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Effectiveness Study of UNL's Pneumatic Crack/Joint Preparation Device

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16. Abstract

The aim of this project was to evaluate the effectiveness of the crack cleaning device (CCD) for improving the current crack/joint preparation practices and for possible adoption as a standard in Nebraska Department of Roads (NDOR). Through the collaborations with NDOR and the City of Omaha, the results of surveys and field tests demonstrated the effectiveness of the CCD over the existing devices. With employing the CCD, improved road maintenance practices are anticipated. Economic analyses show its potential benefit in an economic sense; for example, a saving of about $10,000 per year is expected if replaced for a router. Taken all together, the CCD was analyzed to be the best alternative among all existing methods compared. With the positive results obtained from this project, this research recommends the adoption of CCD in crack/joint preparation work.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

Analytic Hierarchical Procedure (AHP)
Crack Cleaning Device (CCD)
Consistency Index (CI)
Comparison Matrix (CM)
Consistency Ratio (CR)
Equivalent Uniform Annual Benefit (EUAB)
Equivalent Uniform Annual Cost (EUAC)
Georgia Department of Transportation (GDOT)
Horse Power (HP)
Nebraska Department of Roads (NDOR)
Unified Facilities Criteria (UFC)
Department of Transportation (DOT)

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Disclaimer

Executive Summary

The aim of this project was to evaluate the effectiveness of the crack cleaning device (CCD) for improving the current crack/joint preparation practices and for possible adoption as a standard in Nebraska Department of Roads (NDOR). Up to the current stage, the CCD has been upgraded to a 3rd generation through field testing and evaluation/feedback to assemble and provide a more reliable, better functional, and safer crack cleaning device in sole hope of contributing to the current road maintenance practices in the U.S. In this project, brushing, routing, and cutting functions have been incorporated as possible options for the CCD. For validation of the CCD in the field and to gain industry acceptance of the CCD technology, several industry demonstrations and field tests have been conducted. Multiple CCD units have been provided to NDOR for use during the full sealing season in 2012-2013. Also, demonstrations have been conducted at the City of Omaha, NE, road maintenance division. Productivity data along with the crews' feedback were collected during the field tests. The analyzed results showed that the CCD design concepts have been well received by most of the participating industries, who expect that the CCD would positively impact highway road maintenance by improving productivity, safety and maintenance cost. With the feedback and evaluations, the CCD device was upgraded to a 3rd generation to accommodate a few crew's requests in routing cracks. A separate field test was performed on this generation of the CCD device at Georgia DOT District 7 and this test demonstrated that the previously reported weaknesses were fixed and better performance was accomplished.

An AHP analysis and economic analyses were conducted on the proposed device and three existing crack cleaning devices. In the AHP analysis, three factors, such as safety, quality and productivity were considered while the economic analysis examined each of the alternatives in various ways. The AHP indicated the highest importance on the safety factor, then the quality

factor, then the productivity factor in a descending order. Based on these factors, the AHP analysis ranked the four alternatives in order of CCD, air blower, heat lance, and router. The three economic analyses were conducted purely based on an economic sense. The ranks were obtained in order of air blower, CCD, heat lancer, and router. Discarding the option of air blower due to the quality issue, the CCD option was the best option of all in all of the analyses performed herein, especially far better than the most generally used device, a router. In addition, the payback period showed that the investment in purchasing a CCD is expected to get paid back less than a year.

In conclusion, the various field tests and evaluation revealed satisfactory achievements in performance, quality, safety and control, and also high potential in the utilization of CCD in crack cleaning practice. We expect the following benefits from a successfully designed and validated CCD.

1. The proposed device will improve the crack preparation crew's safety. The light-weight device has the ability to largely replace the current NDOR's use of heavy router and (hot) air blasting in crack preparation.
2. The proposed device will significantly reduce the road maintenance cost by speeding up the crack/joint preparation process for sealing, saving equipment cost, reducing a crew size, and lengthening the life of sealed cracks/joints due to the improved quality of sealing.

With the positive results obtained from this project, we recommend the adoption of CCD in crack/joint preparation work over the existing methods.

Chapter 1 INTRODUCTION

Cracks in flexible and rigid pavement occur when stress builds up, and is relieved, in surface layers. Various crack sealing and filling methods can be used to repair pavement surfaces, depending on crack sizes and crack types. In “Materials and procedures for sealing and filling cracks in asphalt surfaced pavement” (FHWA-RD-99-147), the Federal Highway Administration recommends crack sealing for small cracks measuring 5 to 19 mm (Smith et al. 1999). Also, Unified Facilities Criteria (UFC) provides guidelines for crack preparation based on crack size as shown in Table 1 (Basham 2001). Note that UFC’s guideline and the Federal Highway Administration recommendation are not identical but comparable.

Table 1.1 Crack preparation methods based on crack size

Crack size	Hairline cracks: less than 1/4 inch (<6 mm)	Small cracks: 1/4 to 3/4 inch (6 to 19 mm)	Medium cracks: 3/4 to 2 inches (19 to 50 mm)	Large cracks: greater than 2 inches (>50 mm)
Crack cleaning method	No preparation required	Routing to widen the cracks to a nominal width of 1/8 inch (3mm) greater than existing nominal or average width	Sandblast, heat lance or wire brushes, followed by compressed air	Cut and filled, prepared in the same manner as potholes

The traditional procedures for preparing roadway cracks for sealing/filling are largely ineffective, labor intensive, and/or dusty. Further, working crews can be often exposed to safety hazards. A brief summary of merits and drawbacks of each method is described in Table 1.2. Although routing is the best approach among the methods listed below for cleaning cracks, it is not a solution for complete crack preparation. Routing only excavates narrow cracks and still leaves de-icing chemicals on both sides of the crack surface. However, surface preparation is very important for better bonding between surface and sealing material, and thorough cleaning is essential. In addition, the heavy router machine currently used by most of state Department of Transportation (DOT) agencies for routing cracks has several obvious shortcomings, such as heavy weight, unsafe operation, slow mobility, high purchasing cost, and equipment operation/maintenance cost.

Table 1.2 Summary of conventional methods of crack and joint preparation

	Merits	**Drawbacks**
Air Blasting	Effectively expels dust and relatively loose contaminants; convenient and fast	Difficult to clean out vegetation, de-icing chemicals, large debris
Heat Lance	Removes moisture, especially in cold weather	Sealant bond failure caused by overheating; overheating introduces more moisture from frozen ground; high propane price; safety issues (direct flame)
Sandblasting	Efficiently removes de-icing chemicals	Over-blasting can damage the pavement; environmental and health concerns
Routing	Opens small cracks or joints and cleans out debris; effective on straight cracks	Not effective for random narrow or wide cracks (not easy to follow random crack lines); heavy machinery may create new cracks; pulling mechanism is very dangerous in downhill
Wire Brushes	Effectively remove de-icing chemicals and vegetation on medium cracks	Not easy to remove residual debris from narrow and small cracks

In cold weather regions, hot air blasting is a popular crack cleaning method. Hot air blasting typically uses a compressed air heat lance that introduces gas and combustion to the compressed air to provide a jet of hot air to the treated area. However, hot air blasting introduces problems as well. Extreme caution must be taken to ensure the pavement is not overheated, which will result in the asphalt binder becoming brittle and leading to premature failure. Care also should be taken to never allow use of direct flame methods, as the charring effect will lead to soot residues and cause poor initial bonding. Such direct flame problems occur frequently with current practices (Figure 1.1). Further, the heatlance can introduce more moisture when the frozen pavement or soil thaws (Figure 1.2). In addition, hot air blasting does not clean de-icing chemicals that remain in and around the cracks. Furthermore, propane regulators often freeze in cold weather, thus delaying the sealing process.

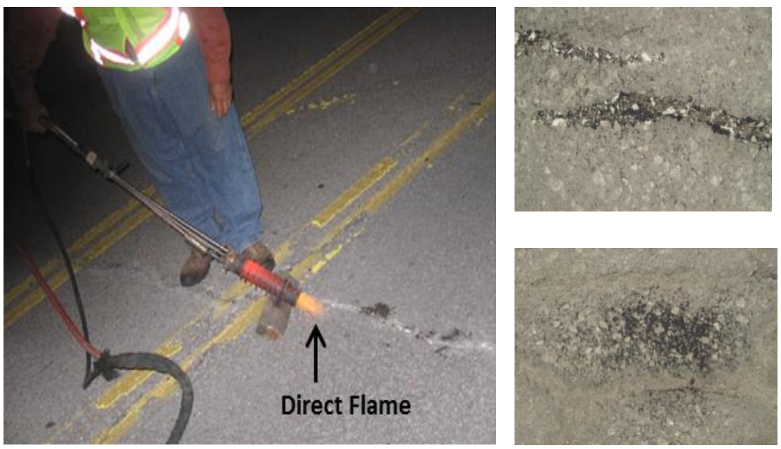


Figure 1.1 Direct flame problem in hot air blasting (heat lance) causing soot residues

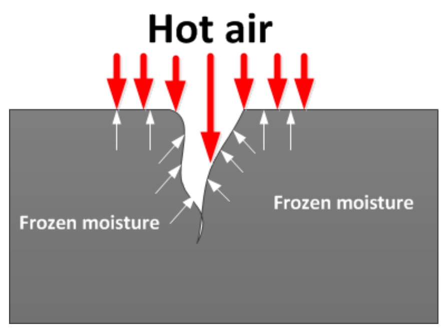


Figure 1.2 Problem when heat is applied to frozen surface

Development of the multi-function crack cleaning device was initiated by a practical request from NDOR for a tool that efficiently prepares pavement cracks and joints for sealing. NDOR was also interested in the tool's ability to remove de-icing chemical buildup that forms in cracks and prevents sealant adhesion. Based on the needs from NDOR, a customizable versatile Crack Cleaner Device (CCD) was developed by the research team. The device utilizes a pneumatically powered rotary attachment to rout cracks and clean stubborn vegetation and accumulated de-icing materials from mid- to large-size pavement cracks. Directly behind the rotary attachment, an air blasting nozzle further expels fine-grained particles.

In this research, the several industry demonstrations and field tests were conducted on multiple versions of the CCD, upgraded based on the feedback/suggestions collected through the processes. NDOR, the City of Omaha, and GDOT individually collaborated with the research team in the testing of the CCD. We were able to receive valuable, constructive feedback, which fostered the development of the CCD in multiple generations. The collaboration helped to gather a tangible, concrete comparison data with the currently employed devices. Thorough survey data sets were also obtained and used along with the comparison data in AHP and economic analyses, which confirmed the CCD's economic feasibility.

Chapter 2 SYSTEM CONCEPT AND FUNCTIONS

The need for the new device was initiated based on the practical request of NDOR for a tool to be developed that efficiently prepares pavement cracks and joints for sealing. The simple and innovative design of this tool is an air powered rotary attachment system with onboard air nozzles that simultaneously blow out the pavement crack behind the rotary attachments. The main parts and functions of the crack cleaning device (CCD) are shown in Figure 2.1. The CCD that incorporates a pneumatically powered rotary motor, allows for a seamless connection between existing maintenance vehicles' air compressor systems, which reduces the need for further retrofit costs and eliminates the need to haul flammable liquids.

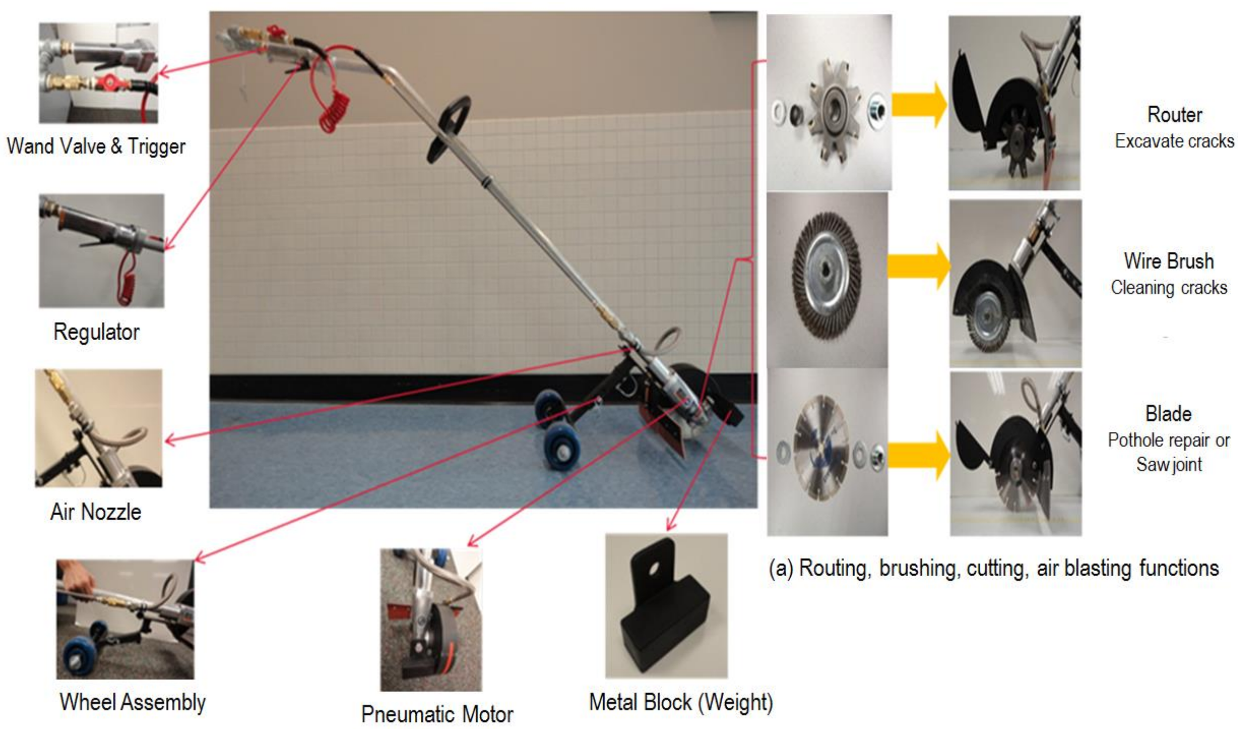


Figure 2.1 Versatile functions of CCD

2.1 Components

2.1.1 Key Components

The basic concept of the innovation incorporates four traditional crack/joint cleaning methods in one device: (1) wire brushing (wire brush), (2) routing (router), (3) saw cutting (blade), and (4) air blasting (air nozzle). The device uses a pneumatically driven rotary wire brush, a rotary router carbide bit to clean cracks of mid- to large size debris and vegetation. Also, a masonry cutting blade can be attached to create a saw joint on the concrete pavement. Directly behind the rotary attachment, an air blasting nozzle on the device (Figure 2.2) is used to simultaneously expel fine grained particulate like concrete dust, fine sand, old sealants, and winter de-icing chemicals from the walls and surfaces of the pavement cracks.

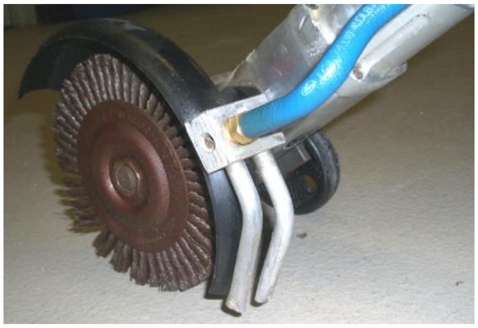


Figure 2.2 Behind wheel air nozzle

The device was constructed with a high torque pneumatic motor, machined aluminum pipes and associated fittings, and a varied selection of the rotary attachments. The device is also equipped with an optional guide wheel, ergonomically designed shaft, and a convenient trigger mechanism. Furthermore, the device can cut a pothole area with a rotary masonry cutting blade in conjunction with a jackhammer before placing a new HMA patch.

2.1.2 Metal Block

A metal block attached to the top of the motor provides weight to push the rotary motor down to alleviate user fatigue and to stabilize the CCD from bouncing torque. The weight of the metal block for routing is 10 lbs, which is 4 times heavier than the smaller block used for brushing and cutting (Figure 2.3).

Figure 2.3 Pneumatically powered rotary motor & metal blocks

2.1.3 Wheel Assembly

The design of the wheel assembly was changed from one wheel on the front right corner to two wheels behind the motor to absorb torque, thus reducing torque-induced fatigue in the CCD operator. This wheel configuration also allows the CCD to be free standing since the wheels are behind the center of gravity. The wheel assembly was designed as foldable for easy transportation but it was found to be too weak during the transportation. Thus in the later version (Figure 2.4(b)), the foldable wheel assembly was replaced with a larger and more stable structure. In addition, the wheels have been upgraded to rubber foam wheels in a larger size to add better stability and mobility.

(a) 2nd Generation : foldable wheel assembly

(b) 3rd Generation : Larger, more stable structure with larger rubber foam wheels

Figure 2.4 Rear wheel assembly design

2.1.4 Air Wand

Although plenty of air comes out of a nozzle behind the rotary attachment to clean loose particles from cracks, a larger volume of air is still needed to clean or chase away dirt, debris and/or vegetation on the pavement surface resulting from the routing or brushing process. Traditionally, a leaf blower or an air wand directly connected to an air compressor is used to clean the pavement surface after cracks are routed. To eliminate this additional task, a detachable air wand (3/8” inner diameter) was innovatively designed that is easily connected to the CCD (Figure2.5). After routing or wire brushing, the air wand can be used to clean cracks and the pavement surface, eliminating the process of disconnecting the CCD from the air compressor to use a traditional air wand to clean the pavement (Figure 2.6).

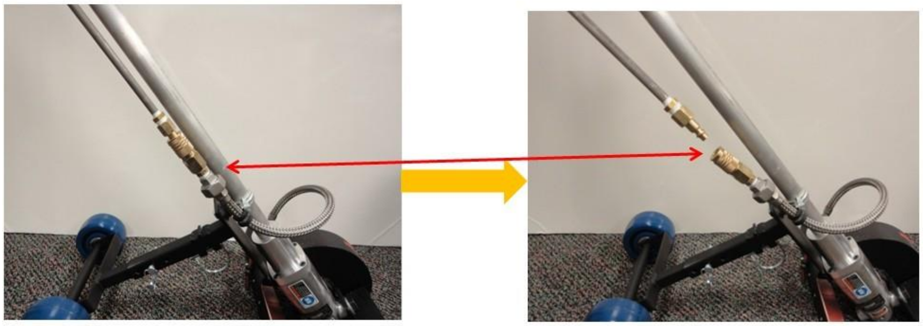


Figure 2.5 Easy connection of air wand

Figure 2.6 Using a detachable air wand for pavement surface cleaning by an NDOR crew

Chapter 3 Performance Tests

Eight CCD units were manufactured and delivered to each NDOR district in Nebraska, along with two-day sessions of training and demonstration. Then, the CCD units had been used by the NDOR crews during the entire crack sealing period of 2012-2013.

3.1 Training and demonstration at the NDOR

Two operation and safety training sessions were conducted for NDOR crews in October 2012 (Figure 3.1). Following the training session, an outdoor demonstration of the CCD was performed (Figure 3.2). Three attachments (blade, router and brush) installed in the CCD were tested on a precast concrete block (Figure 3.3) and on pavement. Also, an old sealant was removed by a router from the sealed joint on the concrete pavement (Figure 3.4).

Figure 3.1 Operation and safety training for NDOR maintenance crews

Figure 3.2. Crack cleaning units for demonstration at an NDOR district yard

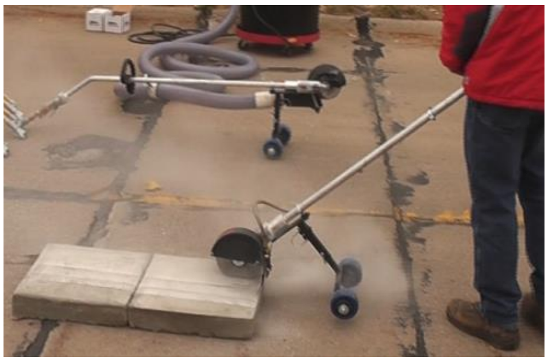


Figure 3.3 Creating saw joints on concrete

Figure 3.4 Removing old sealant from a concrete joint with a router bit attachment

<u>3.2 Field test: routing tests</u>

NDOR was particularly interested in replacing their current crack preparation methods (i.e., rotary impact router, air blasting and heat lancing) with the CCD's integrated routing and air blasting functions. Thus, routing was the main function tested with the NDOR districts.

While each district had used the CCD for the entire sealing season, the research team visited each district to measure the performance of the device from the field operation and get the feedback from the crews. From February to March 2013, several field tests had been conducted with the NDOR districts when they cleaned and sealed cracks on highways during the sealing season

(Figure 3.5). The main purpose of the NDOR field tests was to compare routing and air blowing functions of the CCD with the current NDOR practices of air blowing, heat lancing and routing. Quantitative data and users' feedback were collected during the field tests.

(a) CCD test

(b) Current conventional router comparison test

Figure 3.5 Field tests with the NDOR crews on highways

The routing function of the CCD was tested in conditions equal to those encountered while using conventional crack cleaning methods. Comparison data between the conventional router machine and the CCD based on the NDOR crew's feedback are listed in Table 3.1. The mechanism that integrates routing/wire brushing and compressed air allowed more efficient use of labor by reducing the crew size by one person. In addition, it was obvious that the CCD would be a far more economical alternative in terms of equipment purchase and maintenance cost and productivity, compared to the conventional router. Based on the field operators' statements, it is difficult to pull and control the direction of a heavy router especially against strong wind which is created by the nature or passing vehicles. On a downhill with a strong wind which creates a situation to push the router toward the operator, for example, the operator pays much more attention to push a stopper hard to avoid the dangerous situation that the router could run over him/her. However, the CCD requires pushing motion rather than pulling motion and does not have a large mass to be affected by wind, which allows ease of control over the device; thus providing safer working conditions.

Table 3.1 Field observed and surveyed comparison data between the conventional rotary impact router and the CCD router

	Rotary Impact Router (25 hp)	**CCD Router (1.25hp) (2nd Gen)**	**CCD Router (4.0hp) (3rd Gen)**
Estimated equipment cost	$12,000 + maintenance cost	$1,500 (expected) + no maintenance cost	$2,500 (expected) + no maintenance cost
Average productivity	1.67 miles/day	2.25miles/day	2.4 miles/day
Crew size	7 to 8, including flag person & truck drivers	6 to 7, one person (air blowing) eliminated	6 to 7, one person (air blowing) eliminated
Strength	Heavy, ideal for straight-line cracks or concrete joint	Safe, flexible, easy to load/unload, air blowing function combined	Safe, flexible, easy to load/unload, air blowing function combined
Weakness	Heavy, expensive, difficult for downhill and windy day operations (safety concerns); may create new cracks, not convenient to move	Requires a stronger motor (e.g., 3hp or greater). Weak foldable assembly.	All reported weaknesses are treated
Best working conditions	Longitudinal cracks, straight line concrete joint	Random cracks, longitudinal cracks, transverse cracks	Random cracks, longitudinal cracks, transverse cracks

Note that 3rd Generation was particularly designed with a stronger motor (4HP) for routing purpose while the previous model (1.25HP) can be used for brushing and concrete cutting works.

Through surveys and interviews with the NDOR crews, we identified that the primary concern with crack cleaning was to shorten the crack preparation time so the following crack sealing group would not need to wait. The conventional rotary impact router's general production rate is 12 to 15 ft/min (Smith and Romine 1993). The measured average productivity of the CCD router during the field tests was 26.1 ft/min, which can significantly improve the overall productivity of the crack sealing process (Table 3.2). Although the average performance was enhanced, there is slight inconsistency in the production rates. Transverse and longitudinal cracks are not always straight, that is they have different shapes of curves in different degree. In addition, different types of cracks (random vs. straight, wide vs. narrow), the slope of the roads and direction of working (uphill vs. downhill), and most importantly, the operators skills to handle all these issues are the factors affecting the productivity rates.

Table 3.2 CCD router production data

Test Sites		Average CCD Working Speed (ft/min)	Crack Type	Version of CCD
1	Palmyra, NE	28.8	Transverse cracks	CCD with increased weight and larger air wand
2	Fremont, NE	22.2	Random cracks	CCD with increased weight and larger air wand
3	Lincoln, NE	22	Old sealant removal from concrete joints	First version of CCD
4	Gibbon, NE	22.5	Longitudinal cracks	First version of CCD
5	Holbrook, NE	36.6	Longitudinal cracks	First version of CCD
6	O'Neill, NE	24.6	Longitudinal cracks	First version of CCD
Average		**26.1**		

3.3 Pothole repair for the City of Omaha

Recently a CCD unit was delivered to the City of Omaha road maintenance group for testing in pothole repair. The city's main interest was to test the CCD's ability to cut the asphalt pavement around a pothole area in conjunction with a jackhammer before placing a new patch. It was reported that 1.25HP CCD was enough to cut the pavement around a pothole. It was also suggested to use a lager rotary pavement cutting blade which enables the CCD to cut pavement up to 2” depth.

3.4 4HP CCD field test (3rd Generation)

Through the surveys and interviews, wire brushing and saw jointing functions with the 1.25hp motor were well accepted by the field crews at NDOR and the city of Omaha. However, there were some concerns when the CCD was used for routing cracks and removing old sealants with the 1.25HP motor. About three NDOR districts indicated that the CCD should provide more power and weight to efficiently rout cracks. To reflect the suggestions, a third generation of CCD was made mainly for routing cracks while keeping the previous 1.25 hp version for multi-functional purposes (e.g., brushing and cutting).

As the third generation is mainly designed for routing cracks, it is equipped with a stronger motor and more robust, stable structure while maintaining its ability to maneuver with ease and provide safety and high quality. With the help of Georgia DOT (GDOT) District 7, the new version was tested at the maintenance yard of GDOT District 7 on Feb. 7. 2014. Highly positive evaluation was collected and its high potential as a new alternative in cleaning cracks in pavements was acknowledged through demonstration and testing. The crews pointed out the key benefits as described as follows.

1. It was conveniently equipped with an air blower and the CCD operator can easily use it without requiring an additional labor following a router. This, in return, will entail a great advantage of saving labor costs while allowing better allocation of labor forces.
2. A high quality of crack cleaning was attained with relatively quick production rate.

The following are some other comments and observation from the test.

1. Good stability and easy control of the CCD was achieved even on irregular cracks.

2. The performance was much better than the previous version with a 1.25 HP motor.

Figure 3.6 shows the demonstration and testing conducted at the District 7 maintenance yard. Based on the field test and lab test, the productivity was measured. The main upgrade from the 2^{nd} generation to the 3^{rd} generation was the motor from 1.25 hp to 4 hp. Therefore, the obtained productivity can be deemed reasonable as it shows a slight improvement.

(a) CCD demonstration and test by a research team member

(b) Routed cracks

(c) Testing by GDOT crew

Figure 3.6 Test a 4HP CCD at GDOT District 7

Chapter 4 AHP & ECONOMIC ANALYSES

4.1 Selection of crack cleaning device using AHP

Selecting the right equipment has always been a key factor in the success of any construction project; this is even more so in today's complex, highly industrialized projects with various equipment options available for the same purpose (Shapira 2005; O'Brien et al. 1996; Schaufelberger 1999; Nunnally 2000; Harris and McCaffer 2001; Peurifoy et al. 2006). Various factors need be carefully considered and evaluated, and most importantly, the individual evaluations need be properly combined in a systematic manner. The analytic hierarchy process (AHP) is one of the well-known methods in multi-attribute decision making process. In selection of crack/joint preparation devices, three factors that are deemed the most important, are collected through a survey and examined with the AHP approach.

4.1.1 Concept of AHP

AHP approach was first introduced by Saaty (1980) and has been widely used in various decision making processes. A decision is typically affected by several factors with usually different levels of importance to the decision. The more number of criteria are involved in a decision making process, the greater complexity is entailed to the extent that a systematic process is desired to provide a more transparent and reliable solution to the decision makers. Before analysis is implemented, basic data are to be collected through a survey; a typical survey format is as follows in Table 4.1 (Satty 2008). All of the criteria are compared in a pair and an interviewee is to provide a relative scale of importance for each of the pair.

Table 4.1 Fundamental Scale of Absolute Numbers

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or Slight	

3	Moderate Importance	Experience and judgment slightly favor one activity over another
4	Moderate Plus	
5	Strong Importance	Experience and judgment strongly favor one activity over another
6	Strong Plus	
7	Very Strong or Demonstrated Importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, Very Strong	
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation

4.1.2 AHP analysis on criteria for crack cleaning devices

To perform an AHP analysis, criteria for the selection of crack cleaning devices were set and a survey and interviews were conducted with field crews and superintendents in eight districts at NDOR. The survey criteria are composed of three factors: safety, productivity and quality. Based on the survey results, the following table (Table 4.2) can be formulated as a pairwise comparison matrix (CM). This table is interpreted as follows. Safety factor is 7 times more important than Productivity factor, Safety Factor is 5 times more important than Quality factor, and Quality factor is 5 times more important than Productivity factor. By visual inspection, the interpreted results are seen unfitting, that is, the scales are mathematically not matching, showing a high level of disagreement. The results of an eigenvalue analysis provides important measures of the data, such as 3.18 and [0.9525, 0.0890, 0.2912] for λmax and the weights, respectively; λmax is a measure of consistency, which will be used to compute a consistency ratio, and the weights represent the relative importance of the three criteria (safety, productivity and quality), which will be rescaled such that the sum of the weights is one. Using λmax of 3.18, a consistency ratio (CR) is calculated and compared with a consistency limit value of 0.1. The computed CR value is 0.176 and is greater than the limit value, therefore, this data set is considered invalid.

However, this is, in fact expected from a visual inspection of the surveyed data. Although the data set turned out unacceptable, it still provides important information in terms of their ranking. It is obvious that safety is of paramount, then quality comes in-between safety and productivity: safety > quality > productivity. As proposed by Li (2013), this problematic CM can be managed by an IAHP method to obtain the weights of the three factors while satisfying the consistency check. In our analysis, however, a different approach was adopted to better account for various cases surveyed by different experts and to demonstrate the excellence of the proposed CCD over other crack cleaning devices. Utilizing the mathematical concept discussed previously that knowing relationships of two pairs defines a third relationship by a mathematical formulation. Figure 4.1 describes the logic of this formulation. A CM composed by these exact scales will generate a consistency index of 0.

Table 4.2 Pairwise Comparison Matrix for Criteria

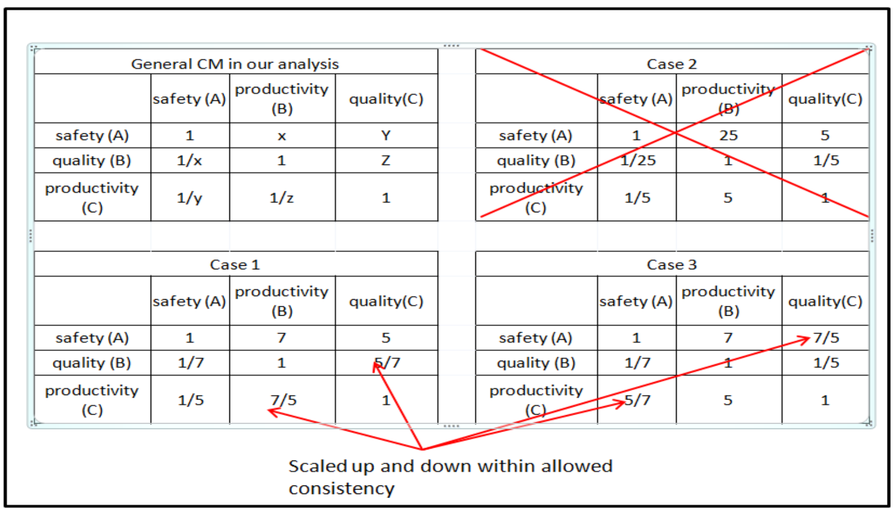
	Safety	Productivity	Quality
Safety	1	7	5
Productivity	1/7	1	1/5
Quality	1/5	5	1

A is x times more important than B = A/B = x
A is y time more important than C = A/C = y
B is z times more important than C = B/C = z
x = f(y,z), y=f(x,z), z= f(x,y)

	Case 1	Case 2	Case 3
First selected	A/B = 7	A/C = 5	A/B = 7
Second selected	A/C = 5	B/C = 1/5	B/C = 1/5
Third derived	B/C = 5/7	A/B = 25	A/C = 7/5

Figure 4.1 Calculation of a Third Scale Using Other Two Scales

In addition to this, the third scale for each case was further scaled up and down within the computed CR less than 0.1 in order to cover a variety of the experts' opinions. Figure 4.2 demonstrates how a third scale was varied and how a CM is formulated using these scales. As shown in Case 2, the derived scale of A/B is 25 and it is way beyond the maximum scale, 9, presented in Table 4.1. It means A is 25 times more important than B. Also considering the first selected scale in Case 2, A is 5 times more important than C. Therefore, it is reasonable to conclude that Case 2 is exceedingly dominated by the criterion A, and it is seemingly not an intended case of analysis. For this reason, Case 2 is discarded in further analysis.



General CM in our analysis			
	safety (A)	productivity (B)	quality(C)
safety (A)	1	x	Y
quality (B)	1/x	1	Z
productivity (C)	1/y	1/z	1

Case 2			
	safety (A)	productivity (B)	quality(C)
safety (A)	1	25	5
quality (B)	1/25	1	1/5
productivity (C)	1/5	5	1

Case 1			
	safety (A)	productivity (B)	quality(C)
safety (A)	1	7	5
quality (B)	1/7	1	5/7
productivity (C)	1/5	7/5	1

Case 3			
	safety (A)	productivity (B)	quality(C)
safety (A)	1	7	7/5
quality (B)	1/7	1	1/5
productivity (C)	5/7	5	1

Figure 4.2 CM per analyzed case

For Cases 1 and 3 with their varying third scales, an eigenvalue analysis was performed to obtain the weights of the criteria and consistency indices. Table 4.3 summarizes the results of the weights of A, B, and C and the corresponding consistency index (CI) and CR values. The weights presented in the table exhibits, as expected, a strong preference in the safety criteria (A) over the other two (B and C), while the quality criteria(C) is preferred over the productivity criteria (B). For further evaluation of the equipment selection, the performance levels with

Table 4.3 Weights of the criteria and their consistency checks

Exact scales

Case 1						Case 3					
vaying z	A	B	C	CI	CR	varying y	A	B	C	CI	CR
0.7143	0.745	0.106	0.149	0.000	0.000	1.4	0.538	0.077	0.385	0.000	0.000
0.2778	0.726	0.076	0.199	0.050	0.096	1	0.487	0.078	0.435	0.006	0.012
0.2857	0.726	0.076	0.197	0.047	0.090	1.5	0.549	0.077	0.374	0.000	0.001
0.3333	0.731	0.081	0.188	0.032	0.062	2	0.592	0.075	0.333	0.007	0.014
0.4	0.735	0.087	0.178	0.019	0.036	2.5	0.624	0.073	0.303	0.019	0.036
0.5	0.740	0.094	0.167	0.007	0.014	3	0.649	0.072	0.279	0.032	0.062
0.6667	0.744	0.104	0.152	0.000	0.001	3.5	0.670	0.070	0.260	0.047	0.090
1	0.747	0.119	0.134	0.006	0.012	3.6	0.673	0.070	0.256	0.050	0.096

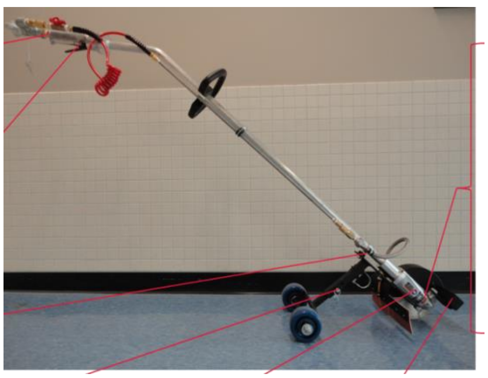
respect to the criteria for each alternative(CCD, router, air compressor, and heat lancer) have been accessed to assign a numerical evaluation . Figure 4.3 shows images of the alternatives. The participating experts and their crews were trained to properly operate CCD, and CCD was tested in crack cleaning work by them. A thorough evaluation with respect to the three criteria was made on CCD based on its performance on the test, and it was also compared with their previously adopted crack cleaning devices. The raw scores (a) of and the scaled scores (b) of the criteria for the alternatives are tabulated in Table 4.4. To evaluate the alternatives for a best recommended selection for a particular case (take an example of Case 3 with y = 1.5), their weights are incorporated into the corresponding scaled scores of each alternative. This evaluation is easily managed in a matrix calculation, and demonstrated in Figure 4.4 below. The same analysis was carried out for all the cases, discussed earlier and shown in Table 4.3.

Table 4.4 The raw scores and scales scores of the criteria for the alternatives

	CCD	**Router**	**Heat Lancer**	**Air Blower**

Raw score (a)	Safety	7	2	5	8
	Productivity	6	4	7	9
	Quality	8	9	2	1
Scaled score (b)	Safety	0.32	0.09	0.23	0.36
	Productivity	0.23	0.15	0.27	0.35
	Quality	0.40	0.45	0.10	0.05

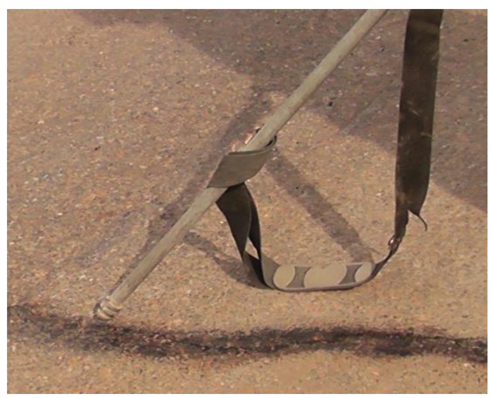
Scale : 1 = poor & 10 = best



(a) CCD

(b) Heat Lancer

(c) Router



(d) Air Blower

Figure 4.3 Crack cleaning devices

A x B = C

	Safety	Prod.	Qual.
CCD	0.32	0.23	0.40
Router	0.09	0.15	0.45
Heat Lancer	0.23	0.27	0.1
Air Blowing	0.36	0.35	0.05

x

	Weights
Safety	0.549
Prod.	0.077
Qual.	0.374

=

	Eval
CCD	0.3412
Router	0.2302
Heat Lancer	0.1828
Air Blowing	0.2449

Figure 4.4 Alternative evaluation based on the weighted criteria

4.1.3 Result of AHP analysis

Individual evaluations were aggregated and plotted in Figure 4.5. Case 1, Case3 and the combined Cases 1 and 3 are plotted in the left, middle, and right of Figure 4.5, respectively. Various cases analyzed are represented by colored circles, and circles of the same color are representations from the same conditioned case. The labels in the horizontal axis indicate the alternatives with 1 for CCD, 2 for a router, 3 for a heat lancer and 4 for an air blower. Generally speaking of the plot, it is apparent that the label 1(CCD) has obtained the highest rank among the alternatives. The left plot of Case 1 ranks the alternatives in order of CCD, air blower, heat lancer, and router. It also shows a small range of dispersion, meaning that it is relatively insensitive to the varying z values. Compared with Case 1, Case 3 indicates more balanced importance factors (lower safety, higher quality), yet in the same order of importance as in Case 1. The rank from this plot is, on average, CCD, air blower, router, and heat lancer. This has a higher level of dispersion, meaning more sensitive to the varying y. Some instances of Case 3 prove this by showing a swap of rank between router and heat lancer, and between router and air blower. Taken all together, the CCD proves to be the best selection, strongly recommended based on the various simulations. More important is that this result is insensitive to the changes in the variables, therefore, the CCD will likely be the most favorable option in any case.

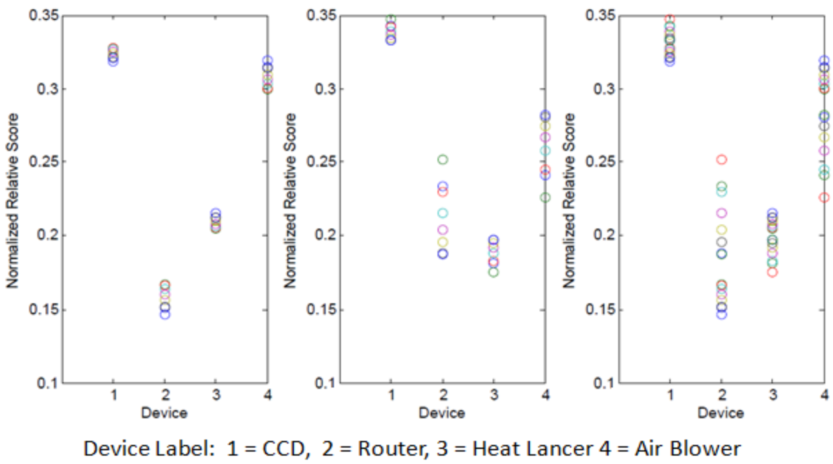


Figure 4.5 Aggregated evaluation of the alternatives; left (Case 1), middle(Case 3), right(combined)

4.2 Economic Analyses

4.2.1 Overview and adjustments/assumptions

AHP analysis demonstrated the excellence of CCD over widely used existing crack cleaning devices, in terms of the performance. With that proved, an economic feasibility analysis follows in this section to reinforce the justification of the adoption of CCD for future cracking cleaning projects. The economics feasibility analysis includes an annual cash flow analysis, a benefit-cost ratio analysis and a payback period analysis. For these particular analyses, the following assumptions and adjustments on the surveyed data are made.

1. Qualitative differences, such as safety and quality, are not considered in the economic analysis. AHP has demonstrated the superiority of CCD over other devices for these criteria, therefore, the economic analysis only focuses on quantitative monetary measures.
2. Cost data obtained from the survey are scaled, if necessary, such that the working hours per day and the working days per season are 8 hours and 40 days, respectively.
3. Labor cost and fuel costs are assumed \$15/hour/person, \$5/gallon for gasoline and \$1.5/lb for propane gas, respectively.

4. In order to avoid complication in economic analyses introduced by different alternative service lives, an annual cash flow analysis is performed. An identical replacement is assumed to be provided at the end of the equipment's service life.
5. The CCD employees a pneumatic motor, which is a relatively simpler mechanical system compared with other devices, such as a router's gasoline engine. Because of its simplicity in mechanical design, it is expected to have a service life at least that of a router. However, a 5 year service life was conservatively assumed for the following economic analyses.

Cost data have been collected along with the performance evaluation per the experts' best knowledge and experience. The collected data indicate that some of the experts completed survey on certain devices only because of lack of enough knowledge and experience in the other devices. Scrutiny of the data reveals that they are matching relatively well without showing any outliers, allowing smooth data transition for an economic analysis. Table 4.5 shows a breakdown list of expense items and components in each item. As per the adjustment 2, the data were scaled and their averages were computed. Note that as an air compressor follows CCD, a heat lancer and an air blower, the fuel cost of the air compressor was added to each of them. As an air blower accompanies with a router, the fuel of the air blower was added to the cost of the router.

A routing task requires one more crew than other devices. Figure 4.6 pictorially demonstrates the need of an additional labor required in the use of router. Using CCD, one laborer can easily operate its air blowing function following the routing function, while a router requires an additional labor to do the same task. An annual (seasonal) expense is calculated by summing up the average operation, maintenance and repair, fuel and labor costs. Table 4.6 shows an example of summarized surveyed cost information adjusted as per adjustments 2 and 3. The equipment costs and seasonal expenses data are extracted into Table 4.7 for further economic analyses. Table 4.7 tabulates the cash flow data computed as explained above.

Table 4.5 List of expense items and their components

	CCD	Router	Heat Lancer	Air Blower	Air compressor
Equipment Cost ($)	2500	12000	2340	100	NA
Number of Cutter	1	5	NA	NA	NA
Cutter Cost($)	76	76	NA	NA	NA
Cutter replacement (per season)	12	3	NA	NA	NA
Fuel (gal/day)	NA	8	NA	NA	14
Propane (lb/day)	NA		30	NA	NA
Crew size for crack clean	1	2	1	1	NA
Crew size for trucks, flags, sealing, etc	6	6	6	6	NA
Working hours per day	8	8	8	8	NA
Working days per season	40	40	40	40	NA
Maintenance	0	62.2	10	10	NA
Repair	0	107	0	NA	NA
Expected equipment service life	5	9	11	11	NA

Table 4.6 An example of summarized surveyed cost information

	CCD	Router	Heat lancer	Air blower
Equipment cost($)	**2,500**	**12,000**	**2,340**	**100**
Operation cost($/season)	400.00	1,200.00	600.00	400.00
Maintenance cost($/season)	855.00	1,074.96	10.00	10.00
Fuel cost($/season)	2,900.00	6,300.00	5,540.00	2,900.00
Crew size for crack clean	1	2	1	1
Crew size for trucks, flags, sealing, etc.	6	6	6	6
Labor cost($/season)	33,600.00	38,400.00	33,600.00	33,600.00
Seasonal Expenses($)	**37,755.00**	**46,974.96**	**39,750.00**	**36,910.00**
Expected service life(years)	**5**	**9**	**11**	**11**

(a) CCD : Cleaned crack

(b) Router : Cleaned crack, requiring a separate application for air blowing

Figure 4.6 Cleaned crack comparison between CCD and a router

Table 4.7 Cash flow data

	CCD	Router	Heat lancer	Air blower
Equipment cost($)	$ 2,500	$ 12,000	$ 2,340	$ 100
Seasonal Expenses($)	$ 37,755	$ 46,975	$ 39,750	$ 36,910
Expected service life(years)	5	9	11	11

Note: seasonal expense includes the average operation, maintenance and repair, fuel and labor costs.

4.2.2 Equivalent annual cash flow analysis

An equivalent uniform annual cost (EUAC) was calculated based on the data in Table 4.7. The equipment cost for each alternative was simply converted to EUAC based on an assumed internal rate of return (IRR) (i = 5%, 10% and 15%), then added to the seasonal expenses to obtain total EUAC. Figure 4.7 graphically displays and compares the EUAC results. The high value on the ordinate means the higher seasonal costs expected from using the corresponding device. The results are almost invariant with respect to the IRR considered. The equipment costs are insignificant compared with the seasonal expenses, therefore the effects of the initial investments with different IRR's are negligible. The EUAC's are in order of Router, Heat Lancer, CCD, and Air Blower from high to low. In addition to the rank, the plot discloses another important fact that the total EUAC of Router is exceedingly higher than the others.

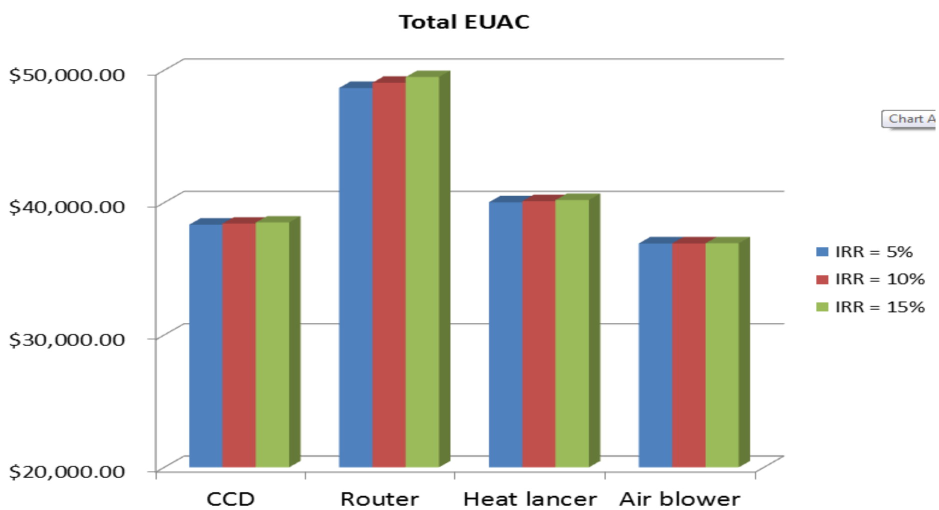


Figure 4.7 Total EUAC of the alternatives

4.2.3 Benefit/Cost ratio Analysis (B/C)

This section carries out a B/C ratio analysis based on the cash flow shown in Table 4.7. Additional assumption made here is that state DOTs make a new purchase of CCD and utilize it in their pavement cleaning work instead of using the devices they previously owned (router, heat lancer, and air blower). Benefits are estimated as the profit coming from using CCD over the other devices, that is, the difference between the annual expenses of other devices and that of CCD. This is the equivalent uniform annual benefit (EUAB). Initial investment is then converted to EUAC based on assumed IRR's of 5%, 10% and 15%. For an alternative to be favorable over one another by a BC ratio analysis, the BC ratio is required to be greater than 1, meaning the projected benefit is greater than the projected costs. Table 4.8 below summarizes the BC ratio results of the alternatives compared with CCD. The cases of router and heat lancer are greater than 1.0, meaning that the benefit exceeds the cost, thus the replacement with a CCD is favored in this sense. However, the case of air blower indicates with its BC ratio less than 1, the use of CCD as an undesired replacement in a purely economic sense.

Table 4.8 B/C ratio compared with CCD

Use of CCD Over				
		Router	Heat Lancer	Air Blower
BC ratio	IRR=5%	16.0	3.45	-1.46
	IRR=10%	14.0	3.03	-1.28
	IRR=15%	12.4	2.68	-1.13

4.2.4 Payback period analysis

A simple payback period analysis was performed to demonstrate the monetary benefits expected from using a CCD over the currently employed device, such as a router and a heat lancer. The annual benefit from using a CCD was deemed as the positive difference between the expense of the currently employed device and that of CCD. Since using a CCD requires an initial investment of purchasing it, the cost for each of the cases (router and heat lancer) will include a purchase of a CCD. Table 4.9 tabulates the initial investment to employ a CCD, the annual benefits, and the corresponding payback period. It is found that the payback period is short, less than one year for a router and less than two years for a heat lancer. This attributes to the fact that the initial investment in a new CCD is relatively small while the monetary expected benefit is high. The author considers that a simple payback period analysis is well enough without taking it into a more detailed analysis, such as a discounted payback period analysis, as the benefits are outstanding and a quick payback is expected.

Table 4.9 Payback period analysis

	Router	Heat Lancer	Air Blower
Initial Investment	$2500	$2500	$2500
Annual Benefit	$9220	$1995	-$845
Payback Period	Approximately a quarter of a year	Approximately one and a quarter years.	NA

Note that an air blower requires a less amount of annual expense than a router. Payback period analysis does not apply to this case, which implies that air blower is economically better than CCD.

4.3 Section summary & analysis of the results

Table 4.10 summarizes the AHP and the three economics analyses (EUAC, BC ratio, payback period) conducted this in chapter. Note that the AHP results are the representation of the average of all of the simulations with varying y and z, where y and z are scales defining the relation between the safety factor and the quality factor, and the relation between the productivity factor and the quality factor, respectively. For the EUAC and BC ratio analyses, the case with IRR of 10% is shown in the table.

Table 4.10 Summary of AHP and Economics analyses

	CCD	Router	Heat lancer	Air blower
AHP Avg Score over all simulations	0.331	0.186	0.199	0.284
EUAC at 10%	$38,414	$49.059	$40.110	$36.925
BC ratio at 10% compared with CCD	1	14	3.03	-1.28
Payback Period	NA	~ 0.25 year	~ 1.25 year	NA

Note that the payback period analysis excludes the case of CCD and that of air blower.

The results from the EUAC and BC ratio economic analyses show the same order of preference of the alternatives; Air Blower > CCD > Heat Lancer > Router. Two important facts can be drawn from the economic analyses besides the rank. First, the results are insensitive to the IRR. Second, the initial investments of the alternatives are much smaller than the annual expenses. These two facts are highly correlated. It is seen from the second observation that the annual expenses are a dominating factor, therefore, the most important consideration. The fact that varying IRR does not have any significant impact on the annual expenses, explains the first observation. Table 4.8 from the B/C analysis presents a better comparison among the alternatives by showing their benefit/cost ratio.

Based on the results of the two analyses, router is far worse than the other alternatives due to the following reasons. First, it needs one more laborer than the other alternatives for air blowing, which adds $15/ hour equivalent to $120/day equivalent to $4800/season. This difference of $4800 is computed based on the general adjustments (40 days / season, 8 hours / day), and it is likely that it could be higher when the actual condition is compared with our assumptions. Even more, when a router is compared with the initial investments of the other alternatives ($2500 for CCD, $2340 for heat lancer, $100 for air blower), this difference is considerable. The additional laborer uses an air blower to blow out loose particles and debris in cracks, which add up more operating and maintenance costs. In addition, a router is relatively heavy equipment compared to the others, which is generally more costly with meticulous maintenance. Although these are not as significant, they partially account for the high costs incurred in the use of router. The discussion made in this section is only within the scope of economics.

Chapter 5 CONCLUSIONS

In this report, crack cleaning field tests were conducted in several districts in Nebraska to evaluate the effectiveness of CCD and compare with the current crack cleaning device. With evaluation/feedback from NDOR and the City of Omaha, the CCD was further upgraded to a 3rd generation. Then, an additional crack cleaning field test was carried out at GDOT District 7. Based on the collective evaluations/comments from NDOR, City of Omaha, and GDOT, high potential in the CCD for improving the crack/joint preparing practice was found. Not only proving its excellence in performance, but a feasibility analysis was carried out to ascertain its practicality in an economic sense.

The advanced CCD has been developed from an initial prototype to a multi-functional device with some real merits. At the close of this project, the research team concludes major findings as follows:

- Several field tests for routing cracks have been performed on highways throughout the state of Nebraska with NDOR crews in each district. Eight CCD units were prototyped and used at each NDOR district for the entire sealing season in 2012-2013. Positive and promising feedback was collected. The feedback shows that the CCD can be used in conditions equal to those present with current crack cleaning methods; it works well on meandering cracks; its use can reduce the crew size by one person (blowing); it increases production rate; and it offers a safer alternative to conventional methods.
- Most of the districts reported that saving time can be achieved with the use of CCD. This serves as the most critical finding knowing that the primary concern of crack cleaning method was saving time.

A few positive feedback were obtained as well with respect to maneuver, control and safety. Some of the negative feedback pointed out to a small motor for routing work, a weak wheel assembly, and short wheel-to-wheel distance. Also, few suggested a heavier metal block to alleviate the physical effort to push down the CCD. Based on the feedback and recommendations from the field evaluations, moderate design modifications mainly for routing task were made, which produced a 3rd generation CCD. The major upgrades are as follows:

1) Increase weight of a metal block from 2.5 lb to 10 lb.
2) Increase Cubic Feet per Minute(CPM) for air wand (at least 3/8" ID)
3) Replace the foldable wheel assembly with a larger and more stable structure
4) Provide rubber foam wheels in a larger size to add better stability and mobility.
5) Use a more powerful motor with larger torque for routing cracks (upgraded from 1.25hp to 4hp)

Testing of the 4hp CCD at GDOT demonstrated the similar benefits, such as reducing the crew size (blowing), high quality, easy control, and saving time. Comparing with the previous version, it was observed that this new generation CCD significantly improves the quality of routed cracks and provides a safer control/maneuver while maintaining all the other advantages the previous version had.

In addition to the field test and analyses, an AHP analysis and an economic analysis were conducted on the CCD and three existing crack cleaning methods. In the AHP analysis, three factors, such as safety, quality and productivity were considered while the economic analysis examined each of the alternatives in various ways. The AHP indicated the highest importance on the safety factor, then the quality factor followed by the productivity factor in a descending order. Although air blower was ranked #2 in AHP analysis and #1 in economic analysis, the quality produced from it may not be acceptable depending on the type of work due to its very limited cleaning capacity. So the adoption of air blower for general crack cleaning method was not recommended. The economic analysis indicates the economic preference levels in order of air blower, CCD, heat lancer and router. With the same reason, the option of air blower was disregarded due to the quality issue; thus, the CCD was the best option of all in all of the analyses performed herein, especially far better than the most generally used device, a router.

It is worth making a brief comparison of the proposed device (CCD) with a router. Total EUAC's for the CCD and a router are approximately $37,000 and $48,000, respectively, and the BC analysis indicated that the replacement of a router with the CCD would deliver a high level of benefit with a BC ratio of about 14. In addition, the payback period (Table 4.10) shows that the investment in purchasing a CCD is expected to get paid back less than a year.

In summary, the various field tests and evaluation revealed satisfactory achievements in performance, quality, safety and control, and also high potential in the utilization of CCD in crack cleaning practice. The AHP analysis shows the CCD to be the best alternatives based on the weighted criteria, such as safety, productivity, and quality. Additionally, the three economic analyses show a high level of economic advantages from the use of CCD over other devices, especially a router. Based on the positive results obtained from this project, this research recommends the CCD for the pavement crack cleaning work for sealing.

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Appendix A. Survey Questions

1. What is the current method being used to clean cracks?
   - Compressed air
   - Router bit
   - Wire brush
   - Other______________

2. What method is currently being used to dry moisture in the cracks before they are sealed?
   - Open flame
   - Shielded flame
   - Nothing
   - Other______________

3. Was the crack cleaning device (CCD) tested against the current method in as equal of conditions as possible?
   - Yes
   - No

4. What was the outcome of the test?
   - Save time
   - About the same time
   - Took longer

5. What would be the expected quality of sealed crack sealing using the CCD?

6. How do you feel about the CCD compared with currently methods?
   - Works excellent
   - Performs average
   - It still needs to improve

7. How many people are used to prepare the cracks for sealant in the current method used?

8. What would be the estimated hourly cost in preparing cracks (not including sealing process)?

9. How did the CCD perform?

10. Where there any troubles with any part of the process? (i.e. – air supply, air motor, attachment, bushing, etc.)

11. How long each attachment lasts in terms of linear length of cracks/joint (e.g., 500ft, 1 mile)?
    - Brush:
    - Routing bit:
    - Blade(concrete vs. asphalt, if any):

12. Does the CCD have enough power to do the necessary work?

13. Any suggestions to improve the performance of the CCD?

Appendix B. Cost/productivity/preference survey questions

	CCD	Router	Heatlancing	Air wand blowing	Air compressor	example answers
equipment cost						$11,500
# cutters per router						5
cutter cost						
cutter replacement frequency (per sealing season)						2 times per season
fuel (gasoline) consumption(gallons per day)						3 gallons
Propane consumption(LBs/ day, and cost/day)			_____lbs/day ________ $ /day			50lbs per day, $70/day
Distance coverage (one lane length) per day (mile)						2.2 miles
No. of working hours per day						8 hours
Average No. of working days per sealing season(e.g., October-March)						80 days
oil change and other maintenance cost per season						$50/ season
Repair cost if any ($/season)						$100/season
Expected equipment service life (years)						7 years

Please identify important factors that you feel more important below:

	Which factor is more favorable over another?	How much the selected factor is favorable over another? (1-5)*
Safety vs. Productivity		
Safety vs. Quality		
Productivity vs. Quality		

*Weights
1: Two factors contribute equally
2: Slightly favor one factor over another
3: Moderately favor one factor over another
4: Strongly favor one factor over another
5: One factor dominates another