that predicted the lifespan and maintenance costs for selected types of equipment	PennDOT conducted statistical analysis that determined anticipated maintenance and operational costs for various types of equipment.	Vance & Renz, 2014

Note: The team focused on literature that was recent, with only one source over ten years old.

As seen in Table 5.2, there has been extensive research in the topic of cost-benefit analysis on large scale DOT asset purchases. This research team attempted to find studies that were regionally close to Ohio and covered similar equipment.

The research team used a computational algorithm known as a Monte Carlo simulation to calculate the production rate and costs of each piece of equipment. The Monte Carlo simulation uses a set of variables, defined by field data, with an average value and standard deviation to solve a set of functions. The simulation runs numerous times while randomizing the variables and solving the set of functions for each variable generated by a set distribution. The results themselves have an average value and standard deviation that may be analyzed further. Ultimately the numerous simulations add reliability to the model. The team used a software known as MATLAB, developed by MathWorks, (Natick, Mass.) to run the Monte Carlo simulations. The results are presented as a normal distribution where the most likely event is able to be determined while still presenting outlier scenarios.

5.2 Production Rate Comparison

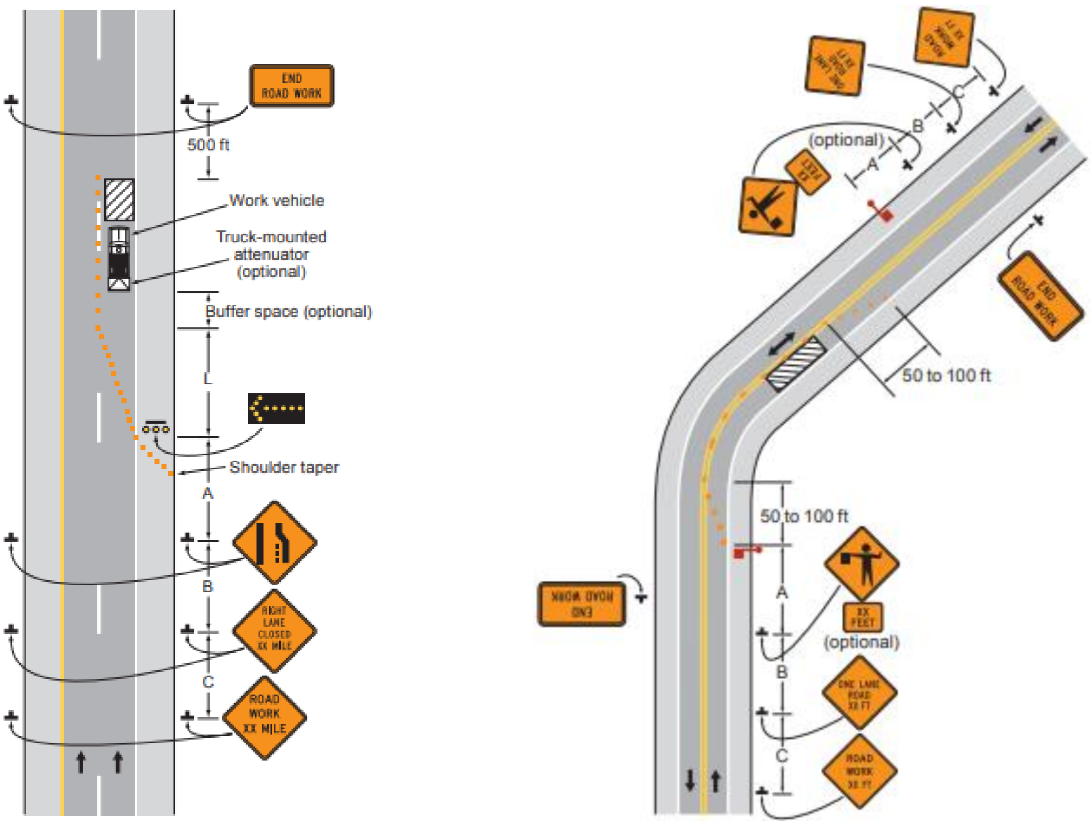
The research team began the comparison of the two pieces of equipment and operations by determining the production rate of each. To do this, the team used the field data collected over the summer and fall of 2018 to modify the model derived in Phase I of this project based on differences in the field data and the estimated values used previously. Chapter IV previously outlined in more detail the field data collected. Table 5.3 outlines the variables used in the MATLAB model.

Table 5.3: Production Rate Variables

Variable	Equipment	Average	Standard Deviation
Shift Length (min)	All	330	30
Time to Site (min)	All	30	10
Time to Refill (min)	VJT	80	20
	Recycler	0	0
Time to Decant (min)	All	60	15
Time to Clean (min)	All	45	15
Time to Clean Filter (min)	VJT	N/A	N/A
	Recycler	2	6

Note: The round trip times for water refill and decant include travel time to the water refill or decant site, time spent refilling water or decanting and travel time back to the cleaning zone. All values obtained from field data.

As seen in Table 5.3, the research team determined that in an eight hour shift, only 330 minutes of that was actually spent operating storm sewer cleaning equipment. The team found that before the equipment could be used, the safety crew had to set up the safety zone around the cleaning site. Figure 5.1 demonstrates the difficulty in setting up the safety zone for storm sewer cleaning operations.



(a) (b)

Note: Information obtained from ODOT Guidelines for Traffic Control in Work Zones (ODOT, 2014).

Figure 5.1: Work Zone Setup (a) Short Term Stationary Lane Closure on a Divided Highway (TA-33), (b) Lane Closure on a Two-Lane Road Using Flaggers (TA-10).

As seen in Figure 5.1, lane closures require a substantial amount of time to setup in order to ensure the safety of the operators. In addition, many routes in District 6 have lane closure restrictions to certain times of the day and required the crew to stop operations to break down the safety zone before afternoon rush hour. The time spent setting up and breaking down the safety zones resulted in the shift length spent operating being shortened. Table 5.4 shows how the field data collected in Phase II differed from the assumptions made in Phase I.

Table 5.4: Field Data Differences from Phase I Assumptions

Item	Equipment	Phase I	Phase II
Shift Length	All	480	330
Time to Site	All	60	30
Time to Refill	VJT	60	80
	Recycler	0	0
Time to Decant	All	120	60
Time to Clean	All	10	45

Note: See *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* (Schneider et. al, 2018).

As seen in Table 5.4, the majority of assumptions in Phase I decreased in value except for the time to clean the structure. This demonstrates the importance of completing field work to validate model parameters. The team made conservative estimates in Phase I which made the VJT more competitive to be cautious due to the technology being new. The production rate comparison was based on the number of storm sewers that each piece of equipment was able to clean in a single shift as seen in Equation 5.1.

$$PR = \frac{t_d - (n_s)(t_s) - (n_r)(t_r) - (n_d)(t_d)}{t_c} \qquad \text{Equation 5.1}$$

where,

PR = Production rate (storm sewers cleaned per shift),
t_d = Time of shift,
n_s = Number of sites,
t_s = Time to travel to site,
n_r = Number of refill trips,
t_r = Time to travel to refill,
n_d = Number of decant trips,
t_d = Time to travel to decant, and
t_c = Time to clean storm sewer.

Table 5.5 presents the number of storm sewers that each piece of equipment is predicted to clean in a shift.

Table 5.5: Storm Sewers Cleaned per Shift

Equipment	Average	Standard Deviation
VJT	3.62	1.21
Recycler	5.51	2.15

Note: The storm sewers cleaned per shift was based on field and historical data provided by ODOT.

The research team used the Monte Carlo simulation and production rate variables determined through field data to calculate the production rate of each piece of equipment. The team found the production rate increase of the equipment options by comparing the production rate of the Recycler divided by the production rate of the VJT. The team determined the production rate increase using Equation 5.2, presented below:

$$PR_i = \frac{PR_r}{PR_v} \qquad \text{Equation 5.2}$$

where,

PR_i = Production rate increase,
PR_r = Production rate of recycler, and
PR_v = Production rate of VJT.

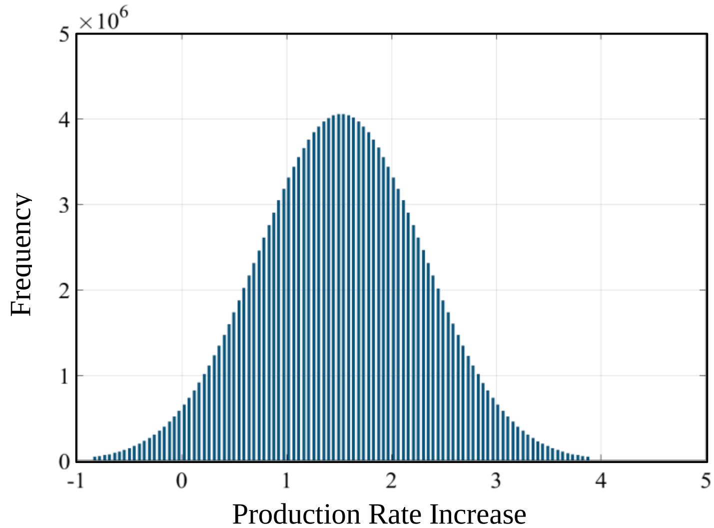
Table 5.6 displays the estimated production rate increase of the Recycler over the VJT produced using the Monte Carlo simulation to include variability in MATLAB.

Table 5.6: Production Rate Increase

Description	Average	Standard Deviation
Production Rate Increase	1.52	0.78

Note: The increase in production rate is based on a normal distribution curve.

As seen in Table 5.6, the production rate increase of the Recycler over the average VJT is estimated to be 1.52, meaning it is 52% more productive than the VJT. The production rate increase is used in the economic analysis to determine if the Recycler is a cost effective piece of equipment where the higher the increase, the more likely it is to be cost effective. Figure 5.2 shows the distribution of results.



Note: Distribution produced by simulating model 10,000,000 times.

Figure 5.2: Production Rate Increase Normal Distribution Curve

This number is supported by the completed customer surveys that estimated a production increase, on average, of between 40-60%. Based on a current work schedule of April through October, there are approximately 145 working days in a cleaning season. It is beneficial that the time ODOT may save by using more productive equipment will allow employees to be used elsewhere on other projects. Table 5.7 shows the difference in number of days worked for each piece of equipment in order to clean the same number of storm sewers.

Table 5.7: Work Day Production Comparison

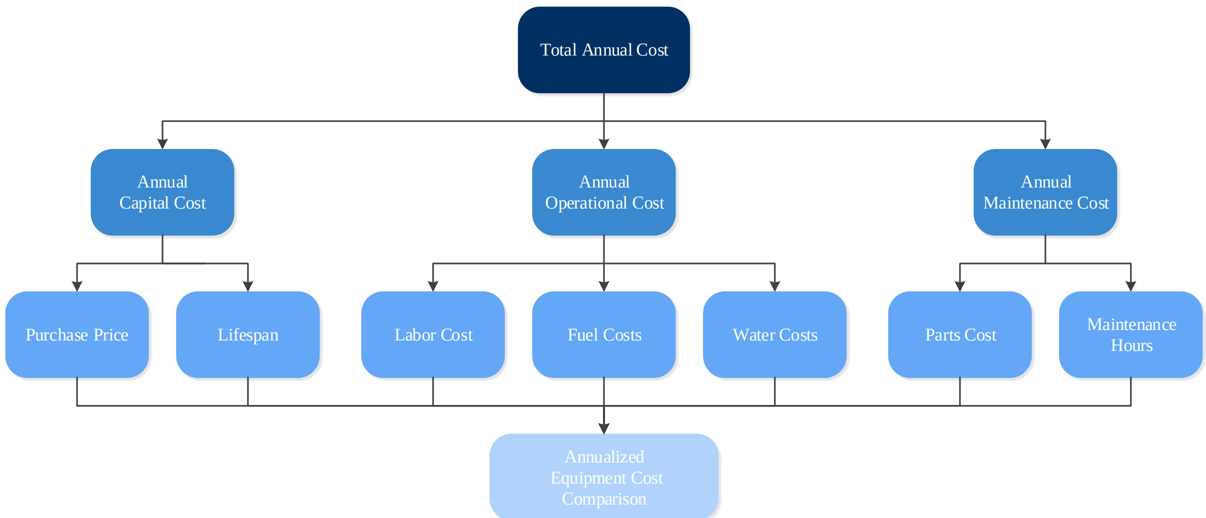
Description	Average	Standard Deviation
VJT Days Worked (days)	145	15
Recycler Days Worked (days)	96	10

Note: The Recycler would complete cleaning the same number of storm sewers in mid-august, compared to late October for the VJT.

As per Table 5.7, the Recycler may clean the same number of storm sewers as the VJT in 49 fewer days. This time savings may either allow District 6 to clean additional storm sewers per year or work 49 fewer days and apply that labor time elsewhere within the district. The Recycler is approximately $230,000 more expensive than the VJT, and that additional capital cost must be offset by an increase in the production rate.

5.3 Annualized Cost Comparison

When comparing the Recycler to the VJT overall, three cost categories are analyzed: capital cost, operational cost and maintenance cost. Each of these categories is computed to determine the annual cost over the lifespan of the product. Figure 5.3 shows the costs and associated variables.



Note: Figured developed in Phase I of this study *"Evaluation of the Ohio Department of Public Transportation's Current Storm Sewer Cleaning Operations – Phase I"* (Schneider et al., 2018).

Figure 5.3: Annual Cost Matrix

The research team used a conservative approach in analyzing the costs associated with the Recycler and VJT. The conservative approach means that when estimated values were required, the Recycler values were held similar to the VJT for production and high for cost and maintenance. Table 5.8 lists the variable's average value, standard deviation, and source used in the annualized cost comparison.

Table 5.8: Cost Analysis Variables

Variable	Equipment	Average	Standard Deviation	Source
Labor Cost ($/hr)	All	36	2	ODOT
Distance to Site (mi)[1]	All	35	10	Estimate
Distance to Water (mi)[1]	All	20	5	Estimate
Distance to Decant (mi)[1]	All	30	10	Estimate
Fuel Cost ($/gal)	All	3.31	0.05	EIA, 2018
Water Cost ($/gal)	All	0.0047	0.0015	OEPA, 2016
Shift Length (hr)	All	5.5	0.5	Field Data
Crew Size (workers)	All	3.56	1.28	Field Data
Annualized Factor	All	0.04	0.02	ODOT
Fuel Efficiency (mpg)	All	3.45	0.35	Field Data
Capital Cost ($)	VJT	$360,000	$89,500	ODOT
	Recycler	$590,105	$15,000	Field Data
Lifespan (yr)	VJT	10	2	ODOT
	Recycler	10	2	Customers

Variable	Equipment	Average	Standard Deviation	Source
Maintenance Part Cost ($)	VJT	10,000	2,000	ODOT
	Recycler	15,000	3,000	Customers
Maintenance Hours (hr)	VJT	40	5	ODOT
	Recycler	80	10	Customers
Water Rate (gpm)	VJT	120	10	ODOT
	Recycler	10	2	Field Data

Note: (1) Distance lengths are round trip. ODOT and customer sources are from phone surveys.

As seen in Table 5.8, the team used field data where applicable to estimate each variable's average value and standard deviation. In cases where field data was not known or able to be collected, estimates given by the ODOT technical liaisons were utilized.

5.3.1 Capital Cost

The research team began the cost comparison by calculating the annualized capital cost of each piece of equipment. The team conducted phone surveys in conjunction with ODOT technical liaison estimates to approximate the current capital cost of the VJT. The Recycler was purchased by the research team at the start of this project so the purchase price including optional features was used. The team understands that there may be a salvage value for equipment if it is sold at an ideal time; however, for this cost analysis, the salvage value is not considered. The annualized capital cost is determined using Equations 5.3 and 5.4.

$$AC_c = (C_c)(AF) \quad \text{Equation 5.3}$$

where,

AC_c = Annualized capital cost ($/yr),
C_c = Capital cost ($),
AF = Annualized factor (yr^{-1})

and,

$$AF = \frac{i}{(1+i)^n - 1} + i \quad \text{Equation 5.4}$$

where,

i = Discount factor, and
n = Life expectancy (yr).

In Equations 5.3 and 5.4, the annualized factor is known as the discount rate and is the ratio of the value of individual yearly payments based on the lump sum cost. The life expectancy of the Recycler and the VJT, based on national and ODOT district surveys and discussions with District 6, is set at 10 years with a deviation of plus/minus 2 years. The outcomes of the annualized capital costs of the Recycler and the VJT are seen in Table 5.9.

Table 5.9: Annualized Capital Costs

Equipment	Average per Year	Standard Deviation per Year
VJT	$46,192	$15,667
Recycler	$75,708	$16,708

Note: Annualized capital costs used an estimated lifespan of 10 years.

As seen in Table 5.9, the VJT has a significant cost savings in terms of annual capital costs. The annualized capital cost is the largest financial advantage that the VJT has over the Recycler, saving approximately $30,000 over the Recycler. The following section will describe the maintenance costs associated with each option.

5.3.2 Maintenance Cost

The research team conducted a phone survey of Recycler customers to estimate the maintenance costs associated with the Recycler. Due to the technology being new, there is little data to help determine what the long-term costs may be. Customers surveyed responded that the Recycler has had a limited increase in maintenance costs over the traditional VJT. The team notes that of the customers surveyed, the oldest Recycler was only just over three years old. It is expected that some additional costs may occur due to the added recycling system onboard the truck; however, future data is needed to clarify this estimate. The team used Equation 5.5 to estimate the cost of maintenance for each piece of equipment.

$$AC_m = \left(C_p\right) + (n_h)(C_l) \qquad \text{Equation 5.5}$$

where,

AC_m = Annualized maintenance cost ($/yr),
C_p = Cost of parts ($/yr),
n_h = Number of maintenance hours (hr), and
C_l = Cost of labor ($/hr).

Table 5.10 presents the annual maintenance costs for both pieces of equipment.

Table 5.10: Annual Maintenance Costs

Equipment	Average per Year	Standard Deviation per Year
VJT	$11,440	$2,010
Recycler	$17,880	$3,025

Note: Annual maintenance costs were determined using a normal distribution curve.

As seen in Table 5.10, the Recycler maintenance costs exceed those of the VJT. While the maintenance costs are higher for the Recycler, they do not have that large of an impact relative to the total annual cost. The research team used conservative estimates based on customer surveys to calculate the estimated maintenance cost due to the limited knowledge of long term issues with the technology. Future analysis should be performed on the long-term maintenance problems that may be associated with the recycling system.

The team notes that the equipment received had some issues upon delivery. In early 2018, BUCHER switched their electronics package to a new controller area network (CAN) bus system. The new CAN bus required several software updates performed by the manufacturer due to it being the first system on a Kenworth chassis. The manufacturer worked with ODOT District 6 to limit interruptions in the operations schedule; however, several interruptions did occur. In addition, the original water level sensors inside the debris body had a manufacturer defect. Several replacements were made by BUCHER before they switched to a new sensor manufacturer which corrected the issue; however, this replacement did not come before additional interruptions were made to the testing schedule.

5.3.3 Operational Cost

While the VJT showed cost savings over the Recycler in both the capital costs and maintenance costs, the operational costs are where the Recycler is expected to make its savings. The increased production rate shown in previous sections is associated with a lower number of days worked to complete the same amount of work. It is estimated that based on a 145 day cleaning season, the Recycler may finish cleaning the same number of storm sewers in 49 fewer days. For the purpose of this study, the research team assumed that the number of storm sewers cleaned in the season would remain the same; therefore, finishing the season earlier translated to labor savings. The operational labor costs were calculated using Equation 5.6.

$$AC_l = (C_l)(t_s)(n_w)(n_d) \quad \text{Equation 5.6}$$

where,

C_l = Cost of labor ($/hr),
t_s = Time of shift (hr),
n_w = Number of workers, and
n_d = Number of days worked.

Table 5.11 displays the annual labor costs associated with each piece of equipment.

Table 5.11: Annual Labor Costs

Equipment	Average per Year	Standard Deviation per Year
VJT	$102,210	$40,156
Recycler	$67,654	$26,601

Note: The annual labor costs account for 39-51% of the total annual costs based on equipment choice.

As seen in Table 5.11, the labor cost savings from the Recycler total over $35,000 per year. The savings associated with labor expenses negates the increased capital cost across a ten year lifespan. The team then calculated the operational water costs using Equation 5.7.

$$AC_w = (C_w)(n_g)(n_d) \quad \text{Equation 5.7}$$

where,

C_w = Cost of water ($/gal),
n_g = Number of gallons of water, and
n_d = Number of days worked.

Table 5.12 outlines the annual water costs for both the VJT and Recycler.

Table 5.12: Annual Water Costs

Equipment	Average per Year	Standard Deviation per Year
VJT	$13,323	$8,269
Recycler	$1,024	$739

Note: In some instances, District 6 may not have to pay water fees; however, this analysis assumes that water fees are paid at all times.

As seen in Table 5.12, the annual water costs of the Recycler save approximately $12,000 over the VJT. The annualized operational fuel costs were calculated using Equation 5.8.

$$AC_f = \frac{\left(d_s + (n_{t_w} * d_{w)} + (n_{t_d} * d_d)\right) * C_f * n_d * 2)}{FE} \quad \text{Equation 5.8}$$

where,

C_f = Cost of fuel ($/gal),
n_{t_w} = Number of trips to water,
n_{t_d} = Number of trips to decant,
n_d = Number of days worked,
d_s = Distance to site (mi),
d_w = Distance to water (mi),
d_d = Distance to decant (mi), and
FE = Fuel efficiency (mpg).

Table 5.13 presents the annual fuel cost estimates for the VJT and Recycler.

Table 5.13: Annual Fuel Costs

Equipment	Average per Year	Standard Deviation per Year
VJT	$29,520	$9,104
Recycler	$11,168	$4,324

Note: Fuel costs may be highly variable and may be expected to rise in the future, creating additional savings for the Recycler in comparison to the VJT.

As seen in Table 5.13, the Recycler creates noticeable savings in fuel costs by limiting the number of days needed to operate as well as water and decant trips. Equation 5.9 was then used to determine the total operational costs per year.

$$AC_o = (AC_l) + (AC_w) + (AC_f) \quad \text{Equation 5.9}$$

where,

AC_o = Annualized operational cost ($/yr),
AC_l = Annualized labor cost ($/yr),
AC_w = Annualized water cost ($/yr), and
AC_f = Annualized fuel cost ($/yr).

Table 5.14 shows the estimated annual operational costs of the VJT and Recycler.

Table 5.14: Annual Operational Costs

Equipment	Average per Year	Standard Deviation per Year
VJT	$145,050	$43,196
Recycler	$79,846	$27,292

Note: The annual labor costs account for 70-85% of the total operational costs based on equipment choice.

As seen in Table 5.14, the Recycler creates significant savings in its operational costs, approximately $65,000 annually. These savings are enough to offset the increased capital and maintenance costs of the Recycler, making it the more cost effective option on an annual basis.

5.3.4 Summary of Annual Costs

This section summarizes the annual and lifespan costs associated with each piece of equipment. Table 5.15 outlines the various cost categories and presents the average values and standard deviations per year.

Table 5.15: Detailed Annual Cost Summary

Equipment	Description	Average per Year	Standard Deviation per Year
VJT	Capital Cost	$46,192	$15,667
	Maintenance Cost	$11,440	$2,010
	Operational Cost	$145,050	$43,196
	Total Annual Cost	$202,682	$46,008
	Total Lifespan Cost	$2,010,100	$563,590
Recycler	Capital Cost	$75,790	$16,531
	Maintenance Cost	$17,875	$3,028
	Operational Cost	$83,094	$28,362
	Total Annual Cost	$173,430	$32,167
	Total Lifespan Cost	$1,707,000	$366,030

Note: Capital cost as of the summer of 2018.

As seen in Table 5.15, the total annual costs of the BUCHER RECycler are approximately $26,000 less than the VJT. When comparing the lifespan cost of ownership, estimated at ten years, the Recycler totals a cost savings of nearly $272,000. The majority of cost savings for the Recycler come from the savings in labor due to lower number of days worked to accomplish the same amount of work. The team notes that this economic analysis uses a conservative approach to the model due to the unique technology and limited past field data.

5.4 Outcome Stability

The results produced by the production rate and economic models in this Phase were similar to those in the Phase I study. Overall, the estimated production rate was slightly decreased based on the field data. The main differences between the models were the input variables used. Table 5.16 summarizes the differences in the outcomes of the production rate models.

Table 5.16: Production Rate Model Outcome Stability

Report	Equipment	Storm Sewers Cleaned	Production Rate Increase
Phase I	VJT	7.8	1.55
	Recycler	12.1	
Phase II	VJT	3.6	1.52
	Recycler	5.5	

Note: See *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* (Schneider et al., 2018) for more information.

As seen in Table 5.16 and mentioned previously, the overall production rate increase did not change by a large magnitude. There was a noticeable difference in the estimated number of storm sewers cleaned per shift however. Based on the field data, the Phase II results were that each piece of equipment would clean roughly half of the Phase I estimate. In addition to the production rate model, the team also compared the Phase I and Phase II economic models. A summary of the differences between the two economic models may be found in Table 5.17.

Table 5.17: Economic Model Outcome Stability

Equipment	Description	Phase I Estimate	Phase II Estimate
VJT	Capital Cost	$46,186	$46,192
	Maintenance Cost	$6,360	$11,440
	Operational Cost	$228,180	$145,050
	Total Annual Cost	$280,680	$202,682
	Total Lifespan Cost	$2,790,000	$2,010,100
Recycler	Capital Cost	$76,351	$75,790
	Maintenance Cost	$12,040	$17,875
	Operational Cost	$144,330	$83,094
	Total Annual Cost	$232,720	$173,430
	Total Lifespan Cost	$2,299,800	$1,707,000

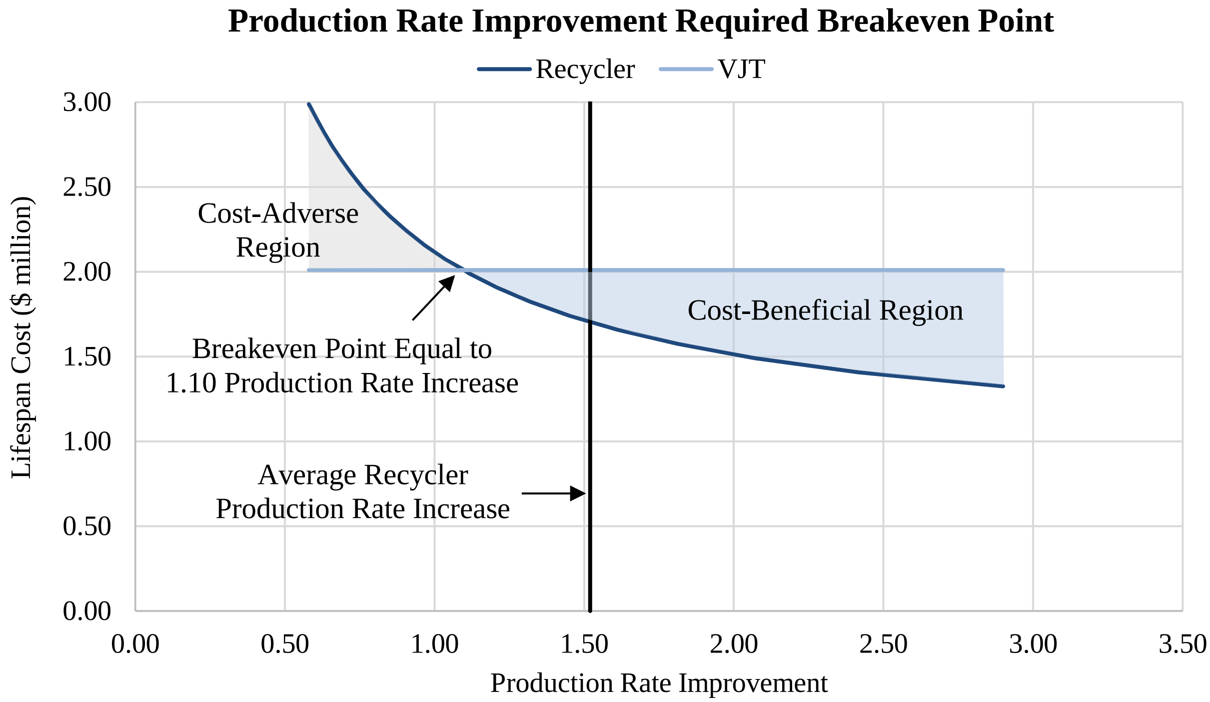
Note: See *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* (Schneider et al., 2018) for more information.

As seen in Table 5.17, the total lifespan cost savings for the Recycler is similar for both Phase estimates. In Phase I, the team estimated that the Recycler lifespan cost was 82.4% of the VJT lifespan cost, a 17.6%

cost savings. In Phase II, the team estimates that the Recycler lifespan cost is 85.1% of the VJT lifespan cost, a 14.9% cost savings. In addition to the slightly lower production rate increase estimate, the largest factor which decreased the cost savings compared to Phase I was the lower magnitude of storm sewers visited. Fewer visits to clean storm sewers results in less trips to decant and refill water, an area where the Recycler saves money on fuel and water fees.

5.5 Break-Even Analysis

The research team wanted to determine at what point the Recycler option makes financial sense given a range of possible production rates. The team estimated what the lifespan cost of the Recycler would be based on varying production rates which equates to the change in days worked. Figure 5.4 presents the final break-even curve estimate.



Lifespan Cost ($ million)	Production Improvement	Days Operated
1.32	2.90	50
1.66	1.61	90
1.99	1.12	130
2.01	**1.10**	**132**
2.32	0.85	170
2.66	0.69	210
2.99	0.58	250

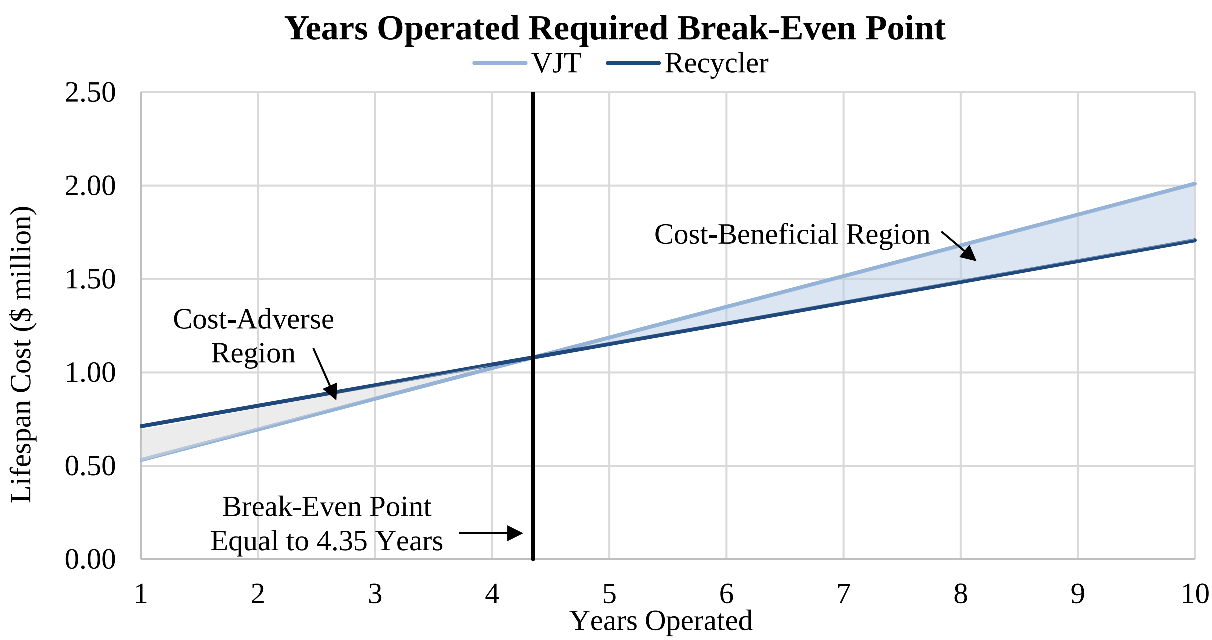
Note: The estimated lifespan cost of the VJT operating on a 145 day schedule is $2.01 million.

Figure 5.4: Production Rate Break-Even Point

As seen in Figure 5.4, the estimated production rate break-even point is approximately 1.10. This means that in order for the Recycler to be financially viable for ODOT, the recycler must be able to clean 1.10

times the number of storm sewers that the VJT is able to clean in the same amount of time. A production rate increase of 1.10 times equates to approximately 132 days of Recycler operations compared to 145 days of VJT operations. This means that the Recycler must be able to clean the same number of storm sewers in 13 fewer days to be cost beneficial. The decrease in days worked results in fewer days worked for employees, resulting in labor cost savings. These labor savings, in addition to fuel and water, offset the capital cost increase when production is 1.10 times greater.

These findings further support the beneficial implementation of the Recycler. The Recycler production rate increase was approximately 1.52 times that of the VJT. While the Recycler improves upon the VJT by a production increase of 52% overall, it also tops the minimum break-even requirement by 42%. In addition to finding the required break-even production rate, the team estimated the years of operation required before a cost savings would be realized. Figure 5.5 presents the results.



Years Operated	VJT Lifespan Cost ($)	Recycler Lifespan Cost ($)
1	530,800	711,400
2	694,870	821,250
3	858,530	931,320
4	1,022,800	1,041,800
4.35	**1,080,400**	**1,080,400**
5	1,152,000	1,152,000
6	1,350,800	1,262,500
7	1,515,700	1,373,600
8	1,680,000	1,484,400
9	1,845,100	1,595,500
10	2,010,100	1,707,200

Note: Actual estimated lifespan of equipment is equal to ten years.

Figure 5.5: Production Rate Break-Even Point

As seen in Figure 5.5, the Recycler starts at a higher lifespan cost when owned for under four years, compared to the VJT. This is due to the higher capital cost associated with the Recycler. As the equipment age approaches four years, the two lifespan costs begin to converge due to the operational savings of the Recycler before finally intersecting at 4.35 years, at which point the Recycler becomes more cost-beneficial.

In order to realize the most cost savings, it is important for state DOTs and contractors to evaluate their specific use for the equipment. Each use case may lead to different production rates depending on types of structure, operator turnover and environmental setting. In order for the Recycler to be cost effective it must remain, on average, 1.10 times as productive as the VJT, equating to 4.35 years of ownership.

CHAPTER VI – IMPLEMENTATION

The purpose of this chapter is to provide an implementation guide in key areas where the Recycler or VJT may exceed. Due to the variable nature of structures that each piece of equipment may encounter, a qualitative comparison allows the team to make assessments for unique structures and settings. This chapter is broken into four individual sections that outline each case study; these sections are described as follows:

- Section One – Operator training,
- Section Two – Hydrodynamic separator cleaning,
- Section Three – Structure density, and
- Section Four – Equipment implementation synthesis.

These structures and settings may be unique to ODOT District 6 and may not apply to all DOTs. Each of these sections is meant to outline the positive and negative aspects of each type of equipment. In some cases both equipment options are viable options while in other cases there is a clear advantage to one piece of equipment over the other.

6.1 Operator Training

The research team evaluated the differences in production rate during and after operator training. To determine what impact training had on the equipment production rate, the team split the Recycler data into two ranges. These ranges included all data collected during the month of July (training) and all data collected after the month of July (post-training). This created a training group of data that included nine structures and a post-training group of data that included 31 structures. Table 6.1 presents the summary of data collected during and after training.

Table 6.1: Operator Training Data Summary

Variable	Group	Average	Standard Deviation
Shift Length (min)	Training	330	30
	Post-Training	330	30
Time to Site (min)	Training	30	10
	Post-Training	30	10
Time to Refill (min)	Training	0	0
	Post-Training	0	0
Time to Decant (min)	Training	70	20
	Post-Training	60	15
Time to Clean (min)	Training	42	20
	Post-Training	49	20

Note: The round trip times for water refill and decant include travel time to the water refill or decant site, time spent refilling water or decanting and travel time back to the cleaning zone. All values obtained through field data.

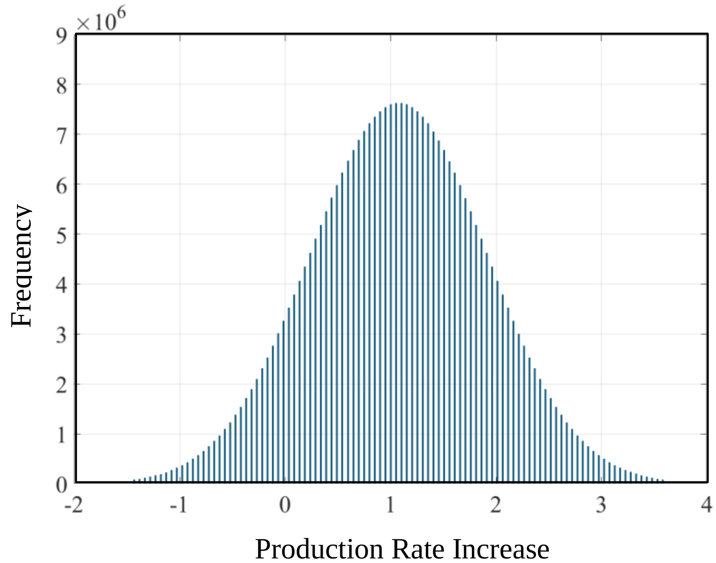
As seen in Table 6.1, there is a slight increase in the post-training data when compared to the pre-training data. The two differences in the data are the decrease in decant times and a slight increase in cleaning times. Table 6.2 presents the production rate increase for operators who have been trained on the Recycler for a month.

Table 6.2: Production Rate Increase for Post-Training Operators

Description	Average	Standard Deviation
Production Rate Increase	1.08	0.84

Note: The increase in production rate is based on a normal distribution curve.

As seen in Table 6.2, the production rate increase was approximately 1.08 times that of the operators during training. This value represents an estimated 8% increase in production for the Recycler over the VJT. Figure 6.1 shows the operator training distribution curve produced using the training and post-training data.

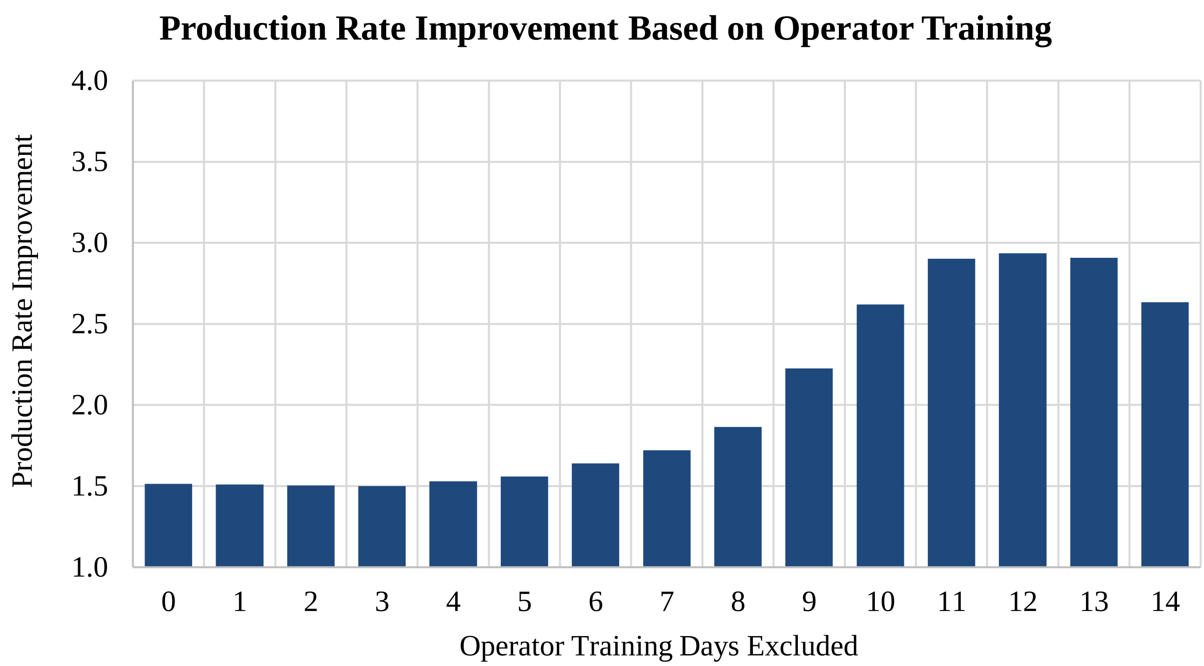


Note: Distribution produced by simulating model 10,000,000 times.

Figure 6.1: Operator Training Production Rate Curve

As seen in Figure 6.1, the most probable production rate increase for fully trained operators is an approximate 8% improvement over untrained operators. This means that for every 10 storm sewers a trained operator may clean, an untrained operator may only clean approximately 9 storm sewers. The team notes that further operator improvement may be realized, as seen in Figure 6.2. BUCHER Municipal provided two weeks of training to ODOT operators after delivering the Recycler and an additional week two months later to complete follow up training. Operator training on the Recycler is vital to ensure that the equipment is utilized in the best way possible and that the production rate realized is maximized.

The research team also evaluated the cumulative average production rates, starting with the full dataset and removing a single day at each step. This presented a chart that compares the production rate improvement of the Recycler over the VJT versus the operator training days excluded. Figure 6.2 shows the results.



Note: Averages are based on a five day moving average.

Figure 6.2: Production Rate Improvement Based on Operator Training

As seen in Figure 6.2, the average production rate improvement of the Recycler over the VJT that includes the full dataset appears near 1.50 for the first half of the testing data. As more of the earlier data is removed from the set, the production rate increases to nearly 3.0 times that of the VJT. The team notes that the averages presented in the second half of the chart exclude the first half of the dataset, reducing the sample size significantly. In addition, variables such as environmental setting, types of structure and degree of blockage may also impact the average values. Figure 6.2 simply shows how the average production rate changes as earlier training data is removed.

The research team used the observations made in conjunction with this sections analysis to develop a table which compare the operator training features included with each piece of equipment. Table 6.3 lists the various equipment options related to the control system and training.

Table 6.3: Operator Training Feature Comparison

Item	VJT	Recycler
Computerized Controls[1]	None	Vacuum/Jet Pressure, Filter Cleaning Time, Recycling Intervals, Partition Movement, Reel Speed, Valve Control & Decanting/Maintenance
Wireless Diagnostics[2]	No	Manufacturer Enabled
Automated Processes[3]	None	Recycling System, Safety Shutoff, Vacuum/Jet Pressure, Vacuum Hose
Additional Training[4]	None	Operator Dependent

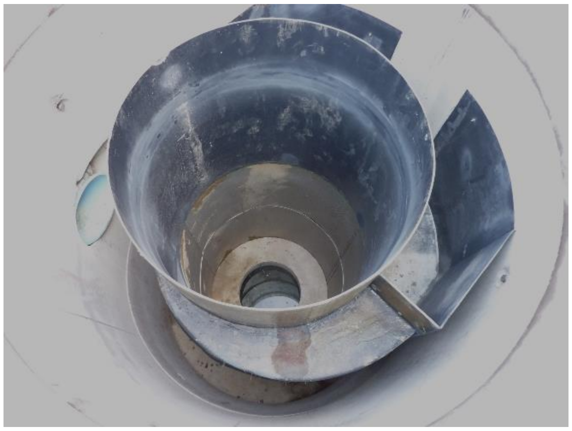
Note: (1) Computerized controls refers to the onboard CAN bus system that is included on the Recycler and used to control its operations, (2) Wireless diagnostics refers to the cellular system incorporated into the Recycler CAN bus system that allows the manufacturer to remotely view error codes, (3) Automated processes refers to operations that happen without operator intervention or manual labor, (4) Additional training refers to the time required for users to learn the operating system, mostly caused by the additional complexity associated with the CAN bus system.

As seen in Table 6.3, the Recycler has features included that help the operator and automate processes. In addition, wireless diagnostic features allow the user and manufacturer quickly address potential error codes and determine the best course of action to take for maintenance. These additional features do add a new layer of complexity to the system which may require additional operator training depending on their level of experience with advanced CAN bus systems.

There are other possible cases in which the Recycler may excel based on where the equipment is operated. One example is if a state DOT or contractor is responsible for maintaining small storm sewers where the six inch vacuum hose may be easier to maneuver. Each agency should evaluate their unique setting to determine which factors will have the largest influence on production and to what extent.

6.2 Hydrodynamic Separator Cleaning

The hydrodynamic separator is a unique structure that presents a few problems to ODOT when attempting to perform maintenance. The structure is typically used as a Best Management Practice (BMP) along high volume roadways. The system consists of an underground vault that creates a vortex which applies a continuous centrifugal force to separate and trap debris, sediment, and hydrocarbons from stormwater runoff (CDS, 2018). Figure 6.3 shows the hydrodynamic separator system during construction.



(a)

(b)

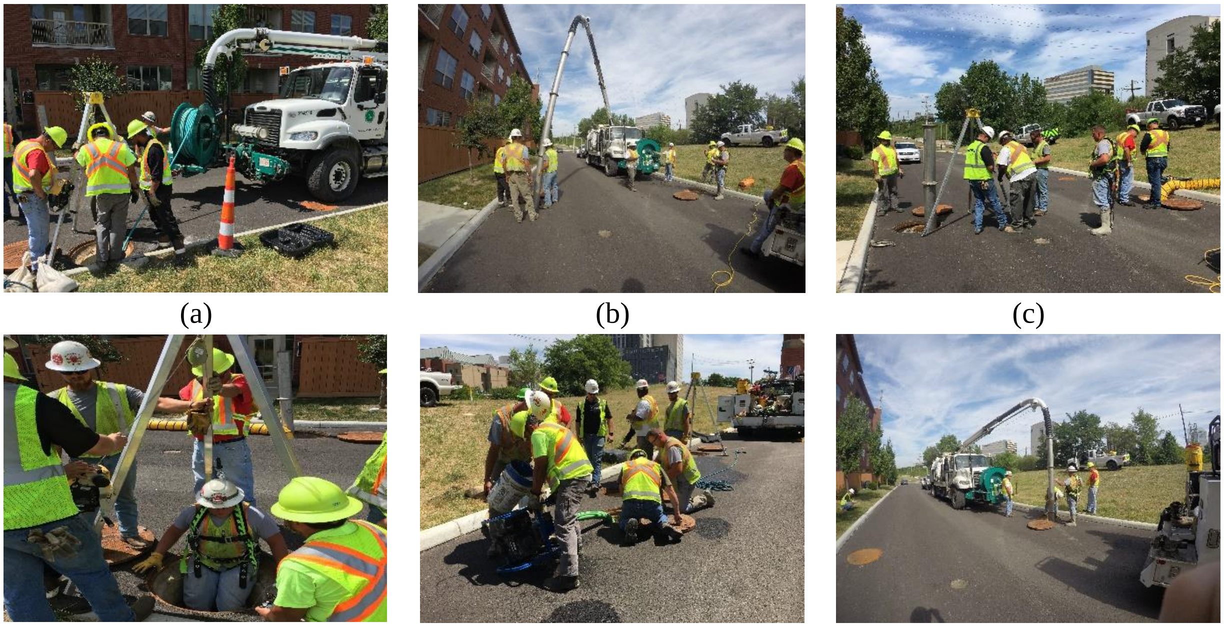
Note: Pictures taken by the ODOT technical liaisons in Winter 2017.

Figure 6.3: Hydrodynamic Separator System along I-70/71 in Columbus, OH. (a) Inside of hydrodynamic separator internal baffle, (b) Series of four hydrodynamic separators.

This type of structure has historically been difficult to perform maintenance cleaning on due to its depth and volume of water it contains. The following sections describe how the maintenance process works using the VJT and Recycler methods.

6.2.1 Traditional Methods

The traditional method of maintenance using the VJT involves plugging the upstream line with sandbags to stop the flow of water. The crew must then use the VJT to remove the floatables and pump the hydrodynamic separator dry so that the VJT may reach the bottom of the structure to remove the settled debris. After the structure is cleaned the crew must remove the sandbags to return the flow of water. Figure 6.4 shows the series of steps that are required to maintenance the hydrodynamic separator using the traditional VJT methods.



(a) (b) (c)

(d) (e) (f)

Note: Pictures taken by the research team in Summer 2018.

Figure 6.4: Hydrodynamic Separator Maintenance Using Traditional VJT Methods. (a, b) VJT cleaning junction chamber so that crew member may be sent in to plug upstream line, (c) Crew waiting for junction chamber air to circulate and achieve acceptable oxygen and gas levels, (d) Crew member lowering into junction chamber to plug upstream line with sandbag, (e) Crew setting up a pump to remove standing water from hydrodynamic separator, (f) VJT cleaning the hydrodynamic separator.

As seen in Figure 6.4, the traditional method of cleaning the hydrodynamic separator involves numerous time consuming steps. In addition, it involves placing a crew member in a confined space, raising safety concerns. This type of structure promotes the greatest opportunity to improve operations using alternative maintenance methods.

6.2.2 Alternative Method using Recycler

The use of alternative methods to maintain hydrodynamic separators is one of the most exciting implementations of the Recycler. The Recycler uses a positive displacement (PD) pump to produce the vacuum needed to remove debris from the structure. The PD pump, paired with a snorkel attachment and onboard air compressor, adds the ability to vacuum at the bottom of a water column. This feature allows the Recycler to clean the hydrodynamic separator without needing to first drain the structure. Figure 6.5 shows the steps involved in cleaning the hydrodynamic separator using the Recycler.

(a) (b)

Note: Pictures taken by research team in Summer 2018.

Figure 6.5: Hydrodynamic Separator Maintenance Using Alternative Recycler Methods. (a) Crew setting up snorkel system and onboard air compressor, (b) Recycler cleaning the hydrodynamic separator.

As seen in Figure 6.5, the Recycler requires fewer steps to prepare, setup and clean the hydrodynamic separator when compared to the VJT seen in Figure 6.9. In addition, the method of cleaning the structure with the Recycler does not require anyone to enter a confined space. As a result of using the Recycler to clean the hydrodynamic separator, ODOT increases their production rate and decreases their safety concerns.

6.2.3 Production Comparison

In order to compare the two pieces of equipment in the most equivalent way possible, the research team tested the equipment on two hydrodynamic separators that were side by side on the same day. These two structures were nearly identical and contained similar debris as a result of being a part of the same BMP system. Table 6.4 shows the results of the testing, broken down into each step of the process.

Table 6.4: Hydrodynamic Separator Production Comparison

Task	VJT	Recycler
Setup	0:09	0:08
Clean Junction Chamber	0:51	0:27
Vent Junction Chamber	1:13	-
Plug Junction Chamber	0:25	-
Decant	0:59	-
Pump Hydrodynamic Separator	1:13	-
Clean Hydrodynamic Separator	0:00	0:31
Breakdown	0:23	0:06
Total Manhours[1]	**5:13**	**1:12**
Total Elapsed Time[2]	**4:15**	**1:12**
Result	**Failure**	**Success**

Note: (1) Total man-hours refers to the amount of total time spent working, (2) Total elapsed time refers to the amount of time at the site and this may differ from the man-hours due to tasks occurring simultaneously.

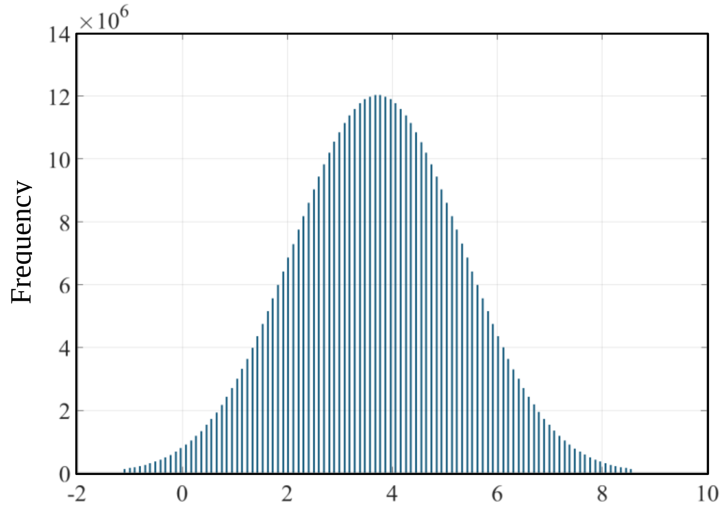
As seen in Table 6.4, the VJT spent 4:15 at the site attempted to clean the hydrodynamic separator. The shift ended before the structure was pumped dry, resulting in a failure to clean the structure. In comparison, the Recycler spent 1:13 at the site and was able to successfully clean the hydrodynamic separator. Table 6.5 presents the increase in production rate when using the Recycler to clean hydrodynamic separators.

Table 6.5: Production Rate Increase for Hydrodynamic Separators

Description	Average	Standard Deviation
Production Rate Increase	3.73	1.61

Note: The increase in production rate is based on a normal distribution curve.

As seen in Table 6.5, the production rate increase of the Recycler over the traditional VJT while cleaning hydrodynamic separators is estimated to be 3.73, meaning it is 273% more productive than the VJT. Figure 6.6 shows the normal distribution curve.



Note: Distribution produced by simulating model 10,000,000 times.

Figure 6.6: Production Rate Increase Normal Distribution Curve

Figure 6.6 indicates that the most probable Recycler production rate estimate is approximately 3.73 times that of the VJT. While rare in District 6, hydrodynamic separators are growing in popularity and is one area where the cost savings potential is very high if given enough structures. Using ODOT TIMS data, there are 61 sets of hydrodynamic separators under ODOT ownership throughout the state. When District 6 has to maintenance the hydrodynamic separators, the additional risk of lowering a crew member into a confined space presents safety concerns, as seen in Figure 6.4. While numerous safety precautions are taken, including the presence of a safety supervisor, the ability to maintain the structure without taking the risk at all is preferred. The research team compared the features of the Recycler and VJT that had positive and negative impacts to their performance. Table 6.6 summarizes these features.

Table 6.6: Operator Training Feature Comparison

Item	VJT	Recycler
Positive Displacement Pump[1]	Optional	Included
Suction Hose Assembly[2]	Manual	Automated
Confined Space Hazard[3]	Required	Not Required
Vacuum Position[4]	Top of Water Column	Top or Bottom of Water Column

Note: (1) Positive displacement pump refers to the type of vacuum used to production suction, (2) Suction hose assembly refers to the type of suction hose that is used and how it is deployed into the storm sewer, (3) Confined space hazard refers to the necessity to place an employee inside the structure and introduce additional safety hazards, (4) Vacuum position refers to the part of the water column in which the vacuum is able to operate.

Table 6.6 shows that here are many advantages to using the Recycler to clean the hydrodynamic separator. These advantages include the ability to vacuum from the bottom of the water column with the use of the positive displacement pump which allows the operators to maintain the water level in the structure. The ability to keep the water in the structure is crucial as it removes the need to place an employee into a confined space to setup pumping equipment to empty the system. In addition, the time it takes to pump the system dry exceeds that of the actual cleaning process. Removing these steps increases both the safety and production rate of the operations while using the Recycler compared to the VJT.

6.3 Structure Density

The research team wanted to see if the type of setting in which the equipment was operating would impact the production rate improvement of the Recycler. The team focused on two main categories: low and high structure density. There are multiple variables that are heavily impacted by the type of setting, such as: time to site, time between sites, time to clean structure, time to refill water and time to decant. The team believes that by presenting the production rates seen in different settings, end users may be able to determine if the Recycler is the best option for them.

6.3.1 Low Density Setting

The first type of setting the team looked at were those with a low density of storm sewers. These areas typically include roads that are two lanes, carry a low traffic volume, and have unique land use factors. Low density areas in ODOT District 6 are predominately in flat regions used for agriculture. The structures in these areas are also generally far from water refilling and/or decanting locations which increases travel time to these sites. In addition, structures are typically spread across a long distance, increasing travel time between sites as well. Figure 6.7 shows an example of cleaning a structure in a low density area with the VJT.

(a)

(b)

Note: Pictures taken by research team in the fall of 2018.

Figure 6.7: Low Density Arterial Storm Sewer Cleaning with VJT (a) VJT cleaning catch basin in low density setting, (b) VJT cleaning underdrain in low density setting.

The storm sewer maintenance on structures in low density areas shown in Figure 6.7 typically require more time than in high density areas. In many situations, low density infrastructure is older, has been inspected less frequently, carries agricultural runoff, and may be damaged by large equipment. Figure 6.8 shows the Recycler working in a low density setting on a storm sewer damaged by agricultural equipment.

(a)

(b)

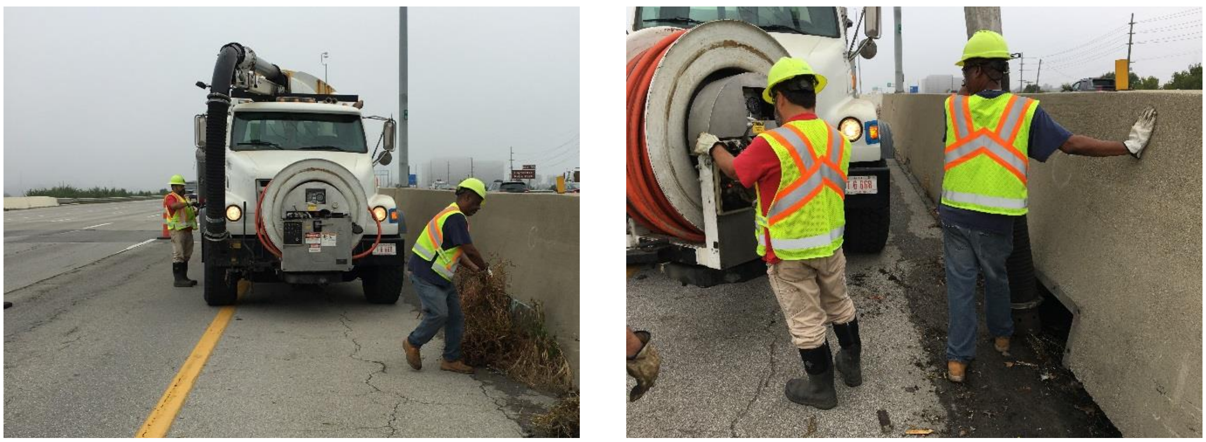
Note: Pictures taken by research team in Fall 2018.

Figure 6.8: Low Density Arterial Storm Sewer Cleaning with Recycler (a) Recycler cleaning lateral line in low density setting, (b) Broken lateral line in low density setting.

The damage to the storm sewer from the agricultural equipment shown in Figure 6.8 is extensive. Additional time at the site was required to locate the line beneath ground cover, hand dredge the line and investigate where the structure may be broken. All of these factors lead to the both pieces of equipment requiring a longer time at the site than in a high density setting.

6.3.2 *High Density Setting*

The second type of setting that the research team studied were structures in high density areas. High density settings are typically at least four lanes wide and are often up to six lanes in Franklin County. These types of roads carry a heavy traffic volume and the surrounding land use is comprised of commercial, industrial and residential uses. The immediate area is typically covered in non-porous pavement leading to an increase of storm water that the storm sewers must handle. In addition, storm sewers in high density settings are commonly clogged by large debris such as car parts or litter due to the heavy volume. While water refill and decant locations are typically closer in proximity, the nature of the limited access on high density roads leads to longer trips to and from the cleaning site. Figure 6.9 shows the VJT cleaning a storm sewer in a high density setting.

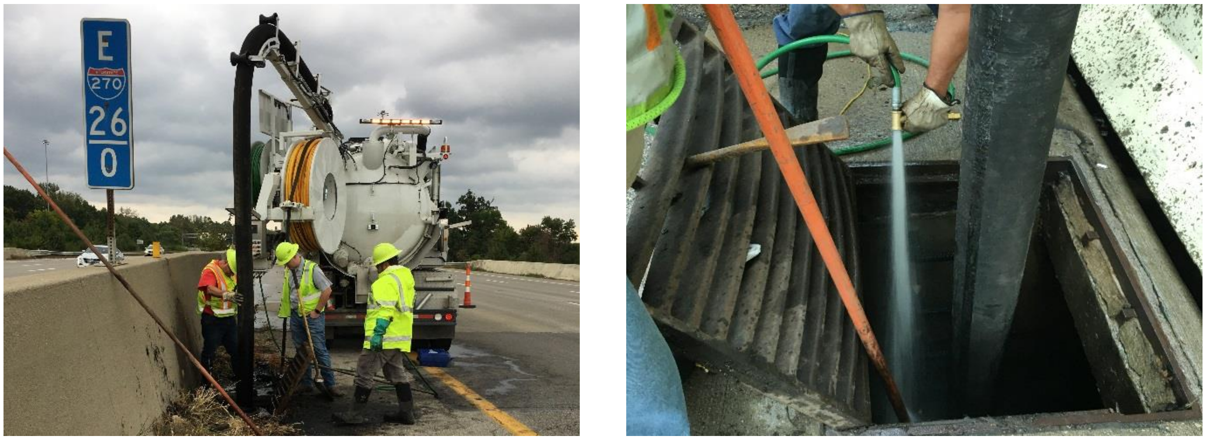


(a) (b)

Note: Pictures taken by research team in Fall 2018.

Figure 6.9: High Density Arterial Storm Sewer Cleaning with VJT (a) VJT cleaning in high density setting, (b) Plated drain cleaning in high density setting.

As seen in Figure 6.9, the VJT may have difficulty accessing certain types of storm sewers in some cases. For example, plated drains have narrow openings which the eight inch vacuum tube on the VJT has trouble fitting into. The operators had to hand shovel debris up to the vacuum tube from the bottom of the structure in this instance. In addition, storm sewers in high density environments are typically closer in proximity to each other and have long lateral lines to jet, leading to an increase in water usage. In addition, the time it takes to setup and breakdown the VJT before and after each cleaning leads to additional time lost. Figure 6.10 shows the Recycler operating in a high density environment.



(a) (b)

Note: Pictures taken by research team in Fall 2018.

Figure 6.10: High Density Arterial Storm Sewer Cleaning with Recycler (a) Recycler cleaning in high density setting, (b) Catch basin cleaning in high density setting.

Figure 6.10 demonstrates how the flexible vacuum hose allows the Recycler to quickly setup and breakdown at each site. In addition, the water recycling technology prevents the Recycler from making additional water refill trips, saving time. The team also notes that the vacuum hose on the Recycler is six inches in diameter with a second four inch attachment that allows the operators to easily access plated drains. The research team linked the most important features of the Recycler and VJT to specific outcomes when cleaning structures that differ in setting. The results of this comparison may be found in Table 6.7.

Table 6.7: Operator Training Feature Comparison

Item	VJT	Recycler
Recycling Capability	No	Yes
Debris Capacity (cy)	9-15[1]	15[2]
Water Capacity (gal)	1500	1500[2]
Suction Hose Diameter (in)	8	6
Suction Hose Classification[3]	Rigid	Flex

Note: (1) ODOT currently operates both a 9 cy and 15 cy VJT. (2) Water tank capacity for the Recycler ranges from 0-1500 gallons. The Recycler uses a moving partition to separate the water and debris sides of a single tank system. As the water tank size increases, the debris tank size decreases to a minimum of 6 cy; however, the partition can be moved to increase the debris tank size during operations. It is also noted that clean water may be stored in the debris tank of the Recycler as well, (3) Suction hose classification describes the style and material in which the suction hose is built.

As highlighted in Table 6.7, the main equipment features that impact the cleaning production rate of structures in varying settings are the ability to recycle, debris and water capacity, suction hose diameter and suction hose classification. As discussed previously in this section, the recycling capability, debris and water capacity allows the Recycler to stay onsite longer, especially in high density settings, resulting in a higher production rate. In addition, the suction hose diameter and classification allow the Recycler to clean certain structures, such as the plated drain, with relative ease.

6.4 Equipment Implementation Synthesis

This section presents a final synthesis of the major differences between the VJT and Recycler equipment options. Similar to the previous sections, the research team created a list of features that had the largest impact on the production rate, safety and effectiveness of each piece of equipment. Table 6.8 presents the summarized findings.

Table 6.8: Operator Training Feature Comparison

Item	VJT	Recycler
Computerized Controls[1]	No	Yes
Wireless Diagnostics[2]	No	Yes
Automated Processes[3]	No	Yes
Additional Training[4]	None	Operator Dependent
Confined Space Hazard[5]	Required	Not Required
Vacuum Position[6]	Top of Water Column	Top or Bottom of Water Column
Recycling Capability	No	Yes
Operator Position	Front	Rear
Operator Feedback	Negative	Positive
Operator Safety Concerns[7]	Operator Strain/Noise Levels	Limited
PD Pump	Optional	Included
Cleans Storm Sewer	Yes	Yes
Cleans Manhole Vault	Yes	Yes
Cleans Hydrodynamic Separator	No	Yes
Customer Rating	-	Positive
Industry Use	Standard	Rare
Capital Cost[8]	$360,000	$590,105
Viability	**-**	**Viable**

Note: (1) Computerized controls refers to the onboard CAN bus system that is included on the Recycler and used to control its operations, (2) Wireless diagnostics refers to the cellular system incorporated into the Recycler CAN bus system that allows the manufacturer to remotely view error codes, (3) Automated processes refers to operations that happen without operator intervention or manual labor, (4) Additional training refers to the time required for users to learn the operating system, mostly caused by the additional complexity associated with the CAN bus system. (5) Confined space hazard refers to the necessity to place an employee inside the structure and introduce additional safety hazards, (6) Vacuum position refers to the part of the water column in which the vacuum is able to operate, (7) Operator safety concerns were developed through discussions with the operators and ODOT management, (8) Capital cost quotes were received in the fall of 2018.

Table 6.8 documents the positives and negatives of both pieces of equipment. The VJT advantages include it being the industry standard for years and a lower capital cost. The Recycler includes many advantages over the VJT however; such as, computerized systems, decreased safety concerns, positive operator feedback, increased production and the ability to quickly clean hydrodynamic separators, among others.

The research team ultimately recommends that each DOT or contactor use this report to determine if the Recycler is the best option for their needs. There are some cases in which the Recycler may not be cost effective. In these cases it is still important to consider the safety factors as well as the advanced technology that is incorporated into the system such as the wireless diagnostics and water savings through the recycling system. However, for the majority of scenarios, the Recycler will be a much more cost effective solution to cleaning storm sewers than the traditional VJT.

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APPENDIX A – ALTERNATE RECYCLER OPTIONS

This report focuses on the BUCHER RECycler 315; however, there are multiple Recycler's that are currently available. The research team completed an extensive review of alternative Recycler options in Phase I of this study: *"Evaluation of the Ohio Department of Transportation's Current Storm Sewer Cleaning Operations – Phase I"* (Schneider et al., 2018). Alternative Recycler options, seen in Table A.1, included; VacAll AJV Recycler, GapVax Recycler, Vactor 2100 Plus Recycler and Camel 1200 Recycler.

Table A.1: Alternative Recycler Options

Equipment	VJT	BUCHER RECycler 315	VacAll AJV[1]	GapVax Recycler	Vactor 2100 Plus	Camel 1200
						
Recycling Capability	No	Yes	Yes	Yes	Yes	Yes
Recycling Technology	N/A	Cyclone	Centrifuge	Cyclone	Centrifuge	Centrifuge
Debris Cap. (cy)	9-15	15[2]	12	10.5	15	12
Water Cap. (gal)	1500	1500[2]	1500	1500	1500	1500
Operator Position	Front	Rear	Front	Rear	Front	Front
PD Pump	Optional	Included	Included	Included	Included	Included
Suction Hose Diameter (in)	8	6	8	6	8	8
Suction Hose Classification[3]	Rigid	Flex	Rigid	Flex	Rigid	Rigid
Suction Hose Assembly[4]	Manual	Automated	Manual	Automated	Manual	Manual
Jetting Hose Diameter (in)	1-1.25	1.25	1	1.25	1	1.25
Cleans Storm Sewer	Yes	Yes	-	Yes	Yes	Yes
Cleans Manhole Vault	Yes	Yes	-	Yes	Yes	Yes
Cleans Hydrodynamic Separator	No	Yes	-	-	Yes	Yes
Customer Rating	-	Positive	Positive	N/A	Positive	Positive
Capital Cost[5]	$360,000	$590,105	$475,000	$750,000	$595,000	$464,000
Viability	**-**	**Viable**	**-**	**Viable**	**Viable**	**Viable**

Note: (1) Representatives from VacAll and their distribution network have not been able to provide the research team with information regarding the VacAll AJV Recycler. VacAll representatives have also not released customer information for the research team to receive customer testimonials. The information provided for the VacAll AJV Recycler was found by the research team through equipment brochures. This information has not been confirmed by VacAll representatives, (2) Water tank capacity for the JHL 315 ranges from 0-1500 gallons. JHL uses a moving partition to separate the water and debris sides of a single tank system. As the water tank size increases, the debris tank size decreases; however, the partition can be moved to increase the debris tank size during operations, (3) The suction hose classification describes the style and material in which the suction hose is built, (4) The suction hose assembly refers to the type of suction hose that is used and how it is deployed into the storm sewer, (5) Capital cost quotes were received in the fall of 2018, (6) Refer to (Schneider et al., 2018) for more information, (7) Equipment references (JHL RECycler, 2017; VACALL, 2017; GapVax, 2017; Super Products, 2017; Vactor, 2017).

As seen in Table A.1, in Phase I, the research team determined that all Recyclers were viable to be able to implement in ODOT District 6. While the team did not conduct field testing on any Recycler other than the RECycler 315, based on equipment demonstrations in Phase I, the team still recommends that all Recycler options listed in Table 40 are viable.

The research team made the recommendation to purchase the RECycler 315 based on the discussions with the technical liaisons. Key criteria that were relevant specifically to ODOT District 6 were; the flexible hose functionality, capacity of the debris tank and increased field operating temperature (Schneider et al., 2018). The team notes that each DOT or contractor may have elements of their assets or regions that are different than District 6. The end used should use Phase I of this report to determine which equipment option may be best suited for their needs. This study should be used to confirm that the Recycler is viable and proven to be economically feasible.

APPENDIX B – TESTING PHOTOS

(a) (b) (c)

Figure B.1: VJT Operations Using Vac-Con 9CY on June 25, 2018 in Union County
(a) Beginning setup, (b) Cleaning of the structure, (c) Jetting line towards field.

(a) (b) (c)

Figure B.2: VJT Operations Using Vac-Con 9CY on June 25, 2018 in Union County
(a) Structure prior to cleaning, (b) Cleaning of the structure, (c) Jetting through structure line.

(a) (b) (c)

Figure B.3: VJT Operations Using Vac-Con 9CY on June 25, 2018 in Union County
(a) Structure prior to cleaning, (b) Cleaning of the structure, (c) Structure post-cleaning.

(a) (b) (c)

Figure B.4: VJT Operations Using Vac-Con 9CY on June 25, 2018 in Franklin County
(a) Structure prior to cleaning, (b) Cleaning of the structure, (c) Jetting through structure line.

(a) (b) (c)

Figure B.5: VJT Operations Using Vac-Con 9CY on June 26, 2018 in Madison County
(a) Work setup, (b) Cleaning of the structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.6: VJT Operations Using Vac-Con 9CY on June 26, 2018 in Madison County
(a, b) Work setup, (c) Cleaning of the structure.

(a) (b) (c)

Figure B.7: VJT Operations Using Vac-Con 9CY on June 26, 2018 in Madison County
(a) Structure prior to cleaning, (b) Cleaning of the structure, (c) Refill at West Jefferson Garage.

(a) (b) (c)

Figure B.8:VJT Operations Using Vac-Con 9CY on June 26, 2018 in Madison County
(a) Collapsed underdrain, (b) Attempting to jet structure, (c) Structure from opposite side of road.

(a) (b) (c)

Figure B.9: VJT Operations Using Vac-Con 9CY on June 26, 2018 in Madison County
(a) Truck prior to decant, (b) Decanting at Columbus WWTP, (c) Post Decanting.

(a) (b) (c)

Figure B.10: VJT Operations Using Vactor 2100 on June 27, 2018 in Union County
(a) Zone setup, (b) Cleaning of the structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.11: VJT Operations Using Vactor 2100 on June 27, 2018 in Union County
(a) Structure prior to cleaning, (b) Structure post cleaning, (c) Searching for collapsed pipe.

(a) (b) (c)

Figure B.12: VJT Operations Using Vactor 2100 on June 27, 2018 in Union County
(a) Structure prior to cleaning, (b) Cleaning of Structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.13: VJT Operations Using Vactor 2100 on June 27, 2018 in Union County
(a) Zone setup, (b) Cleaning of the structure, (c) Zone breakdown.

(a) (b) (c)

Figure B.14: VJT Operations Using Vactor 2100 on June 28, 2018 at ODOT Richwood Garage
(a, b, c) Structure during cleaning.

(a) (b) (c)

Figure B.15: VJT Operations Using Vactor 2100 on June 28, 2018 in Union County
(a) Zone prior to cleaning, (b) Inner structure prior to cleaning, (c) Cleaning of the structure.

(a) (b) (c)

Figure B.16: VJT Operations Using Vactor 2100 on June 28, 2018 in Union County
(a) Structure prior to cleaning, (b) Cleaning of the structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.17: VJT Operations Using Vactor 2100 on June 28, 2018 at ODOT Richwood Garage
(a) Jetting line towards adjacent structure, (b) Vacuuming and jetting (c) Vacuuming excess debris

(a) (b) (c)

Figure B.18: VJT Operations Using Vactor 2100 on June 29, 2018 at ODOT Richwood Outpost
(a) Front-left profile of Vactor truck, (b) Preparing to run the jet, (c) Jetting through the structure.

(a) (b) (c)

Figure B.19: VJT Operations Using Vactor 2100 on June 29, 2018 at ODOT Richwood Outpost
(a) Structure prior to cleaning, (b, c) Cleaning the structure.

(a) (b) (c)

Figure B.20: VJT Operations Using Vactor 2100 on July 3, 2018 in Union County
(a, b) Jetting through the structure, (c) The structure post jetting.

(a) (b) (c)

Figure B.21: BUCHER RECycler 315 Operations on July 9, 2018 at ODOT District 6 Headquarters
(a) Left profile of truck, (b) Drivers side view of cab, (c) Front-right profile of truck.

(a) (b) (c)

Figure B.22: BUCHER RECycler 315 Operations on July 9, 2018 at ODOT District 6 Headquarters
(a) Master control panel, (b) Bucher reps showing the main tank, (c) Back-left view of the main tank.

(a) (b) (c)

Figure B.23: BUCHER RECycler 315 Training Operations on July 10, 2018
(a) Structure prior to cleaning, (b) Structure during cleaning, (c) Vacuum and jet operating off sway arm

(a) (b) (c)

Figure B.24: BUCHER RECycler 315 Training Operations on July 10, 2018
(a) Structure during cleaning, (b, c) Simultaneous cleaning and jetting of structure.

(a) (b) (c)

Figure B.25: BUCHER RECycler 315 Training Operations on July 10, 2018
(a) Simultaneous cleaning and jetting of structure, (b, c) Removing debris from nozzle of the jet hose.

(a) (b) (c)

Figure B.26: BUCHER RECycler 315 Training Operations on July 11, 2018
(a) Simultaneous cleaning and jetting of structure, (b) Equipment zone, (c) Large debris within structure.

(a) (b) (c)

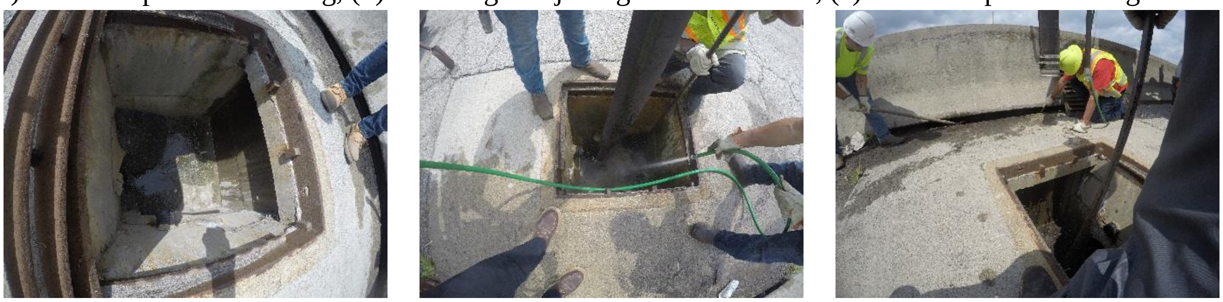
Figure B.27: BUCHER RECycler 315 Training Operations on July 11, 2018
(a) Right side profile of the RECycler, (b) Structure prior to cleaning, (c) Operators cleaning the structure.

(a) (b) (c)

Figure B.28: BUCHER RECycler 315 Operations on July 16, 2018 at Westerville Outpost
(a) Filling at Westerville Outpost, (b) Water level on operating screen, (c) Water level on side panel.

(a) (b) (c)

Figure B.29: BUCHER RECycler 315 Operations on July 16, 2018 in Franklin County
(a) Structure prior to cleaning, (b) Cleaning and jetting of the structure, (c) Structure post cleaning.



(a) (b) (c)

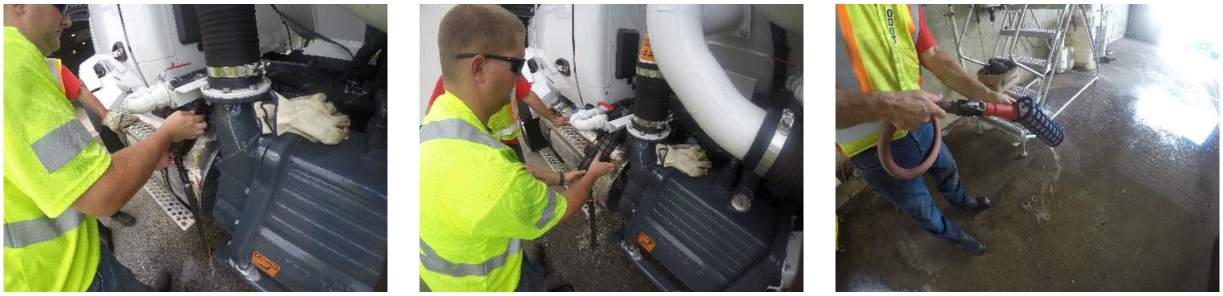
Figure B.30: BUCHER RECycler 315 Operations on July 16, 2018 in Franklin County
(a) Prior to cleaning, (b) Using a spud bar and hose to loosen debris, (c) Clearing under the median wall.

(a) (b) (c)

Figure B.31: BUCHER RECycler 315 Operations on July 16, 2018 in Franklin County
(a) Structure prior to cleaning, (b) Simultaneously cleaning and jetting of the structure, (c) Post cleaning.

(a) (b) (c)

Figure B.32: BUCHER RECycler 315 Maintenance on July 16, 2018 at ODOT Westerville Outpost
(a) Draining the three filters, (b) The filters enclosure, (c) Using fresh water to clean the filters.



(a) (b) (c)

Figure B.33: BUCHER RECycler 315 Maintenance on July 16, 2018 at ODOT Westerville Outpost
(a) Draining the tube filter, (b) Releasing the filter from the enclosure, (c) Cleaning filter.

(a) (b) (c)

Figure B.34: BUCHER RECycler 315 Maintenance on July 16, 2018 at ODOT Westerville Outpost
(a) Opening the enclosure of the large drum filter, (b) Enclosure after filter is removed, (c) Cleaning filter.

(a) (b) (c)

Figure B.35:VJT Operations Using Vactor 2100 on July 16, 2018 in Franklin County
(a) Front controls and spool, (b) Main operating control panel, (c) System gages.

(a) (b) (c)

Figure B.36: VJT Operations Using Vactor 2100 on July 17, 2018 in Franklin County
(a) Structure prior to cleaning, (b) Cleaning of the structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.37: VJT Operations Using Vactor 2100 on July 17, 2018 in Franklin County
(a, b) Jetting the underdrain of the structure, (c) Structure cavity post jetting.

(a) (b) (c)

Figure B.38: VJT Operations Using Vactor 2100 on July 17, 2018 at Columbus Decanting Station
(a) Preparing to dispose of waste, (b) Tank raised disposing waste, (c) Hosing to clear of excess waste.

(a) (b) (c)

Figure B.39: BUCHER RECycler 315 Operations on July 18, 2018 in Franklin County
(a) Preparing to dispose of waste, (b) Tank raised disposing waste, (c) Hosing to clear of excess waste.

(a) (b) (c)

Figure B.40: BUCHER RECycler 315 Operations on July 18, 2018 at Columbus Decanting Station
(a, b) Disposing all the liquid waste, (c) Preparing fresh water hydrant for cleaning.

(a) (b) (c)

Figure B.41: BUCHER RECycler 315 Operations on July 18, 2018 at Columbus Decanting Station
(a) Draining tank of liquid waste, (b) Rear open dumping the solid waste, (c) Rinsing of all excess waste.

(a) (b) (c)

Figure B.42: BUCHER RECycler 315 Operations on July 19, 2018 in Franklin County
(a) The RECycler and Vac-Con preparing, (b) RECycler running the jet, (c) Vac-Con jetting structure.

(a) (b) (c)

Figure B.43: VJT Operations Using Vac-Con 9CY on July 19, 2018 in Franklin County
(a) Simultaneous cleaning and jetting of structure, (b) Right profile view of truck, (c) During cleaning.

(a) (b) (c)

Figure B.44: BUCHER RECycler 315 Operations on August 22, 2018 in Franklin County
(a) Cleaning the structure, (b) Operators cleaning and spraying debris with small hose, (c) Post cleaning.

(a) (b) (c)

Figure B.45: BUCHER RECycler 315 Operations on August 28, 2018 in Franklin County
(a)Structure prior to cleaning, (b) Cleaning of the structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.46: BUCHER RECycler 315 Operations on August 30, 2018 in Madison County
(a) Operators setting up zone, (b) Structure pre-cleaning, (c) Structure post cleaning.

(a) (b) (c)

Figure B.47: BUCHER RECycler 315 Operations on August 30, 2018 in Madison County
(a) Operators setting up zone, (b) Cleaning of the structure, (c) Structure post cleaning.

(a) (b) **(c)**

Figure B.48: **BUCHER** RECycler 315 **Operations** on September 25, 2018 in Union County
(a) Operators setting up zone., (b) Cleaning of the structure, (c) Structure post cleaning

(a) (b) (c)

Figure B.49: BUCHER RECycler 315 Operations on September 26, 2018 in Franklin County
(a, b) Structure prior to cleaning, (c) Structure post cleaning.

(a) (b) (c)

Figure B.50: BUCHER RECycler 315 Operations on September 26, 2018 in Franklin County
(a) Structure prior to cleaning, (b) Cleaning of the structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.51: BUCHER RECycler 315 Operations on September 26, 2018 in Franklin County
(a) Right profile of vehicle, (b) Rear view of vehicle with control panel,(c) Truck and operators.

(a) (b) (c)

Figure B.52: BUCHER RECycler 315 Operations on September 27, 2018 in Madison County
(a) Operators setting up zone, (b) Running the jet and vacuum on structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.53: BUCHER RECycler 315 Operations on October 2, 2018 in Franklin County
(a) Structure prior to cleaning, (b) operators clearing in and around catch basin, (c) post cleaning.

(a) (b) (c)

Figure B.54: BUCHER RECycler 315 Operations on October 2, 2018 in Franklin County
(a) Structure prior to cleaning, (b) operators cleaning catch basin, (c) post cleaning.

(a) (b) (c)

Figure B.55: Vactor 2100 Operations on October 2, 2018 in Franklin County
(a) Structure prior to cleaning, (b, c) During the cleaning procedure.

(a) (b) (c)

Figure B.56: BUCHER RECycler 315 Operations on October 3, 2018 in Franklin County
(a) Vacuum operating on structure, (b) Cleaning debris around cavity, (c) Structure post cleaning.

(a) (b) (c)

Figure B.57: Vactor 2100 Operations on October 3, 2018 in Franklin County
(a) Operators setting up zone, (b) Performing vacuum on structure, (c) Gutter after cleaning.

(a) (b) (c)

Figure B.58: BUCHER RECycler 315 Operations on October 4, 2018 in Franklin County
(a) Structure prior to cleaning, (b) During cleaning, (c) Structure after the cleaning processes.

(a) (b) (c)

Figure B.59: BUCHER RECycler Operations on October 9, 2018 in Franklin County
(a) Structure prior to cleaning, (b) Cleaning operations, (c) Structure after cleaning.

(a) (b) (c)

Figure B.60: BUCHER RECycler Operations on October 9, 2018 in Franklin County
(a) Structure prior to cleaning, (b, c) During cleaning operations.

(a) (c)

Figure B.61: BUCHER RECycler Operations on October 9, 2018 in Franklin County
(a) View of the truck while zone is being setup, (b) Prior to cleaning, (c) During the cleaning procedures.

(a) (b) (c)

Figure B.62: BUCHER RECycler Operations on October 9, 2018 in Franklin County
(a) Catch basin before cleaning, (b) Operators cleaning the structure, (c) Structure post cleaning.

(a) (b) (c)

Figure B.63: BUCHER RECycler Operations on October 9, 2018 in Franklin County
(a) Operators preparing area, (b) Structure before the cleaning process, (c) Catch basin after cleaning.

(a) (b) (c)

Figure B.64: BUCHER RECycler Operations on October 9, 2018 in Franklin County
(a) Structure prior to cleaning, (b, c) Using vacuum and jet to clean the catch basin.

(a) (b) (c)

Figure B.65: BUCHER RECycler Operations on October 9, 2018 in Franklin County
(a) Structure prior to cleaning, (b, c) Operators running vacuum and jet on structure and after cleaning.

(a) (b) (c)

Figure B.66: BUCHER RECycler Operations on October 11, 2018 in Madison County
(a, b) Attempting to jet through cross drain while vacuuming water, (c) Structure after attempted cleaning.

(a) (b) (c)

Figure B.67: BUCHER RECycler Operations on October 11, 2018 at ODOT West Jefferson Garage
(a) Structure prior to cleaning, (b) Running the vacuum on structure, (c) Post cleaning.

(a) (b) (c)

Figure B.68: BUCHER RECycler Operations on October 11, 2018 at ODOT West Jefferson Garage
(a, b) Running vacuum and small hose on the structure, (c) After cleaning the structure.

APPENDIX C – FIELD DATA RESULTS

Table C.1: June 2018 Field Data

Day	Truck	County	Environment	Blockage	Structure	Setup	Jet	Vacuum	Breakdown	Pause/Idle	Refill	Decant	Filter Cleaning
6/25/2018	Vac-Con	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:06:00	0:21:00	0:03:00	0:05:00	0:00:00	0:00:00	0:00:00	0:00:00
6/25/2018	Vac-Con	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:04:00	0:08:00	0:00:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
6/25/2018	Vac-Con	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:03:00	0:04:00	0:00:00	0:02:00	0:00:00	1:48:00	0:00:00	0:00:00
6/25/2018	Vac-Con	Franklin	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:10:00	0:23:00	0:05:00	0:07:00	0:15:00	0:00:00	1:36:00	0:00:00
6/26/2018	Vac-Con	Madison	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:01:00	0:18:00	0:00:00	0:04:00	0:05:00	0:00:00	0:00:00	0:00:00
6/26/2018	Vac-Con	Madison	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:12:00	0:32:00	0:04:00	0:07:00	0:02:00	1:00:00	0:00:00	0:00:00
6/26/2018	Vac-Con	Madison	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:04:00	0:05:00	0:00:00	0:09:00	0:00:00	1:35:00	0:00:00	0:00:00
6/26/2018	Vac-Con	Madison	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:02:00	0:06:00	0:00:00	0:04:00	0:00:00	0:00:00	0:18:00	0:00:00
6/27/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:04:00	0:07:00	0:00:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
6/27/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:01:00	0:06:00	0:00:00	0:22:00	0:16:00	0:00:00	0:00:00	0:00:00
6/27/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:03:00	0:09:00	0:05:00	0:03:00	0:15:00	0:00:00	0:00:00	0:00:00
6/27/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Manhole	0:03:00	0:00:00	0:03:00	0:09:00	0:00:00	0:00:00	0:00:00	0:00:00
6/27/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:07:00	0:05:00	0:06:00	0:03:00	0:03:00	0:35:00	0:00:00	0:00:00
6/28/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:02:00	0:00:00	0:05:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
6/28/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:01:00	0:17:00	0:02:00	0:06:00	0:00:00	0:00:00	0:00:00	0:00:00
6/28/2018	Vactor	Madison	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:05:00	0:28:00	0:28:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
6/28/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:03:00	0:06:00	0:00:00	0:06:00	0:00:00	0:00:00	0:00:00	0:00:00
6/28/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:03:00	0:04:00	0:00:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
6/28/2018	Vactor	Madison	Rural Arterial	Sand/Dirt/Clay	Manhole	0:06:00	0:06:00	0:08:00	0:02:00	0:07:00	1:29:00	0:00:00	0:00:00
6/29/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:01:00	0:14:00	0:14:00	0:03:00	0:00:00	0:00:00	0:00:00	0:00:00
6/29/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:02:00	0:09:00	0:00:00	0:24:00	0:10:00	0:00:00	0:00:00	0:00:00
6/29/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:01:00	0:02:00	0:00:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
6/29/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Lateral Line	0:01:00	0:02:00	0:00:00	0:03:00	0:00:00	0:00:00	0:00:00	0:00:00

Note: Data collected by research team.

Table C.2: July 2018 Field Data

Day	Truck	County	Environment	Blockage	Structure	Setup	Jet	Vacuum	Breakdown	Pause/Idle	Refill	Decant	Filter Cleaning
7/3/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Lateral Line	0:02:00	0:09:00	0:00:00	0:08:00	0:00:00	0:00:00	0:00:00	0:00:00
7/3/2018	Vactor	Union	Rural Arterial	Sand/Dirt/Clay	Lateral Line	0:02:00	0:03:00	0:00:00	0:03:00	0:00:00	0:00:00	0:00:00	0:00:00
7/16/2018	Recycler	Franklin	Urban Arterial	Sand/Dirt/Clay	Catch Basin	0:15:00	0:02:00	0:00:00	0:03:00	0:05:00	0:00:00	0:00:00	0:00:00
7/16/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:02:00	0:07:00	0:00:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
7/16/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:04:00	0:28:00	0:00:00	0:02:00	0:13:00	0:00:00	0:00:00	0:00:00
7/16/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:18:00	0:00:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
7/16/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:04:00	0:21:00	0:00:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
7/17/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:05:00	0:40:00	0:40:00	0:05:00	0:00:00	0:00:00	1:10:00	0:00:00
7/17/2018	Vactor	Franklin	Urban Highway	Sand/Dirt/Clay	Manhole	0:07:00	0:56:00	0:10:00	0:02:00	0:17:00	0:00:00	0:00:00	0:00:00
7/18/2018	Recycler	Franklin	Urban Highway	Large Debris	Manhole	0:05:00	0:40:00	1:05:00	0:02:00	0:33:00	0:00:00	0:00:00	0:00:00
7/19/2018	Recycler	Franklin	Urban Arterial	Sand/Dirt/Clay	Vortex.	0:03:00	0:28:00	0:00:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
7/19/2018	Recycler	Franklin	Urban Arterial	Sand/Dirt/Clay	Vortex	0:04:00	0:00:00	0:02:00	0:06:00	0:09:00	0:00:00	0:00:00	0:00:00
7/19/2018	Vac-Con	Franklin	Urban Arterial	Sand/Dirt/Clay	Vortex	0:03:00	0:22:00	0:00:00	0:23:00	0:50:00	0:00:00	0:00:00	0:00:00
7/19/2018	Vac-Con	Franklin	Urban Arterial	Sand/Dirt/Clay	Vortex	0:03:00	0:00:00	0:08:00	0:09:00	1:04:00	0:00:00	0:36:00	0:00:00

Note: Data collected by research team.

Table C.3: August 2018 Field Data

Day	Truck	County	Environment	Blockage	Structure	Setup	Jet	Vacuum	Breakdown	Pause/Idle	Refill	Decant	Filter Cleaning
8/22/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:05:00	0:00:00	1:10:00	0:10:00	0:00:00	0:00:00	0:00:00	0:00:00
8/28/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:07:00	1:17:00	1:04:00	0:05:00	1:08:00	0:00:00	0:00:00	0:12:00
8/30/2018	Recycler	Madison	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:02:00	0:24:00	0:24:00	0:02:00	0:17:00	0:00:00	0:00:00	0:00:00
8/30/2018	Recycler	Madison	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:04:00	0:22:00	0:00:00	0:03:00	0:00:00	0:00:00	0:00:00	0:00:00

Note: Data collected by research team.

Table C.4: September 2018 Field Data

Day	Truck	County	Environment	Blockage	Structure	Setup	Jet	Vacuum	Breakdown	Pause/Idle	Refill	Decant	Filter Cleaning
9/25/2018	Recycler	Union	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:04:00	1:29:00	0:41:00	0:04:00	0:32:00	0:00:00	0:00:00	0:00:00
9/26/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:04:00	0:15:00	0:31:00	0:08:00	0:08:00	0:00:00	0:00:00	0:00:00
9/26/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:04:00	0:00:00	0:06:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
9/26/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:03:00	0:15:00	0:00:00	0:07:00	0:02:00	0:00:00	0:00:00	0:00:00
9/27/2018	Recycler	Madison	Rural Arterial	Sand/Dirt/Clay	Catch Basin	0:08:00	1:23:00	1:34:00	0:03:00	1:44:00	1:16:00	0:00:00	0:00:00

Note: Data collected by research team.

Table C.5: October 2018 Field Data

Day	Truck	County	Environment	Blockage	Structure	Setup	Jet	Vacuum	Breakdown	Pause/Idle	Refill	Decant	Filter Cleaning
10/2/2018	Recycler	Franklin	Urban Highway	Grease	Catch Basin	0:04:00	1:28:00	1:28:00	0:01:00	0:06:00	0:00:00	0:00:00	0:00:00
10/2/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:31:00	0:03:00	0:06:00	0:05:00	0:00:00	0:00:00	0:00:00
10/2/2018	Vactor	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:04:00	0:27:00	1:12:00	0:05:00	0:32:00	0:00:00	1:34:00	0:00:00
10/3/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:03:00	0:10:00	0:23:00	0:04:00	0:07:00	0:00:00	0:00:00	0:00:00
10/3/2018	Vactor	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:05:00	0:08:00	0:08:00	0:05:00	0:10:00	0:00:00	0:00:00	0:00:00
10/3/2018	Vactor	Franklin	Urban Highway	Sand/Dirt/Clay	Plated Drain	0:05:00	1:02:00	1:02:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
10/4/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:03:00	0:02:00	0:02:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
10/4/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:03:00	0:03:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
10/4/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:02:00	0:02:00	0:02:00	0:00:00	0:00:00	0:00:00	0:00:00
10/4/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:05:00	0:05:00	0:01:00	0:00:00	0:00:00	0:00:00	0:01:00
10/4/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:23:00	0:23:00	0:03:00	0:12:00	0:00:00	0:00:00	0:06:00
10/6/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:05:00	1:42:00	1:42:00	0:01:00	0:00:00	0:00:00	0:00:00	0:15:00
10/6/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	1:36:00	1:36:00	0:01:00	0:00:00	0:00:00	0:00:00	0:16:00
10/6/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:02:00	1:34:00	1:34:00	0:10:00	0:00:00	0:00:00	0:45:00	0:15:00
10/6/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:05:00	2:01:00	2:01:00	0:04:00	0:46:00	0:00:00	0:00:00	0:23:00
10/6/2018	Vactor	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:10:00	7:14:00	7:14:00	0:15:00	2:13:00	0:00:00	0:00:00	0:00:00
10/9/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:08:00	0:08:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
10/9/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:03:00	0:04:00	0:04:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
10/9/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:02:00	0:09:00	0:09:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
10/9/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:08:00	0:08:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
10/9/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:04:00	0:04:00	0:01:00	0:01:00	0:00:00	0:00:00	0:00:00
10/9/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:01:00	0:03:00	0:03:00	0:02:00	0:01:00	0:00:00	0:00:00	0:00:00
10/9/2018	Recycler	Franklin	Urban Highway	Sand/Dirt/Clay	Catch Basin	0:03:00	0:35:00	0:35:00	0:04:00	0:11:00	0:00:00	0:00:00	0:00:00
10/11/2018	Recycler	Madison	Rural Arterial	Grease	Catch Basin	0:02:00	0:06:00	0:08:00	0:01:00	0:00:00	0:00:00	0:00:00	0:00:00
10/11/2018	Recycler	Madison	Rural Arterial	Grease	Catch Basin	0:01:00	0:08:00	0:08:00	0:03:00	0:00:00	0:00:00	0:00:00	0:00:00
10/11/2018	Recycler	Madison	Urban Arterial	Sand/Dirt/Clay	Lateral Line	0:04:00	0:35:00	0:30:00	0:08:00	0:01:00	0:00:00	0:00:00	0:00:00

Note: Data collected by research team.

APPENDIX D – DATA COLLECTION SHEET

Evaluation of The Ohio Department of Transportation's Current Storm Sewer Cleaning Operations

General Information					
Observer:		Date:			
Operating Crew:		Safety Crew:			
Equipment Make/Model:					
Location Information					
County:		Road:			
County MM:		State MM:			
Latitude:		Longitude:			
Environmental Information					
Precipitation:	Sunny	Cloudy	Light Rain	Heavy Rain	Snow
Visibility:	Excellent	Satisfactory	Poor		
Timing Information					
Arrival Time:		Departure Time:			
Start Time:		End Time:			
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Time:	Task:				
Interruptions:	_______ minutes; caused by:				
If Cleaning Location					
Environment:	Rural	Urban	Residential	Industrial	
Road Type:	Highway	Arterial	Residential		
Blockage Type:	Grease	Sand/Dirt/Clay	Roots	Large Debris	Other (notes)
Structure Type / Size:		Recycling Use:			
Water Use:		Debris Use:			
Reason to Leave:					
If Water / Decanting Location					
Location Name:					
Refill/Decant Time:		Refill/Decant Quantity:			
Additional Information					
Notes:					

The University of Akron
Department of Civil Engineering

Ohio Department of Transportation
Daily Data Sheet #

Figure D.1: Field Data Collection Sheet

APPENDIX E – SURVEY RESPONSES

Table E.1: Customer Survey Original Responses (Questions 1-8)

Company	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 7a	Question 7b	Question 8
Clear-Flow	Trusted JHL- ran RECyclers- took a chance on it	60-70% more efficient	Same standard of cleanliness- less downtime	Had a need- utilized immediately	2017	Add'l nozzles	Pipelines- sewers- surface drains	**No Response**	**No Response**	**No Response**
National Water Main Cleaning	Tested based on cleaning effectiveness- vacuum power	**No Response**	**No Response**	Thrown right in- own 20 jet vacs, works like a regular VJT when recycling not needed	2018	No	Pipes-	6-36"	**No Response**	**No Response**
National Water Main Cleaning	Never had RECycler- demoed a couple- used out in the field- works great on limited water project	Production is the same as old models- save time running for water	Same standard	Ran as soon as purchased	2018	No	Sanitary lines and storm drains	6-30"	**No Response**	Sewer grit
Robinson Pipe	Demoed for a week- liked recycling options-	Reduces man hours by 25%- production rate the same	About the same	Bit of a learning curve- more difficult to learn how to operate than old trucks	2015	No	Sanitary and combined pipes	**No Response**	**No Response**	Sewer grit

Note: Survey completed in the summer of 2018.

Table E.2: Customer Survey Original Responses (Questions 9-17)

Company	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Comments
Clear-Flow	Rags and cloth	**No Response**	**No Response**	Operators perform daily checks- greasings and visual inspection	Yes	Unsure-will contact with	Unsure-will contact with	Unsure-will contact with	No- would buy another	Superior to American Vactors
National Water Main Cleaning	None	**No Response**	**No Response**	Daily- filters, greasing- preventative maintenance based on hours- check filters more often	No	Rental unit, too recently purchased to give figures	Rental unit, too recently purchased to give figures	Rental unit, too recently purchased to give figures	Have only operated for one month; too early to tell	Good for pipes with some existing flow-
National Water Main Cleaning	Fine silty materials clog filters- need to run clean water through at end of day to unblock filters	1	**No Response**	Daily checks- standard for vactrucks- filter cleaning at end of day- mechanic schedule based off mileage or hours based on truck maintenance schedule	No	Too new for maintenance costs	Unsure- no more than any other VJT	Unsure	Clean larger diameter lines- looking at getting larger hose sizes and larger pumps- 80 gal/min pump on recycler to 170 gal/min for standard VJTs	**No Response**
Robinson Pipe	Grease	**No Response**	**No Response**	Standard maintenance for the truck- extra hour or two a week for cleaning filters	Yes- but so would a VJT	Slightly higher than the standard VJT- parts are foreign	**No Response**	25-30% in labor- additional savings in water costs	Yes- selected a different model- might buy a third	**No Response**

Note: Survey completed in the summer of 2018.

Table E.3: ODOT District Survey Original Responses (Questions 1-9)

District	Date	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9
1	8/14/2018	Vactor, Vac-Con	30 minutes/structure	100%	1999,2012	20 years	$300,000	$20000/year	$5000/year	Catch Basins, Sewers
2	8/15/2018	Hydrojetter, VJT	3-5/day	85%-90%	2014	10 years	$241,970.51	$65,689.49	$1000/day	Catch Basins, Sewers
3	8/15/2018	VJT	10/day	90%-95%	2014	20 years	$300,000	**No Response**	**No Response**	Catch Basins
4	8/16/2018	VJT	15-20/day	95%	No **Response**	No **Response**	**No Response**	**No Response**	**No Response**	Catch Basins, Pipes
4	8/16/2018	VJT	6-10/day	95%	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	Catch Basins. Pipes
4		Vactor	Varies- up to 15/day	80-90%	Call Allen Brown	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
4	8/27/2018	Vac-Con	**No Response**	**No Response**	2010 and 2014	No Response	No Response	$26,000 to $48,000	Rater at $133.62	**No Response**
5	8/17/2018	Vactor	2-3/day	90/%+	Current model 3 years old	10 year life cycle	Unsure- over $200,000	**No Response**	**No Response**	Catch Basins, Pipes
5		Vactor	**No Response**	**No Response**	2014	10 years	$300,000	**No Response**	**No Response**	**No Response**
7		Vactor	1-10/day	95%	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	Catch Basins, Culverts
7	8/15/2018	Vactor	4/5 a day (if truck doesn't break)	95%	2006-2008	Want to get 20 years out of it	Unsure	Very expensive- $20,000 on the low end	Mostly labor- traffic control- standard ODOT hourly rate	Pipes
8	8/15/2018	Vactor	1-3/day	Clear and flowing	5 to 10 years ago	Unsure	Unsure	Unsure	Unsure	Catch Basins, Pipes
9	8/14/2018	VJT	6/day	90%	2014	15 years	$450,000	$10000/yr	**No Response**	Catch Basins, Pipes
10	8/16/2018	2015 Kenworth Vactor; 2008 O'Brien Jetter	Varies	100%	2015	Replaced on 8 year cycle	$389,000	$12,000/yr	1710 gallons of fuel in 2018; 921 in 2016, 1150 in 2017	Catch Basins, Culverts
11	8/14/2018	Vactor	6/day	100%	2001	12 years	**No Response**	$25,000	**No Response**	Catch Basins, Culverts
12	8/28/2018	Camel VJT	Using all 3 trucks, each truck can get 2 to 3 per day	90%<	2011 to 2016	Want to last for 8 years	Unsure- Dan Monaco	Unsure- Dan Monaco	Unsure- Dan Monaco	Catch Basins, Culverts, Pipes

Note: Survey completed in the summer of 2018.

Table E.4: ODOT District Survey Original Responses (Questions 9a-15)

District	Question 9.a	Question 9.b	Question 10	Question 11	Question 12	Question 12.a	Question 12.b	Question 13	Question 14	Question 15
1	2*2-3*3(catch basin) 4"-36"(pipes)	4'(catch basin) 36"(pipes)	Mud, Stones	Stones	3	Operators, Safety	$20/hour	Rare/Water	1 day	200hours, 5000miles
2	2'*2'	2'-4'	Sediment, Vegetation	Vegetation	2	Operators	$23/h	Rare/Failed to clean(collapsed pipe)	150 days	Hourly, Mileage
3	36"*36"	5'	Dirt, Mud, gravel	None	2	Operators	$17.50/h	Rare, Water/Debris	125 days	Hourly
4	2'*2', 12"-48"	6'-8'	Soil, Gravel, Leaves, Trash, Rocks	Rocks	4	Operators	$18/h	Rare, Water/Debris	**No Response**	**No Response**
4	2'*2', 12"-48"	2'-25'	Trees, Vegetation, Trash, Gravel, Sediment, Soil	Trash	2	Operators	**No Response**	Often, Water/Debris	**No Response**	**No Response**
4	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
4	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	Unsure	Hourly based maintenance
5	12" and up	Up to 8'	Sand, gravel, litter	No- large particles	1 operator, 1 assistant	1 operator, 1 highway tech	$20	Depends if they have to vacuum-can get 2 full loads a day	On emergency-can winterize-200 days out of year	Operators do daily greasing and prechecks- hourly and mileage checks on motors/oil changes
5	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
7	8"-60"	2-8'	Dirt, trash	**No Response**	Varies	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
7	12-24"	On right of way-20/30 feet away at most	Mud, corn fodder	Corn fodder packs into equipment	4 to 5	HT3s	Varies- $18 to $22/hr	Dump	Once every 3-5 years	Mileage/monthly
8	Pipes- 8 to 18"; unsure on culverts	Up to 4 ft	Sticks, trash	Very large debris/rock	Work zone for Cincinnati- 5 person crew;	Operators and HT3's	$17 to $22	Usually don't have to- scheduled breaks	Unsure	Daily walk-arounds; E services every 5,000 miles
9	12"-48"	4'	Silt, Trash	Silt, Trash	2	HT3s	$20/hour	Equipment Failure, 4-5/year	25 days	Mileage, Hours
10	12" or larger, 4x8 box culverts	18'	Rock, sediment, and vegetation	Large rocks and salt brine	2	HT3s	$20.50/hr	Once	128 days in 2017	E inspection every 8,000 miles, F at every 30,000 miles
11	2*2-4*4	3'-15'	Rocks, Sediment, Soil, Trash	Trash	4	Operator, Traffic Control	**No Response**	Water/Debris, 3-4/day	100 days	Mileage, Hours
12	12"-48" pipe	**No Response**	Styrofoam, hubcaps, plastic, car parts	Asphalt waste	2 to 3	HT3s	$19	Dumping- twice a day- 30 min drive to decant location	240 days	Biweekly maintenance

Note: Survey completed in the summer of 2018.

Table E.5: National DOT Survey Original Responses (Questions 1-7 / Alabama-Indiana)

State	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 6a	Question 6b	Question 7
Alabama	Hydrojetters- contractors use Vacuum Trucks	5 to 10 on a day- clean based on problem calls	100%	N/A	N/A	Cross-drains- corrugated, concrete	15-24"	**No Response**	Soils, Aggregates, Roadway Trash
Alaska	Vacuum Truck	8-10 minutes per structure	80-90%	Contracted Out	N/A	Catch Basins, Manholes, Oil Grid Separators	Varies- type I,II,III Catch Basins and Drains	Varies	Gravel, Sediment, Litter
Arizona	Vacuum Truck and Water Truck	2 per day to one week per culvert	90%<	Rentals	Rentals	Large box culverts	**No Response**	**No Response**	Sediment, Litter
Arkansas	Backhoes and Manual Cleaners	Unsure	80-90%	Unsure	N/A	Corrugated and concrete pipes, box culverts	18" diameter pipes to 6x6 box culverts	**No Response**	Silt
California	Vactor 2100	Varies on type of drain and material	100%	1990s	None	Inlets and box culverts	Varies	**No Response**	Sediment and vegetation
Colorado	Vactor , skid steer	3 to 4/day	90-95%	N/A	None	Vaults	N/A	5to15ft	Trash/Litter Gravel, Mud/Soil
Connecticut	Vactor Recycler	**No Response**	**No Response**	**No Response**	2016	Drainage Pipes	24" diameter	Greater than 2'	Debris, Sediment, and Leaves
Delaware	Vac-Con	2,000 ft/day	90%<	Used Vac-Cons for last 30 years	1500 gallon tank, 1" hose	Catch basins	18"x30"	2'-6'	Sand, silt, trash, leaves, vegetation
Florida	Vac-Con	Varies	100%	Contract	Contract	Pipes, underdrains, catch basin, culverts	8in to 50in	3ft to 15ft	Leaves, Branches, Silt, Mud, Car Parts
Georgia	Hydrojetter	Varies	90%-100%	1980s	No	Underdrains	18in	1ft-2ft	Sediment, Soil, Grass
Hawaii	Hydrojetter; Vacuum Truck	Low	Low	**No Response**	Catch boxes and manholes	**No Response**	**No Response**	**No Response**	Roots
Idaho	Vactor 2100	Track by man hours- varies on conditions of pipes- 1 to 10 a day	Gets 98% of debris out	2012	Cameras- options through Vactor	All	Pipe- 24" diameter, Culvert 3'x6'x4'	**No Response**	Silt and Gravel, Vegetation
Illinois	Vactor 2100	Unsure- do case by case and sanitary as well	90%<	2006, 2014, 2018	Yes-	All	4' diameter catch basin; 12" diameter pipe	4'-8' deep	Leaves, Trash, Sediment
Indiana	Model Year 2012 Vacall model 1015 MY 2005 Vacall catch basin cleaner / sweeper truck MY 2015 Vactor 2100 Jet Vac MY 2007 Vactor 2115-J6 MY 2012 Vacall 2112 MY2004 No info MY 2005 Vacall catch basin cleaner / sweeper truck	15-20 structures/day	80%	N/A	N/A	Cleanout Inlets, Catch Basins, Manholes, Culverts	Up to 36" Diameter, 1'x6' to 2'x2' (Catch Basins)	Culverts 2' - 100', most 3'-5'. Inlets, Catch Basin, Manholes 7'-50'	Dirt, Silt, Leaves, Limbs, Trash

Note: Survey completed in the summer of 2018.

Table E.6: National DOT Survey Original Responses (Questions 1-7 / Indiana-New Hampshire)

State	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 6a	Question 6b	Question 7
Indiana	Hydrojetter; Vacuum Truck	40-50/day(hand), 15-20/day(Vactor)	100%	**No Response**	**No Response**	Catch Basin, Curb Inlets, Big Culverts, Small Culverts	Small up to 4ft, Large 4-20ft, Bridge 20ft-Greater, Varies	**No Response**	Leaves, Litter,
Iowa	Hydrojetter	Variable-2 to 3 a day	85-90%	Built in-house	Built in-house	Box Culverts, Catch Basins	**No Response**	**No Response**	Sand, Gravel, Dirt, Tree Limbs,
Kansas	Hydrojetter; Backhoe	When Needed	100%	**No Response**	No	Underdrain, Culverts	24in or less	**No Response**	Silt, Vegetation
Kentucky	Skid Steer	2/day	100%	2017	no	pipes,	24-36 in 50-60ft	15 ft or less	Soil
Louisiana	Vacuum Truck	20-30 catch basins	100%	2003	Standard	Catch Basins	2.5x1.5	4-5 ft	Mud, Litter
Maine	Vacuum Truck	20-30 pipes in urban areas- fewer in rural areas	90%<	**No Response**	**No Response**	Catch Basins, Pipes and Underdrains	6'x8'x4' basin, 2'x2' inlet	4 ft	Sediment- Winter Road Sand
Maryland	Hydrojetter/Street Sweeper	Time per inlet/foot-500 gal-10min	Clean- waste taken to landfill	Unsure	Nozzles	Sweeper: box culvert, Pipe-hunter for pipes	3x4 to 4x6 box culverts	Varies-typically 4 ft or shallower	Litter/vegetation/road fill
Massachusetts	Backhoe; Vactors	30 structures per day for clamshell-Vactors as needed	75-80%	Contracted Out	Contracted Out	Manholes, catch basins, drop inlets,	12" diameter pipe, 2-3 meter basin	2 meters	Road Sediment
Massachusetts	Vacuum Truck	**No Response**	70% for pipes, 85% for catch basins	Contracted Out	Contracted Out	Pipes and catch basins	4' diameter, 2' high	**No Response**	Sand and Leaves
Michigan	Hydrojetter	**No Response**	90% to 100%	**No Response**	**No Response**	Culverts	12in to bigger	5ft	Sediment, Vegetation,
Minnesota	Vactor trailer, backhoe, Vactor truck (no longer use, current renting one), Excavator,	8/day	Effective in Urban Areas	2009	None	Pipes, Underdrains, Catch Basins and Culverts	15in to 60in, vaults, 7ft arch on lake superior, 18 to 24in common	15 to 20 ft	Silt/Sand, Beaver Dams, Sticks, Mud
Mississippi	Contracted out to companies with vacuum equipment	Unsure	Unsure	Contracted out	Contracted out	Side/cross drains	15"-18" diameter pipe	3'-4' deep	Silt
Missouri	Vac-truck- unsure of model-recently purchased	Unsure	90%<	2018	None	Catch Basins, Culverts, Pipes and Inlets	15"-30" diameter pipes	**No Response**	Silt
Montana	Hydrojetter	10/year	Very Effective	2012	None	Culverts	36 in or less (diameter)	**No Response**	Mud, Gravel
Nebraska	Culvert Washer, Backhoe,	10/day	95%-100%	2005	None	Culverts	24in-36in, 30ft-40ft	2ft-3ft	Sand, Silt
Nevada	Vactor 2100	Varies	95%<	**No Response**	CM Pipe, concrete boxes, drop inlets,	**No Response**	**No Response**	Sediment	Large sediment particles
New Hampshire	Vacuum Truck- Contracted out	Varies on conditions-8-16 a day	90%	**No Response**	**No Response**	Storm Drains, Catch Basins	2' to 8'	3' to 25'	Road Sand

Note: Survey completed in the summer of 2018.

Table E.7: National DOT Survey Original Responses (Questions 1-7 / New Jersey-South Dakota)

State	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 6a	Question 6b	Question 7
New Jersey	Vac-Truck- varies based on contractors- video inspections	Varies on condition of pipe- 15 min to multiple days	Very clean	Unsure	Unsure	Inlets/outfalls	4-30"	**No Response**	Vegetation/Stones/Garbage
New Mexico	Vactor Trucks-	Depends on condition of structure	100%	2018	Standard Attachments	Pipes/culverts	24"-72" diameter pipe; 10x10 culverts	**No Response**	Sand and gravel
New York	Vac-Con M2106V	Depends on blockages	Some residue- take water truck out	2011	Nozzles	All of the above	18"x24" culverts; 18" pipe	**No Response**	Varies- Shale, Litter, Sediment
North Carolina	Backhoe	3/day	good	Multiple Years	No	Pipes, catch basins	3X3ft	4 to5ft	Sand/Silt, Vegetation
North Dakota	Small Excavators/water Jetter	Varies	75% clean	**No Response**	**No Response**	Corrugated steel or concrete pipe, box culverts, bridge decks	24" diameter to 200 ft	**No Response**	Sediment
Oklahoma	Vacuum Truck	5-10/year	Small: less 50%; Larger: over 50%	Contract	No	Culverts	18in to 10ftx10ft (Vaults)	2ft to 30ft to 40ft	Silt, Mud, Drift
Oregon	Vactor Truck, tank trailer	10-15/day	100%	2017	Different Heads	Pipes, Underdrains, Catch Basins, Culverts	6in-24in, 6ft for bigger culvert	3ft-10ft	Rocks, Sediment, Soil, Wood chips
Oregon	Vactor Truck, Excavator	2-5/day, 1/few days	100%	2015	Different Heads	Pipes, Underdrains, Catch Basins, Culverts	2ft	5ft-100ft	Rocks, Sediment, Sage Brush, Vegetation, Trash
Oregon	Vactor	32/day	85%	1997(sold) 2018(new)	Vactor	30%Catch Basins, 70%Culverts	18in Culverts, Catch Basin Varies	Culverts 2ft-20ft, Catch Basins 2ft-4ft	Straw, Mud, Rock
Oregon	Jet Rudder	15/day	90%-100%	2009(sold) 2017(new)	Unsure	Pipes, Underdrains, Catch Basins, Culverts	12in to 24in	3ft to 20ft	Rocks, Silts
Pennsylvania	Vactor	Job-site dependent	Very Clean	2008 or newer	**No Response**	Sewer Grates and Expansion Girders for Bridges	18" square to 2'x4' inlets	**No Response**	Soil
Pennsylvania	Truck Mounted Vactor- A&H Equipment	**No Response**	**No Response**	2011	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
Rhode Island	Stetco catch basin cleaning trucks, hydrojetters, VJTs, and track loaders	Cleaned 7700 structures in last fiscal year-	90%- but depends on condition of pipe and area	Recently purchased- 2 to 3 years ago for most equipment	Custom built based on state specs	All of the above	2x2 box culverts- 4 to 6 ft diameter catch basins, 6" to 36" for pipes	**No Response**	Leaves, sticks, sediment, mud, trash
South Carolina	Backhoe, Pipe washer	**No Response**	100%	Varies/county	No	Pipes, Underdrains, Catch Basins, Culverts	15in-84in, 2x2-larger	1ft-2ft	Soil, Sand, Leaves, Branches, Trash
South Dakota	Hydrojetters and vacuum trucks	300 feet of pipe per 5,000 gallons- can get 2 80-100 ft pipes in a day	90%<	2017	Nozzles	Pipes, box culverts, drop inlets	Inlets- 2x3 to 3x4; pipes up to 48"	**No Response**	Farm Debris, Cornstalks, Runoff, Sedimentation

Note: Survey completed in the summer of 2018.

Table E.8: National DOT Survey Original Responses (Questions 1-7 / Tennessee-Wyoming)

State	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 6a	Question 6b	Question 7
Tennessee	Hydrojetter and cameras	1 to 10 depending on conditions	90-95%	2003	Speced out during bid process- 1500 gal tank	Pipe and box culvert	8-12" pipe to box culverts	**No Response**	Silt, Vegetation and Trash
Texas	Skidsteer, Vacuum Truck	As Needed	85%-95%	Contracted	Contracted	Culverts, Underdrains, Curb Gutter	Varies	4ft-5ft	Silt, Soil, Grass, Rocks
Utah	Vactor 2100	6 to 8	90%	2001	Extra tanks	Catch basin inlets, storm drains, pipes	46"x38" box	8'-16'	Plastic bottles, bags, styrofoam, sediment
Vermont	Rent vacuum trucks- subcontract- Vactors	Hired case-by-case- 40 per day	85-90%	**No Response**	**No Response**	All of the above	4' barrrel catch basin or 18-24" culvert	4-5 ft	Sediment
Virginia	Vactor Truck	N/A	100%	10-15 years old	No	Culverts	12-18-24 in,	5-10-25 ft	Leaves, Mud, Soil
Virginia	Sterling LT7501 (Vactor)	15 min/structure	100%	2006	No	Culverts, Inlets	Culverts 12"-36". Inlets 4'x4'	0-12'	Leaves, Sticks, Stones, Grass, Mulch, Sand, Clay, Trash, Glass Bottles
Washington	Vactor 2100- International	Varies- 5 to 20 per day depending on location	90%	Unsure	Unsure	Catch basin, grate inlets	2x4 grate inlets, 2x2 catch basins	10-15 ft deep	Sediment
West Virginia	Hand, Backhoe, Hydrojetter	2/day	Vary	**No Response**	No	Culverts	18-24 in, 30 ft	4ft	Stone, Mud, Sticks, Aggregate
Wisconsin	1 Vactor, 2 VacAlls	4-5 month cleaning season- 5-7,000 per truck per season	90%<	7 to 15 years old	On Vactor- bought all options	Inlets, inlet feeds, mini sewers	2' diameter	4' deep	Leaves, Sand, Gravel, Litter
Wyoming	Vac-Truck	Varies	95%	**No Response**	Barrel culverts, drains, inlets	Barrel culverts, drains, inlets	**No Response**	**No Response**	Large Rocks

Note: Survey completed in the summer of 2018.

Table E.9: National DOT Survey Original Responses (Questions 8-15 / Alabama-Kansas)

State	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15
Alabama	Beaver dams	2 to 3, more for flaggers	None	As needed	Unsure	Unsure	Unsure	Looking into VJT
Alaska	Large pieces of litter	2	None	Contracted Out	Contracted Out	Contracted Out	Contracted Out	No Changes
Arizona	Larger cobble	5	**No Response**	Daily walk-around checks- as needed	Unsure	Hydrovac rental $100/hr	Unsure	None
Arkansas	Silt and Beaver Dams	5 to 6	Depends	Continuous Maintenance	Unsure	Unsure	Unsure	No changes
California	None	3 to 4	Varies	Daily; 3 months- vacuum checked daily and weekly	Unsure	Unsure	Unsure	**No Response**
Colorado	Trash	4	None	Monthly	**No Response**	**No Response**	**No Response**	No Changes
Connecticut	None	2	Varies	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
Delaware	Large pieces of solid debris (bricks, rocks, etc.)	2 for truck; flaggers vary	Run out of water and dump debris	Chassis hit every 10,000 miles, vacuum serviced every 100 hours- weekly greasing	Unsure	Unsure	Unsure	Hose reel on curbside
Florida	Styrofoam	2 to 3	Rarely	Contract	Contract	Contract	Contract	No Changes
Georgia	Soil	3 employees	1 for water	100 hours pump, truck miles	$ 200.00	**No Response**	$ 36,000.00	No Changes
Hawaii	**No Response**	**No Response**	Frequent- every time it gets used	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
Idaho	Heavy, sandy soils are abrasive	6	3-4 times for heavy blockages	Daily checks and greasing; fans and pumps every 800 hours	Unsure	Unsure	Unsure	No
Illinois	No- large pieces of trash don't get pulled up	2	None because of extra trucks- maybe more water	Daily maintenance: oil, fluid, fuel, walk rounds- scheduled maintenance for oil changes	Unsure	Unsure	Unsure	No- satisfied with product
Indiana	Leaves, Limbs, Trash	4 (Laborer, 2 operators, driver)	Never	6000 hours	Not Tracked	Not Tracked	Not Tracked	Preferred a 2" diameter hose over 1" diameter hose
Indiana	Depends On Structures, Small Culvert Corn Stocks, Catch Basin Litter	Vactor 3, 1 Traffic Control	Rarely	**No Response**	**No Response**	**No Response**	**No Response**	No Change
Iowa	Tree limbs	3	Emergency traffic control when needed	As Needed	Unsure	Unsure	Unsure	Would like a Vactor truck unit- not likely to get one
Kansas	Silt	1	Never	When Needed	0	150	**No Response**	No Changes

Note: Survey completed summer of 2018.

Table E.10: National DOT Survey Original Responses (Questions 8-15 / Kentucky-Nevada)

State	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15
Kentucky	Large Rocks, Stones, Bottles	3 to 5	Not Often	Monthly	Low	Minimal	Low	Hose rubs against edge of pipe, placed plastic around hose
Louisiana	All of it	5	Dump- no more than 3 times	Oil, fuel and inspections daily-very labor intensive	$20,000 annually	Unsure	Unsure	Safer to subcontract for large projects than risk your equipment
Maine	Larger stones	1-2 contractors, 2-4 DOT traffic control, 4 person team for camera	Leave to dump debris in set locations	Unsure	Unsure	Unsure	Unsure	New contracting allowed for competition across contractors- goes from hour rates to lump sum-
Maryland	Anything larger than 10" for sweeper; cinder blocks for pipe-hunter	2 for broom truck, 3 for interstate; 2-3 for pipe-hunter	Yes- for debris and water- frequency varies by job site	Based on mileage, oil and air filter- C service full-scale check	Unsure	Unsure	Unsure	State mass purchases equipment- state has good grasp of equipment; no changes in 30 year career- bad for picking up salt
Massachusetts	Litter and tree roots	4 2-man Crews	Continuous Operations	Contracted Out	Contracted Out	Contracted Out	Contracted Out	GPS-AVL asset management and sediment racking
Massachusetts	None	2	Unsure- seldom	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
Michigan	Vegetation	**No Response**	**No Response**	Yearly	N/A	N/A	N/A	Keep them maintained
Minnesota	Beaver Dam	Driver, Operator, 2 Equipment	Never	Monthly	10000/year	75/hr trailer, 105/hr truck	250000 (old truck), 25000/yr (rented truck)	Use Vactors, Augers
Mississippi	None	Contracted Out	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
Missouri	None	2 to 3	Twice a day	Unsure	No maintenance costs yet	Unsure	Saves $10,000 a week vs renting one	Would buy cameras and nozzles
Montana	Gravel	Operator, Drive, Hose	Never	As Needed	Low	Low	Low	Increased Tank Capacity
Nebraska	Sediment	2 to 3	Never	150*hours	$1,000	**No Response**	$67,800	None
Nevada	**No Response**	**No Response**	Mileage, but daily preventative maintenance	**No Response**	**No Response**	Unsure	No	**No Response**

Note: Survey completed summer of 2018.

Table E.11: National DOT Survey Original Responses (Questions 8-15 / New Hampshire-Rhode Is.)

State	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15
New Hampshire	Larger stones	2 for truck	Does not leave	Contracted Out	Contracted Out	Contracted Out	Contracted Out	None
New Jersey	None	4-5 people	Varies	Determined by contractors	Hourly labor and equipment costs- $500/hr	Hourly labor and equipment costs- $500/hr	Unsure	No changes
New Mexico	None	2 to 5	Water refill if water truck not tailing	Daily preventative maintenance	**No Response**	**No Response**	**No Response**	Purchasing is done statewide instead of a district-by-district system
New York	Shale-like materials	2 to operate truck	Water/debris	Daily inspections, maintenance cycle for every 3 months- heavy wear on suction hoses	Unsure	Unsure	Unsure	Injuries when started due to hoses and stay on top of maintenance
North Carolina	Large Volumes of Silt	5	Never	Weekly	2000/structure	5000/structure	150000	No
North Dakota	Clay soils	Unsure	Refill water tank	Check every 40 hours	40000	Unsure	Unsure	Higher power water jetter
Oklahoma	Mud	5	Never	As Needed	Urban: $200,000 to $300,000; Rural: $1,200 to $1,300	**No Response**	$800,000; $900,000	Ability to Clean Smaller Structures
Oregon	Rocks, Mud	3	Refill Water 1-2/day	Daily, Miles, Yearly	$20000/year	$27000/year	**No Response**	More Compacted to Fit Into their areas
Oregon	Rocks	Operator, Controls	4-6/Days, Lack of Water	Yearly	**No Response**	**No Response**	$200,000	None
Oregon	Rocks	2	Incidents/Accidents, Water(4/day)	Miles, Yearly	$8000 (1997)	$2000/day(2018)	$450000 (2018)	None
Oregon	Rocks	4(2 included traffic)	Refill Water 2-3/day	Manual Recommendation, Monthly	N/A	$18.20/hour(2019)	**No Response**	None
Pennsylvania	None	3-4 people- situation dependent	Scheduled Breaks	Maintenance intensive- done by fuel consumption- operator notes for flushing system	Unsure	Unsure	Unsure	**No Response**
Pennsylvania	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**	**No Response**
Rhode Island	Leaves and beaver dams	One operator on CB truck, drainage crew has 3 to 4 trucks and a trash/traffic control truck; pickups follow- 8 to 10 people	Unsure on number- usually for dumping- starting to see restrictions on type of debris they can dump at landfills for free	Daily equipment pre and post inspections- annual maintenance- repairs as needed	Unsure - allotted $20 million to replace equipment over the last 2 years	**No Response**	**No Response**	Drainage crew liked larger model of the catch basin cleaning trucks-

Note: Survey completed in summer 2018.

Table E.12: National DOT Survey Original Responses (Questions 8-15 / South Carolina-Wyoming)

State	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15
South Carolina	Soil, Sand	2	Did Not Finish for Day, Never	Hours	**No Response**	**No Response**	**No Response**	None
South Dakota	Unsure	2 to 3	Yes- refill for water	Vacuum truck-mileage based- majors vs minors- based on hours-	Deprecation costs	**No Response**	**No Response**	**No Response**
Tennessee	No	2	Rarely leave- leave for refills	100-150 hours; trucks serviced 7500 miles	Unsure	Unsure	Unsure	No- maybe add a handheld nozzle
Texas	Rock, Soil	Varies	Check Other Jobs, Dump Debris, 2to4/day	Contracted	Contracted	Contracted	Contracted	None
Utah	No	2 to 4	To dump debris- twice in a 10 hour shift to refill with water	Weekly Maintenance	**No Response**	**No Response**	$30,000 a year in labor and maintenance	No- maybe something smaller- automatic transmission
Vermont	Waste covering external grate	2- sometimes flaggers	Rarely	**No Response**	**No Response**	**No Response**	**No Response**	No- new MS4 permits- will require state to purchase one rather than contract
Virginia	Leaves	2 operators, 2 traffic control	1-2/day, dump debris, refill water	Yearly	**No Response**	1000/month. Contract fee 100/hour	$20,000	None
Virginia	Sand, Stones	1 to 2	Only to Dump- as needed	Daily, per mile	Fixed Cost	Fixed Cost	Fixed Cost	Corrosion Prevention on Inside of Vactor Tank
Washington	No	2 to 5	Only to dump- varies	Usage- 6 to 8 months out of year	Unsure	Unsure	Unsure	No
West Virginia	Sticks, Mud	2	Lack of Water, Once Daily	Monthly	Low	Low	Low	No Changes
Wisconsin	No	4	Situationally dependent	Preventative maintenance and walk -around daily	Unsure	Unsure	Unsure	Immediate replacements- sell at auction
Wyoming	No	**No Response**	**No Response**	Contractor	Contractor	Contractor	Contractor	No research done by WY- very expensive

Note: Survey conducted summer of 2018.