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1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA19-3176	N/A	N/A

4. TITLE AND SUBTITLE Research to Support Crack Cleaning Operations in Moving Lane Closures	5. REPORT DATE January 6, 2020
	6. PERFORMING ORGANIZATION CODE AHMCT Research Center, UC Davis
7. AUTHOR Duane Bennett, Alireza Mounesisohi, Travis Swanston, and Bahram Ravani: Principal Investigator	8. PERFORMING ORGANIZATION REPORT NO. UCD-ARR-19-09-30-04
9. PERFORMING ORGANIZATION NAME AND ADDRESS AHMCT Research Center UCD Dept. of Mechanical & Aerospace Engineering Davis, California 95616-5294	10. WORK UNIT NUMBER N/A
	11. CONTRACT OR GRANT NUMBER 65A0560 / 65A0749 Task ID: 3176
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation P.O. Box 942873, MS #83 Sacramento, CA 94273-0001	13. TYPE OF REPORT AND PERIOD COVERED Final Report July 2017 – September 2019
	14. SPONSORING AGENCY CODE Caltrans

15. SUPPLEMENTARY NOTES

N/A

16. ABSTRACT

This report describes the study, testing and development of an innovative high production joint crack cleaning machine capable of supporting high production sealing operations. The research team evaluated existing methods and equipment of joint crack preparation and presented to the Caltrans panel team a strawman concept complete with operational and technical specifications necessary to operate a longitudinal joint crack cleaning machine paired with the Sealzall machine on highways. The panel members and researchers selected impact routing as the means of cleaning, which was then adapted and optimized to nearly double the current impact routing cutting speeds of conventional impact routing equipment. The research team designed a mechanism that supports vehicle mounting and collects ejected dust and debris. In addition, the team developed and tested an automated guidance system that automatically identifies the AC/PCC joint crack interface and guides the impact router cutters adjacent to the PCC slab edge.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Longitudinal Crack Cleaning, Sealzall, Sealing Preparation, Moving Closure Operation, Joint Crack Cleaning, Router Cleaning, Joint Crack Tracking	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. SECURITY CLASSIFICATION *(of this report)*	20. NUMBER OF PAGES	21. COST OF REPORT CHARGED
Unclassified	95	None

DISCLAIMER

The research reported herein was performed by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, for the Division of Research, Innovation and System Information (DRISI) at the California Department of Transportation. AHMCT and DRISI work collaboratively to complete valuable research for the California Department of Transportation.

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AHMCT

Advanced Highway Maintenance and Construction Technology Research Center

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Research to Support Crack Cleaning Operations in Moving Lane Closures

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Prof. Bahram Ravani: Principal Investigator

Report Number: CA19-3176
AHMCT Research Report: UCD-ARR-19-09-30-04
Final Report of Contracts: 65A0560 / 65A0749

January 6, 2020

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

Research Objectives and Methodology

The California Department of Transportation (Caltrans) maintains approximately 10,000 miles of longitudinal pavement edge joints with Asphalt Concrete (AC) shoulders throughout California. Sealing these longitudinal joints (also referred to as cracks) takes priority over other types of crack sealing operations since 75% of water and debris enters the pavement structural section along these edges. Proper longitudinal crack preparation is an essential requirement specified by all major sealant manufacturers to achieve maximum adhesion, cohesion, and corresponding seal longevity. Vigorous physical cleaning to remove debris and vegetation is the best method to achieve optimum sealing results. Caltrans' common crack cleaning practices, such as compressed air and wire wheels, fail to remove packed debris or rooted vegetation. Cutting methods such as routing with conventional equipment provide extraordinary crack cleaning results but are labor-intensive and slow.

Caltrans has expressed a need to obtain a joint crack cleaning machine capable of quickly and efficiently preparing longitudinal AC/Portland Cement Concrete (PCC) joint cracks, regardless of condition. The cleaning machine ideally would be moving lane closure compatible to operate with the Sealzall crack sealing machine. Caltrans District 11 maintenance crews successfully utilized the Sealzall to seal longitudinal joint cracks at up to 13 miles a day. The crack cleaning machine would expand the utility of the Sealzall, which has been limited to sealing cracks that do not require intense cleaning, such as newer shoulders. This report describes the study, testing, and development of an innovative high production joint crack cleaning machine capable of supporting high production sealing operations. The research team evaluated existing methods and equipment of joint crack preparation and presented to the Caltrans panel team a strawman concept complete with operational and technical specifications necessary to operate a longitudinal joint crack cleaning machine paired with the Sealzall machine on highways. The panel members and researchers selected impact routing as the primary means of joint crack cleaning.

In developing a router crack cleaning machine based on the adopted concept, two major design challenges needed to be addressed. First, a higher production router head had to be designed, which could be truck-mounted and optimized to increase efficiency to nearly double the current impact routing cutting speeds of conventional impact routing equipment. Secondly, an appropriate router guidance system had to be developed to guide the router cutter head along the joint crack. This research succeeded in developing proof of concept hardware and systems, which demonstrated the feasibility of developing a moving closure crack cleaning machine.

An impact router head testing device was fabricated and utilized to cut AC pavements at the Advanced Highway Maintenance and Construction Technology (AHMCT) research test site to verify that the 3 mph cutting speed could be achieved. This validation testing represented the worst case scenario because cutting solid pavement is much more difficult that cleaning existing cracks. The conclusion was that the impact router cutter head should be capable of higher router speeds when operating on actual cracks. Consequently, a detailed design of a truck-mounted impact router system was developed that is capable of single pass cleaning while enabling workers to remain in the truck cab during operation on the highway.

Due to the irregular nature of highway transition joint cracks, the crack cleaning machine guidance scheme had to be adaptable in operation. Consequently, a semi-automatic guidance scheme was adopted where the system operator is provided with both manual and automatic tracking functionality. The manual control utilizes a single-axis joystick to move the router head laterally. The automatic tracking control developed in the research utilizes sophisticated Artificial Intelligence (AI) tools to identify the PCC slab edge of the joint crack and position the router adjacent to the edge. The second phase of this research included the development and demonstration of the feasibility and precision of the guidance system in automatically identifying and tracking AC/PCC joint cracks at speeds up to 3 mph. The conclusion of the guidance system development and testing was that the crack cleaning machine concept is an achievable design, but additional guidance system development will be necessary in future research to solidify the system operator interface and control capabilities.

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List of Acronyms and Abbreviations

Acronym	Definition
AC	Asphalt Concrete
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
AS	Academic Surge
ASICs	Application Specific Integrated Circuits
ATIRC	Advanced Transportation Infrastructure Research Center
Caltrans	California Department of Transportation
CCD	Charged Couple Device
cfm	cubic feet per minute
CNN	Convoluted Neural Networks
Co	Cutter Offset
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
DAQ	Data Acquisition
DC	Direct Current
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
eGPU	External Graphical Processing Unit
fps	Frames per Second
FHWA	Federal Highway Administration

Acronym	Definition
GigE	Gigabit Ethernet
Gp	Guide Point
GPU	Graphical Processing Unit
GUI	Graphical User Interface
HD	High Definition
HPU	Hydraulic Power Unit
I/O	Input / Output
LED	Light-emitting Diode
LVDT	Linear Variable Differential Transformer
MAZEEP	Maintenance Zone Enhanced Enforcement Program
mph	miles per hour
PCC	Portland Cement Concrete
PID	Proportional-Integral-Derivative
PM	Particulate Matter
PTO	Power Take Off
R&D	Research & Development
RAM	Random Access Memory
ReLU	Rectified Linear Unit
SHRP	Strategic Highway Research Program
SR	State Route

Acronym	Definition
TAG	Technical Advisory Group
TFT	Thin Film Transistor
TMA	Truck Mounted Attenuator
TPU	Tensor Processing Unit
USB	Universal Serial Box

Acknowledgments

The authors thank the California Department of Transportation (Caltrans) for their support, in particular Al Herrera with District 11 Maintenance; Daniel Roberts and Austin Wilson of District 3 Maintenance; Carlos Lomeli of District 6 Maintenance; Srikanth Balasubramanian and Douglas Mason of Pavement Maintenance, and Alex Gutierrez and Thai Nguyen of the Division of Equipment. The authors acknowledge the dedicated efforts of Arvern Lofton, Justin Unck, and Joe Horton with the Division of Research, Innovation and System Information who have made this work possible.

Chapter 1: Introduction

Problem

Approximately 1/3 of the Caltrans highways (over 16,000 miles) consist of Portland Cement Concrete (PCC) pavements. This correlates to roughly 10,000 miles of longitudinal pavement edge joints with Asphalt Concrete (AC) shoulders that Caltrans maintains. Sealing these longitudinal joints (also referred to as cracks) takes priority over other types of crack sealing operations since 75% of water and debris will enter the pavement structural section along these edges. The maintenance required to seal theses cracks represents a significant maintenance budget item, but when properly applied, good seals produce significant cost benefits to Caltrans in the form of reductions in concrete spalling and extending the interval between major shoulder rehabilitations. To capitalize on these benefits, the applied seal must last an expected 5-year minimum. Proper longitudinal crack preparation is an essential requirement specified by all major sealant manufacturers to achieve maximum adhesion, cohesion, and corresponding seal longevity. Vigorous physical cleaning to remove debris and vegetation is the best method to achieve the best sealing results. Caltrans' common crack cleaning practices, such as compressed air and wire wheels, fail to remove packed debris or rooted vegetation. Cutting methods such as routing provide extraordinary crack cleaning results but are labor intensive.

Need

Caltrans Maintenance expressed a need for safer, more effective, and efficient methods to thoroughly prepare longitudinal pavement edge AC/PCC joints and lane to lane PCC/PCC joints prior to conducting sealing operations on mainline highways. The conventional methods that Caltrans maintenance crews employ fail to remove heavy packed debris and rooted vegetation, which subtracts years from the effective seal service life. Improved longitudinal joint preparation methods that promote thorough joint cleaning prior to sealing need to be identified, thereby maximizing service life of the applied seal. In an ideal situation, the equipment supporting this operation would be:

- A streel legal, self-contained machine, possibly combined with a trailer
- Able to clean longitudinal joints in a single pass
- Able to collect and manage all generated dust and debris
- Capable of moving closure operations on mainline highways
- Able to operate at a continuous speed of two to five miles per hour
- Operated by workers from within the truck cab, thus eliminating direct highway traffic exposure

- Easily reconfigurable to clean shoulder-to-lane joints from the median or outside shoulders
- Adjustable to account for variable joint crack widths
- Able to accurately track joint cracks filled with packed debris and vegetation

Objective

The objective of this research is to develop a design for an innovative joint crack cleaning machine utilizing existing technologies.

Scope

This research will examine and identify innovative longitudinal pavement edge joint cleaning and preparation strategies for use in moving lane closure operations. The proposed research is to develop conceptual designs and methods focusing particularly on the incorporation of commercially available and customizable equipment. The design concepts developed will consider and incorporate (as much as possible) the features identified in the "Need" section above. Design concepts will include preliminary deployment implementation and operational plans.

This research will complete Stages 1 and 2 of the Caltrans Division of Research, Innovation and System Information (DRISI) Five Stages of Deployment. As a result of this research, a potential follow up project will begin construction of equipment designed under this research to allow for field testing of the developed equipment and methods. The follow up project would complete Stage 3.

Background

Caltrans District Maintenance crews are tasked with maintaining roughly 16,500 lane miles of rigid pavement highways throughout the state, which represents 33% of Caltrans total pavement inventory[1]. This corresponds to 2,716 center lane miles of Portland Cement Concrete (PCC) highways, which translates to 10,864 miles of longitudinal edge joints by using a multiplier factor of four on the center lane miles. Ideally, a functional seal is maintained on all longitudinal highway edge joints to prevent water intrusion, which undermines the road sub-base and is a major source of pavement failures. Of all the pavements cracks found on the highway, sealing the edge joints are the upmost priority because 75% of the water and debris is introduced through these edge cracks/joints[2]. According to the Federal Highway Administration (FHWA) study results, properly

[1] 2013 State of the Pavement Report, Caltrans Division of Maintenance Pavement Program, 2013

[2] Richard Barksdale, Russell Gary Hicks (1979). Improved Pavement Shoulder Joint Design. NCHRP Report ISSN 0077-5614

installed hot applied rubberized asphalt joint seal should be expected to remain effective for an average of five years, with the predominant failure mode being adhesion or cohesion loss[3]. Therefore, on a five-year seal life basis, Caltrans Maintenance crews would need to perpetually seal approximately 2,173 miles of longitudinal edge joints a year to achieve the ideal goal of full maintainability of these pavements. Utilizing conventional manual applied sealing methods, a Caltrans Maintenance crew of five and three vehicles can seal approximately one mile of longitudinal edge joint a day with an additional three-man crew and vehicle if the optional compressed air blast crack cleaning is employed. Therefore, Caltrans Maintenance crews would need to conduct over two thousand sealing operations a year every year to fully maintain their complete inventory of highway longitudinal edge cracks/joints. Considering the wide range of other high priority mandatory highway maintenance tasks Caltrans crews are compelled to accomplish, such a specific level of commitment would be difficult to sustainably achieve.

Sealzall Sealing Solution

The successful development and deployment of the Sealzall high production prototype machine in Caltrans District 11 has provided Caltrans Maintenance crews with a far more safe and efficient method of sealing, which could realistically make the goal of maintaining a functional seal on its full inventory of longitudinal edge cracks/joints feasible. The Sealzall is unique in that its design specifically supports moving lane closure operations on the highway, which is the key feature to the dramatic increases in sealing production and worker safety. Caltrans District 11 crews routinely seal an average of 8 miles of mainline highway cracks a day without any direct worker exposure to traffic on the highway. Utilizing the Sealzall reduces the Caltrans Maintenance task of maintaining the complete inventory of longitudinal joint/cracks from 2,173 days a year down to just 271 days a year where two Sealzall machines could reasonably accomplish this goal. In moving closure sealing operations with Maintenance Zone Enhanced Enforcement Program (MAZEEP) support, the Sealzall can also seal other areas on the highway, like highway ramps and merges, where the conventional manual sealing operations cannot realistically and efficiently access.

Since conventional crack cleaning methods are not suitable for moving closure operations, the Sealzall has been operating without employing pre-cleaning measures. Instead, District 11 had focused on a program to seal only joint cracks one or two years after asphalt shoulder rehabilitation. This way the cracks have opened up slightly, but have not been filled with debris and vegetation. Restricting Sealzall operations exclusively to newer highway shoulders

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[3] Office of Infrastructure Research and Development - FHWA, ERES Consultants. (1999). LTPP Pavement Maintenance Materials: SHRP Crack Treatment Experiment, Final Report. FHWA-RD-99-143

severely limits where Caltrans can conduct high production sealing operations. The development of a high production moving closure type crack cleaning machine would eliminate this restriction and open up the Sealzall for operation on all highway joint cracks statewide. More importantly, developing a crack cleaning machine that can remove the workers from the roadway will significantly increase the safety of operations, which is of prime importance to Caltrans.

Crack Debris and Vegetation

Highway debris consists of fine gravel, dirt dust, sand or other types of incompressible matter small enough to fill in a pavement crack. Removing this debris is a key factor in attaining seal longevity. In-lane cracks on the highway are fairly debris free and can be sealed effectively with little or no cleaning. In the worst cases, a simple blast of compressed air is typically all that is needed to clean the cracks prior to sealing (Figure 1). This is due in large part to traffic flow creating a vacuuming effect as high-speed traffic passes over. The in-lane debris and moisture is sucked out and continuously blown out to the sides of the road where it inevitability collects in the longitudinal edge cracks. So, whereas the in-lane cracks are reasonably debris free and dry, unsealed longitudinal edge joint cracks are continually being loaded with debris and moisture that fosters the growth of vegetation. In addition, vegetation does not survive well within the traffic lanes, but thrives away from traffic along the edge where it is minimally impacted by traffic. Longitudinal crack vegetation grows in virtually every part of the state, even in its most desolate desert areas.

In-Lane Highway Joint Crack **Shoulder Transition Joint Crack**

Figure 1. Joint Crack Comparison at the Same Highway Site

Vegetation removal from longitudinal cracks is one of the biggest challenges to crack cleaning methods and devices. The varieties of weeds that can thrive in the harsh environment of a highway crack are very durable and sturdy. Their thick roots reach very deep in the crack and tightly grip the jagged edge of the AC shoulder. Air blasting has little to no effect to remove vegetation from a joint crack. Wire brushing may remove most of the upper growth of vegetation, but the main body and root stem remain. Wire brushing, generally in the direction of the longitudinal joint crack, enables some of the vegetation sprouts to lay over in the void and spring back up during sealing. Consequently, the main body of the vegetation remains just below the pavement surface and releases gasses when contacted with 350 degree plus sealant. This reaction creates pores in the seal, which enables the vegetation to grow up through the seal. Vegetation growing through a seal is both unsightly and provides a path for water to enter the crack degrading the seal longevity.

Conventional Crack Preparation Methods

Caltrans Maintenance is often in the position of needing to seal older longitudinal joint cracks, which have been open long enough on the highway to become filled with packed debris and vegetation. Even though, generally, accepted best practices dictate that all cracks must be clean before applying sealant, often the effort involved to adequately prepare a packed crack utilizing conventional methods is far more time consuming than the sealing process itself. There are four main conventional crack cleaning methods, two of which contact the pavement and the other two are non-contact. The contact category includes a powered wire wheel and router/cutters. The non-contact group includes an air blast and heat lance. These methods can be employed individually or combined to a greater effect.

Air Blast: Currently, Caltrans' primary method of cleaning highway cracks involves a worker on foot blasting compressed air directly down into the void to remove loose debris. A separate vehicle and crew are necessary to conduct these cleaning operations, which occur in the same lane closure ahead of the sealing operation. High pressure air blasts are effective at removing dust and loose debris, but much less effective at breaking up and removing packed debris from the void. Furthermore, an air blast alone has little to no effect on removing vegetation held in by sturdy roots. Even scraping the vegetation out of the crack by hand with a sharp tool is difficult and time consuming because the jagged AC edge acts to anchor and shield the roots.

Heat Lance: A heat lance is a combination of a compressed air blast and a propane burner. A worker on foot blasts the super-heated air directly down into a pavement crack (Figure 2). The pavement must be dry when sealant is applied; otherwise, the seal will not adhere to the surfaces of the crack. Utilizing a heat lance is often necessary in chronically wet areas and damp regions to dry the crack prior to applying sealant. Since heat lances blast out an intense flame and prone to starting roadside grass fires, consequently this tool is rarely utilized by Caltrans.

Figure 2. Heat Lance Tool (Courtesy of Cimline Mfg.)

Figure 3. Wire Wheel Tool (Courtesy of Asphalt Kingdom)

Wire Wheel: Motorized wire wheel devices are essentially surface cleaning tools where a worker on foot guides the spinning wire wheel along highway joint cracks (Figure 3). Typically, the width of the wire wheel is greater than most joint cracks, and therefore cannot generally clean down into cracks below the pavement surface. While cleaning the crack surface promotes sealant overband adhesion, the wire wheel is not effective at clearing debris or vegetation from within the crack. It removes the upper shoots of vegetation but not the body and roots; sealing over them is often problematic. Vegetation shoots leave pores in the sealant where the weeds can continue to grow and create a pathway for moisture to continue entering the crack. The remaining vegetation survives the hot sealant and continues to grow, thus compromising the seal. Prior highway joint crack cleaning testing conducted during the Sealzall project has clearly demonstrated that sealing over any significant amount of vegetation significantly compromises the appearance and longevity of the seal.

Router cleaning: Router cleaning involves using a cutting blade to form a crack sealing reservoir, which consistently produces the greatest seal performance. Router cleaning is the only cleaning procedure that positively removes all debris in a single pass. In AC pavements, routing is used to create an optimal sealant reservoir for narrow cracks and joints prior to sealing. Impact routers and pin routers are the two most common types of router cleaning devices. Router cleaning is a standard practice when preparing cracks for sealing in climates with large seasonal freeze thaw cycles and in situations where a crack reservoir is necessary. Pin routers are typically utilized for router cleaning cracks in PCC pavements and impact routers for cracks in AC pavements, or AC to PCC transitions.

Both PCC and AC mainly consist of a fine gravel aggregate matrix bonded together in a tight matrix. The major difference between the two is with the binder that holds the matrices together. In PCC the binding agent is Portland cement, which makes the pavement hard and inflexible. Cutting PCC pavements is difficult, slow, and expensive and therefore should be minimized. Diamond saws and carbide cutting discs are often used in construction of PCC pavements, but for a series of reasons are not suitable for large scale highway crack cleaning operations in support of sealing operations. As was previously mentioned, in-lane PCC joint cracks are relatively clean from traffic effects and can usually be sufficiently cleaned with an air blast. Under special circumstances like needing to remove old sealant, a conventional pin router is generally utilized (Figure 4). The diameter of the carbide pin cutter is selected to be slightly less than the width of the PCC joint crack. Thereby, the cutter is mostly cutting relatively soft debris and old sealant while minimizing contact with the far harder PCC pavement side walls.

In AC pavements the binding agent is bitumen, which is a highly viscous liquid and not a solid material. The viscous binder gives AC pavements their flexibility. AC pavements are therefore far easier to cut than PCC pavements, especially when utilizing an impact cutter routing machine fitted with carbide tipped star cutters. Cutting through the hard rock aggregate that makes up the majority of the AC pavement matrix would be difficult, so instead the impact router takes advantage of the soft binder and breaks the matrix bond by chipping the aggregate free. Impact routers are ideal for cleaning deep into joint cracks removing all debris and vegetation in a single pass (Figure 5). Impact routing has been long established as the most efficient means of cutting a uniform crack sealing reservoir into AC pavements. The freewheeling carbide tipped star cutters are cost effective consumables when cutting through AC pavement but wear much quicker when contacting PCC pavements. Therefore, when routing longitudinal AC/PCC joint cracks, guiding the impact router along tangent to the edge of the PCC slab is important to minimize contact with the hard PCC and to cut only AC shoulder pavement. An air blast often is not sufficient to dislodge packed debris and vegetation from a longitudinal edge joint crack as opposed to router cleaning, which dependably creates the desired sealant reservoir in a single pass.

Figure 4. Pin Router (Courtesy of Salsco Inc.)

Figure 5. Impact Router Freewheeling Cutters

Literature

There has been many small scale and narrowly focused crack cleaning effectiveness studies conducted over the past couple of decades supported by a wide range of highway research agencies. Of these, the FHWA sponsored the Strategic Highway Research Program (SHRP) H-106 project, one of the most detailed studies completed to date[4]. The H-106 test plan was specifically designed to be broad-based by including all popular sealing materials and the preparation and application techniques recommended by their manufacturers. Highway test sites were selected to include a variety of climate and weather conditions, and the application of the seals were tightly controlled. The performance of these seals was studied over a six-year trial period while being exposed to ordinary traffic and pavement stresses on the highway. The conclusion was that crack sealing is cost effective when the cracks are properly prepared, and the longest effective seal life is achieved when a crack sealing reservoir is created.

A small-scale Canadian cost-benefit study examined seal performance with different routing shape factors and used seal longevity to evaluate the practice in a cost-benefit framework[5]. The conclusions were similar to the SHRP H-106 study in that: 1) A rout size of 40 X 10 mm promotes good bonding, 2) In general, the consequences of not sealing cracks in flexible pavements are increased rehabilitation cost and decreased service life, 3) Routing and sealing cracks can minimize secondary crack growth and increase service life by at least 2 years, and 4) The life-cycle cost analysis indicates that rout and seal treatment is a cost-effective pavement maintenance procedure.

Research Methodology

The research approach began with a review of commercially available equipment and methods used for crack cleaning operations. A Caltrans Technical Advisory Group (TAG) was established early in the project, and regular meetings were held with the Caltrans Task Manager and the panel. AHMCT and the TAG worked collaboratively during the research to guide the research effort. The proposed work aimed to investigate methods of mechanizing crack routing/cleaning processes to address the common problems (slow speed, labor intensive, and worker exposure) associated with crack routing/cleaning. The focus was on router cleaning and perhaps vacuuming and air blasting tools to clean cracks. The outcome is a proposed conceptual design and detailed specifications of equipment and methods enabling Caltrans maintenance to

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[4] SHARP H-106, LLPP Pavement Maintenance Materials: SHRP Crack Treatment Experiment, Final Report, K. Smith, A. Romine, ERES Consultants, FHWA-RD-99-143, 1999

[5] Crack Sealing in Flexible Pavements: A Life-Cycle Cost Analysis, J. Ponniah, G. Kennepohl, Work Zone Safety and Pavement Markings and Materials, TRB Volume 1529, 1996

increase the efficiency of longitudinal crack cleaning operations, especially high production, moving lane closure highway operations. System design emphasized near-term development and pursued off-the-shelf components or equipment to streamline the potential future building of the design by Caltrans Division of Equipment or a third party vendor.

The proposed joint crack cleaning machine project includes the development of an appropriate guidance system. In the case of longitudinal joint cracks, the guidance scheme had to be capable of tracking a void potentially packed with debris and vegetation at a continuous moving closure speed up to 3 mph. The first phase of the guidance development was a laboratory based proof of concept demonstration. The second phase of guidance system development focused on tracking actual pavement joint cracks. Finally, the detailed joint crack cleaning machine conceptual design and guidance technology development results will be documented in the final report.

Overview of Research Results and Benefits

This research resulted in the development of innovative technologies that improve the quality of longitudinal edge joint preparation methods and tools available to Caltrans maintenance crews to apply the highest quality seals possible on the highway. Maximizing joint seal service life through improved cleaning and preparation methods enables Caltrans to maximize the benefits of joint sealing including reducing concrete spalling, increasing the interval between major shoulder rehabilitations, and level of service paybacks. Additionally, reductions of worker exposure through faster operations, extended maintenance intervals, and increased in-vehicle operations maximizes worker safety, a key Caltrans' goal.

Chapter 2: System Requirements Development

This section presents a list of highly interdependent functional and performance characteristics, which will serve as the synthesis of the high production moving lane closure joint crack cleaning machine design. These essential system criteria were either established in the project proposal, derived from the project search information, or based on the operational characteristics of the Sealzall machine presented in the Caltrans Implementation of the Sealzall machine development final report[6] and input from Caltrans Division of Maintenance personnel. Since the principal objective of this machine development project is to extend the utility of the Sealzall sealing machine to Caltrans, these functional and performance requirements should be considered as the minimal design requirements necessary to achieve the basic purpose of this machine development effort. These basic machine design functional and performance requirements were presented to the Caltrans stakeholders' panel to ensure conformity with their expectations.

Machine Performance Requirements

The following list presents the basic essential performance requirement goals which must be achievable when designing the joint crack cleaning machine should the design be intended to pair with the Sealzall in highway sealing operations. These functional requirements are defined in the report as system capabilities, or how equipment operates.

Moving Closure Operation

The key to the Sealzall high production capabilities is its ability to operate in a moving lane closure on the highway. Developing a high production joint crack cleaning machine to compliment the Sealzall would likewise need to be able to operate in a moving closure and at an equivalent speed. The maintenance vehicles protected by an attenuator truck in a moving highway closure must keep close enough together to both visually and dynamically avert passing traffic from turning into the closure between the vehicles and potentially striking the back of the unprotected maintenance vehicles in the operation (Figure 6). The maximum safe spacing distance is associated with the passing traffic speed, which reduces even further near ramps and merges. Therefore, to be compatible with moving closure operations, equipment must possess a sufficient level of automation to enable the system operator to control the process remotely from the confines of

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[6] Deployment Support and Caltrans' Implementation of the Sealzall Machine Final Report, 2014 CA13-2215, D. Bennett, S. Velinsky, Advanced Highway Maintenance and Construction Technology Research Center

the vehicle cab while moving in the highway closure. As with the Sealzall operation, the driver can periodically steer out of the traffic lane and stop to load sealant blocks or access any part of the machine. Since the proposed joint crack cleaning machine must move together mirroring the Sealzall, the joint crack cleaning machine operational scheme must include simultaneously taking these pauses as well. Pauses may be an opportunity to off-load collected joint crack debris off the side of the highway.

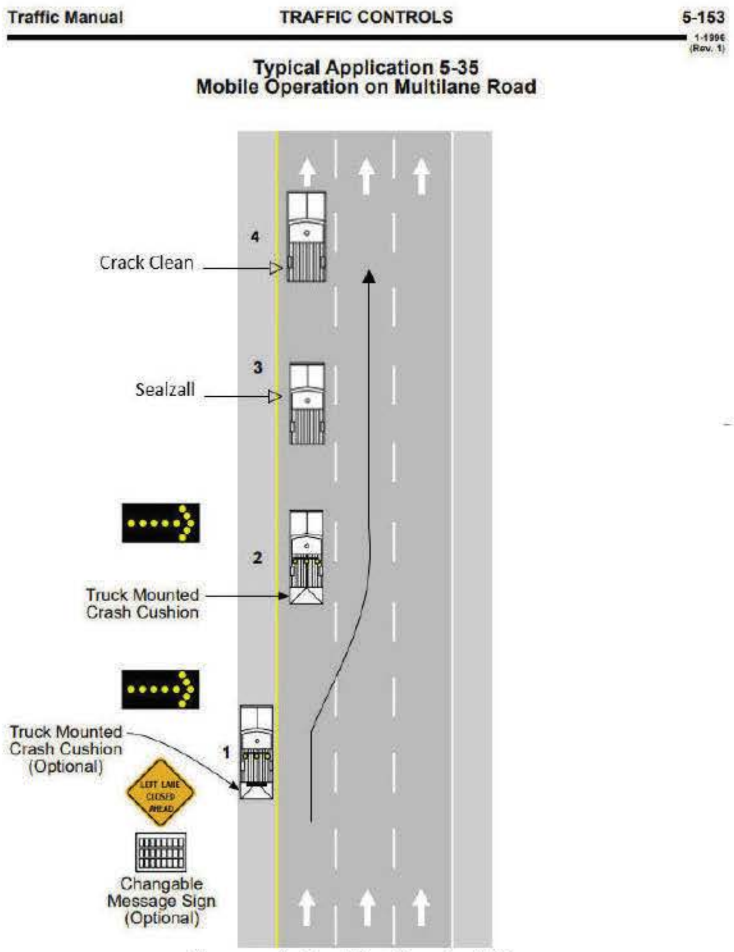

Figure 6. Traffic Control Flow

Single Pass Cleaning

For a high production longitudinal joint crack cleaning machine to effectively pair with the Sealzall in a highway moving lane closure, the joint crack cleaning machine must be capable of cleaning the joint crack at an average speed of 3 mph. Since the Sealzall sealing process is moving continuously and both machines must stay relatively close together in the closure, the cleaning method must clean efficiently in a single pass. When operating in moving lane closures, the Sealzall will occasionally stop in the lane to adjust sealing aspects and/or for abbreviated sealant refills. During these intervals, the crack cleaning operation must pause as well to maintain safe vehicle spacing necessary for attenuator truck protection from passing highway traffic. The opposite is also the case. Should the joint crack cleaning machine need to pause in the lane for any reason, the Sealzall must pause as well to avoid a collision.

Crack Tracking Guidance

The Sealzall machine can operate without any type of guidance system hardware because the sealing shoe is wide enough that the driver's steering alone is enough to seal longitudinal joint cracks effectively. The driver can easily steer the vehicle keeping the 4"-wide sealing shoe over the edge of the concrete slab at 3 mph. This contrasts with longitudinal crack cleaning operations that requires guidance directly over the joint crack to effectively clean the crack, regardless of the type of cleaning method. This higher level of precision prevents a driver in a large truck from guiding a crack cleaning head based solely on vehicle steering. Some type of refined tracking scheme must be employed to accurately track the edge of the concrete slab for any type of vehicle-based joint crack cleaning machine. Adding to the difficulty of longitudinal joint crack guidance schemes is that the cracks are packed full of debris and vegetation, which camouflages the joint transition. A clean longitudinal joint crack has a high contrast at the pavement transition and a shadow in the void to simplify the image processing for guidance tracking purposes.

Machine Functional Requirements

The following list presents functional requirements that a crack cleaning machine design must incorporate to successfully pair with the Sealzall machine in highway sealing operations. These functional requirements are defined in the report as equipment, or hardware configurations.

Single Pass Cleaning

Traditionally, crack cleaning operations are conducted with workers on foot. When heavily packed debris and rooted vegetation is encountered, the cleaning method usually requires additional passes to dislodge stubborn debris. For the joint crack cleaning machine to operate in a moving closure on mainline highways in conjunction with the Sealzall machine, a single pass is the only feasible cleaning approach. Consequently, the cleaning method selected for the joint crack cleaning machine must be capable of cleaning any type of crack debris in a single pass at speeds up to 3 mph.

Vehicle-based

In general, vehicle-based equipment is the preferred configuration when developing machines to conduct highway maintenance operations because of the naturally greater level of worker safety and production efficiency benefits. This extends to the crack cleaning application, and is required for the design concept to support Sealzall moving closure operations. Operating the machine remotely from the cab and thereby removing workers from direct traffic exposure during operation is a desirable feature. A standard truck platform with the appropriate gross vehicle weight should prove sufficient. One possible upgrade would be the addition of dual steering to the truck. Having the driver seated on the side of the vehicle adjacent to the longitudinal joint crack enhances the driver's ability to steer the vehicle along the joint crack using just an external reference point. Seating the driver on the opposite side of the cab greatly degrades steering ability and will most likely require some form of secondary joint crack tracking display providing the driver a visual cue in which to steer the vehicle. Caltrans can decide if the additional time and expense involved in obtaining a dual steer truck for this development is justified, during a potential future fabrication stage.

Figure 7. Vehicle-Based Sealzall Sealing in Highway Traffic on Interstate 5

Joint Crack Guidance System

All conventional crack cleaning methods, which clean down into the crack, require precise alignment with the joint crack to be effective at dislodging debris from the void. Even the slightest offset from the void dramatically reduces the efficiency of the cleaning method. Consequently, tracking the cleaning device along the longitudinal joint crack requires far greater precision than can realistically be achieved by distant observation from the truck cab alone. Once vehicle steering becomes uncoupled from router guidance, the inclusion of some form of lateral tracking system becomes obligatory. Regarding the crack cleaning machine, fundamentally a guidance system must be developed that can make the fine tracking adjustments necessary to accurately follow the concrete slab edge. The choice of a router guidance system will focus on the simplest possible method, which can effectively track a straight PCC slab edge continually at speeds up to 3 mph. Nearly all of the highway slab edges are straight, but in order to mitigate the occasional incongruities encountered, a manual control component of the guidance system must also be incorporated.

Independent Lateral Tracking

A means to move the crack cleaning head laterally in relation to the vehicle will be an important functional requirement regardless of the type of guidance scheme selected for the crack cleaning machine. If a manual guidance scheme is utilized, steering the vehicle alone will not provide the necessary resolution to enable the driver to accurately follow a longitudinal joint crack. If an automated guidance scheme is to be utilized, a mechanical means to drive the cleaning head to the commanded position would be mandatory. Presumably, the lateral actuation mechanism would be configured and mounted to the side of the vehicle bed behind the truck cab and produce motion perpendicular with the side of the vehicle. Since conventional crack cleaning methods are not adversely affected by minor angular misalignments, providing a secondary degree of movement to keep the lateral mechanism parallel to the joint crack in operation was judged to be unnecessary. The travel length of the lateral actuation mechanism would be minimized to make the mechanism compact, but long enough to enable the driver to comfortably steer the vehicle within the lateral stroke travel distance of the cutter head. The initial prediction is that a lateral stroke of 16 inches should be a reasonable length.

Manage Dust and Debris

A proposed joint crack cleaning equipment design must account for the collection and handling of a substantial amount of debris generated by a high production automated cleaning process. In a mainline highway moving lane closure, all maintenance vehicles involved must stay at prescribed spacing distances based on Caltrans traffic safety practices. Therefore, the cleaning machine should ideally mirror the characteristic operational movements of the Sealzall machine, which is mostly continuous with brief stops to load sealant blocks. During the Sealzall stops on the highway, the crack cleaning machine must be capable of unloading the collected debris on the side of the highway. Large capacity dust collection systems rely on the introduction of water to reduce the level of dust that passes through the system and is exhausted back into the environment. Since the collected dust and debris is to be unloaded along the highway, it must be relatively dry to be in conformance with storm water restrictions. However, lessening the amount of water usage on conventional dry filter vacuum systems increases their particulate emissions, thus potentially violating air quality restrictions. Therefore, a cyclone type vacuum filter component, which provides superior dust filtration with a minimum of introduced water should be considered for incorporating into a crack cleaning machine design.

Chapter 3:
Strawman Concept Development

The strawman concept selected for the moving closure crack sealing machine development is centered on a router cleaning process since it is the only conventional method capable of effective single pass crack cleaning. The router cleaning equipment will also be configured as a self-contained vehicle mounted system to be consistent with the identified design parameters, the specific operational requirements, and the expected machine performance. The strawman rout-cutter concept design can be logically categorized into four distinct elements, the cutter head, lateral tracking, machine configuration, and auto guidance concepts. Each of these conceptual elements will be explored in detail including potential alternatives whenever possible, especially with regards to the overall machine configurations and guidance schemes. The final design criteria to be established either in consultation with the Caltrans TAG and presented in greater detail in the detailed conceptual design section of this report or determined later during a potential future fabrication phase of this machine.

Strawman Routing Head Concept

Impact router cleaning was selected as the foundation for the joint crack cleaning machine strawman concept development. Standard commercially available manual impact routing equipment will serve as the starting point for the further development of a higher production router specifically optimized for vehicle mounting and suitable for mainline highway operation in moving lane closures.

Figure 8. Standard Manual Impact Router for Joint Crack Cleaning

Impact Router Pavement Cutting Utility

Traditional manually operated impact router equipment is limited to Climb Cutting, which is a term defined as mill cutting where the cutter rotation is in the direction of feed (Figure 9). The resulting reaction cutting force can be separated analytically into two component forces. One force component helps lift the cutting head up out of the pavement (Normal Force), and the second force component helps drive the cutting head in the direction of feed (Horizontal Force). A heavy weight router machine keeps the cutters down into the pavement, and the feed force propels the router forward along the pavement crack. The worker controlling a conventional non-driven manual router pushes against the router, resisting the generated forward force that propels the router forward along the crack. Self-driving manual router equipment is commercially available and eliminates the worker-imposed resisting force by providing a uniform surface speed, drastically reducing worker physical exertion. Climb Cutting is not a suitable technique for the high-speed router cleaning machine development because any increase in routing speed directly translates into an equal increase in the cutting reaction force, which is acting to drive the cutter head to climb up and out of the pavement cut. Overcoming climbing forces becomes increasingly problematic at high routing speeds. The better solution is to reverse the Climb Cutting reaction forces by switching the cutting direction to Conventional Cutting.

Conventional Cutting is a term defined as mill cutting where the cutter rotates opposite the direction of feed (Figure 9). The resulting reaction cutting force can be analytically separated into two component forces. One force component drives the cutter down into the pavement (Normal Force) and the second force component is in the opposite direction acting to oppose the cutter feed (Horizontal Force). For higher speed router applications, Conventional Cutting reaction forces are straight forward to mitigate. Virtually any size normal force component can be resisted with a heavy-duty caster wheel placed between the router frame and the concrete slab at the edge of the highway. Likewise, the horizontal force component resisting cutter feed rate of virtually any magnitude is mitigated by utilizing a truck chassis to drive the router cutter. Therefore, utilizing a truck platform for the crack cleaning router is essential. The vehicle platform for the router cleaning machine also provides the necessary power to overcome the considerable routing head cutter forces necessary to drive the router forward when cutting pavements at higher speeds.

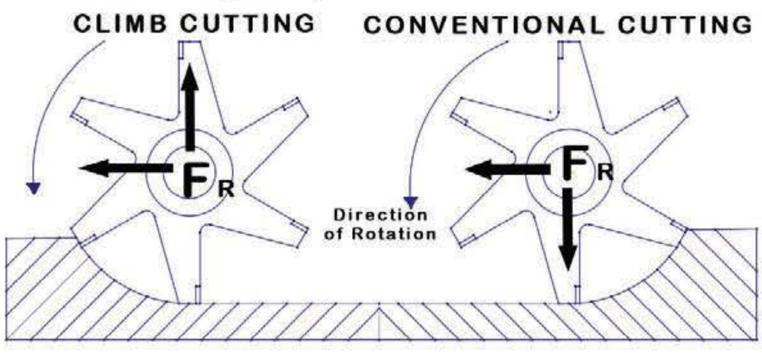

Figure 9. Reaction Forces of Rotational Cutting Types

Sealant Reservoir Creation Principle

Crack cleaning as a preparation for crack sealing is conducted to improve the quality and longevity of the crack seal. The shape of a seal is a major contributing factor to the longevity of any type of working cracks. Edge joints, especially between AC shoulders and PCC highways, experience a high level of thermal cycling due to the dissimilar pavement materials, thinner shoulder pavement thickness and exposure to more edge subbase settling. As the pavement cools, the joint crack widens compelling a functional seal to stretch an equivalent amount. The force required to stretch the seal is entirely generated by the two sealant bonding surfaces on either side of the joint crack. Should either side loose adhesion, the sealant will fail causing a new crack to form. The thickness of the seal determines the magnitude of the tensile forces pulling at the bonding surfaces (Figure 10). A thinner seal profile has the lowest tensile forces and is more likely to remain bonded to both sides of the joint crack. Conversely, if the seal profile is too thin the seal will lose cohesion and be ripped apart or simply flow down into the joint crack when the pavement becomes hot. Various research projects over the years have sought to determine the best seal shape factor for the best balance of adhesion and cohesion to achieve optimum seal longevity. A combination of a routed channel and an overband, generally referred to as a recessed overband, has provided the best performance in field trials[7]. The overband feature favors pavement adhesion while the routed channel enhances sealant cohesion. A common rout channel shape is a 5/8" square, but exact dimensions of the ideal rout shape varies dependent on the application and climate factors**Error! Bookmark not defined.**.

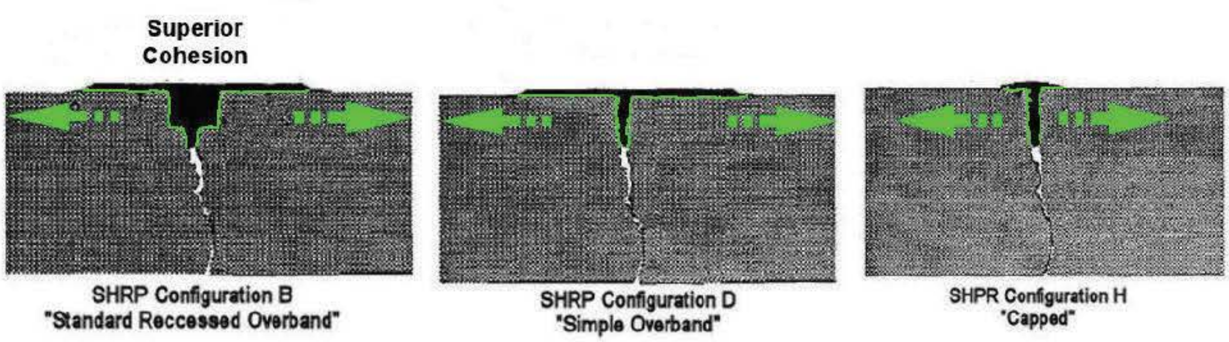

Figure 10. Adhesion Surface Area by Seal Configurations (SHRP 107a)

The crack cleaning equipment design should support the creation of a seal shape profile, which could be optimized for Caltrans based on field trials. For tighter joint cracks, impact routing uniquely provides the benefit of creating a uniform sealant reservoir to optimize seal life. For joint cracks in advanced stages of decay, the rout shape must have enough adjustability to be configured to a more appropriate wider cutting path. The routing equipment developed for the router cleaning machine should therefore possess the ability to produce a variety of rout shapes, which ideally could easily be adjusted by the worker to achieve the desired cut profile. The impact router flywheel design creates the opportunity for the star cutters to be staggered with spacers on the flywheel pins, which produces different cut widths and when combined with variations in the depth enables the router to be configured to cut an agency's favored shape factor (Figure 11). Typically, either a square 1 to 1 cut shape factor, or a low profile 4 to 1 or greater cut shape factor is utilized for longitudinal joint crack sealing.

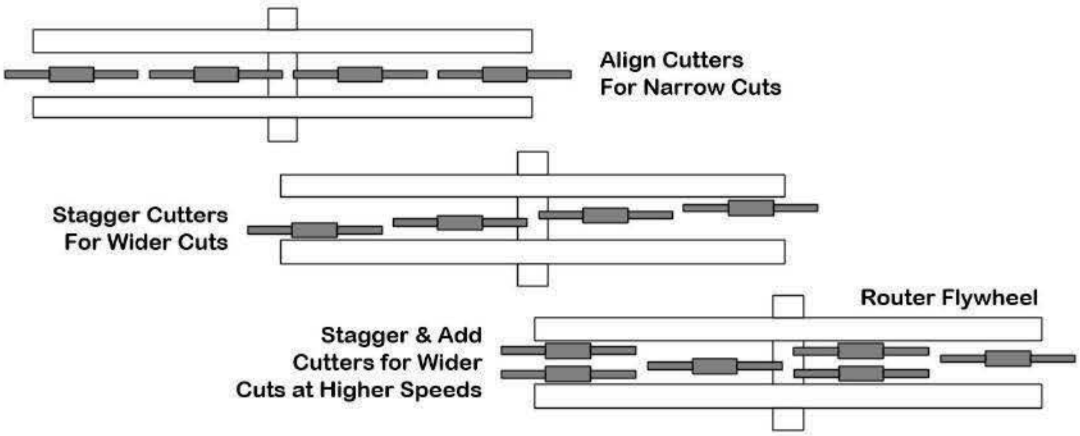

Figure 11. Varying Router Cut Widths

Another benefit gained with the impact router crack cleaning method is that typically longitudinal cracks are sealed/filled only during the colder times of the year when cracks are at their widest. Routing a sealant reservoir eliminates this restriction and enables effective joint crack sealing year-round independent of the ambient outside temperature.

Consumable Impact Cutters

Impact star cutters consist of a cast steel body with a center hole and eight carbide tipped cutting fingers. The router flywheel has a set of equally spaced cutter pins, which are mounted perpendicular to the flywheel. Star cutters' center hole loosely slips over the cutter pins and are free to spin in relation to the flywheel. Star cutters with different length fingers are available to produce the desired range of cut depths. The star cutter fingers can cut only in one direction, but the cutter cutting direction can be reversed by flipping how the cutter is placed on the cutter pins. Star cutters are intended to be regarded as consumables, and the cost effectiveness of these cutters is essentially dependent on the cutter life. Carbide cutters can be cost effective at cutting asphalt pavements primarily due to the use of a flexible binder that enables the cutter to break apart the hard-stone matrix. Cutting PCC pavements with carbide cutters is far less cost effective because the binder in PCC pavements is ridged, which compels the carbide cutter to cut directly through the hard-stone matrix. Typically, diamond dust tipped cutters are utilized when cutting through PCC pavements. Consequently, when cutting/cleaning typical AC/PCC longitudinal transition joint cracks with impact star cutters, only the asphalt side of the joint is to be cut avoiding contact with the PCC side. Minimizing or eliminating any contact between the star cutter and the PCC slab will extend cutter life and vastly improve cost effectiveness of the impact routing process. Impact star cutters have forged steel bodies, which are complicated to manufacture. Identifying several sources of these consumable cutters is an important factor to ensure a steady supply will continue to be available. AHMCT was able to identify a suitable list of suppliers capable of supplying the carbide tipped impact star cutters in a wide array of shapes to meet the future needs of a joint crack cleaning machine.

Augmenting Impact Router Design

Traditional impact cutter routing equipment is operated at relatively slow surface speeds, generally averaging 1 mph with an upper limit under 2 mph. As previously discussed, these routing machines are configured solely to Climb cut for an assortment of reasons, but the primary reason is that the resulting cutting forces act to drive the router in the direction of cut. This aids tremendously in the effort to manually handle and guide the impact cutter router while chasing a joint crack. The trade-off is that as the router surface speed is increased further, the cutter head rides up out of the crack and walks along the pavement surface. Therefore, to achieve a 3 mph cutting speed to potentially pair with the Sealzall machine, the cutting type would ideally change to Conventional cutting and the router design optimized. A variety of factors, which have been optimized over the years for manual Climb Cutting impact router performance, may need to be changed to optimize high speed Conventional cutting performance. Other design modifications may be necessitated due to the type of longitudinal transition joint crack targeted to clean. Achieving higher operational speeds, in general, are not as important in the design of a crack cleaning machine as improving safety of workers by removing them from the roadway.

Star Cutter Diameter: Surface flatness is one issue that is often problematic for transition joint cracks, which is usually inconsequential in standard in pavement cracks. Transition joints of dissimilar pavements such as AC/PCC are particularly prone to misalignment. The PCC slab is relatively stable, but the AC shoulder will rise with pavement lipping or fall with sub-base failure to create a commonly found mismatch in these surfaces. The standard-length star cutters cannot reach a lowered AC shoulder and lacks the flywheel clearance to create the desired cut profile for lifted AC shoulders (Figure 12). In either case, the height mismatch cannot account for in standard length ¾" finger star cutters. Long fingered star cutters are twice the standard length of regular cutters (Figure 13). Their 1½" finger reach can account for an inch of surface mismatch and still produce the desired cut profile. Therefore, the router cleaning machine strawman design will specify the use of long star cutters to ensure the machine's capability of cleaning the type of transition longitudinal joint cracks that the Sealzall machine seals on highways.

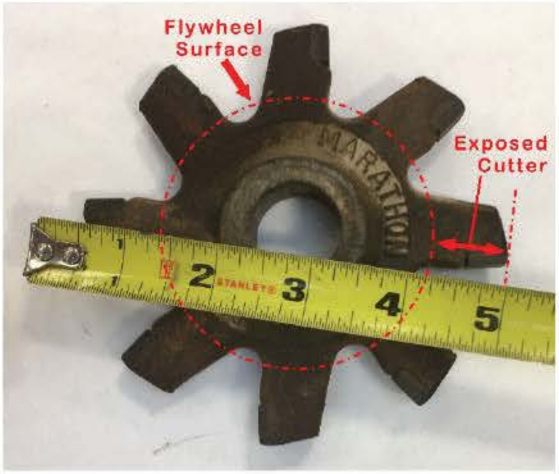

Figure 12. Standard 4½" ∅ Star Cutter

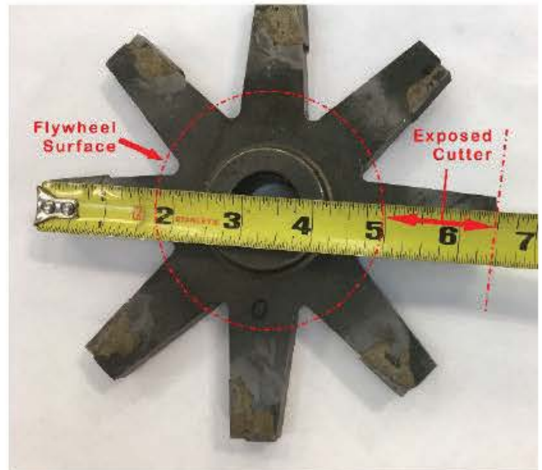

Figure 13. Long 6½" ∅ Star Cutters

Flywheel Diameter: Standard manual impact cutter routers are designed to operate with six equally spaced standard length 4½" diameter carbide star cutters. Therefore, the outer diameter of the router is designed only large enough to accommodate the six cutters with a reasonable gap in between. This works out to a standard 12" outer diameter flywheel (Figure 14). To utilize deep cutting long finger star cutters on a standard flywheel router, the manufacturer recommends installing only three long cutters. Reducing the number of cutters by 50% on the flywheel greatly reduces the cutting efficiency. Instead, for the router cleaning machine strawman design to utilize the long star cutters, the flywheel diameter would need to increase to an 18" diameter to accommodate all six long star cutters (Figure 15).

Figure 14. Standard Impact Router Flywheel

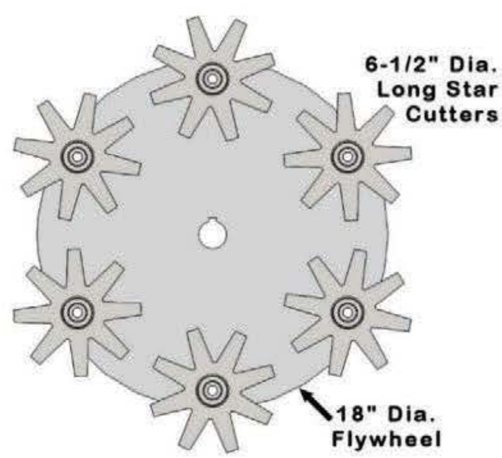

Figure 15. Larger Router Flywheel Diameter

Impact Router Machine Adaptation

The design of standard manual impact router equipment will serve as the basis of the router cleaning machine cleaning head. However, the design will require several major adaptations for the ability to operate from a vehicle platform and to obtain the higher cutting rates necessary to keep pace with the Sealzall machine.

Impact Router Drive System: Standard manual impact routers are powered by gasoline engines, which are mounted directly above the cutter flywheel to act as ballast weight to counteract the upward resulting cutting force generated by Climb Cutting. Since the crack cleaning strawman concept involves changing to Conventional Cutting, there is less of a need to place a heavy downward counteracting weight over the cutting head. This enables the gasoline engine to be replaced with a hydraulic motor of equal power. The hydraulic motor is compact enough that it can be placed in-line and directly drive the flywheel center shaft and eliminate all the many drive transmission parts needed in the gasoline engine version. Switching to hydraulic drive also drastically reduces the size of the impact router enclosure facilitating the mounting of the device to a vehicle platform.

Impact Router Encasement: The router encasement which surrounds the flywheel serves as both a mounting frame and a containment enclosure to manage dust and debris generated by the impact cutters. For standard manual impact routing machines, the router encasement must contain an opening, so the system operator can directly view the cutter flywheel to guide the router along the pavement crack. For the crack sealing machine, since a guidance system must be employed because the operator will not have a direct line of sight to the router mounted to a truck platform, the router encasement can therefore be closed fully. Full enclosure around the impact cutter flywheel greatly improves the containment of the generated dust and debris and supports the collection by a vacuum system. An encompassing wire brush skirt with a fabric internal fin will act as a compliant interface to the variable height pavement surfaces.

The standard manual impact router machine design fixes the spatial relationship between the cutter head, enclosure, and drive engine. Therefore, the depth of cut adjustment can only be generated by raising and lowering the entire router assembly. This is accomplished by mounting the support wheels on a pivot controlled by a linear actuator, which varies the distance between the router assembly and the pavement surface. The downside to this arrangement is that the router cutting head is always extended below the enclosure by at least the depth of cut, which presents a safety hazard especially to the operator's feet. For the crack sealing machine strawman concept, the change to a direct drive hydraulic motor drive system enables the router flywheel cutter to fully retract into the enclosure when not cutting. To accomplish this the flywheel cutter can be mounted to a swing arm with a pivot attached to the enclosure at one end and a four-bar linkage at the other end of the swing arm (Figure 16). A linear actuator connected between the enclosure and a pivot point between two of the links translates linear motion into vertical adjustment of cut and serves as a locking mechanism to shield the linear actuator from much of the large vibrational forces generated by freewheeling impact cutting. The router enclosure rides on a single caster over the surface of the concrete slab at a fixed height.

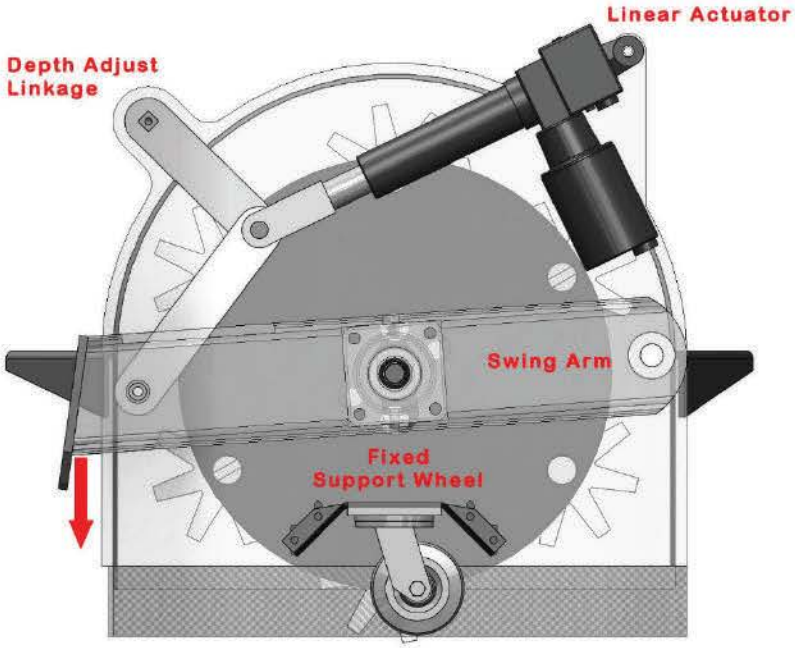

Figure 16. Retractable Impact Cutter Flywheel

Impact Router Mounting Frame: The crack cleaning impact router would logically be attached to the side of the truck platform and capable of shifting laterally and retracting for transport. The router would need to be operable off either side of the vehicle to operate with the Sealzall machine in moving lane closures. The approach would be to permanently attach a retractable routing device to each side of the vehicle. Obviously, one router device would be utilized at a time in operation on the highway, so the supporting power and vacuum systems would not need augmenting. The size and weight of the router enclosure would preclude the router device from being attached along the side of the truck cab or in front of it. Consequently, the router device must be attached to the side of the truck platform body. The attachment must be both rigid enough to account for the tremendous impact cutting forces and yet compact enough to be retracted to within the confines of the truck platform for transport to and from the highway work site. The attachment must also support controlled lateral translation during operation with approximately 14" of travel to reduce the dependency on truck platform steering.

The impact router attachment design for the router cleaning machine strawman concept consists of a mounting frame, which connects the router enclosure to the truck platform bed frame. The mounting frame will be symmetrical, such that the same frame can be attached to both sides of the truck body. The mounting frame design attaches to the router providing a single degree of freedom lateral motion, which was determined to be sufficient to accomplish the router machine objective. Configuring the router bolted connection joints as pivots would be required should this option become necessary.

The mounting frame will be attached to the underside of the flatbed in the space between the truck frame rails and the outside edge of the truck bed and between the rear axle and the truck cab. A retractable router design keeps the router close to the ground and allows for a more compact router mechanism, enabling the router to fold up under the truck body for transport. The router will be driven by an in-line direct drive hydraulic flywheel motor that greatly reduces the overall size of the router enclosure, which aids with the router fitting underneath the truck body. The mounting frame concept is a pair of simple two link swing linkages each connected to the truck bed by a pivot. Connecting a hydraulic cylinder between the truck bed and the vertical link and another between the links can produce both of the desired positions. While the router is deployed (Figure 17), the stowage cylinder creates a ridged three link triangle transferring the lateral motion from the truck bed down to the router enclosure. The cylinder between the links provides an adjustable downward force on the router. Retracting both cylinders folds the router up and under the truck bed (Figure 18). In the retracted position, the underside of the router is exposed in a convenient position to access and change the consumable star cutters.

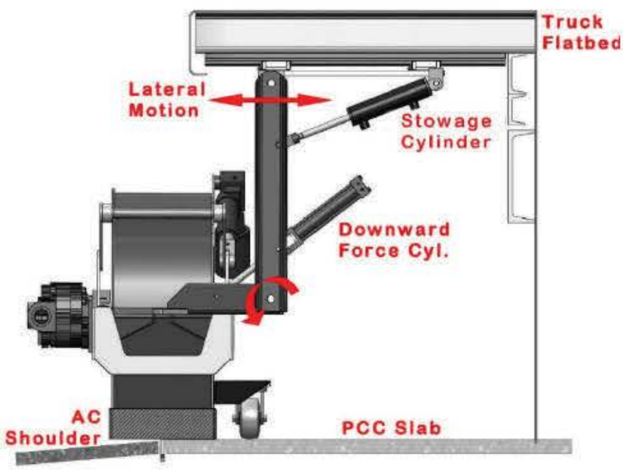

Figure 17. Router Mounting Frame

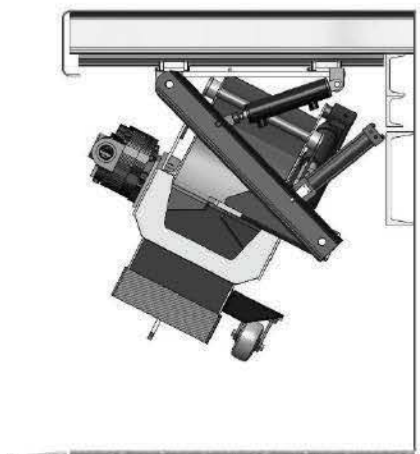

Figure 18. Mounting Frame Retracted

Supplemental Crack Cleaning Capabilities

The expectation that the impact router will completely clean out the joint crack and potentially even cut a crack reservoir assumes that the joint crack is narrow enough that the freewheeling impact cutters will span the full joint crack width. This is the case for newer transition joint cracks and older unsealed joint cracks with stable pavement sub-bases and intact asphalt shoulders. However, the development of the router cleaning machine is intended to extend the application of the Sealzall sealing operation to older and degraded longitudinal transition joints where the asphalt bordering the joint crack interface has deteriorated and chipped away to the point that the joint width may be far wider than the router width itself. In these cases, the sealing adhesion mechanics are somewhat different. A high-quality bond to the slab is still imperative, but a small amount of debris and dust left behind from the impact cutting and vacuuming will have a minimal impact on the overall seal quality. Potentially, a compressed air blast could be directed into the joint crack trailing the cutter head to help remove all remaining loose dust and debris from the void. Establishing a clean PCC slab edge is an especially important factor to promote sealant adhesion. Any remaining debris or dust left behind on the AC side in the case of a degraded shoulder will have little effect on the seal life. To support additional crack cleaning, a compressed air blast could be added. A high volume and pressure rotary screw compressor would be the preferred equipment utilized. The compressor may be integrated in with the auxiliary power engine or be a common self-contained trailered unit.

Strawman Lateral Tracking Concept

The mounting frame connecting the router to the truck body will be designed with a lateral translation component, which will enable the router to track the joint crack edge independent of the position of the vehicle. The strawman lateral tracking design will utilize a sliding router mounting to the truck bed, which always keeps the router parallel to the vehicle. A linear actuator provides the lateral tracking capability. The mounting frame consists of a mirrored pair of multiple swing arm linkages, which will be connected by pivot joints to a single flat base plate. The base plate will attach to four bearing sliders that slide on a pair of linear slide bearing rails, which will be attached to the bottom of the truck bed stringer channels. The slide plate, driven by a single linear positioning cylinder, will move linearly in a direction perpendicular to the truck body. The linear cylinder must generate a significant force to stabilize and control the impact router while cutting pavement. Therefore, an electrical over hydraulic cylinder will be utilized for the crack cleaning strawman design. The hydraulic power unit will have to be configured with two pumps to utilize a hydraulic positioning cylinder. The main hydraulic pump should be a load sense flow pump, which is ideal to provide the consistent flow necessary to power the router cutter drive motor. The smaller secondary pump should be a pressure compensated pump with an accumulator to develop a consistent hydraulic pressure necessary to accurately drive the linear cylinder. An auxiliary power unit will most likely be necessary to provide this additional hydraulic power. When controlling the tracking of the router, the positional control can be provided by either a manual joystick or automatically controlled by the digital controller. The system operator will have the necessary controls to instantly switch back and forth between the two control options with the joystick controller. A closed loop hydraulic controller will accelerate and hold the commanded position utilizing either a common Linear Variable Differential Transformer (LVDT) or an Intellinder™ absolute position feedback sensor.

Strawman Machine Configuration Concept

A truck platform is an essential element of the router cleaning machine strawman concept to support both the moving closure operation and to provide a greater level of dust and debris management than manual routers. Ideally, the crack cleaning system would be vehicle independent or at least be easily attached to a common Caltrans fleet flatbed truck. This way long-term mechanical issues with a specific truck could be mitigated by switching vehicles. Likewise, the attachment of the other major crack cleaning support systems, such as the debris vacuum system, air compressor and power units will focus on universal mounting designs that support vehicle interchangeability. A machine design configuration, which provides flexibility with replacement system contingencies, will be the preferred objective.

Vehicle Platform

Since the router enclosure blocks any possibility of a direct view of the cutters, there is no benefit in attempting to provide a direct view of the joint crack from the truck cab. Therefore, unlike the Sealzall machine, a dual steering truck will not be required. The router cleaning machine can be designed to be adaptable to any type of standard issue Caltrans truck having an appropriate load rating. Due to the continuous slow-moving nature of moving closure operations, a hydraulic power take off (PTO) would not be useful for applications. The vehicle configuration of Caltrans moving highway closure operations does not require the crack cleaning truck to have a Truck Mounted Attenuator (TMA) mounted to the vehicle. Since the router device is attached under the truck's deck, ideally a truck chassis with enough clear space under the deck to fit the router somewhere between the cab and rear wheels would be necessary.

Dust and Debris Handling Equipment

A tremendous amount of dust and debris is ejected from longitudinal joint cracks during the cleaning process (Figure 19). Ideally, all this material would be collected at the point of cleaning in accordance with the local air quality regulations. For the router cleaning machine strawman concept, an industry standard dry excavation type vacuum system with a 1,000-cfm vacuum pump and cyclone filter unit was selected (Figure 20). These units can be purchased mounted to a skid, trailer mounted, or attached directly to truck beds. The vacuum collection tank size will be approximately 600 gallons based on the operational mode of off-loading the collected debris on the side of the highway periodically. A secondary polyethylene filter provides filtering of the air down to ½ micron to ensure a long blower life. The filter can be cleaned and used over and over with proper maintenance and care.

Figure 19. Impact Router Debris Cloud

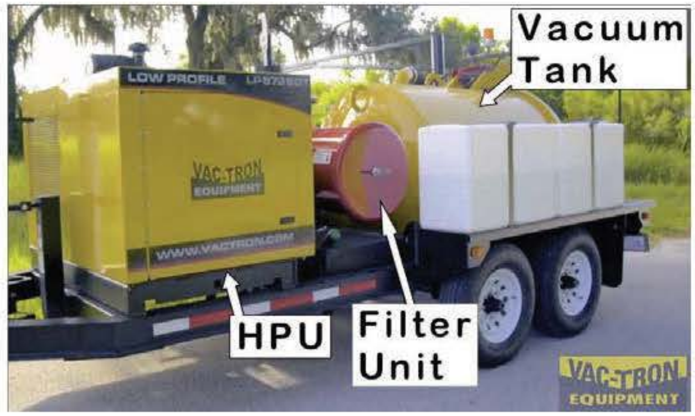

Figure 20. Vacuum System

Machine Configuration

The strawman concept of a router cleaning machine will be vehicle-based and contain three major components. 1) The impact router mounting frame, which both stows and operates from beneath a truck flatbed. The mounting of the router underdeck leaves the truck body surface free for the mounting of other support equipment. 2) The debris management vacuum system. The vacuum system must reside on the same platform as the router to collect the significant dust and debris cloud generated by the pavement routing process. 3) Sufficient hydraulic power to operate the hydraulic router motor in addition to the vacuum system. A separate auxiliary, hydraulic power unit (HPU) will need to be installed to power the router. The hydraulic systems included with commercial vacuum systems will presumably lack the extra capacity necessary to sufficiently power the router.

The following are possible router cleaning machine configurations, which include all three of the essential components.

Truck Mounted Configuration: The router cleaning machine could be configured with the dry excavation vacuum system and the auxiliary HPU mounted to a truck chassis and/or chassis. The router would be mounted to the underside of the truck flatbed. This type of direct mounting makes the crack sealing machine compact and light, but also very vehicle dependent.

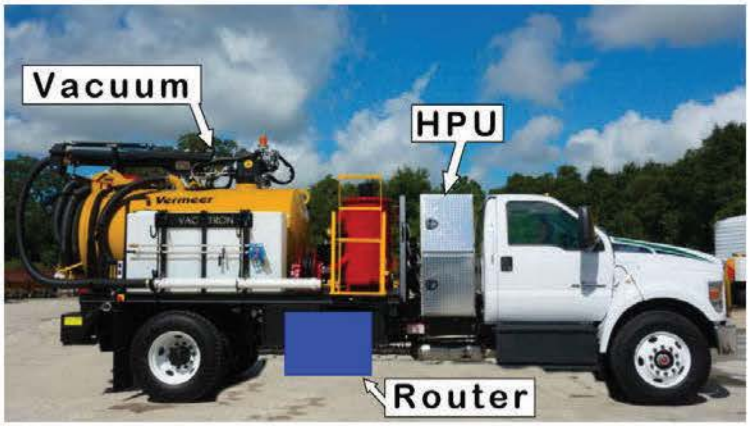

Figure 21. Truck Mounted Configuration

Roll-Off Configuration: The router cleaning machine could be based on a roll-off truck bed with a commercially available skid mounted air vacuum dry excavation system attached to the deck. This configuration would be less vehicle dependent because in the case of truck mechanical problems, a replacement vehicle could conceivably be switched out. The mounting of the router under the flatbed deck would have to be designed to mount to the truck chassis, which would most likely make switching trucks somewhat more complex.

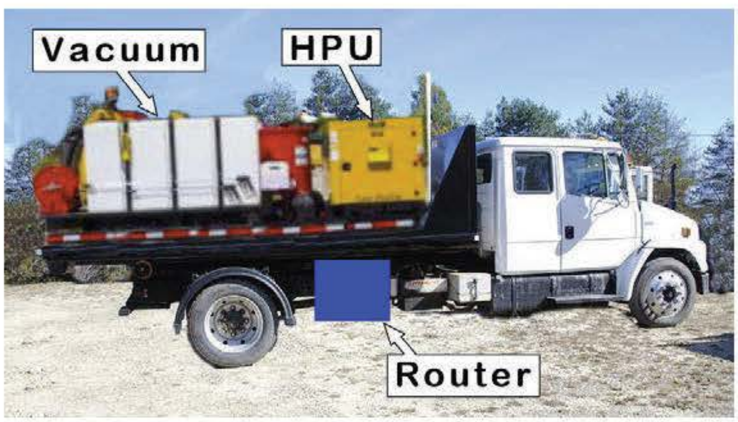

Figure 22. Roll-Off Configuration

Trailered Configuration: The router cleaning machine could also be configured with a standard flatbed truck body and a trailer mounted commercially available air vacuum dry excavation system. This arrangement would be the most straightforward to construct and minimally vehicle dependent, but the overall length of the combination is problematic. In the Sealzall moving closure operation, often the space to pull off the highway out of traffic is quite limited and pulling out in the lane typically involves backing the vehicle. Maneuvering a long vehicle and a trailer combination, especially backing a trailer on the side of the highway, may pose a major driving challenge.

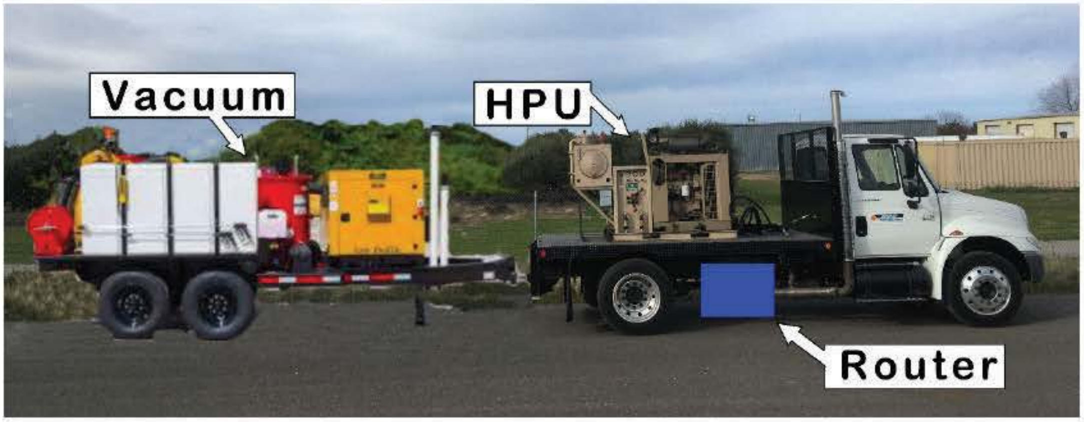

Figure 23. Trailered Configuration

These three potential router cleaning strawman configurations were presented to the Caltrans TAG last quarter which. All three of the strawman configurations satisfy the draft operation requirement options and would perform equally on the highway in moving lane closure operations supporting the Sealzall operation. The preferred configuration that the Caltrans TAG will adopt would most likely be based on cost or available equipment.

Strawman Debris Management System

Conventional manual pavement impact routing equipment is commercially available with dust control options (Figure 24). These systems collect the dust cloud, but the heavier debris is left on the pavement to be collected or dispersed by other means. The router cleaning machine debris management system must vacuum clean the joint crack in a single pass since the Sealzall machine trails directly behind the joint crack cleaning machine to seal the joint cracks. Crafco Inc. also offers a vacuum system designed specifically for pavement crack cleaning. The Crafco Crack-Vac™ is a self-contained unit, which conforms to Particulate Matter (PM)10 pollution abatement standards (Figure 25). The Crack-Vac™ utilizes a single stage 10-micron polyester filter element. Since the router cleaning machine utilizes a cutter head and operates at least double the conventional routing speed, a commercially available vacuum excavator unit seems to be a more capable match of vacuum collection systems. Both the excavation and high production routing crack cleaning require vacuuming up large amounts of small debris and dust at a high flow rate, the collection of solids and the effective filtering of dust from the exhaust air discharge. Therefore, industry standard vacuum excavation systems can be utilized for the router cleaning machine with only a few minor adaptations. The configuration of the router cleaning machine vehicle platform will dictate how the vacuum excavation equipment is mounted, but the performance specifications of the system will remain consistent.

Figure 24. Crafco™ Manual Router with Dust Control Option (Image Courtesy of Crafco Inc.)

Figure 25. Crafco™ Crack-Vac (Image Courtesy of Crafco Inc.)

Cyclonic Filtration Unit

Vacuum excavation equipment filtration systems typically employ some version of a cyclonic filtering device to separate the larger debris out of the vacuum flow before reaching the last stage of the polyethylene canister filter element. The efficiency of the cyclone filter is a critical factor in reducing polyethylene filter clogging exacerbated by large debris. The polyethylene filter size and water injection rate determines the level of fugitive dust mitigation and prevents large particles of debris from passing through the vacuum excavation pump. The silencer for the vacuum is inside the cylinder as well and reduces the noise level of the high-speed air leaving the unit. A four-way valve on the filtration unit enables the unit to go from vacuum to pressure by simply raising or lowering a lever without needing to lower the engine speed. The reverse pressure works to offload liquid materials and dislodge material from a clogged vacuum hose. Finally, the polyethylene filter provides the final defense for the vacuum pump. This filter cleans the air down to ½ a micron to ensure a long blower life. The filter can be cleaned and used over and over with proper maintenance and care.

Debris Off-loading

As previously described, the router cleaning machine would ideally mirror the movement and pace of the Sealzall machine while operating in highway moving lane closures. The debris collected by the on-board vacuum system from the routing process must be stored on the vehicle until it can be off-loaded. The sheer volume and weight of the debris collected will necessitate periodic off-loading of the collected debris during the operation. A conventional ¾" by ¾" rout profile will generate approximately 150 gallons (2,500 lb) of dust and debris per mile, or 600 gallons (10,000 lb) for a 1½" by 1½" rout profile. Since the Sealzall machine is periodically pulled off the highway onto the shoulder to reload sealant blocks inside the Sealzall kettle, this would be an opportune time to off-load the collected debris. The collected debris could be temporarily discharged off the right of way on exposed dirt sections for later pick up. The generated crack debris consists mainly of a combination of asphalt, small gravel and native soils, which in most cases will not present a hazard if temporally stored along the shoulder of the highway.

Figure 26. Vacuum Debris Off-Loading (Image courtesy of Vac-Tron)

Pavement debris vacuum systems are generally configured with the debris collection container mounted longitudinally and the dump hatch opening toward the rear (Figure 26). To empty the vacuum container, the dump hatch is opened, and the container tilted up to dump the debris out the opening. This configuration would often prove to be problematic for the router cleaning machine because the Sealzall and thereby router cleaning machines would ordinarily be kept on or near the highway shoulder during dumping due to limited shoulder space and soft shoulder conditions. Consequently, maneuvering the dump hatch off the side of the highway to dump off the highway shoulder would be problematic.

The Vac-Tron company has developed a remote debris tank option, which mitigates these potential off-highway debris dumping issues (Figure 27). Depending on the specific configuration of a future fabrication phase of the router cleaning machine development, the Vac-Tron remote collection tank may serve as a model to design the router cleaning machine debris dumping design.

Figure 27. Vac-Tron Vacuum System with a Remote Collection Tank (Images Courtesy of Vac-Tron Equipment)

Crack Cleaning Vacuum Unit Selection

Several manufacturers offer vacuum excavation units, which are similar in performance and would easily support the router cleaning machine. The selection of a unit will be dependent on the specifics of the router cleaning machine configuration, which would be determined in a subsequent fabrication phase of the equipment development.

Strawman Auto Guidance Concept

Impact router freewheeling carbide star cutters are intended to only cut into softer AC pavements and tend to wear out prematurely when in contact with the harder PCC pavements. Therefore, the precise tracking of the router cutter along the PCC slab close enough to clean the joint crack, but at a safe enough distance to minimize the possibility of frequent incidental contact with the PCC edge is essential. The router enclosure obstructs any possibility of a direct view of the impact cutters, and the substantial size and generated forces of the router cutter limits the mounting of the routing device to the truck bed area behind the truck cab. Consequently, a camera system will be a common element in all of the potential guidance schemes taken under consideration. Due to the size of the router mechanism, a camera can be mounted to capture an image ahead of the router or behind it, but a single camera will not be able to image both areas simultaneously. The camera and view ahead of the router will be referred to henceforth in this report as the "Leading-view" while the camera and image of the area trailing the router will be will be referred to as "Trailing-view". As related to the crack cleaning application, the major difference between the content of these images is that in the Leading-view image the joint crack presumably filled with debris while in the Trailing-view image the crack is ostensibly cleaned. This is an important distinction when taking into consideration the necessary slab edge tracking precision and the probability that the crack debris and vegetation will obscure the slab edge.

Guidance Control Schemes

The logical approach to utilizing cameras to track a path while moving is to focus on the Leading-view image because it directly represents the path to follow. For the crack cleaning application, the practical reality is that the approaching joint crack is usually filled with debris and vegetation that conceals the sharp distinction between the mostly white PCC slab and the gray/black AC shoulder. In addition, a clear division between the different pavements can be further hidden by old sealant, paint stripe, raised pavement markers, and AC slurry fog seal overspray. Another problem with the Leading-view image is that the router enclosure creates a large blind spot obscuring everything within approximately one and a half feet of the router cutter (Figure 28). An alternative guidance approach capitalizes on the fact that once the machine is properly aligned, the joint crack in the Trailing-view image is clean, thereby exposing the PCC slab edge and making identification more effective. The Trailing-view image is subject to the same router blind spot issue as the Leading-view image, but starting with more accurate edge identification translates into corresponding improvements in router tracking accuracy.

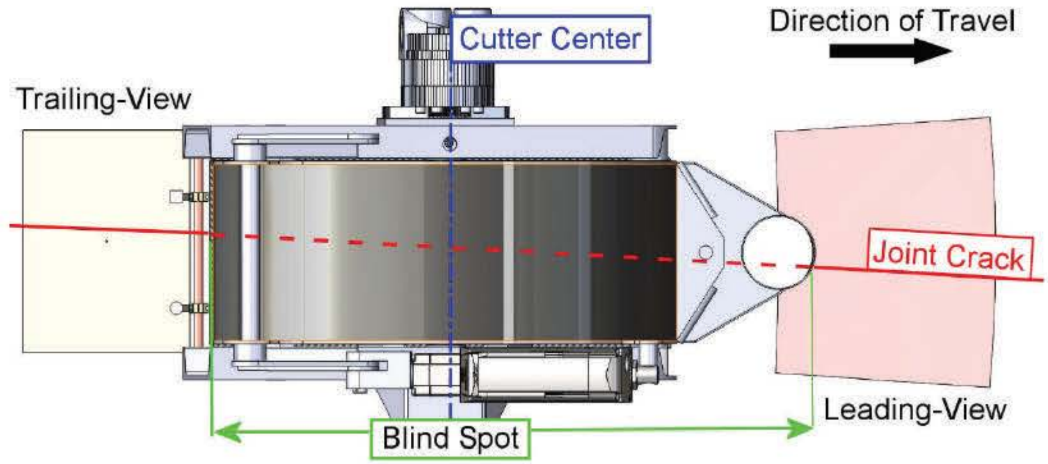

Figure 28. Camera Image Blind Spot

Accounting for the blind spot is a common issue regardless of which guidance scheme is under consideration. Since vehicle steering is the lone link between the position of the longitudinal joint crack and the vehicle, significant lateral drift could occur while passing through the image blind spot. A logical mitigation for the blind spot would be to connect a path between the Leading-view and Trailing-view camera images, but this approach becomes problematic as well when considering the obscured Leading-view image and the utility involved in connecting the images for tracking purposes. Another mitigation method utilizes a single image, preferably the more accurate Trailing-view image to project the crack path though the blind spot. Since the PCC slab edge is inherently straight, the location of the router is relatively predictable if combined with a means of extrapolating the path. There are three logical strategies to project the joint crack path through the blind spot and determine the spot where the router cutter must be placed to remain adjacent to the PCC slab edge. Potential guidance schemes appropriate for the crack cleaning machine range from a basic manual tracking method to a sophisticated fully automated tracking method with a semi-automated tracking method rated somewhere in between the two in its level of complexity.

Manual Scheme: A manual tracking scheme was initially considered to be a valid strategy with popular appeal by the Caltrans TAG. The tracking scheme involved a worker in the vehicle watching a live Leading-view video image of the longitudinal joint crack and directly controlling the router position (Figure 29). An indicator on the live crack video image would indicate the current position of the cutters, and the worker would jog one degree of freedom on a joystick controller to move both the indicator and cutter head laterally to the desired position. This is certainly the most basic control scheme possible and, on the surface, seems feasible. However, when applied to the crack cleaning machine, the manual tracking scheme proves to be a tedious task requiring a person to continuously focus and react. The guiding image must have enough resolution to guide a point on the screen to within half an inch of the joint crack, so the image is focused down to an order of magnitude greater than the resolution (approximately 6 inches). Within this small field of view, the video image of the joint crack is moving at 3 mph or 53 in/sec. At this rate of speed, even small changes in joint crack positions are very difficult for a human brain to process and uncomfortable for a person to follow with a cursor. An example video with the appropriate image magnification was recorded of a worker trying to follow a clean joint crack with a pointer at 3 mph. This video presented what the image would look like to follow a clean joint crack at 3 mph and shown to the Caltrans TAG. Upon viewing the sample video, the Caltrans TAG reaction was to direct a change of direction toward a more automated guidance approach.

Semi-Auto Guidance Scheme: The semi-automated (Semi-Auto) guidance scheme combines automated tracking capabilities with supervisory control. This scheme involves both a Leading-view and Trailing-view video image. The automated tracking feature processes only the Trailing-view image to identify the clean joint crack and provide automated tracking, while the system operator focuses primarily on the approaching joint crack in the Leading-view image. The basic principles of the semi-auto scheme are that the slab edge is generally straight and high-speed tracking can only occur under automated tracking control. When incongruities in the slab edge are encountered, the supervisory control is the means at which the router can be manually navigated through these incongruities at a much-reduced speed. The driver in the semi-automated scheme is only required to steer the vehicle nominally along the longitudinal joint crack. The lateral actuator provides the precise router tracking control necessary to limit contact with the PCC slab. The system operator determines the most appropriate source of lateral actuator control and switches between manual and automated tracking control during operation. So where problems with the PCC incongruities exist, the driver will (presumably) observe the problem and slow down to allow the system operator to disengage the semi-automatic guidance system in favor of the manual system. After passing the localized issue, the semi-auto system will be re-engaged.

Once the system has processed the Trailing-view image to identify the PCC slab edge and is outputting a projected router tracking path, the system operator can switch to automated guidance mode and a controller will track the router autonomously. To generate the automated lateral guidance positioning control, the Trailing-view image is digitally processed with an edge detection algorithm to identify the PCC slab edge accurately and calculate a projected lateral router position, which will henceforth be referred to as "Semi-Auto Tracking" in this report. The cutter head moves laterally to the commanded position to follow the joint crack (Figure 30). The theory being that the routed crack is easier to follow, and the PCC slabs are generally straight. The system operator can supervise the auto guidance and override it by moving the lateral joystick if necessary. The system operator would also have the task of starting the routing as well as initially creating enough routed joint/crack so the auto guidance can lock on. An image processing system and logic controller would need to be developed for this approach. Image processing techniques are only applied to the trailing camera in order to create automated tracking capabilities.

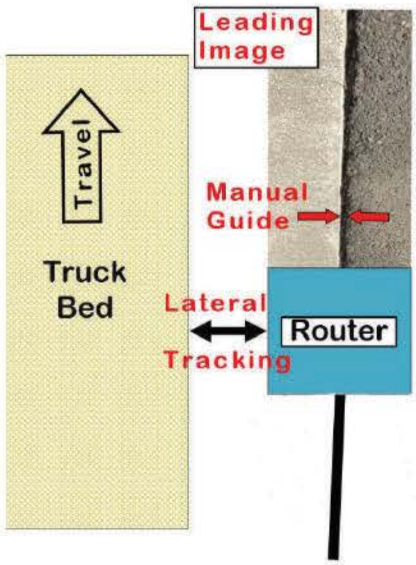

Figure 29. Manual Guidance

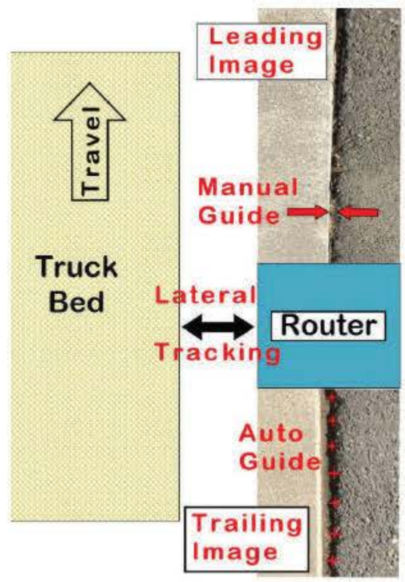

Figure 30. Semi-Auto Guidance

Full-Auto Scheme: A third guidance scheme is fully automated (Full-Auto), which eliminates the manual guidance component altogether by digitally processing both the Leading-view and the Trailing-view image to generate two separate joint crack tracking position locations (Figure 31). Establishing the joint crack location position both ahead of the router and the other behind the router eliminates the reliance on extrapolation to guide the router cutter. Since the two joint crack location points straddle the cutter, a straight geometric line could be projected between the points creating a more accurate predicted cutter position and enhancing the overall accuracy of the guidance scheme. There are many application issues to be resolved and a sophisticated logic algorithm would need to be developed to resolve and consolidate the different data inputs. In theory, the Full-Auto controller would provide the bulk of the router guidance task. The system operator will have to monitor the approaching joint crack and override capability should the joint crack become completely obscured, and the digital image processing fails to identify the PCC edge. The manual override control would be a far slower speed than the automatic guidance control system could support.

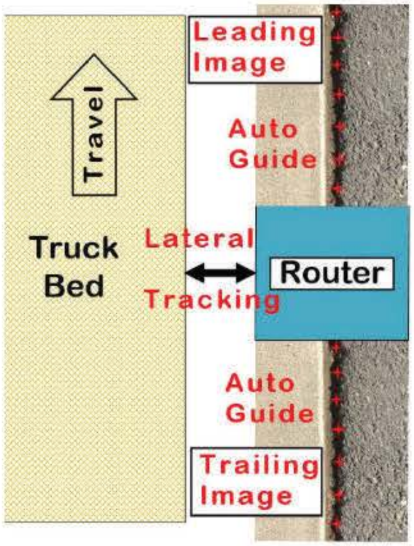

Figure 31. Full Auto Guidance

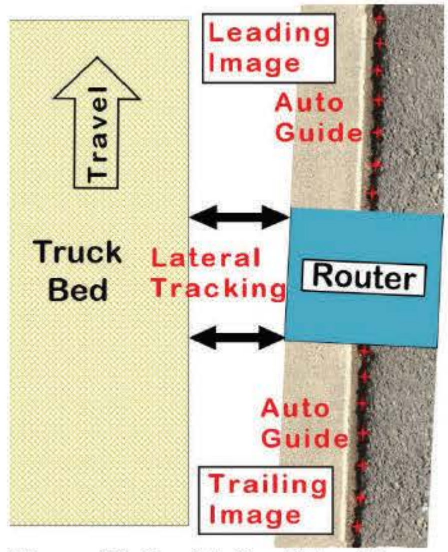

Figure 32. Dual Lateral Tracking

Lateral Orientation: The mechanics of the impact star wheel router enables the cutter wheel to cut the pavement independent of orientation, even sideways. Since a router can run efficiently at slight angles to the joint crack while in operation, the addition of a second lateral degree of freedom to angle the router to ensure it runs parallel to the joint crack is not a necessity. When considering the Auto tracking scheme, the addition of a second lateral actuator may be a worthwhile consideration to orientate the router parallel with the joint crack and potentially improve tracking accuracy (Figure 32).

Vehicle Positioning Assist: The travel distance of the lateral actuator tracking the router from the side of the vehicle needs to be relatively short and compact to enable the routing mounting mechanism to be compact enough to fit under the truck bed. The shorter the lateral travel the more accurately the vehicle platform needs to be steered along the joint crack. Since the driver will not have a direct view of the joint crack from either side of the vehicle and the router will be mounted behind the cab, some type of steering reference must be supplied to the driver. A simple method may be to provide the driver a view of the Leading Image on either a heads-up display or perhaps a wearable display like a Google Glass Explorer Unit. An additional video image may prove to be necessary should the Leading Image not be pointed far enough down the highway to assist the driver in visualizing a continuous steering path. Another method may be to display an offset distance provided by either the Leading or Trailing video images. The offset display could be as simple as a series of light emitting diode (LED) indicators mounted in a row in a heads-up display. The further the vehicle strays from the joint crack either left or right, the more LED's illuminate to indicate to the driver to steer in the direction to reduce the number of illuminated LED indicators.

Figure 33. Left Side View from Cab

Figure 34. Right Side View from Cab

Strawman Semi-Auto Guidance Scheme

The three generic forms of guidance schemes described above were presented to the Caltrans TAG along with a video demonstration of what the system operator would see in a purely visual guidance scheme image traveling at 2-3 mph. The TAG concluded that either a solely visual guidance scheme, or a fully automated guidance would not be acceptable. The Caltrans TAG advised pursuing a semi-automated type of guidance scheme with the exact details to be formalized during development. Therefore, the router cleaning machine strawman concept will be designed based on a form of a semi-automated guidance scheme. An added advantage of the Semi-Auto guidance scheme is that it supports the development of both the manual guidance and the automated guidance capabilities and enables each of these guidance styles to be tested on actual highway joint cracks. This way the system operator will have the flexibility to operate both and to develop an operational balance, which provides the best possible guidance precision for a variety of joint crack conditions on the highway.

System Operator Dependent Tracking Capability: The strawman Semi-Auto guidance scheme will depend heavily on the system operator's ability to directly control the router position based on visual information. Since the system operator will have a minimal view of the joint crack and no direct view of the cutter head, a camera system capable of producing a high-quality image of the joint crack is essential. The Leading-view image will be useful information for the system operator to initiate the router and to guide the router manually where the PCC slab edge has incongruities. The driver would likely depend on this image as well to steer the vehicle along the joint crack. A target pointer will be displayed on the Leading-view image, which indicates the approximate lateral position of the router cutters.

In operation, the driver would likely steer the vehicle to place the joint crack near the center of the Leading Image and stop. Then, the system operator using the joystick control would manually position the router over the joint crack by referencing the target pointer on the Leading Image. The system operator would then lower the router cutter and the driver would slowly move the vehicle forward to route the joint crack. The system operator may want to make minor adjustments to the router position as the vehicle moves ahead. Once the clean joint crack appears in the Trailing-view image and the PCC slab edge is identified by the digital processing system, the system operator can switch to autonomous tracking. In rare occurrences, the system operator may encounter a jog in the PCC slab edge ahead of the router while in the autonomous tracking mode. To navigate the jog, the driver would reduce the vehicle's speed, and the system operator would manually control the router tracking by using the joystick controller to guide the router through the area of incongruity. Impact routers can cut AC pavement laterally, which supports lateral tracking functionality. Once the straight edge reappears in the Trailing-view image and the digital processing system recognizes an edge, the autonomous tracking control can be reengaged by the system operator, and the driver can accelerate the vehicle back up to 3 mph.

Autonomous Tracking Capability: The digital image processing of the Trailing-view image will provide the input to the edge detection algorithm, which will plot points along the AC/PCC pavement transition. The data points and an offset value will be used to extrapolate a lateral position, which an offset value will be added to determine the commanded position for the router cutter. The lateral actuator will be moved to the commanded lateral position. This process will be repeated many times a minute to produce an autonomous routing tracking system. Potential future developments may include projecting the extrapolated autonomous path directly onto the Leading-view image for additional information for the system operator to consider. Therefore, should the autonomous plotted path appear to diverge from the visual cue, the driver can slow the vehicle, and then the system operator can manually control the router tracking until the autonomous projected path centers back onto the joint crack. In this way the system operator can supervise the autonomous tracking system and provide an extra level of tracking precision.

Chapter 4: Detailed Mechanical Design

The strawman concepts presented in the preceding section were presented to the Caltrans project advisory panel. The panel in general endorsed the strawman concept and selected the semi-auto guidance scheme for further development. Several of the major components, such as the vacuum and truck platform, can be utilized with minimal adaptations based on a variety of commercially available options. The panel agreed that components that afford flexibility, like the selection of a vehicle configuration and vacuum system, are to be decided later in a potential future fabrication phase. Therefore, these components will not be developed further than the strawman concept phase in this report. Other major router cleaning machine components, such as the impact router, require adaptation from common equipment designs. This adaptation requires a performance evaluation of the standard equipment and a redesign to accomplish the required functionality. Other components such as the guidance system are original equipment developments and will need to be entirely custom built utilizing associated technologies whenever possible. The detailed development process of the cutter head, lateral tracking components will be developed together mainly in the first phase of this project while the guidance system will be developed and demonstrated primarily in the second phase.

Impact Cutter Head Optimization Testing

Impact router cutting is the predominant means of preparing AC pavement cracks for sealing in the northern regions of the United States and much of Canada for many years. Several manufactures offer similar versions of self-contained manual types of impact router machines, all based on the same basic design that has changed little over time. A search for published studies and patent claims associated to the impact cutting process have revealed little about the basic mechanics of impact cutting or the factors necessary to effectively achieve cutting efficiency. Conventional impact router equipment shares a set of common design parameters, which is suspected to have been developed empirically in the field over time. A detailed study of the impact cutting process must be conducted to determine which design parameters need to be changed and which are important to maintain for optimizing the routing head's capability of achieving the goal of nearly doubling the conventional routing speed. The evaluation of these impact cutter specifics will be used to enhance the detailed design and development of the crack cleaning router.

Specific impact router characteristics that need to be evaluated include:

- Efficient flywheel rotational speed

- Maximum feed rate
- Rotational speed / Feed rate interdependency
- Star cutter arbor diameter clearance
- Star cutter side clearance
- Resultant cutting forces
- Stabilizing forces
- Drive motor power

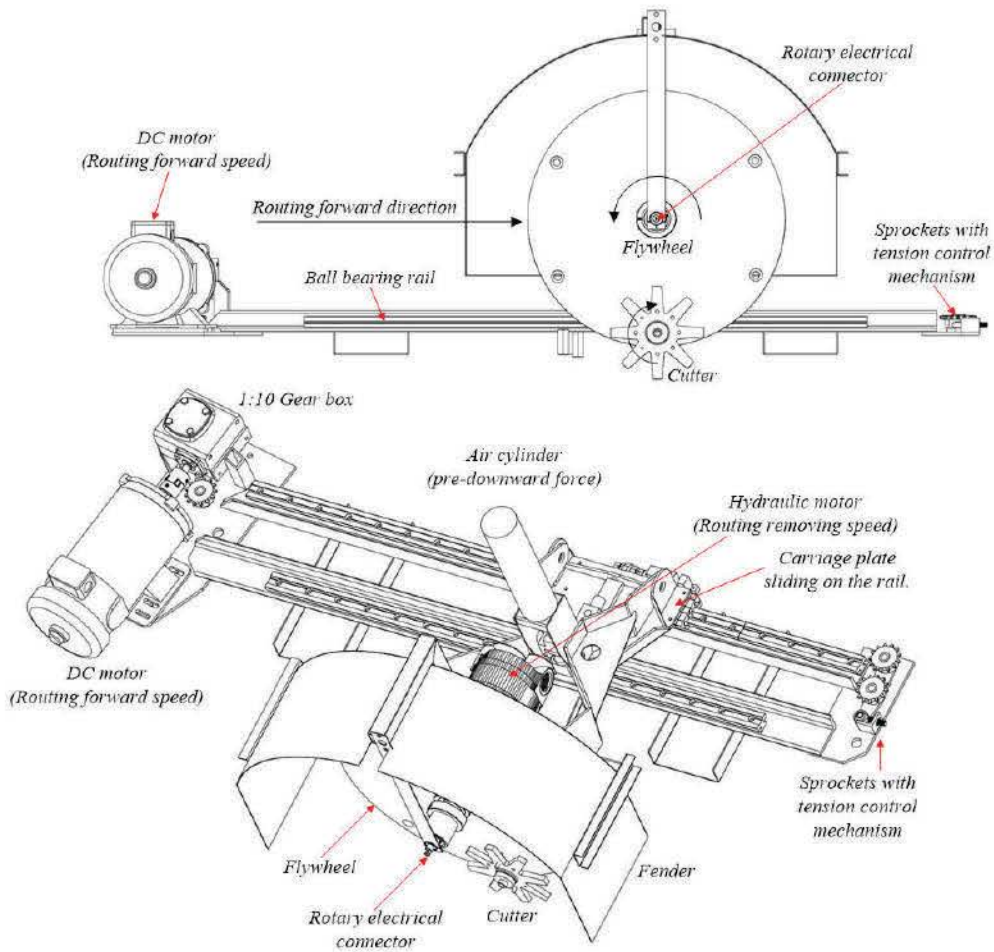

Figure 35. Router Test device

Router Test Device

A router test device was developed as a means of evaluating the fundamental impact router cutting characteristics necessary for the design of the high production crack cleaning router (Figure 35). The device is capable of measuring cutting forces while varying key cutting parameters, such as rotational and surface speeds, to optimize cutting efficiency. The design of the test router is very different from the design of the crack cleaning router. The test device's sole purpose is to control, isolate, and measure all the key driving and resulting cutting forces associated with the process of freewheeling the impact cutting of AC pavements. The crack cleaning router design is considerably more stout and compact than the router test device, but does not provide the prospect for either force isolation or measuring point locations. Since the test device is not nearly as robust as the crack cleaning router, the testing will be conducted with only a single cutter. Conventional impact routers typically have six-star cutters mounted on the flywheel. These freewheeling cutters are staggered laterally on the arbor pins to create the desired width. The cutter testing in this study will be conducted with only a single cutter, thereby reducing the force magnitude and speeds to one sixth of the full device. In this way, star cutting efficiencies can be determined by comparison and contrast without having to deal with the full force and speeds of impact routing.

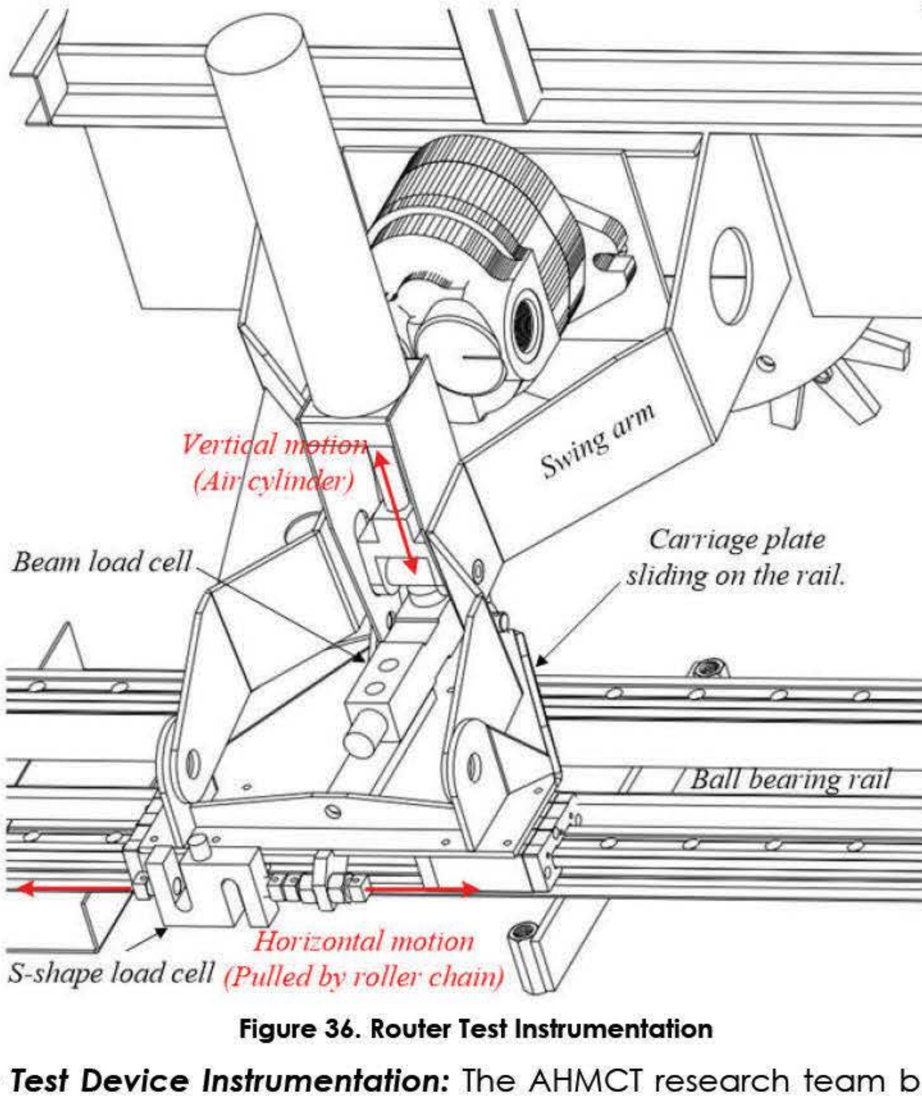

Figure 36. Router Test Instrumentation

Router Test Device Instrumentation: The AHMCT research team built a router test device, which was heavily instrumented and capable of measuring cutting forces while varying key cutting parameters, such as rotational and surface speeds, to optimize cutting efficiency (Figure 36). The sensor package on the router test device consists of a beam and S shape load cell, which measure the reaction cutting forces. Two magnetic proximity switches calculate the feed rate and the star cutter spin rate. All these signals were recorded as analog and digital data by two Data Acquisition (DAQ) instruments during pavement cutting tests. Testing with the test router device will be key in determining the optimum impact cutting parameters required to achieve the goal of increasing the routing cutting speed up to the needed 3 mph speed to support moving lane closure operations with the Sealzall machine. The router test device and hydraulic power unit were then mounted to the forks of the AHMCT forklift truck, which serves as a stable base for the test device. The forklift mounting also provides a means of accessing actual AC roadway pavements for cutting tests and enables the complete system to be easily transported out to the Advanced Transportation Infrastructure Research Center (ATIRC) asphalt track to conduct operational testing.

Detailed Router Attachment Design

The router designed for the crack cleaning attachment will be based on many of the common aspects of a conventional manual impact router design, which has been evolving for over thirty years. The general layout of the cutter head design is similar to conventional impact router equipment, but enlarged to accommodate the larger diameter deep cutting star cutter blades. The increase in production rate of the revised cutter head will be accounted for in the control of the routing head and not with any significant changes to the cutting head. The use of a truck platform to drive the cutter head provides the gains in power and control necessary to nearly double the routing speed of conventional manual impact routers. The router cleaning machine design parameters necessitate that crack cleaning operations can be conducted on both the left and right side of the vehicle. Since the router cutting head is not symmetrical, for a variety of factors, it cannot be simply swapped from one side to the other. Therefore, a left and right-hand version of the router device will be necessary. Only one of these routing heads will operate at a time, so all the router power and support systems are sized to support a single head in operation. The underdeck router mounting mechanism will also need to be duplicated and mirrored on both sides of the vehicle.

Routing Attachment Cutter Head Assembly

The conventional router cutting head assembly (Figure 37) design had to be adapted to support a vehicle-based, high-production longitudinal joint crack cleaning operation. The revised router design includes significant modifications to the cutter flywheel, swing arm, and router enclosure to deliver higher feed rates and be compact enough to operate ideally in the space outside of the chassis rails and under the flat bed of a standard truck. One of the modifications to accomplish this goal was to switch from the conventional engine and pulley system uniformly found on manual pavement routers to a simpler direct drive hydraulic gear motor. The output shaft of the hydraulic gear motor was inserted and keyed inside the end of the drive shaft, which is in-turn nested into the cutting flywheel. With the cutter flywheel driven in-line, the cutting depth adjustment was redesigned to be internal to the routing head. This is unlike conventional manual impact router designs, which rely on a linkage connected to the support wheels to raise and lower the router off the pavement (Figure 38). The revised router design utilizes a swing arm linkage to raise and lower the cutter flywheel inside the static router enclosure, which helps to manage the vacuum flow though the enclosure when against the pavement surface. A static router enclosure improves worker safety and benefits the debris and dust collection scheme. The revised router enclosure was designed to be completely enclosed to capture and contain all the debris and dust generated by the cutter. Conventional routers have open enclosures to provide a worker an unobstructed view of the cutting patch to guide the router along the crack.

Figure 37. Conventional Router Engine Drivetrain and Encasement

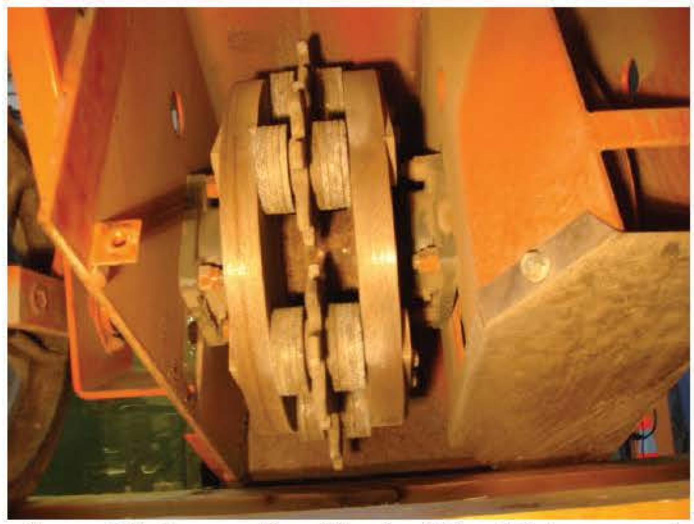

Figure 38. Conventional Router Wheel Linkage and Cutter Flywheel

Router Attachment Flywheel Assembly: A flywheel cutter assembly is a universal feature inherent to all types of impact router equipment. Other than slight size differences, the many rudimentary design aspects of the flywheel remain unchanged in the design developed here (Figure 39). It is comprised of two parallel thick steel circular plates of equal size welded to a common center hub. Matched holes in the two plates enable cross pins to support the freewheeling star cutters. The flywheel is subjected to tremendous vibrational impact forces while cutting, so the geometry and materials of the flywheel and fasteners are specifically selected to withstand prolonged exposure to this extreme loading condition.

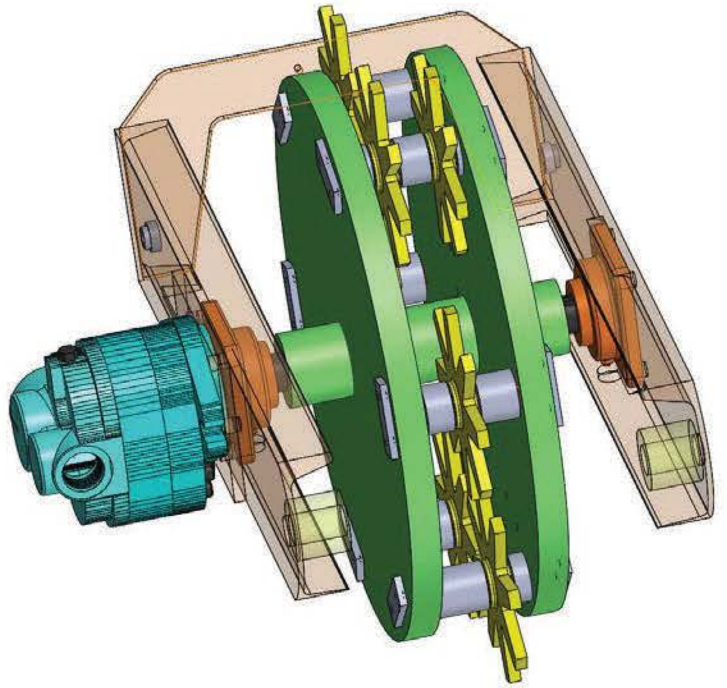

Figure 39. Router Attachment Flywheel Cutter Assembly

The star cutters can be arranged laterally on the flywheel cross pins to produce different width cuts. The six carbide tipped cutting fingers found on standard star cutters are ½" wide at the tip. Arranged at the widest spacing with two extra cutters, the maximum cutting width that can be attained is 2¼" (Figure 40). The most popular cutting widths are ¾" to 1" wide for the square channel profile, which is almost exclusively utilized when routing in-lane random cracks. Longitudinal AC/PCC joint cracks' routing typically favor a low-profile cutting width range of 1½" to 1¾" wide with a shallow cut depth of ½" deep or less. The rout width is driven by crack sealing best practices regarding shape factor and the geometry of longitudinal joint cracks. Conventional routers utilize bunches of thin steel washers added to the cross pins to position the cutters at the desired spacing. The revised router flywheel will switch to thick steel washes, which will be color coded, to expedite star cutter width alignment. To change star cutters or the cutting width, cross pin retainer blocks are unbolted from the side of the flywheel and the pins removed to free the star cutter and spacers.

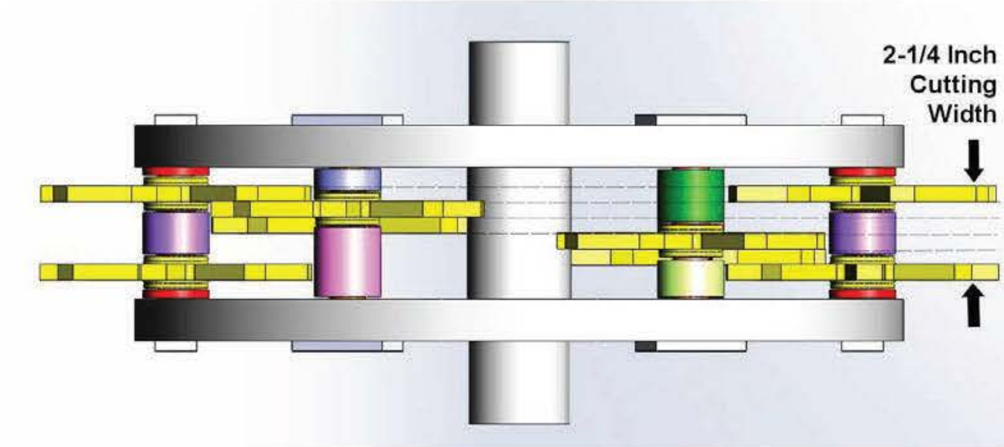

Figure 40. Staggering Star Cutters for Maximum Width

Router Attachment Depth Adjustment - Swing Arm Assembly: Conventional routers contain support wheels attached to twin linkages driven by an electric motor linear actuator that raises and lowers the wheels, thereby controlling the routing depth. This arrangement creates a gap between the encasement and the pavement providing scant control of ejected dust and debris. Since a worker operating a conventional router needs to maintain a direct line of sight to the cutter impact area to track the crack, the router encasement must be open at least on the side facing the worker. Cutter depth adjustment by raising the wheels is suitable for conventional router enclosures, which are inherently open. Since the router cleaning machine router is vehicle-mounted with a remote guidance scheme, the router encasement can be fully enclosed. The router attachment design employs a swing arm weldment and twin linkages to create the vertical motion of the router cutter flywheel inside the router encasement (Figure 41). The swing arm assembly attaches to the router encasement at three points including the fixed pivot end of the swing arms, a lateral rotation pin connecting the twin linkages and the base swivel of an electric motor linear actuator that drives the twin four bar linkages. The four bar linkages are designed such that the load line is nearly straight at full depth, thereby locking the linkage and shielding the linear actuator from much of the vibrational impact loading generated by impact cutting. The hydraulic drive motor is bolted to one of the swing arms aligned with the standard NEMA C-Face adapter plate welded to the outside surface of the swing arm. The hydraulic drive motor is keyed directly into the end of a steel drive shaft, which extends through two mounted spherical bearings attached to the inside surface of both swing arms. The flywheel assembly is attached between the bearings on the drive shaft.

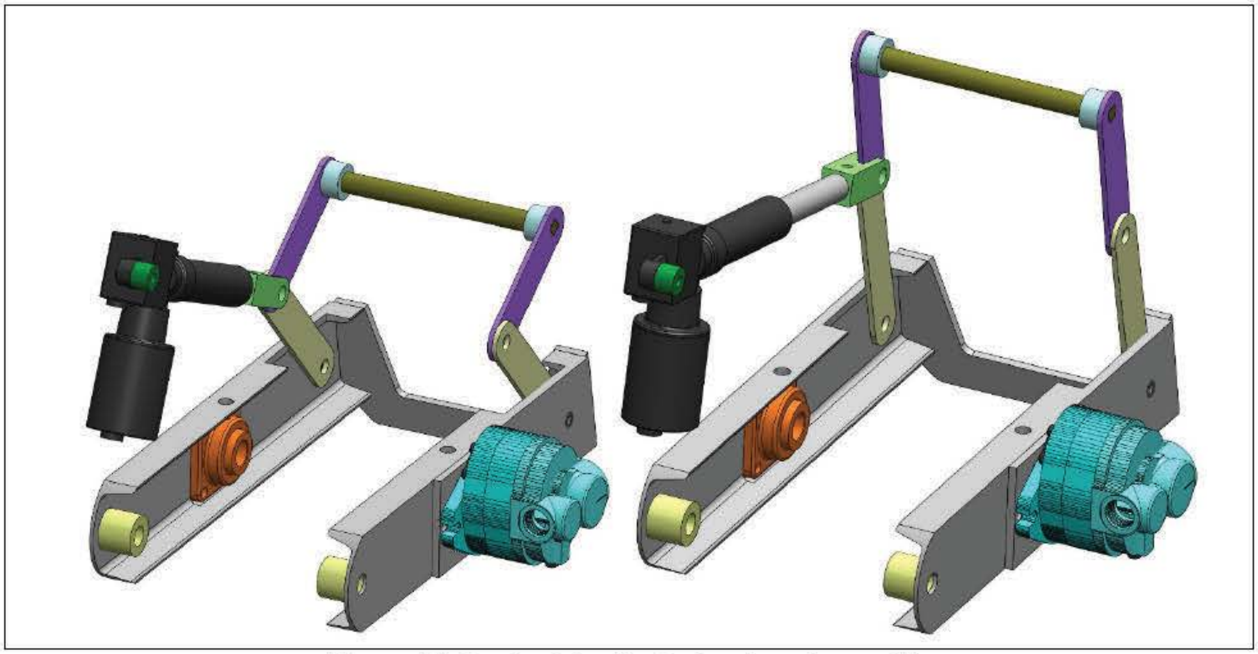

Figure 41. Revised Router Swing Arm Assembly

Router Attachment Encasement: The primary goal of the revised router encasement design was to establish full containment of the large amount of dust and debris generated by impact cutting joint cracks. Conventional manual routing operations are conducted exclusively in stationary lane closures on the highway. In a closed lane, a generated dust cloud does not present much of a hazard to passing traffic separated a lane width away. Since the router cleaning machine when operating in moving lane closures is only a few feet away from passing traffic, a dust cloud would be viewed by approaching motorists as a formidable obstacle to avoid. The switch to a static router encasement for the revised router design enables a more functional seal between the encasement and the pavement surface to be maintained while cutting. The vacuum system inlet port is deliberately located on the lower leading edge on the encasement in the general area where solid debris would normally strike the inside of the encasement. This allows debris and dust to flow directly out of the encasement minimizing the amount of internal debris rebounding and improving collection efficiency. The air inlets necessary to support the air flow to the vacuum enters through the two slots on either side of the encasement where the flywheel drive shaft passes through. A wire brush strip skirt surrounds the router encasement and extends down to the pavement forming a compliant seal, which accounts for the inherent pavement unevenness that commonly exists in the transition between the dissimilar pavement types. The collection chute of the router encasement is in the lower lead surface of the router enclosure where ejected debris is most likely to be directed.

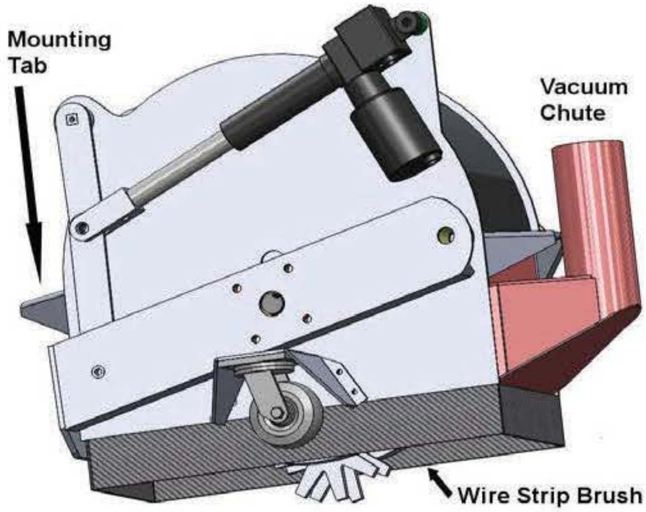

Figure 42. Revised Router Encasement

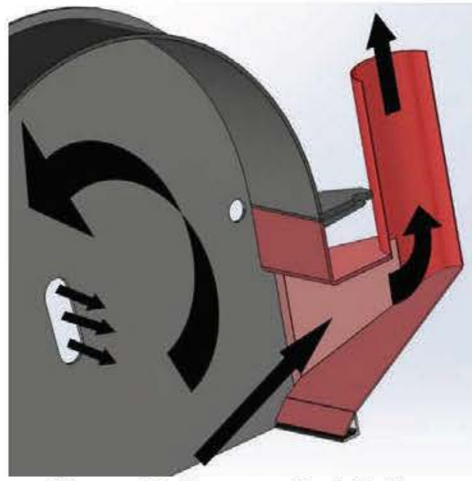

Figure 43. Vacuum Debris Flow

Routing Attachment Vehicle Mounting

To support the project goal of moving lane closure operations on the highway, the router vehicle mounting design must be capable of both securely holding the router cutting head alongside the vehicle during operation and enable the router to safely retract inside the confines of the vehicle for transport. While deployed, the mounting must provide a means of translating the cutting head laterally to track the longitudinal joint crack. Ideally, the vehicle mounting would also enable the router to be deployed and retracted remotely from inside the cab to reduce worker exposure to traffic. The router attachment for the router cleaning machine is intended to be a bolt-on accessory as much as possible. The vehicle platform would ideally be a flatbed body permanently fastened to an appropriately sized truck chassis. The router frame would be bolted to the underside of the flatbed requiring only a few holes to be drilled into the truck bed and no welding. There will be a right and left-hand version of the swing arm frame for one set to be mounted on each side of the vehicle. Therefore, a flatbed truck with enough clear space underdeck on both sides of the chassis to mount both router mechanisms is one of the few essential vehicle constraints. The routing head vehicle mounting consists of a mirrored pair of folding swing frames each attached to a lateral slide platform.

Router Swing Frame: The vehicle mounting for the revised router cutting head is designed to tuck up under the deck on the outside of the chassis frame rails for transport and swing out from under the flatbed truck deck and rigidly lock in place for crack cleaning operations. Each swing arm assembly is comprised of a pair of hydraulically actuated two position three bar linkages, which form a rigid planer frame. Both swing arm assemblies are connected to a common base plate and operate in unison to control the position of the routing head. When the two hydraulic cylinders that drive the swing arm assembly are extended, the swing arms lock into an operational configuration (Figure 44). The upper cylinder presses the vertical member against the brace plate and a brace pin on the vertical member inserts into the side support tab to resist bending forces normal to the action plane (Figure 45). This longitudinal force is what drives the router forward while cutting. The horizontal member applies a downward force on the router cutting head to resist the router cutting head from riding up on the pavement and bouncing while cutting. The downward force is generated by the lower hydraulic cylinder with a proportional valve providing variable control either manually or automatically by the system controller.

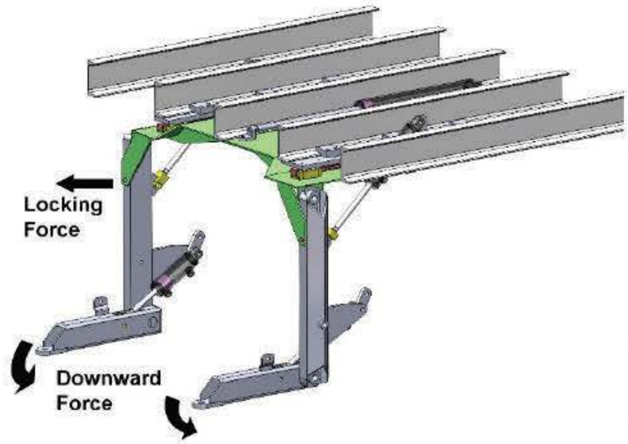

Figure 44. Router Swing Frame - Deployed

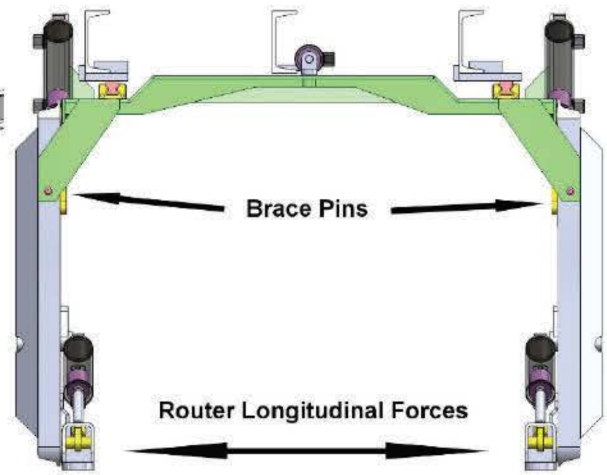

Figure 45. Swing Mounting Side Forces

Reversing the hydraulic cylinders retracts the swing frame bringing the router up and under the truck bed. The movement of each pair of lower and upper cylinders are coupled with the hydraulic spool-type flow divider synchronizing circuit. The movement of each pair of cylinders to extend and retract will be more efficient if programed in a coordinated motion profile, providing the system operator a basic two-position selector control. In the retracted position, the router is lifted and tilted toward the outside of the truck to provide simple access to the flywheel to replace worn star cutters or change the cutter configuration to obtain a desired cut width. The swing frame can be locked in the retracted position by inserting four locking pins as a fail-safe measure when accessing the retracted router or during transport.

Lateral Slide Platform: The lateral slide platform serves as the active connection point between the router and truck bed for the router cleaning machine (Figure 46). The assembly bolts to the underside of the flatbed cross rails and provides 14 inches of controllable lateral travel to support longitudinal joint crack tracking control. The slide plate lateral slide was designed with a 14" stroke hydraulic actuator. A hydraulic actuator was selected over a planetary roller high-force electronic ball screw actuator because an HPU is already required for the router drive motor.

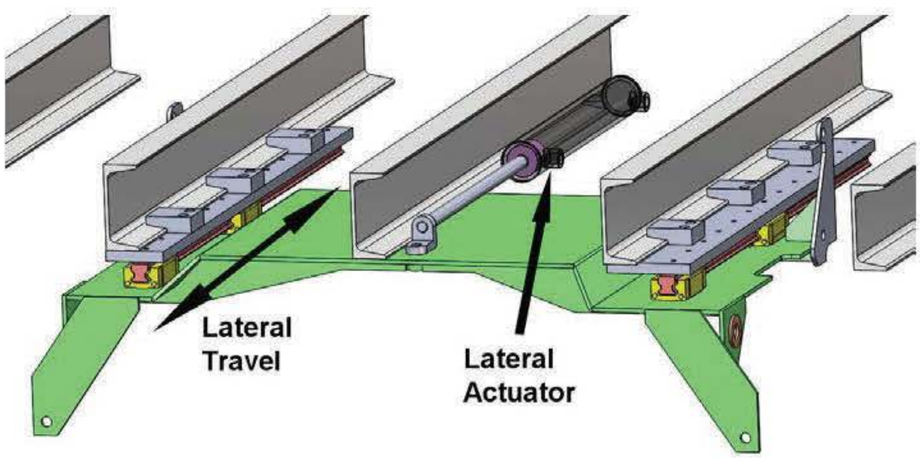

Figure 46. Lateral Slide Platform

Router Enclosure Vacuum Connection

The router enclosure design was refined to include an integrated vacuum chute and wire brush skirt. Since the router cleaning machine is intended to be operated in moving lane closures on the highway, all dust and debris generated must be collected and contained. The router enclosure is the collection point of the vacuum recovery system. The vacuum inlet requires enough air flow into the router enclosure, which would naturally act to contain the dust cloud created by the cutter. However, the heavier bits of debris are less affected by the vacuum flow. To aid in the collection of heavier debris bits, the vacuum inlet is placed in the trajectory path of the cutting discharge to directly capture and remove the heavier debris. Sealing the interface between the pavement surface and the router enclosure is a compliant wire brush strip, which allows for a small amount of vacuum flow to permeate but acts to contain loose debris until it can be vacuumed up.

Chapter 5: Detailed Semi-Automated Guidance System Development

The strawman semi-automated tracking scheme presented previously was determined to be the most efficient and effective means of guiding the router cutter head along a highway longitudinal joint crack. The specific operational characteristics necessary for semi-automated PCC slab edge tracking are unique, which necessitated its custom development. The main function of the tracking system is to provide a reliable and accurate means of positioning the router cutters close along the PCC slab edge while minimizing any direct contact with it. Accomplishing this task was further complicated by the absence of a direct view of the cutting area, the high rate of travel speed and the joint crack being obscured by debris, vegetation and old sealant (Figure 47). The router cleaning head enclosure covers approximately a two-foot square area obstructing any possibility of a direct view of the local contact area of the router cutter contact area. The router enclosure is filled with dust and debris during operation, so obtaining a camera image inside is not feasible. Consequently, the adopted solution utilizes a remote camera to capture an image of the slab edge after it has been cleaned by the router and the PCC slab edge is clearly visible (Figure 48). Since the PCC slab edge is inherently straight, the identified edge can be reliably projected ahead to guide the router cutter.

Figure 47. Obscured Crack in Leading View

Figure 48. Routed Crack in Trailing View

The semi-automated tracking scheme developed for the longitudinal joint crack cleaning machine involves guiding the cutter head based on the exposed slab edge trailing the router (Figure 49). The tracking process begins by capturing a digital image of an area immediately trailing the router enclosure. Digitally processing the image with an edge detection algorithm identifies a straight-line path representing the slab edge. The tracking program then extrapolates the edge path to the router cutter and calculates an offset distance between the current router cutter position and the slab edge. This offset value is then converted into a commanded position that the lateral actuator moves the router to. A joystick controller is also required to provide the system operator manual lateral positional control to initiate tracking and to mitigate slab edge incongruities.

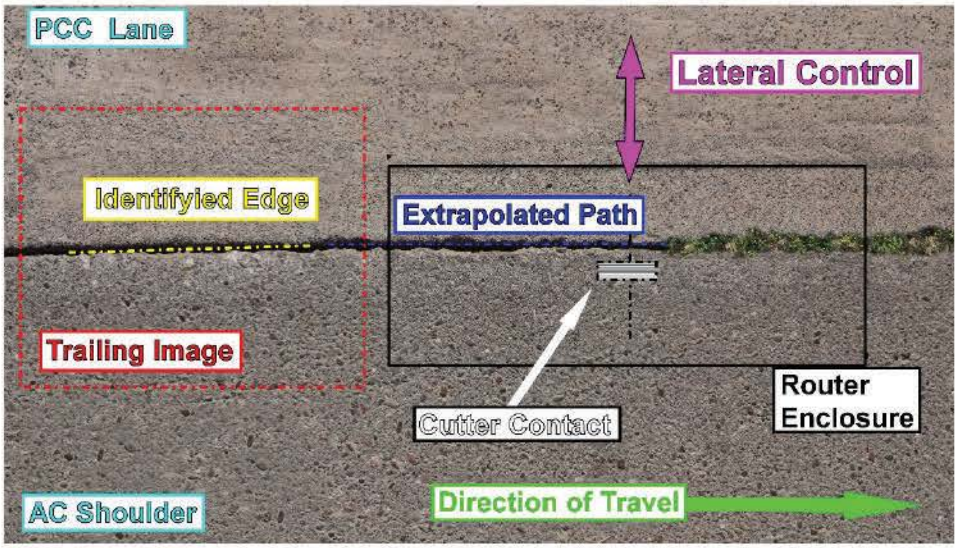

Figure 49. Semi-Automated Tracking Scheme

The detailed design of the router automated tracking system consisted of the development of four separate components, which were integrated together to be capable of independently positioning the router cutter along the edge of a PCC slab regardless of debris or surface obstructions. A supervisory control application was developed to handle the component integration and provide a proof of concept demonstration. The four components developed to accomplish this task include a pair of remote imaging cameras, an edge identification program, an edge path extrapolation program, and a lateral positioning component.

Remote Imaging Cameras

Leading-view Video Image Functionality

The Leading-view camera streams a video image of the longitudinal joint crack just ahead of the router. This image serves two purposes, first it assists the driver steering the vehicle in alignment with the joint crack and secondly, provides the system operator a live video image of the approaching longitudinal joint crack. The Leading-view image is streamed directly onto a cab-mounted thin film transistor (TFT) display screen for observation purposes only. At least initially, the

Leading-view image data will not pass through the control computer as a means of moderating computer hardware processing power requirements. The camera selected for this phase of the development is an InVid Tech Paramount security camera (Figure 50). This camera has 1080P HD quality image, motorized auto-focus telephoto lens with auto iris, and digital noise reduction. The Leading-view camera is mounted just above the Trailing-view camera, which is affixed to the end of the cantilevered arm providing an unobstructed view centered on the approaching longitudinal joint crack (Figure 51). The cantilevered arm is mounted directly to the truck bed, such that the Leading-view image frame of reference is fixed to the truck and does not travel laterally with the router.

Figure 50. Leading-view Camera

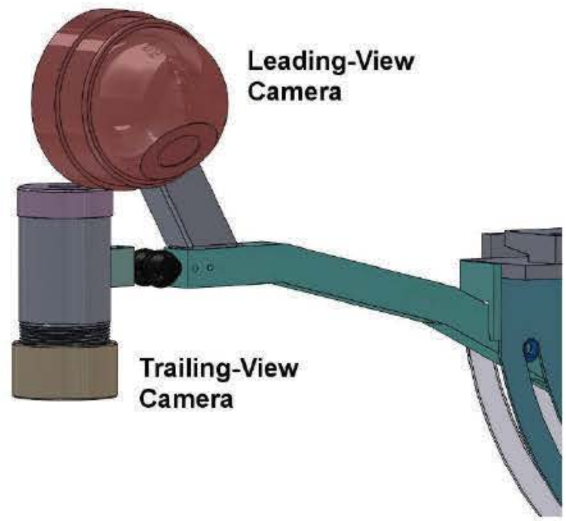

Figure 51. Tandem Camera Mount

Driver Steering Assist: Since the router operates off both sides of the vehicle and the truck cab obstructs much of the area adjacent to the vehicle, the prospect of providing the driver a direct line of sight view of the router is impractical. Some type of visual cue must be provided to the driver to facilitate the vehicle being steered along the longitudinal joint crack keeping the center of the router's lateral center of travel near the joint crack. The most basic pointer scheme would involve displaying a live video image from a remote camera in the truck cab. A cross-hair target could be attached to the display screen representing the center of the lateral actuation range. The cross hair could be either a digital representation or a physical mark on the image display. The router lateral travel distance should be enough to enable a driver to follow a cue simply by steering the vehicle while looking at a video display. However, relying on the driver to focus his or her attention on a display screen while driving in a moving lane closure on the highway may be viewed as unsafe. A possible mitigation might be to display the Leading-view image to the driver on a head-up type display or a wearable display such as Google Glass™.

An alternative but more complicated method of providing a visual cue to the driver would be to utilize the digital edge-tracking algorithm to display an indicator representing the lateral offset of the identified joint crack as related to the lateral position of the Trailing-view image. The machine controller could convert the lateral offset value into LED indicator lights on a head-up display bar. The larger the offset valve a larger the number of red LED indicator lights would be illuminated for both left and right sides of center. Center would be indicated by a single green LED indicator. The LED display is far less distractive to the driver because it requires less thought.

System Operator Preview: The Leading-view image will also be important for the system operator to have a preview of the joint crack to look for approaching irregularities in the PCC slab edge. Especially when the controller is autonomously tracking the joint crack, the system operator could be looking ahead in the Leading-view image watching jogs in the PCC slab edge, ramp merges, or bridge decks. When spotting such amoralities, the system operator could indicate to the driver when to slow the vehicle down. Then, the system operator can take manual control of the lateral actuation by simply moving the joystick off-center and steer the router through the incongruity with the proper manual actions.

Trailing-view Video Image Functionality

The Trailing-view image is taken from a fixed position centered over the middle of the lateral positioning travel distance at a height of approximately 40" and normal to the pavement surface (Figure 52). The Trailing-Image camera is mounted to the end of the tandem camera mounting, which is affixed to the truck body and therefore unaffected by the lateral travel of the router. The high-resolution Trailing-view camera will be enclosed in a specially designed protective aluminum weather tight housing to prevent physical damage from occurring to the camera in this exposed position.

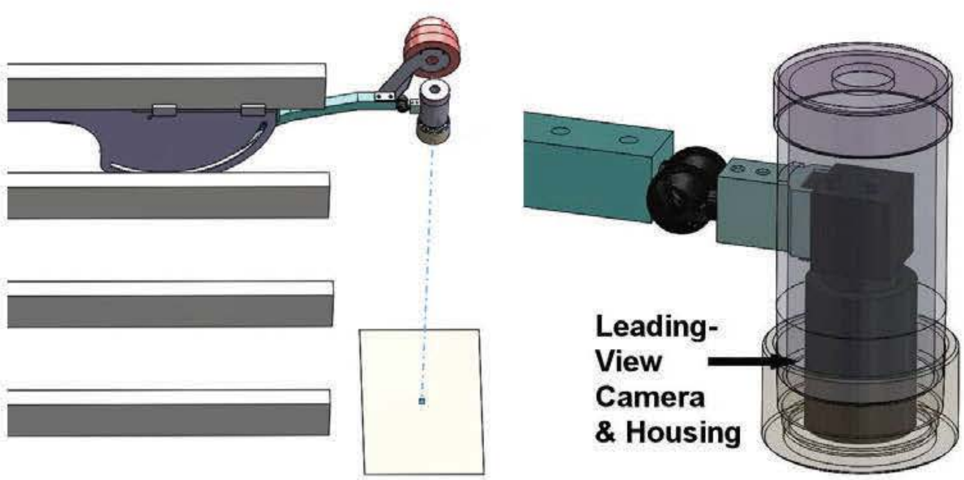

Figure 52. Trailing-view Camera Mounting and Housing

Camera Selection: The crack cleaning machine is expected to operate in moving traffic lane closures at continuous speeds up to 3 mph. Therefore, the

Trailing-view camera must be capable of capturing a high-quality image perpendicular to the pavement surface while moving at speed. A standard aperture shutter speed camera will typically smear the pixels at speeds of 3 mph resulting in a blurred image (Figure 53). For the cleaning machine application, a special machine vision camera with a variable high-speed shutter is necessary to mitigate the image blurriness issue. The camera selected for capturing the Trailing-view image is a relatively inexpensive machine vision FLIR Blackfly 52 frames/second CCD camera, which interfaces with the image processing computer via a fast GigE connection. The Blackfly has a software controllable high-speed shutter and an extensive open-source library of driver software to assist with the custom crack sealing machine integration. The Blackfly camera has an exposure range down to 0.019 ms, which based on initial tests, virtually eliminates pixel blurriness at the targeted 3 mph (Figure 54). Since the digital imaging program processes one image at a time, the program needs only to grab the most current high-resolution camera image available from a computer buffer, as needed. The Trailing-view camera is therefore configured to save a continuous stream of still images at a definable rate as opposed to a video format, which would necessitate some additional level of data compression and negatively affect the image resolution.

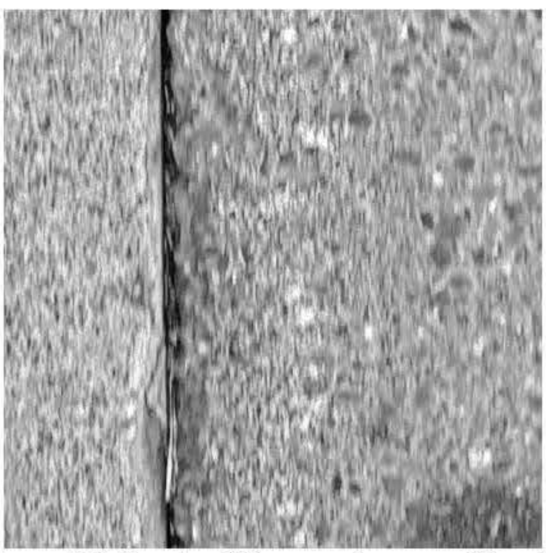

Figure 53. Standard Camera Image at 3 mph

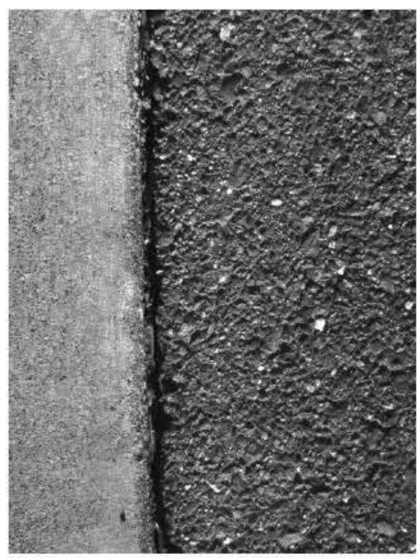

Figure 54. Blackfly Camera Image at 3 mph

The router cutters would ideally be guided to within a half of an inch of the PCC slab edge for proper cleaning without contacting the PCC edge and dulling the carbide cutter tips (Figure 55). For the tracking system to be capable of attaining this level of accuracy, the Trailing-view camera must have an image resolution of at least an order of magnitude greater than half the positioning tolerance. Consequently, the Trailing-view camera should have at least a 0.015" resolution for a 12" to 16" image width. This calculates to a camera CCD line resolution of approximately 1,000 pixels, which fits in the common resolution range of machine vision cameras. The FLIR Blackfly camera selected has a 1/3 CCD format and a 1280 x 960-pixel resolution (Figure 56).

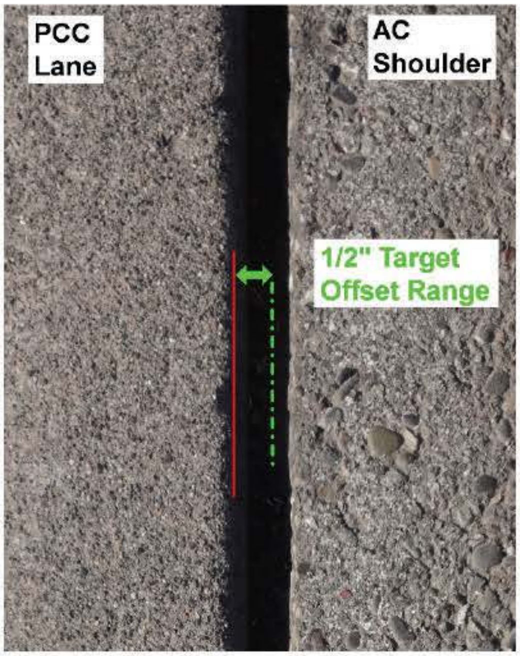

Figure 55. Guidance Tracking Tolerance

Figure 56. FLIR Blackfly Camera

The consequences of tracking errors outside the expected range has been evaluated as well. The worst case is when the tracking error results in the carbide cutter making contact with the PCC slab. A routing test was conducted with a conventional manual impact pavement router to determine the result of such an occurrence. The router was configured for a 1½"-wide cut to purposely strike the PCC slab with a ¾"-wide overlap while router cleaning the longitudinal joint. The result was only minor cosmetic chipping of the surface of the PCC slab as can be seen in Figure 57. Apparently, since the star cutters are loose on the cross pins and free spinning, the cutters can push away from the hard PCC surface without cutting through it or causing perceivable vibration to the cutter head. The second case is when the tracking error drives the router further away from the PCC slab edge. How detrimental such an offset is to crack preparation and the associated seal performance is primarily dependent on the condition of the AC shoulder pavement. Older brittle AC pavements are oxidized and brittle in the transition zones, such that router cutting anywhere close to the PCC edge will chip away and dislodge any adjacent pavements and debris exposing the PCC slab edge. Newer AC shoulder pavements are more flexible and remain closer to the PCC slab edge. Consequently, the tracking offset on the newer AC pavement shoulders is less tolerant of router offset. Fortunately, the visual transition for these newer pavements are also far more acute, which increases the accuracy of the edge recognition process. Therefore, the effects of tracking errors on the stated target range are not considered catastrophic for offset errors within twice the targeted range.

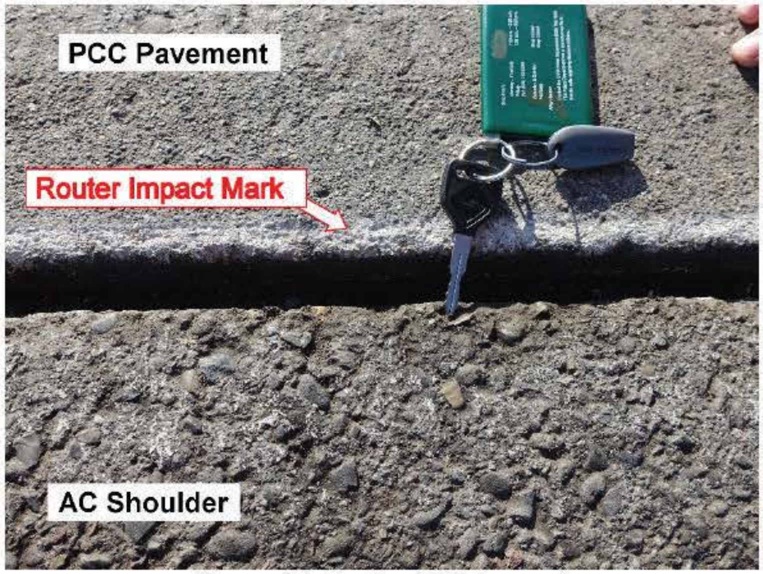

Figure 57. Router PCC Impact

Edge Identification Program

Precise PCC slab edge identification is the foundation of the guidance system automated tracking feature, which is contingent upon developing a means of digitally processing the Trailing-view image and reliably identifying the PCC slab edge that runs through the frame. When the surface of the joint crack transition is clean, the color difference between the mostly white PCC pavement and the mostly dark color of the AC pavement would be easily identifiable with traditional image processing techniques. However, on actual PCC highways, the surface adjacent to the transition joint is often obscured by lane striping, old sealant, and pavement markers that introduces error and greatly reduces the reliability of traditional object identification techniques. A new field of intelligent image processing technology is emerging, which is well suited at detecting classified objects within a digital image. Computer Deep Learning is the generalized term for this technology and represents a large array of artificial intelligence machine learning algorithms. Whereas traditional image processing applies a fixed set of predetermined filters that must be programed, deep learning provides a framework where the filters are developed by the program internally through a process of learning based on supervised training. Given the uncertain nature of the Trailing-view highway pavement image, a deep learning image processing framework has the potential to provide the best possible object identification results for the crack cleaning guidance system.

Deep Learning Architecture

Deep Learning is a subset of Machine Learning Algorithms which are part of a broader family of machine learning methods based on artificial neural networks. Of the many different classes of deep learning models, Convoluted Neural Networks (CNN) are most commonly applied when analyzing visual imagery, which is the case with the crack cleaning machine. A CNN is a computational model that works in a similar way to the neurons in the visual cortex of the human brain, often referred to as a perceptron. A section of the input image is processed through a series of convolutional layers each consisting of various numbers of perceptron nodes. Each node interrupts the image pixel input data and outputs prediction data to connected nodes in successive layers for further interpretation (Figure 58). CNN architecture often is comprised of an input and an output layer, as well as multiple hidden layers. The hidden layers typically consist of convolutional layers, ReLU layers, an activation function, pooling layers, fully connected layers, and normalization layers. Convolution is a vector multiplication operator (Tensor) used extensively in the image processing technique to blur and sharpen images and preform edge enhancements (Figure 59). In a CNN model, multiple convolutional layers are responsible for distinguishing features based on weights and biases learned from the training data set. CNN performance is due primarily to separable convolutional filters, which reduce the number of parameters involved in the computation and reusability of weights. The CNN model evaluates the correctness of feature recognition and uses regression methods, which adjusts the weighting values to optimize the models' output prediction accuracy.

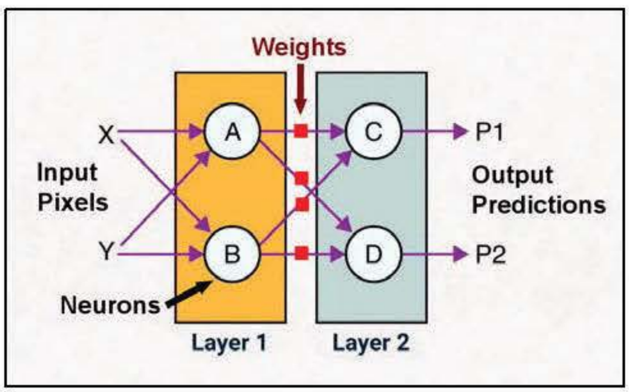

Figure 58. Perceptron Function

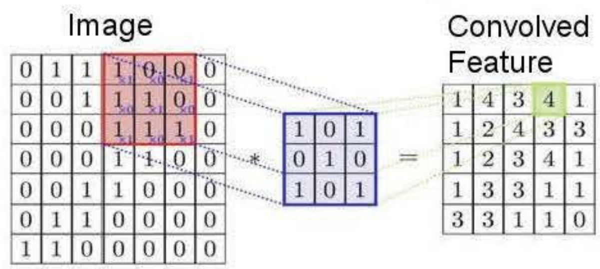

Figure 59. Convolution Filter

When implementing a CNN model, first the program must be taught to recognize features based on classifying a large series of supervised learning images and then pre-processing them into an appropriate data input format. Deep learning development is done in two stages. A CNN algorithm is initially "trained" by entering a large set of labeled data on a powerful computer or a network of computers, and the neural network architecture "learns" to recognize features directly from the data. Learning occurs by adjusting the "weights" that are magnification factors applied to the connections between convolutional layers. Once the degree of identification accuracy is satisfactory, the fully trained model can then be employed to interpret, or recognize similar features in real-time data, which is often referred to as "inferencing". The final output prediction appears on the source image as a bounding box encompassing the identified feature accompanied by a percentage value representing the programs confidence in its prediction accuracy.

Edge Identification Trials

Initial trials were conducted of the deep learning scheme to determine the suitability of this method in identifying longitudinal pavement joint cracks. A large series of longitudinal AC/PCC transition joint crack images were captured by The Trailing-view camera. These images were formatted to be suitable as supervised CNN training input and then entered into the algorithm for processing on the eGPU device. The resulting inferenced algorithm was utilized to identify the PCC slab edge. The algorithm draws a rectangle around the identified object and lists an accuracy value, which represents how closely the identified object coincides with the inference processing (Figure 60). The inferencing succeeded in regularly identifying the joint crack in sample Trailing-view images with 99 percent accuracy.

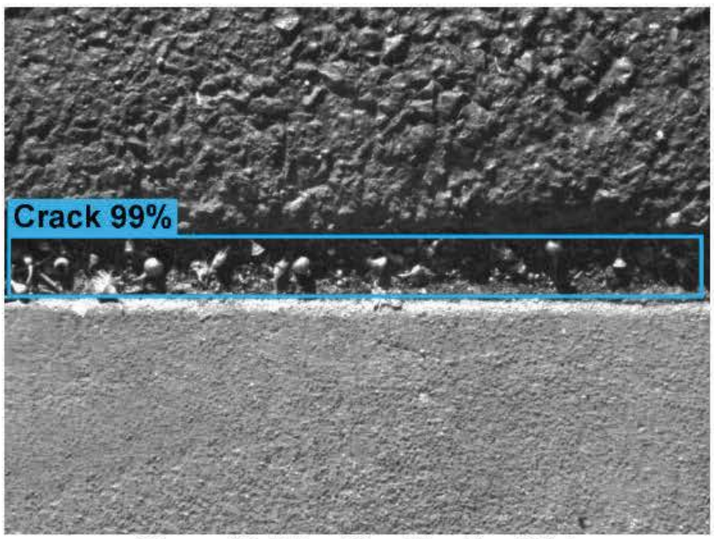

Figure 60. Edge Identification Trial

Edge Path Extrapolation Program

Once the edge identification program has identified a slab edge path, a mathematical equation and computer code was written, which runs on the control computer, to calculate the extrapolation and lateral router position necessary to place the router cutters adjacent to the PCC slab edge. The transformation equations developed for path extrapolation are presented in Appendix A. Since the crack cleaning guidance scheme involves extrapolating the identified edge path some 30 inches further ahead on the longitudinal joint crack, any small geometric positional inaccuracies become considerably magnified. Additionally, the Trailing-view camera moves with the steered vehicle, so the joint crack is unconstrained within the image. Since the vehicle orientation will be changing slightly from one image to the next, the joint/crack will be continually shifting and rotating slightly within the image. The edge tracking program must compensate for this inherent movement of the image frame of reference and calculate an accurate router lateral position to keep the inside edge of the router cutter adjacent to the PCC slab edge. Therefore, for the semi-automated tracking scheme to be effective, a way of mitigating inaccuracies inherent to this approach had to be established.

The edge path once identified must be transformed into a lateral position of the inside edge of the router cutter. Entering a crack path line and guide point positions in a Trailing-view image outputs a router lateral position. The transformation program requires that the Trailing-view camera be initialized, and key geometric dimensions between the router and the guide points must be defined. These measurements are the critical constant values necessary to make the transformation calculation. The hardware and equations necessary to initialize the Trailing-view camera are presented in Appendix B.

Router Alignment Relationship

The router cutter head moves laterally to follow the joint crack independently while the Trailing-view camera is fixed to the vehicle platform. The geometric relationship between the router and Trailing-view camera could be calculated in theory, but because of the large circuitous framework involved, an accurate relationship measurement would be difficult to determine and maintain. Instead, a means of directly linking the Trailing-view image to the router cutter head was established to consolidate accuracy errors.

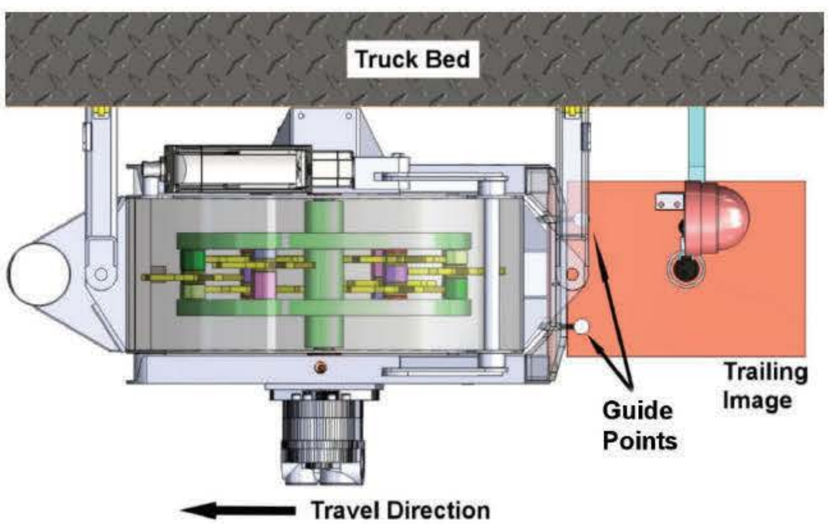

Figure 61 Router Guide Frame

Router Guide Points: Guide points are discs affixed to the router housing such that they remain visible in the Trailing-view image during operation, providing a direct link between the physical position of the cutter head and the processed Trailing-view image (Figure 61). Since the guide points travel laterally with the router, the guide points and the joint crack drifts laterally in the image with vehicle steering. Therefore, positioning the guide points to always remain visible in the Trailing-view image is essential.

Once the location of the edge path and guide points has been identified in the Trailing-view image, this positional information must be transformed into a lateral position of the router to place the cutters adjacent to the PCC slab edge. The transformation extrapolates the identified slab edge path forward the longitudinal distance to the router cutters, while the guide points establish the router frame of reference. A tracking vector can then be calculated indicating the current position of the router cutter. The tracking vector will have a constant magnitude equal to the fixed distance between the Trailing-view image and the center of the router cutter and an angle representing the orientation between the Trailing-view image and the identified joint crack straight-line path. A position transformation equation calculates the difference between the tracking vector and the extrapolated PCC slab edge line to determine the current lateral offset value. The lateral offset value is then converted into a position command by the control program, and the router moved laterally to remain adjacent to the slab edge.

Camera Initialization: When preparing the guidance system for operation, the first step is to initialize the Trailing-view camera, which spatially links the image to the pavement and to the cutter head. The Trailing-view camera must be aimed directly downward perpendicular to the pavement surface and nominally parallel to the side of the vehicle platform. A procedure to initialize the camera position is presented in Appendix A.

Router to Guide Point Geometry: The router star cutters spaced with washers on the flywheel cross shafts to produce different cutting widths. After all of the cutters have been installed on the flywheel, the distance between the inside edge of the cutters and the flywheel center must be measured. This distance is an important constant essential to calculating the edge path extrapolation and router lateral positioning. The equations associated with guide point geometry are presented in Appendix A.

Lateral Positioning Component

Lateral Positioning Operation

Lateral actuator control is interrelated with how the equipment is to be operated. The crack cleaning machine is envisioned to be operated by a vehicle driver and a router system operator. The critical basis of the crack cleaning machine tracking scheme is based upon the safe assumption that the highway PCC slab edge be relatively straight and contiguous. A highway joint crack necessitating cleaning prior to sealing ostensibly is filled with debris and vegetation and therefore obscures the slab edge. The straight edge assumption facilitates the use of the Trailing-view image of the cleaned joint crack to extrapolate forward a path to effectively guide the router. The logical exceptions to this assumption would be occasional mismatches between PCC slab edges and potentially when initiating the cleaning process. Due to these anomalies, the lateral actuator control must be based on a supervisory control model. In-cab displays provide the system operator a view of both the Leading-view image of the upcoming joint crack and the Trailing-view image with the identified slab edge path graphics included. The system operator manually positions the router along the slab edge with a single axis joystick at a greatly reduced vehicle speed. As the auto tracking begins to accurately identify the PCC slab edge, the system operator can press a button on the joystick to engage the automated tracking control and alert the vehicle driver to speed the vehicle up to 3 mph. Any subsequent joystick movement returns the lateral control back to manual joystick control. This supervisory control scheme enables the system operator to watch ahead for approaching slab edge incongruities and instructs the driver to reduce the vehicle speed so that the system operator can retake lateral positional control of the router, prepare for the upcoming incongruity, or initiate the tracking program.

Lateral Positioning Mechanism

One of the unique characteristics of impact routers is that the free spinning star cutters do not generate any cutting side forces, which consequently enables the router to cut AC pavements in any direction. Unlike standard ridged circular cutter blades that are prone to jamming while cutting with even the smallest of angular misalignment, alignment does not affect impact router efficiencies. This permits the lateral actuation system to have only a single axis of travel even though the orientation between the steered vehicle platform and the joint crack is always offset at some relatively small angle. Consequently, the lateral positioning system developed for the crack cleaning machine will consist of a single actuator with a positional feedback sensor controlled by a closed-loop controller. The positioning controller is continually reading the current lateral actuator position and comparing it to the commanded position. Should a positional error difference be detected, the computer controller calculates the offset and sends a signal to the actuator controller to return to the targeted position. To move the actuator, a new position is passed to the controller by either the guidance program or the manual joystick, and the PID controller calculates the necessary motion profile to move the lateral actuator at the new position.

A hydraulic cylinder would be the logical choice of a lateral actuator for the crack cleaning machine because hydraulics both deliver the necessary force to guide the cutter head and that fluid systems are ideal at withstanding the large vibrational forces generated by impact cutting highway pavements. The flow of hydraulic fluid to the cylinder establishes cylinder piston position. A hydraulic servo valve is required to precisely control hydraulic fluid flow thereby controlling cylinder piston position. The hydraulic cylinder must be integrated with either a

LVDT or linear potentiometer sensor, which outputs an analog electrical signal representing the actual cylinder piston position. A positional control program developed to run on the system control computer will process the cylinder input signal and compute an analog signal to the servo valve to attain precise cylinder positioning. The control computer will output an analog electrical signal to drive the hydraulic servo valve. Since only a single lateral actuator is necessary, the detailed router mounting frame can be simplified down to a single hydraulic cylinder driving a sliding base plate with two arms that attach to either end of the router (Figure 62). The whole router mounting frame and lateral actuator mechanism is designed to fit under a standard truck bed when retracted and extend out from the side of the truck bed in operation (Figure 63). This leaves the entire truck bed surface free for the mounting of any essential machine support systems, such as an HPU, vacuum and/or air compressor.

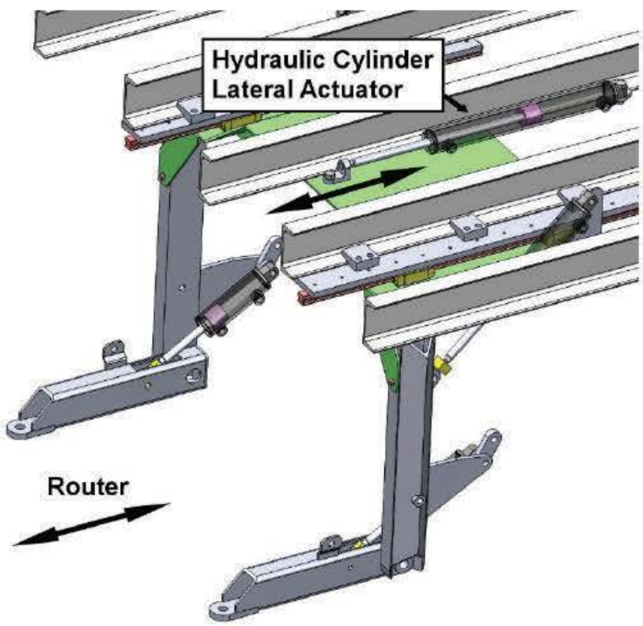

Figure 62. Lateral Actuation Mechanism

Figure 63. Truck Mounted Router

A hydraulic power source will be necessary to power both the router flywheel motor and the lateral positioning cylinder. However, the hydraulic power circuits necessary to efficiently operate each of these components is fundamentally different. The flywheel motor requires an open hydraulic circuit to sustain a constant hydraulic flow to maintain a constant motor rotational speed. Fluctuations in flywheel cutter forces are automatically accounted for in load sense circuits by varying the pump pressure to maintain the targeted flow rate. As opposed to the hydraulic cylinder lateral positional control, which performs best with a closed constant pressure hydraulic circuit, displacements of the lateral hydraulic cylinder cause brief pressure fluctuations in the hydraulic circuit before the variable displacement pump reacts. Hydraulic pressure accumulators are often added to closed hydraulic circuits to mitigate these pressure fluctuations and improve system performance. Open constant flow and closed constant flow hydraulic circuits are incompatible and must be separated. HPUs can be designed to support the simultaneous operation of both open and closed hydraulic circuits, but only if two circuits remain internally separated. These combination power units share a common power drive train, hydraulic oil, fluid reservoir and oil cooling resources.

Supervisory Control System

System operator manual control and supervision of the automated tracking process is a key aspect of the semi-automated tracking scheme. Cutter head deployment, engaging the router cutting system, initiating the tracking process, monitoring the accuracy of the auto tracking process, watching for and navigating slab edge incongruities, starting, and stopping the router at highway structures, all rely on the system operator directly controlling the router cutting system. Even under manual control, most of the key router cutting system components still require a minimal level of computer control and integration to function. Consequently, the control computer performs the central role in the operation - integration communication and data display linking the many essential components that comprise the router cutting system (Figure 64). The addition of the automated tracking capability to the router cutting system primarily involved the addition of computer code to the control computer with only minor accommodations to component interconnectivity.

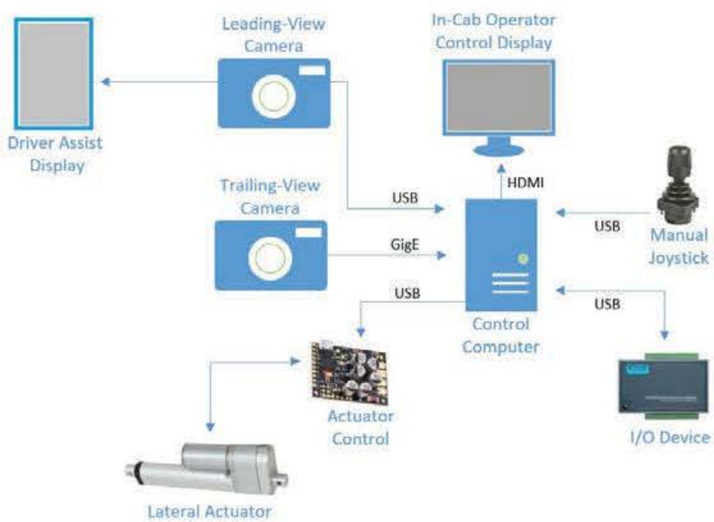

Figure 64. Supervisor Control Diagram

Application Code: The machine application code was developed to integrate the separate system components and establish the overall function of the system. The individual component manufacturers provide computer applications, which enable a computer to interface with their devices to configure, communicate, and operate them. For the crack cleaning machine design, this includes components like the camera, actuator board, and the joystick. These type of software products enable a user to access the functionality of the components but at the same time do not provide the code to interface with a user's specific application. A custom computer application code had to be developed to integrate these components in a system, which produces the desired machine functionality. Components utilized in this project were selected in large part based on the manufacturer's level of available integration support code. The application code runs on the control computer and interfaces with associated external components providing a stack of data available to both the manual and automated tracking codes. Outputting a lateral position is the primary function of the application code. The position output value is defined either by the system operator directly with the joystick or calculated independently by the automated tracking program, which is based on pavement image processing. Supervisory logic enables the system operator to instantaneously switch back and forth between the control modes. Any abrupt position change commands are analyzed for errors and filtered to maintain smooth continuous router tracking lateral motion.

Input and Output Devices: Many of the basic controls necessary to operate the router cutter system can be effectively operated and monitored with simple switches and gauges mounted on or near the individual components. For standard equipment applications that are intended to be operated manually and/or operated in a protected work zone where ready access is available, basic controls will suffice. The crack cleaning machine is designed to operate in a moving lane closure in live traffic on mainline highways. Consequently, access to remote component controls and gauges are not accessible during operation. Therefore, access to critical controls and the monitoring of remote components should be routed into the truck cab for system operator access during operation. The most efficient method of introducing this remote access functionality is to route essential machine controls and signals through the control computer. Connecting through the control computer simplifies wiring complexities through the cab when utilizing a remote USB, Input/output (I/O) device.

Chapter 6: Guidance Proof of Concept Development

The second phase of the crack cleaning machine development project focused primarily on developing the strawman joint crack guidance scheme into a proof of concept guidance system capable of both manually and automatically tracking AC/PCC edge joint cracks. The deployable version of the router cleaning machine will be vehicle-based to operate on highways in moving closure operations. The guidance system demonstration was developed to parallel the full router system as closely as possible. Consequently, the guidance system demonstration was conducted on actual longitudinal AC/PCC joint cracks. Since the strawman guidance scheme relies on following a routed joint crack, the demonstration on joint cracks selected for testing were either relatively clean or routed manually to represent the appearance of an actual joint crack. To represent the position of the router cutters, a laser pointer was mounted to the end of a lateral actuator pointing down normal to the pavement surface. The laser spot projection onto the longitudinal AC/PCC transition joint crack provides a clear visual indicator as to the accuracy of the slab edge-tracking system. To resemble the expected movement of the actual vehicle-based crack cleaning machine, the Trailing-view image will be free to drift both laterally and rotationally while moving along at 3 mph, which captures the camera images that are then digitally processed to identify the PCC slab edge. An algorithm then projects the identified edge forward a distance equivalent to the actual router, and a lateral offset value is passed to the lateral actuator to position the laser pointer to the target spot. A joystick will also be included to support manual lateral control.

Edge-tracking Prototype Development Test Site

The guidance system development for the crack sealing machine involves the integration of several complex components with computer operation code. The individual components are first developed separately in the laboratory and then physically combined onto a single platform to develop computer code to fully integrate the system. The integrated system is then taken to a pavement test site to conduct performance adjustments. The final step is to conduct tracking demonstrations on actual longitudinal AC/PCC joint cracks. A roadway test site had to be identified to perform the integration and demonstration steps. A highway test site was investigated first because the mainline highway is where the deployable crack cleaning machine is intended to operate. Initial highway joint crack images were taken on Hwy CA113, which is one of the few highways near AHMCT with longitudinal AC/PCC transition joint cracks. The consistently high traffic count and high vehicle travel speeds on this roadway made stopping even briefly to take pictures hazardous, impractical, and perhaps unlawful. Since longitudinal AC/PCC transition joint cracks are typically only found on interstate highways, the prospect of identifying compatible off-highway sites to rout clean, video, and run testing becomes quite limited. A section of old Highway 40 still remains as rural Road 32A in Yolo County and parallels Interstate 80 terminating at the western end of the Yolo Bypass Causeway. This 3-mile stretch of road has PCC travel lanes with AC shoulders and contains longitudinal transition joint cracks with light traffic and a posted 25 mph speed limit. The pavement on this roadway is old and spalled, but in reasonably good shape for the purposes of image collection for this research project. The roadway shoulders are small, which forces the test vehicle to block the traffic lane during testing and data collection. Consequently, the prevailing vehicle and truck traffic on this roadway site is blocked, which creates enough of a traffic hazard that testing and demonstration of the slab edge-tracking system over extended intervals would not be safe or practical either. Therefore, the development, testing, and demonstration site of the crack cleaning machine guidance system was restricted to testing on roads closed to traffic and adjacent to AHMCT center facilities. A suitable site is located outside of the AHMCT offices in the Academic Surge (AS) building on campus. The AS site consists of a longitudinal AC/PCC transitional joint crack almost identical to the Road 32 site and very similar to highway joint cracks. The AS longitudinal transition joint crack is sufficiently clean and wide that additional router cutting was not necessary. The guidance system developed on the AS test site will perform similarly on highway pavements with the possible exception of joints bordered by old sealant, and/or paint stripes.

Guidance Demonstration Test Cart

The deployable crack cleaning machine will ultimately be vehicle-based, but developing the integrated tracking system coding while attached to a vehicle would present many hardships, especially in relationship to the AS test site. Instead, the individual components under development were integrated together onto a single mobile frame to support the overall system development and guidance system proof of concept demonstration. A specially designed test hand cart was designed for this purpose, which can be pulled by hand along the AS longitudinal transition joint to simulate the crack cleaning machine operation on the highway. The test cart was designed to fit through a standard door, so the integration platform can be operated in the laboratory for development and rolled outside to be tested at the AS pavement test site adjacent to the AHMCT offices. The test cart was constructed with T-slotted aluminum structural framing hardware and is supported by three caster wheels. The key components incorporated onto the test cart include the PCC slab edge detection, edge projection, and lateral tracking capability of the developed guidance system. These components are arranged on the test cart in the same dimensional relationships as they would be designed on the deployable vehicle-mounted router cleaning system (Figure 65). Additional support components will include the lateral control joystick, laptop computer, Leading-view camera, and lighting mitigations. A laser pointer attached to the end of the lateral actuator projects a laser spot down on the pavement surface representing the position of the router cutting patch. A video of the laser spot following the projected PCC slab edge serves as the dynamic indication of the tracking system's accuracy.

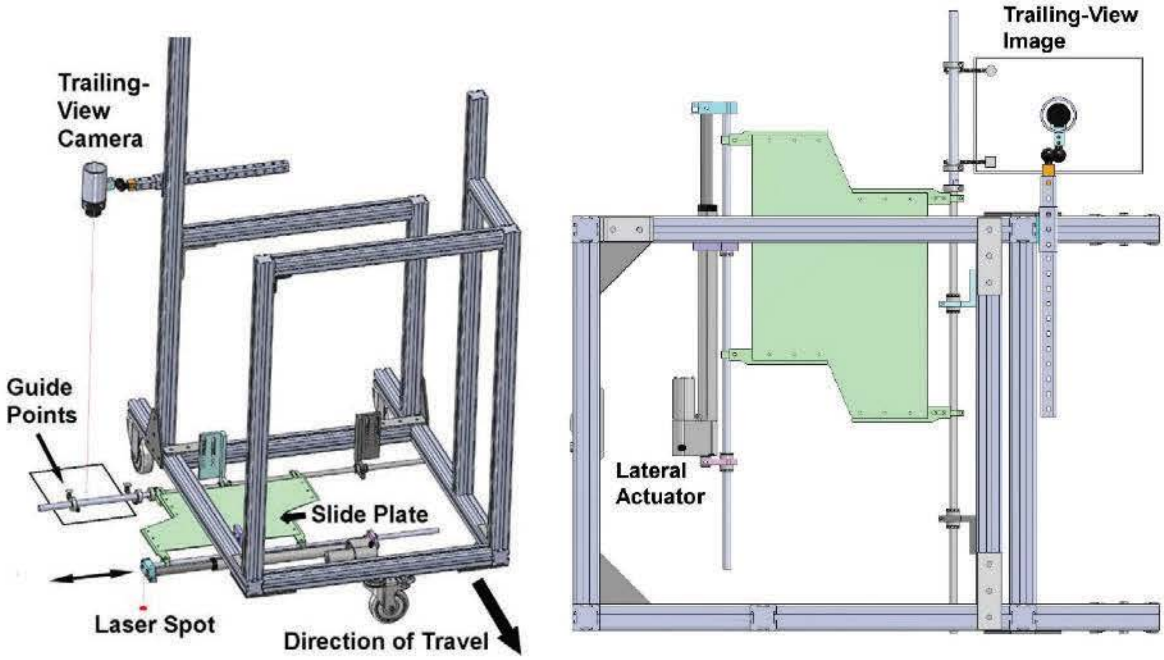

Figure 65. Guidance Development Test Cart

Camera Test Cart Mountings: The Trailing-view camera image is an essential component for the edge-tracking system. The Blackfly camera selected for this purpose is designed to be enclosed in an aluminum protective housing in the vehicle mounted full router design. To simplify the camera lens adjustments during the test cart development, the Blackfly camera will be attached to the test cart with a fully adjustable mounting without the designed camera protective housing. The height and orientation of the Blackfly camera determines the size, shape, and position of the Trailing-view image. Any changes in camera position typically necessitate lens adjustments as well. Conversely, the Leading-view camera is not directly associated with the edge-tracking scheme but is purely useful for demonstration purposes. A camera mount bracket was fabricated, which attaches to the Blackfly mounting and places the surveillance camera nearly in line with the Trailing-view camera. The surveillance camera image is displayed on the test cart. Both cameras are affixed to the T-slot framing with telescoping tubing to enable easy repositioning of the cameras as necessary during testing (Figure 66).

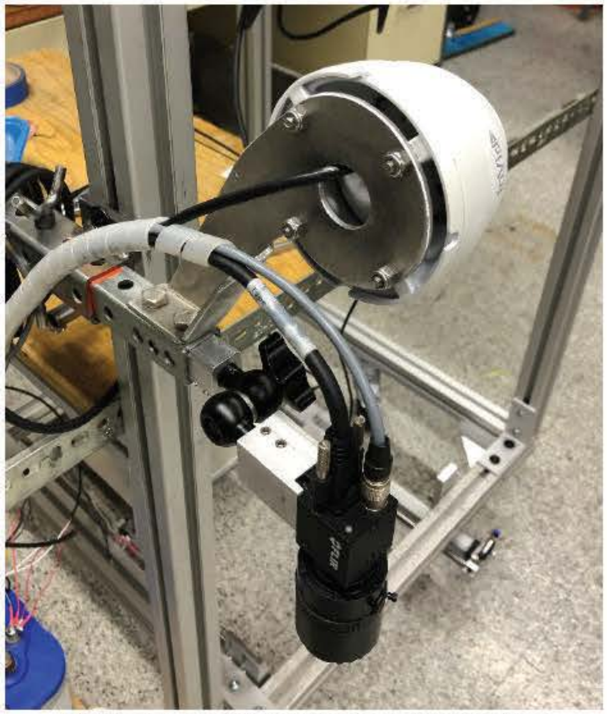

Figure 66. Test Cart Camera Mounting

The vehicle-based guidance system demonstration consists of tracking a pointer along the PCC pavement slab edge of an actual roadway at a continuous travel speed up to 3 mph. Since the pointer device will be a lightweight laser light, only a light-duty lateral actuator will be necessary. Consequently, a 12Vdc motor driven Potentiometer feedback linear actuator was selected with a 14" distance and a 2 in/sec extension speed. A mounting frame was designed and fabricated to attach the linear actuator to the test cart frame with sufficient adjustability to support guidance system development. A linear slide bearing rail is incorporated into the actuator mounting to facilitate the attachment of the guide points mechanism.

Guide Points Mechanism: The guide points frame attaches to the router enclosure in the deployable router design. For the test cart design, a guide point rail was incorporated, which slides the guide points as they would if attached to the router. To accomplish this, a guide points mechanism was developed that directly couples the guide points to the movements of the lateral actuator while maintaining the same spacing as it would be in the deployable router cleaning machine. The guide point mechanism simply consists of a pair of parallel linear bearing slide rails connected by a shear plate that couples the bearing rods to move together (Figure 67). The guide points are mounted to a shaft that clamps to the driven bearing rod, enabling the test cart to be narrowed to more easily fit through doorways. The guide points screw into collar clamps on the shaft providing positioning flexibility in all directions.

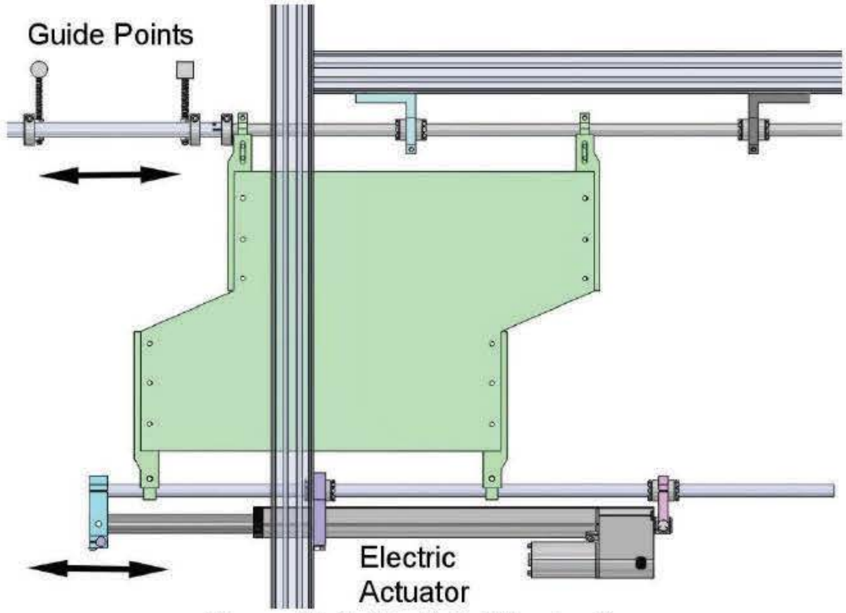

Figure 67. Guide Point Mechanism

Linear Actuator Control: A stand-alone Jrk-G2 motor control board was utilized to provide direct closed-loop control of the lateral actuator brushed DC drive motor. This control board features integrated support for a variety of control interfaces, but for the crack tracking demonstration, the digital USB interface was deemed most suitable. A linear potentiometer was incorporated into the lateral actuator such that an analog position signal was generated over the entire length of travel. The Jrk-G2 board is configured with software to associate the potentiometer reading with the position of the linear actuator. Once configured, the motor control board drives the linear actuator to the commanded offset position provided by the tracking control program.

Test Cart Computer

The leading image is not a necessity for the purposes of testing but may be useful for the overall system development and demonstration purposes. The camera selected for the proof of concept is an inexpensive security camera. A single 12V DC marine battery powers the mobile power system for the test cart. Some of the components on the test cart operate on 12V DC power and were directly connected to the battery. The two exceptions were the computer, which operates on 19.2V DC and the Leading-view display screen, which operates at 13.6 V DC. Step-up AC to DC power converters had to be added to the cart for the test cart to be a self-contained mobile platform.

Edge-Tracking Hardware

The CNN application developed for crack cleaning machine guidance demonstration runs on a laptop computer for mobile power availability reasons. The Linux operating system laptop computer has a sufficiently powerful central processing unit (CPU) but contains the standard energy-efficient on-board graphics chip, which is generally not powerful enough to support efficient deployment of machine learning programs. External Graphics Processing Units (eGPU) have been developed to provide the necessary graphics processing power capabilities to efficiently deploy CNN applications on computers that cannot take an internal card, which is the case for laptop computers. The teaching and optimization phases of CNN applications is neither time sensitive or computer resource restrained because this process is conducted in the laboratory development stage. The deployment of the trained CNN hierarchy (inferencing) is highly dependent on processing time, especially with the real-time nature of the crack cleaning operational application. To achieve efficient CNN inference performance, specialized computing hardware have been developed specifically for CNN inferencing applications capable of accelerated parallel processing of the large number of tensor conversions involved. These Tensor Processing Units (TPU), which were initially developed for only proprietary use, have recently become commercially available.

External GPU: Google Inc. has deployed their third generation TPU based on their Edge, Application-Specific Integrated Circuits (ASICs). Edge computing is a distributed computing paradigm, which brings computer data storage closer to the location where it is needed. The machine learning runtime used to execute models on the Edge TPU is based on TensorFlow Lite that is only capable of accelerating forward-pass operations, which means it is primarily useful for performing inferences. For the crack cleaning guidance demonstration, a Coral USB Accelerator was purchased and utilized to accelerate the trained CNN inferencing up to 50 frames per second (fps) to accommodate the crack cleaning machine target of a continuous 3 mph machine travel speed. The Coral is a plug-in USB device, which provides powerful Machine Learning inferencing capabilities for mobile applications.

Chapter 7: Guidance Proof of Concept Demonstration

The proof-of-concept guidance system demonstration will be conducted with the developed guidance system mounted on the test handcart platform.

Once the handcart test platform was assembled and the individual system components were integrated, a software application, the Supervisory Control Program, was developed to control the system.

Supervisory Control Program

The Supervisory Control Program is written in Python 3 and is composed of six primary components:

Main Application Process: Handles system startup, shutdown, and the user interface

System Controller: Orchestrates the crack-following operation by managing the other controllers; also, receives commands from, and provides status updates to, the Main Application Process

Video Controller: Configures and manages the Trailing-view camera device, and transforms and caches camera images

Detection Controller: Manages the TPU device and analyzes camera images to estimate crack position

Actuator Controller: Manages the motor controller device

Joystick Controller: Manages the joystick device and generates notifications of joystick events

Each of these six components runs in a separate Linux user process with its own Python interpreter. Inter-process communication between the components is handled by transferring serialized communication objects (e.g., commands, responses, events) over anonymous Linux pipes. The supervisory control program data flow is shown in Figure 68. This program has a basic graphical user interface (GUI) that displays the most recent Trailing-view camera image (Figure 69) overlaid with graphical elements that illustrates the behavior of the Detection Controller.

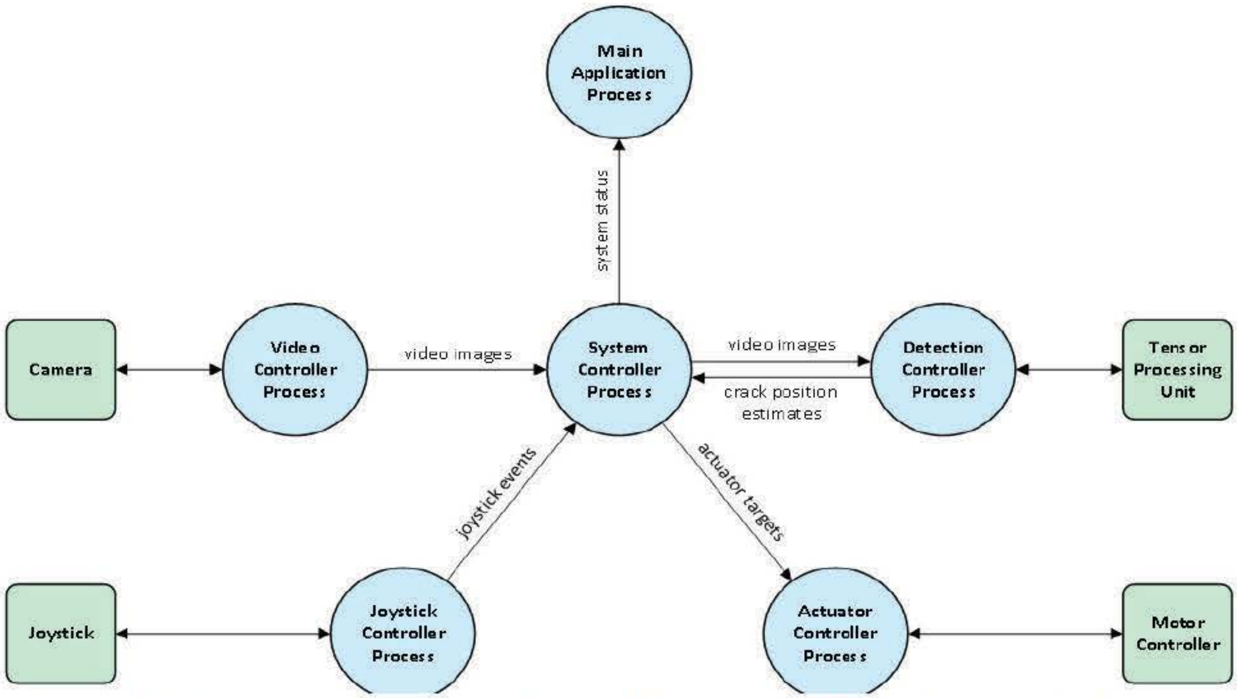

Figure 68. Operator Supervisory Control Program Architecture and Data Flow

A handful of other system parameters and metrics is also displayed for system monitoring and research and development purposes.

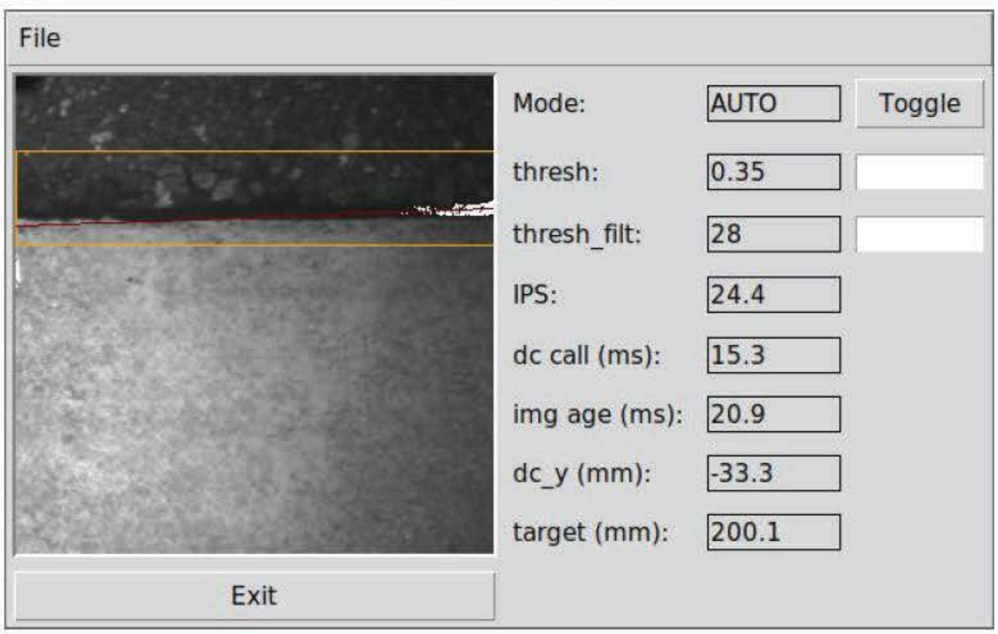

Figure 69. Supervisory Control Program GUI

The program has two modes of operation: Manual Mode, in which the actuator is completely under joystick control, and Auto Mode, in which the actuator is under autonomous control. The current mode may be toggled by pressing the joystick button, or by clicking the "Toggle" button on the GUI.

Additionally, while in Auto Mode, any joystick movement will trigger a transition to Manual Mode.

Auto Mode operation can be summarized as a continuous loop consisting of the following action steps:

1. The most recent Trailing-view camera image is acquired from the Video Controller
2. The image from Step 1 is passed to the Detection Controller
3. The Detection Controller provides a crack position estimate based on the image from Step 2
4. A target actuator position is calculated from the crack position estimate of Step 3
5. The Actuator Controller is commanded to change the motor controller target to the position calculated in Step 4

Slab-Edge Identification Module

The key component to the guidance system is the Slab-Edge Identification Module. This module is housed within the Detection Controller and estimates crack positions through the analysis of the Trailing-view camera images. A flow chart describing how this module works is shown in Appendix B. The first step shown in this flowchart is the CNN module, which applies the CNN model to an image. The model used for the CNN is called mobilenet_v2. This model takes 300 x 300-pixel images and detects the crack based on the samples that the model was trained on. To train this model, over 200 crack images were labeled and transferred on another trained model offered by Google. If the image is not in a 300 x 300 dimension, the code properly crops and resizes the image to be inputted to the CNN.

To accelerate the CNN model inferencing procedure, a TPU called Coral Edge is used. Note that without the TPU, the system would require a GPU, which would increase the complexity and cost of the system. The CNN may or may not find the crack. If it detects the crack, then the bounding box is transferred to the next level to be used by an intensity filter. If it doesn't find the crack, then the previous bounding box will be overlaid on the current image. Note that the width of the bounding box will increase by 40 percent every time. This is because the crack might have slightly moved since the last image shot and using the exact bounding box might be slightly off the crack location. A saturation limit of 100 pixels is used to prevent increases in the bounding box width in case the crack is not detected in a few consecutive images.

A secondary filter applies a separate intensity filter only to the contents of the bounding box region instead of the entire region. This will improve the operational efficiency and CPU time. The intensity filter has a threshold value. This value is then used to find the coordinates (x and y values) of the image within the bounding box, which has a much darker than average color intensity. After the x and y values are collected, they are fed into a linear regression function to return the equation of a line in terms of its slope and y-intercept. Next, an extrapolation process is used to transform the slope and y-intercept into the world frame. For this process to work well, the camera must be adjusted upright with respect to the road surface and properly attached to the body of the truck. Using proper kinematic transformation, the output is transferred to move the actuator.

Guidance System Testing

First, the guidance system was tested in the laboratory utilizing a photograph of a joint crack. The set up used in the laboratory is shown in Figure 70.

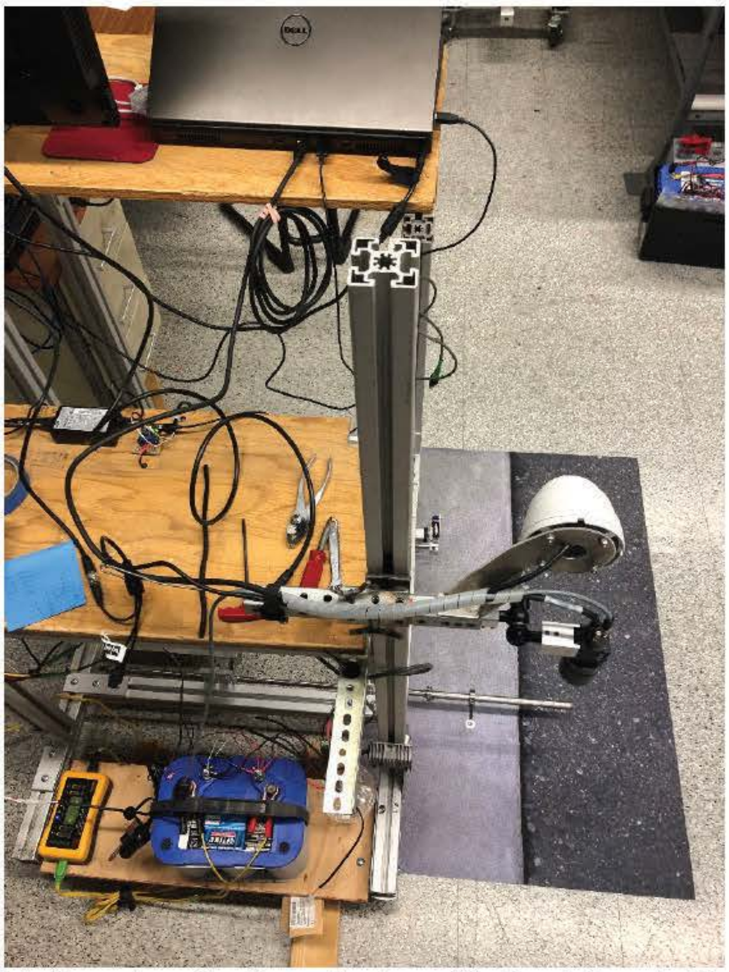

Figure 70. Laboratory Testing of a Longitudinal Crack Photograph

The fully integrated guidance system test cart was moved out to a test site for field testing and further adjustment as shown in Figure 71. This Figure shows the cart being rolled along the short section of a PCC slab guided by hand at speeds of up to 3 mph. The laser pointer mounted to the end of the lateral actuator projects a red spot on the pavement surface and down into the crack as depicted in Figure 72. Several runs were conducted at varying speeds, and the laser spot remained within the necessary 1/2" range adjacent to the PCC slab edge.

Figure 71. Integrated Guidance Test Cart

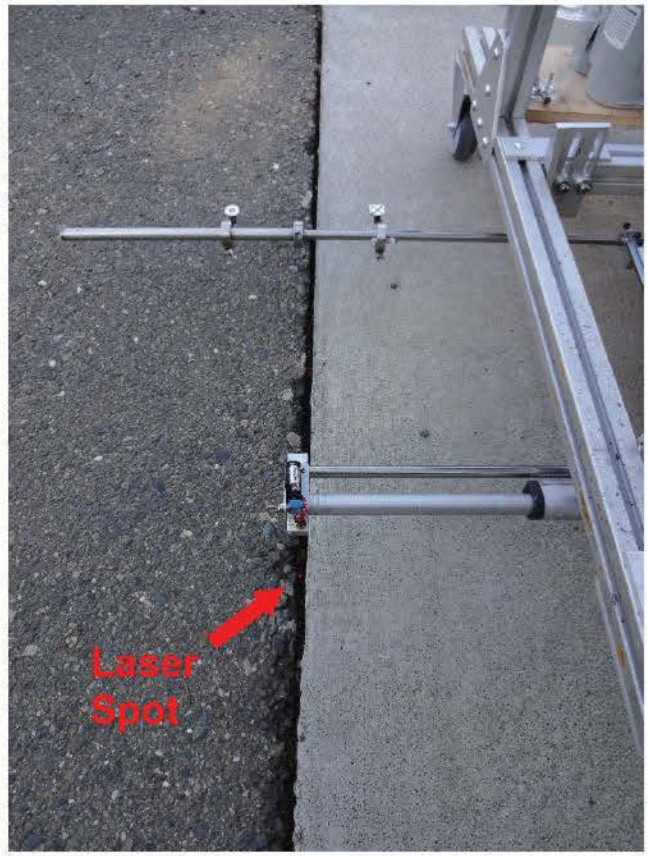

Figure 72. Laser Spot

Chapter 8: Conclusions and Future Research

Conclusions

The main deliverable for this research project was a detailed design of a high production joint crack cleaning machine capable of single pass longitudinal joint crack cleaning at a continuous target speed of 3 mph. The machine was also designed to be capable of operation in a moving lane closure to ostensibly support Sealzall operation. Two key original technologies had to be established and demonstrated to prove the viability of a deployable joint crack cleaning machine. The first challenge was to prove that an impact router cutter could be modified to operate at 3 mph and secondly, that an efficient and accurate router guidance scheme could be developed and demonstrated. This research project succeeded in resolving these two key engineering challenges. To verify the router high production efficiency, an impact router test device was designed, fabricated and tested on actual AC pavements. The results of worst case testing indicated that routing production speeds at or above 3 mph are readily attainable. Based on these test results, a detailed impact router head and under bed truck mounting CAD design was created.

The second technology development was to demonstrate an effective PCC slab edge tracking system. The adopted goal of this project was to develop a semi-automated guidance system where a system operator can supervise the router operation and switch as necessary between manual and automated tracking control modes. This research succeeded in developing and demonstrating a small-scale automated joint crack identification and tracking system mounted on a rolling hand-cart. The edge identification technique processes a digital image of the joint crack and uses CNN tools to identify the PCC slab edge. The edge path is then extrapolated forward to the area where the router will occupy. The accuracy of the tracking demonstration on actual AC/PCC joint cracks was within the ½" tolerance goal. The remaining components that comprise the crack cleaning machine are generally commercially available systems and hardware, which will require minimal engineering adaptions to incorporate.

This research is significant in that it invents an altogether original machine, which Caltrans could build and deploy on the highway with the potential to deliver significant worker safety benefits, increase worker productivity, and improve joint crack sealing performance. Providing Caltrans Maintenance crews a means to conduct high production crack cleaning in preparation for sealing in a moving lane closure operation reduces obstacles such as traffic obstruction restrictions, labor scarcity and traffic safety concerns, which will promote the widespread use of the machine.

Future Research

The next steps in developing a deployable crack sealing machine are the continued development of guidance system capabilities, the development of an overall machine operator interface and the fabrication of a vehicle-mounted router cleaning mechanism capable of supporting limited-scale highway field trials. The testing of the guidance system on actual highway joint cracks is essential in fully developing the tracking control program, establishing driver steering assist, validating router efficiency, creating a semi-automated supervisory control system, and forming machine operational methods.

A significant amount of program development will be required to expand the demonstration guidance programming into a deployable system appropriate for highway operation. Program enhancements would involve a combination of refining tracking efficiency and enhancing imaging functionality. Continued training of the CNN program will be required to improve slab edge identification accuracy especially during field trials when the capturing of actual router highway joint cracks images commences. The identification program capabilities will need to be extended to handle actual highway joint crack inconsistency scenarios. A guide point transformation program and a Trailing-view camera initialization program must be developed to maximize the accuracy of router lateral positioning. Potentially, a representation view of the router contact patch could be generated in software that utilizes stored images from ahead of the router to erase the router head and debris shroud from the current image, thereby providing the system operator a virtual direct view of the joint crack under the router.

An operator interface will need to be developed for the deployable version of the machine, which provides access to the joint crack image(s), router controls and router tracking information, preferably all on a single display. The overall crack cleaning control scheme will most likely require a separate driver and system operator. Field-testing of the crack cleaning router should help in establishing the number of workers needed and a logical division of command and control duties which will then be incorporated into the control program interface and the image displays(s) configuration.

To support limited-scale field trials, a single router cutter head attachment should be fabricated based on the design created for this project and mounted to a flatbed truck. On the bed of the truck, a self-contained hydraulic power unit could be mounted to power the router flywheel motor and the various router head storage cylinders. A trailer-mounted dry excavation type vacuum system could be rented during field-testing to manage debris collection. The vacuum system would be connected to the router enclosure via a large diameter rubber duct hose, and a compressed air blast may also prove to be a necessary addition.

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Appendix A

Router to Guide Point Geometry: The router star cutters spaced with washers on the flywheel cross shafts to produce different cutting widths. After all of the cutters have been installed on the flywheel, the distance between the inside edge of the cutters and the flywheel center must be measured. This distance represents the cutter offset (Co) value, which is an important dimensional constant needed to establish the geometric relationship between the guide points of the router cutter (Figure 73). The values Gp_{y1}, Gp_{y2} and Gp_{x1} are established with the following equations and applied in the transformation calculation.

where: $Gp_{X1} = \frac{Gp}{2} - Co \qquad Gp_{y2} = Gp_{y1} = Gp_y$

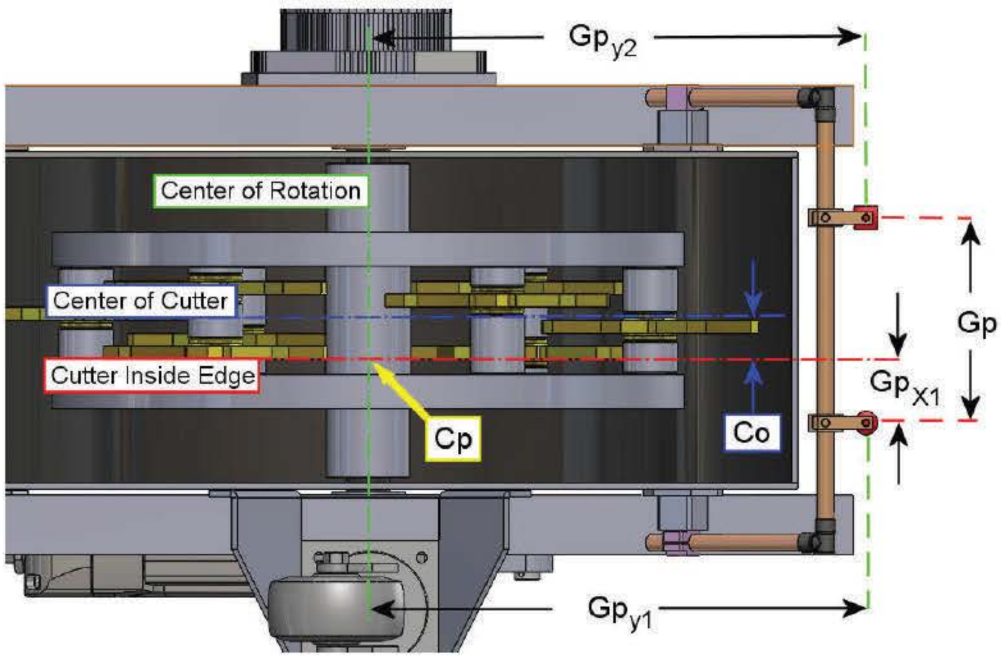

Figure 73. Router to Guide Point Geometry

Appendix B

Router Cutter Plot: The intersection of the router cutter's center of rotation and the cutter inside edge is the point (Cp) that represents the router cutter location for the tracking purposes. Since the router is moving independently in the lateral direction and assuming that the router is not necessarily aligned with the Trailing-view image, the location of the point (Cp) must be calculated to be projected on the base coordinate system (Figure 74). The first step in the calculation is to determine the angle of the router in relation to the Trailing-view coordinates based on the guide point positions.

$\sin Cp\emptyset = \frac{G1_y - G2_y}{GP}$ for: $G1_y > G2_y$

The following equation calculates the lateral (X-axis) distance to the point (Cp) in relation to the Trailing-view coordinate system.

$R_x = G1_x + \sin Cp\emptyset(Cp_y) + \cos Gp\emptyset(Gp_{x1})$ for: $G1_y > G2_y$

The following equation calculates the longitudinal (Y-axis) distance to the point (Cp) in relation to the Trailing-view coordinate system.

$Ry = G1_y + \cos Cp\emptyset\left(Gp_y\right) - \sin Cp\emptyset\,(Gp_{x1})$ for: $G1_y > G2_y$

Note: When $G1_Y$ is less than $G2_Y$, then the sign of the second addition-subtraction operator in each equation is reversed.

Crack Path Extrapolation: The crack recognition program, which identifies the slab edge crack, outputs a line equation representing the crack path. To extrapolate the crack path line to the router, the value (R_y) is entered into the following line equation to determine the length of (M_x).

Solve for M_x: $M_x = \frac{R_y - b}{m}$

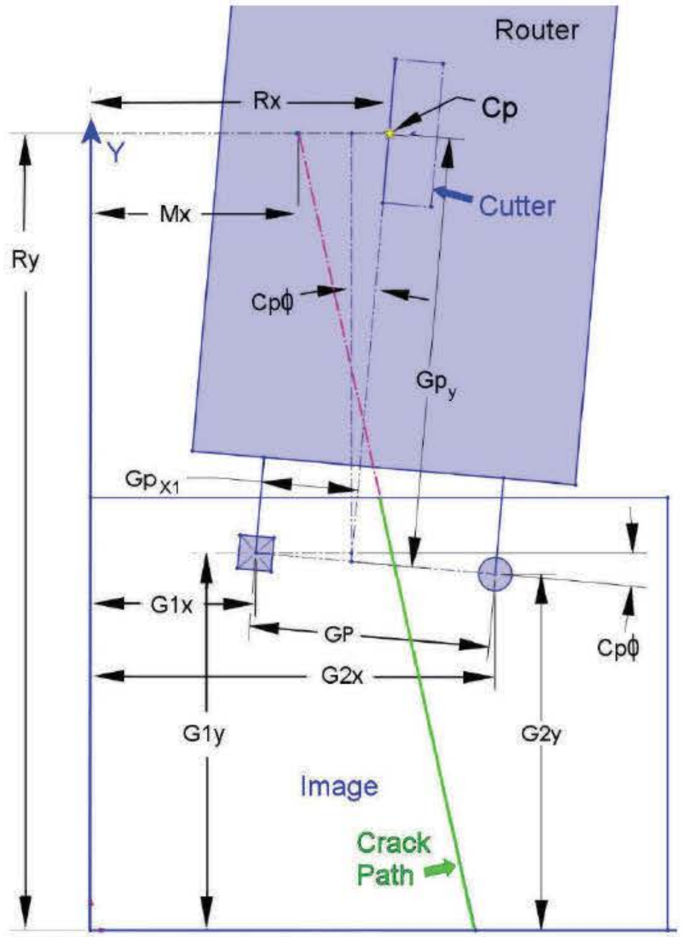

Figure 74. Trailing-view Coordinate System

Router Tracking Position: The router lateral offset can be determined by subtracting the current router position (Rx) from the calculated lateral position of the slab edge (Mx). The position command output to the lateral actuator control board is equal to the value of (Mx). A logic filter is applied to check for unusually large offset values enabling some form of a decision to be made before sending the position command to the lateral actuator.

$$Offset\ Value = R_x - M_x$$

Appendix C

A simple aiming check to determine if the camera is perpendicular to the surface is to place a rectangular object on the pavement surface in the camera's viewport, and it should appear rectangular in the captured image. If the rectangle appears trapezoidal, then the camera aiming requires further adjustments. To assist with camera aiming, an initialization fixture has been designed that places an additional two guide points in the Trailing-view image creating a guide point rectangle. An initialization program processes the image and identifies the position of the four guide points. The length of the opposite sides of the guide point rectangle will be equal (i.e. Gp = Gp' and Hp = Hp') when the camera is normal to the pavement surface.

$$Gp = \sqrt{\left(B_{Gp}y - A_{Gp}y\right)^2 + \left(B_{Gp}x - A_{Gp}x\right)^2} \quad Gp' = \sqrt{(C_{Gp}y - D_{Gp}y)^2 + \left(C_{Gp}x - D_{Cp}x\right)^2}$$

$$Hp = \sqrt{\left(D_{Gp}y - A_{Gp}y\right)^2 + \left(D_{Gp}x - A_{Gp}x\right)^2} \quad Hp' = \sqrt{\left(C_{Gp}y - B_{Gp}y\right)^2 + (\,C_{Gp}x - B_{Gp}x)^2}$$

Once the guide point rectangle has been confirmed, a physical link between the Trailing-view image and the pavement surface is established. This is accomplished by measuring the distance between the guide points (Gp) in both pixels and a unit of length (inches) and dividing the pixel value by the unit distance to determine the pixel size. The pixel size is then multiplied by the camera resolution to calculate the Trailing-view image size, which serves as the coordinate system for the transformation calculation.

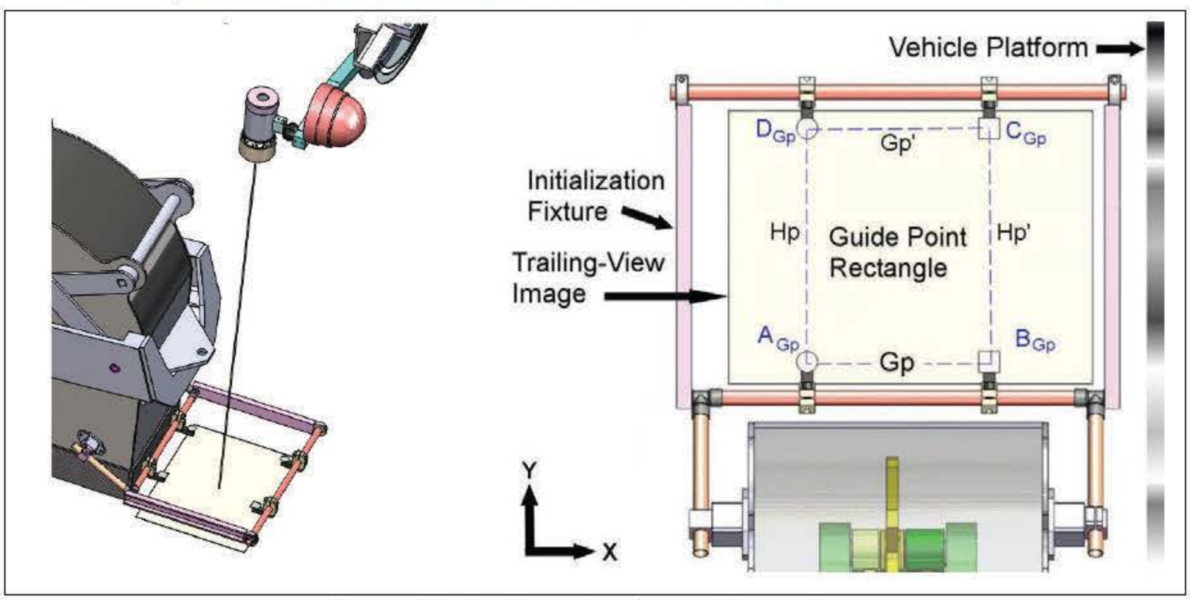

Figure 75. Trailing-view Image Dimensions

Appendix D

Slab-Edge Identification Module Flowchart

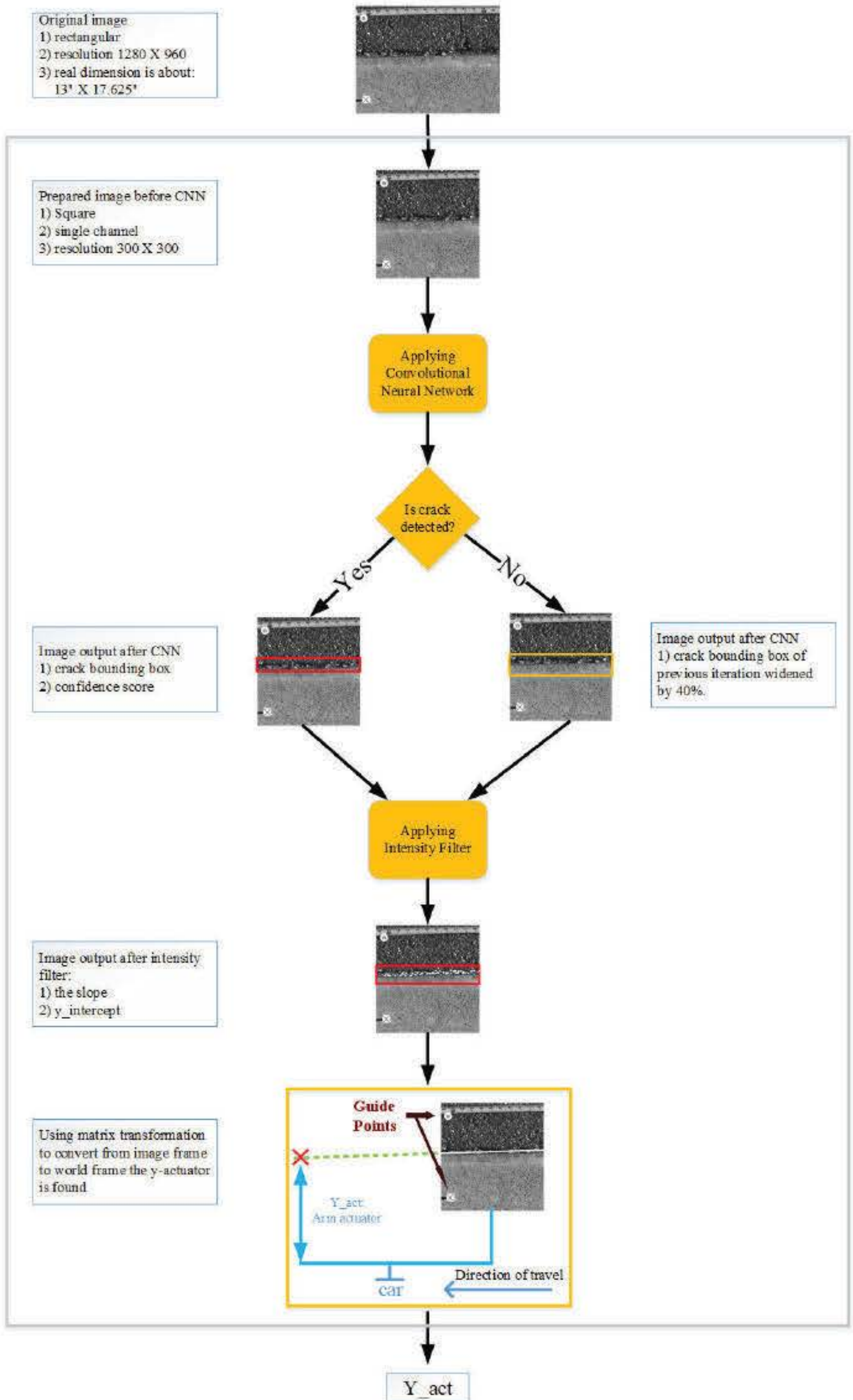

Figure 76. Slab-Edge Identification Module Flowchart