Center for Environmentally Sustainable Transportation in Cold Climates

Continued Field Evaluation of Precutting for Maintaining Asphalt Concrete Pavements with Thermal Cracking

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13. ABSTRACT (Maximum 200 words) In continuation of a previously completed project entitled *Evaluate Presawn Transverse Thermal Cracks for Asphalt Concrete Pavement*, this project was a further effort to understand important variables in the thermal cracking process through continued field monitoring of three precutting test sites in Interior Alaska. The test sites included (1) Phillips Field Road, precut in 1984 (≈ west ¼ mile of this road), (2) Richardson Highway precut in 2012 (≈ MP 343–344), and (3) Parks Highway precut in 2014 (≈ MP 245–252). Preliminary results at relatively short periods (up to 4 years) indicate that precutting is an economically promising way to control natural thermal cracks. Even short-term economic benefits appear to range between about 2% and 21%. The degree to which precutting works for an AC pavement appears to be a function of the thickness and general structural robustness of new construction. Shorter precut spacing, along with stronger and/or thicker pavement structures, looks promising with respect to crack control. Continuing evaluation and monitoring of test sections are needed to recommend an effective design methodology and construction practice for Alaska and cold areas of other northern states.			
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CONTINUED FIELD EVALUATION OF PRECUTTING FOR MAINTAINING ASPHALT CONCRETE PAVEMENTS WITH THERMAL CRACKING

Final Report

by

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EXECUTIVE SUMMARY

This report presents a continued effort to evaluate the precutting technique for maintaining asphalt concrete (AC) pavements with full-width transverse thermal cracking.

A recent study of Alaska's main system of asphalt paved roads evaluated thermal crack sealing/filling and found that little if any maintenance was necessary over the life of the pavement if natural full-width thermal cracks were more or less linear in shape and without bifurcations, spalling, or other severe forms of damage. Precutting of full-width thermal cracks is intended to provide an ideal pattern from which easily maintained natural thermal cracking will develop, as will be explained. Development of well-formed thermal cracking at predictable locations by way of precutting (specifically aimed at improved maintenance) was the objective of this research.

Precutting is akin to the way in which a diamond-scribed line aids accurate cutting of glass. It had been observed and documented in Alaska and elsewhere that precuts can, depending on certain variables, heavily influence the location of natural thermal cracking, even to the point of incorporating development of the natural cracks within the precuts themselves. A precut becomes "active" after a natural thermal crack has developed within it.

Three Interior Alaska precutting test sites were included in this study: (1) Phillips Field Road within the Fairbanks city limits, precut in 1984 ($\approx$ west ¼ mile of this road), with a single evaluation in 2016, 32 years after its construction, (2) Richardson Highway about 20 miles east of Fairbanks, precut in 2012 ($\approx$ MP 343–344) with four field surveys (2013, 2014, 2016, and

2017), and (3) Parks Highway about 100 miles south of Fairbanks, precut in 2014 ($\approx$ MP 245–252) with three field surveys (2015, 2016, and 2017).

The precut section at Phillips Field Road was the ADOT&PF's first attempt to investigate precutting as a method for potentially reducing thermal crack maintenance in Alaska. The 1984 construction of this section included a new 2-inch AC layer on new base course plus 4 to 6 feet of new embankment. The precutting treatment consisted of cutting thin slots through the pavement to within about ¼ inch of the bottom of the new AC layer at a spacing of 50 feet. Since then the section has received heavy traffic for the entire 32-year period. Thirty-two years of casual observation plus a final careful inspection and mapping of thermal cracks in 2016 indicated that precut treatment is a great success, as very few natural transverse thermal cracks developed outside of the precut locations. In this precut test section, many individual precuts became active.

In 2012, a 1 mile precut section was built during a Richardson Highway repaving construction project, which involved only about the top 6 inches of the existing pavement structure, leaving thermal cracks in the underlying unbound materials. The test section included four subsections of ¼ mile each: Subsection 1, a control subsection with no precutting; Subsection 2, with precuts at 25-foot spacing; Subsection 3, with precuts at 40-foot spacing; and Subsection 4, with irregular spacing, that is, precutting only at original thermal crack locations. Within subsections 2, 3, and 4, precut depths of 0.5, 1.0, and 1.5 inches were used to examine the effect of that variable. Preliminary study of this section was presented in a report entitled

Evaluate Presawn Transverse Thermal Cracks for Asphalt Concrete Pavement (Liu et al. 2015). Precut test sections were built within a 1-mile section of the Alaska Department of Transportation and Public Facilities (ADOT&PF) Richardson Highway Mile 340 to 346 project in 2012. Crack surveys and data collection were conducted at the test sections to compare various precut strategies (variations of cut spacing and depth) with the locations of natural major transverse cracks both before and after construction. Preliminary findings from field observations based on data obtained in 2013 and 2014 and numerical analysis results showed that the precutting technique is promising in controlling thermal cracking in AC pavements.

In 2014, a 10-mile reconstruction project near Healy, Alaska, included precuts in four separate roadway sections representing major variations in new embankment thicknesses and pavement structure designs used within the project, for a total of almost 12,000 centerline feet of experimentally precut roadway.

Conclusions:

- Conclusions regarding the Phillips Field Road precut test section were based on 32 years of casual observations and a final careful inspection and mapping of thermal cracks in 2016. The 1984 construction of this section included new pavement plus 4–6 feet of new embankment. This test section received heavy traffic for the entire 32-year period. The precut treatment is considered a great success, as very few natural transverse thermal cracks developed outside of the precut locations. In this precut test section, many of the precuts became active.

- Conclusions regarding the Richardson Highway – Moose Creek and the Parks Highway – Healy precut test sections were based on preliminary results in relatively short periods. Continuing evaluation and monitoring of test sections are needed to be able to recommend an effective design methodology and construction practice for Alaska and cold areas of other northern states. Precutting treatments at these sites indicate the technique to be an economically promising way of controlling natural thermal cracks. Considering the cost of precut installment and crack sealing maintenance, even short-term economic benefits, evaluated after 3 to 5 years of service, appear to range between about 2% and 21%. For reasons previously discussed, indications are that continued field observations will increase these percentages.
- According to preliminary results, shorter precut spacing along with stronger and/or thicker pavement structures appears promising with respect to crack control. Also, there may be an optimum precut depth that produces the best results, although an optimum was not determined as part of this study.
- Crack sealing after precutting using a thin blade (1/8-inch width) is likely not necessary for the life of the pavement, whether or not the precut becomes an active thermal crack.

Recommendations:

- For all new construction that includes new AC pavement and at least 4 feet of new embankment, use the precutting technique with the expectation of achieving nearly complete control of transverse thermal crack locations. Long-term economics should be highly beneficial. It is anticipated that little or no sealing/filling of transverse thermal cracks will be required for the design-life of the pavement.
- For all new construction that includes new AC pavement and less than 4 feet of new embankment, use the precutting technique with the expectation of achieving significant control of transverse thermal crack locations. Long-term economics are predicted to be positive and, in terms of required crack sealing, may provide a 20% cost advantage compared with no precutting.
- Recommended precutting interval = 35 feet.
- Recommended precut depth = ¾ of total asphalt concrete pavement thickness.

CHAPTER 1.0 INTRODUCTION

1.1 Problem Statement

Road-width thermal cracks (major transverse cracks) are perhaps the most noticeable form of damage on asphalt concrete (AC) pavements throughout colder areas of Alaska; they affect long-term maintenance costs and the driving public's perception of road performance. Low-temperature cracks are extensive enough that a significant portion of the Alaska Department of Transportation and Public Facilities (ADOT&PF) Maintenance and Operations budget is allocated to sealing and associated work required to repair them.

Long-term observation of Alaska pavement performance and decades-old field tests in Minnesota and Alaska have demonstrated that a lower-cost but equally effective form of maintenance is feasible. Saw cutting of slots across the pavement (precutting thermal cracks, Figure 1.1a) has shown promise in controlling the location and physical characteristics of subsequent thermal cracks as well as localized pavement degradation (spalling) usually associated with natural thermal cracking (Figure 1.1b). However, a systematic approach has not been developed to implement application of precutting in AC pavements. Variables in the thermal cracking process must be further understood. Furthermore, development of a precutting technology needs to consider (1) new pavements placed on new embankments and (2) new pavements placed on existing embankments—the latter having already developed thermal cracking in the sub-pavement aggregate. It was decided that both forms of new pavement construction (with and without new embankment) would be evaluated regarding the possible benefits of precutting.

(a) Precut (b) Natural crack

Figure 1.1 Cracks on the road

The efficacy of precutting transverse cracks is based on past observations indicating that (1) sooner or later nearly all AC pavements in Alaska develop natural transverse thermal cracking, and (2) transverse precuts installed during construction can provide weakened locations where natural cracking can later occur. When a natural transverse thermal crack develops within a precut, the natural crack is said to have become *captured,* and the precut is said to have become *active.* The width of an active precut crack varies as a function of local air temperature in the same manner as any natural transverse thermal crack.

Regarding thermal crack formation, the subject of this report, the ADOT&PF currently recognizes two distinct and common types of thermal cracks simply produced by air temperature variations. The major transverse thermal crack type is shown in Figure 1.1b. The identifying features of this crack type are that the crack **extends completely across the paved road surface** and is **at least generally perpendicular to the centerline**. These thermal cracks extend through the pavement layer and well into the granular material below. Although they are often nearly linear features, the cracks may exhibit various irregularities including doglegs and single or multiple bifurcations.

A second common type of thermal cracking forms a grid-like (box-like) pattern, in Alaska termed *lesser thermal cracks*. These cracks, which do not extend below the asphalt pavement, are not addressed in this report.

1.2 Background

In the fall of 1984, a new 2-inch AC layer was constructed on new base course and several feet of new embankment at the Phillips Field Road test section. This project was the ADOT&PF's first attempt to investigate precutting as a method for potentially reducing thermal crack maintenance in Alaska. The basic idea at that time was that if thermal cracks could not be prevented, perhaps it would be possible to create a more acceptable, more easily maintainable form of transverse thermal cracking. The precutting treatment consisted of cutting thin slots through the pavement to within about ¼ inch of the bottom of the new asphalt concrete layer. The thin saw cuts were made perpendicular to the road's centerline and from pavement edge to pavement edge at a spacing of 50 feet. The 50-foot precutting interval was chosen because it was the average of many measurements of natural thermal crack spacing from previous research in Interior Alaska. Though the Phillips Field Road precut section appeared, through informal observation, to remain in very good condition for more than 30 years, there had been no formal evaluation of this test section since its 1984 construction.

In 2012, a 1-mile precut section was built in a Richardson Highway repaving construction project. As opposed to the new embankment and pavement placed at Phillips Field Road, the Richardson Highway construction involved only about the top 6 inches of the existing pavement structure—leaving the old system of transverse thermal cracks in the underlying unbound materials. The test section included four subsections of ¼ mile each: Subsection 1, a control subsection with no precutting; Subsection 2, with precuts at 25-foot spacing; Subsection 3, with precuts at 40-foot spacing; and Subsection 4, with irregular spacing, that is, precutting only at original thermal crack locations. Within subsections 2, 3, and 4, precut depths of 0.5, 1.0, and 1.5 inches were used to examine the effect of that variable. Counts of natural transverse thermal cracks at various times from this project revealed that precutting exerted significant control over the frequency of natural thermal cracks appearing since repaving. Since the construction in 2012, precutting in subsections 2 and 3 has resulted in less visible new thermal cracking than has appeared in the control section (Subsection 1). Note that, according to an evaluation of these test sections in late 2014, subsections 1, 2, and 3 each exhibited a higher count of natural thermal cracking than the count prior to the 2012 construction; this was both unexpected and significant, as it suggests that the 2012 construction process itself may have somehow accelerated the thermal cracking process. Only the precutting method used in Subsection 4 actually decreased the natural thermal crack count from the preconstruction (pre-2012) count. The degree to which various precut depths might influence natural thermal cracking had not been determined at the time that those findings were reported.

In 2014, a 10-mile reconstruction project near Healy, Alaska, included precuts in four separate roadway sections, for a total of almost 12,000 centerline feet of experimentally precut roadway. Four sections were needed to represent major variations in new embankment thicknesses and pavement structure designs used within the project. The newly constructed Parks Highway sections had not been evaluated prior to work done for this report.

1.3 Objectives

The objective of the proposed research was to increase the understanding of important variables in the thermal cracking process through long-term field monitoring that can address new pavements placed on new embankments, and new pavements placed on existing embankments—the latter having already developed thermal cracking in the sub-pavement aggregate—and to develop a systematic approach for implementing application of precutting in AC pavements. The objective was achieved through continuing to evaluate the three sites in Interior Alaska where pavement had been precut:

(1) Phillips Field Road within Fairbanks city limits, precut in 1984 (≈ west ¼ mile of this road).

(2) Richardson Highway about 20 miles east of Fairbanks, precut in 2012 (≈ MP 343–344).

(3) Parks Highway about 100 miles south of Fairbanks, precut in 2014 (≈ MP 245–252).

1.4 Research Methodology

The following tasks were completed to fulfill the objective of this research:

- Task 1: Literature Review
- Task 2: Field Monitoring
- Task 3: Comparison of Thermal Cracking and Analysis
- Task 4: Reporting and Recommendations (Deliverables)

1.4.1 Task 1: Literature Review

As this study was a follow-up study of the previously completed project, *Evaluate Presawn Transverse Thermal Cracks for Asphalt Concrete Pavement* (Liu et al. 2015), efforts under Task 1 focused on reviewing practices of precutting methods used in other northern states such as Oregon and Minnesota, for reference and comparison.

1.4.2 Task 2: Field Monitoring

Task 2 involved monitoring the Richardson and Parks Highways precut sections periodically, and a single evaluation of the Phillips Field Road precut pavement section, including pavement surveys, photos, and documenting the intensity and extent of transverse cracks and other distress types observed. Types of field evaluation procedures and data collected included the following:

- Count non-precut cracks (natural cracks) and record crack spacing within each test section
    - Compare counts between various sections and subsections
    - Create graphic crack "maps" as part of the reporting process
- Describe the morphology of the various natural crack types that appear within each section/subsection

Reporting included performance observations and results of appropriate measurements (such as crack width, crack depth, crack patterns, deterioration around precut locations, etc.). High-quality photos were included.

1.4.3 Task 3: Comparison of Thermal Cracking and Analysis

Field surveys had been conducted to evaluate thermal cracks in other northern states such as Washington, Montana, and Minnesota. In Task 3, information from those studies was compared with Alaska data collected from Task 2. Results were also compared and correlated with those from the previously completed Alaska project. A cost analysis was conducted to assess the savings on maintenance costs due to the precutting application.

1.4.4 Task 4: Reporting and Recommendations (Deliverables)

Task 4 provided a final report with implementation recommendations concerning precutting practices for ADOT&PF during construction of AC pavements. Recommendations included specifics regarding precut spacing, precut depth, and advisory statements concerning cost-effectiveness.

CHAPTER 2.0 LITERATURE REVIEW

The complete literature review is contained in Appendix A of this report. The following is a brief summary of the review.

Thermal cracking is a common form of distress in AC pavement in the northern United States and Canada. It generally occurs transversely across the width of the pavement (Anderson 2001). Specifically, in Interior Alaska, road-width thermal cracks (major transverse cracks) are possibly the most noticeable form of damage on AC pavements.

All of the states that evaluated precutting, excluding Alaska, evaluated the saw-and-seal technique to control transverse thermal cracking. Alaska's experiments involved precutting without sealing. In general, precut spacing of 40 feet or less was most effective in preventing thermal cracking. The test sections in Iowa experienced complete sealant failure within the joints without detriment to the pre-sawn joints. Other states experienced varying rates of sealant adhesion with promising results pertaining to thermal crack mitigation by precut joints.

Significant documentation of precutting effectiveness was published in the older literature. However, in recent years, little information on the implementation and results of the saw-and-seal technique has been published.

CHAPTER 3.0 FIELD PROJECT DESCRIPTION

3.1 Phillips Field Road

The Phillips Field Road test section was constructed in October 1984 in Fairbanks, a city in Interior Alaska. Phillips Field Road is heavily traveled, providing access to many industrial businesses near the center of Fairbanks (Figure 3.1). Although most of Phillips Field Road was repaved prior to 2015, one small section of much older pavement (from 1984) remained near Peger Road, where precuts were sawed almost completely through the pavement during construction at 50-foot spacing. Records containing details of the 1984 construction and precutting work on Phillips Field Road could not be found during research done for this report.

Figure 3.1 Phillips Field Road

3.2 Moose Creek Project (Richardson Highway)

The Moose Creek experimental site was constructed in 2013 as part of the Richardson Hwy MP 340–346 Resurfacing (Moose Creek), Project #63362. The experimental cuts were variously spaced (25 feet, 40 feet, and special spacing) and at three different depths (0.5, 1.0, and 1.5 inches). The asphalt concrete layer was 2 inches thick, Type II-B mix with PG 52-28 binder. A crushed asphalt base course (about 4 inches thick) was beneath the asphalt layer. Precut work was performed by an employee of Great Northwest, Inc., the construction project's main contractor, on the southbound lanes. During cutting, traffic control consisted of closing a single lane of the two southbound lanes. The single lane closure allowed cutting of approximately two-thirds of the 2-lane width from one side of the road. After all cuts were partially completed, the lane closure was switched to the adjoining lane to allow completion of the saw cuts. The cuts extended from edge to edge of the pavement (full two-lane width, including shoulders) at each cut location. Saw cutting of the 111 full-width slots required three entire workdays. Weather during the sawing operation ranged from partly cloudy to rainy, with temperatures between 50°F and 80°F.

The equipment used was a Saw Devil walk-behind saw machine with a 12-inch diamond saw blade (1/8-inch thick) and a flatbed truck with a 300-gallon tank of water for cooling the saw blade. The time required to lay out and cut the first two-thirds of each line was approximately 12 minutes, or about 15 minutes total per line plus time required to move the cutting operation from one lane to the other. This time was averaged over several of the different depths of cuts. Figures 3.2 and 3.3 show the saw equipment and the type of thin diamond saw used at Moose Creek.

Figure 3.2 Saw Devil equipment and operator

Figure 3.3 Thin diamond saw blade

The Moose Creek experimental site consisted of 10 sections, including the control section. The total length of the experimental section was 1.2 miles, between Station 989+95 (MP 343.8, 64°43′08″ N Lat., 147°13′01″ W Long.) and Station 1043+38 (MP 342.6, 64°42′49″N Lat., 147°11′06″ W Long.). No saw cutting was done within the control section; saw cutting was done in the other nine sections. For sections receiving precuts, the cuts were made to the various depths and spacing indicated in Table 3.1.

Table 3.1 Design of Moose Creek project

No.	Pavement Structure	Section	Saw Spacing (ft)	Saw Depth (in)	HMA (in)	Depth/ HMA Thickness Ratio	Total Section Length (ft)	ADOT&PF Stations
1	I	Control	-	-	-	-	1320	989+95 to 1003+15
2		Precut	25	0.5	2	1/4	400	1003+15 to 1006+92
3			25	1	2	1/2	400	1007+17 to 1011+57
4			25	1.5	2	3/4	400	1011+97 to 1015+97
5			40	0.5	2	1/4	400	1016+37 to 1020+37
6			40	1	2	1/2	400	1020+77 to 1024+77
7			40	1.5	2	3/4	400	1025+17 to 1029+17
8		Cut on locations of pre-existing cracks	-	0.5	2	1/4	392	1030+60 to 1034+52
9			-	1	2	1/2	385	1035+11 to 1038+96
10			-	1.5	2	3/4	420	1039+19 to 1043+39

3.3 Healy Project (Parks Highway)

The Healy test sections were first introduced when the University of Alaska Fairbanks (UAF) and ADOT&PF teamed up to create and implement the "Work Plan for Special Design Features and Crack Sealing Maintenance for IM-OA4-4(15) Parks Highway M.P. 239–252 Rehabilitation" (Liu and McHattie 2013). This work plan laid out the need for such research and the steps to implement research and data collection to accomplish the desired results. The work plan originally called for (1) locating and recording the location of all existing transverse cracks before demolishing the pavement, (2) precutting new slots into the roadway after construction, and (3) continued monitoring of those precuts. Unfortunately, the locations of the existing transverse cracks were not recorded before the demolition of the existing pavement. However, construction, precutting, and monitoring of the experimental sites did occur as indicated in the research work plan.

Precuts were installed on the Parks Highway near Healy during summer 2014 as part of "Parks Highway MP 239–252 Rehabilitation, Project #61275." Quality Asphalt Paving, the contractor, employed a surveyor equipped with an accurate GPS receiver to locate and mark the location of each precut by using the work plan's designated stationing and crack separation distances. Precuts were marked on the asphalt with spray paint using the rabbit-track technique (Figure 3.4), in which short dashes are sprayed across the full width of the road. The crack layout process took approximately one full day with six individuals working, including one surveyor, three laborers, and two flaggers.

Figure 3.4 Surveyors laying out precuts with rabbit-tracks

The precut sawing process required one laborer to operate the saw, two traffic control flaggers, and one water truck driver periodically. The saw operator started on one side of the road at the edge of the shoulder and began to saw cut toward the other side of the road. Traffic would be routed through one-way by the flaggers until the saw reached the centerline. Once the saw was in the opposite lane, traffic would be stopped until the remainder of the road was cut. Saw cutting of the 318 full-width slots required approximately seven entire workdays. Weather during the sawing operation ranged from partly cloudy to rainy and snowy, with temperatures between 30°F and 60°F.

The precuts were sawed into the pavement using a walk-behind saw machine similar to that of the “Saw Devil” brand with a 12-inch diamond tooth blade 1/8-inch wide (Figure 3.5). Other equipment included one pickup truck with a water tank and equipment lift and one water truck to refill the water tank. ADOT&PF used a ruler during construction inspections to ensure cut depth compliance with the precut plan (Figure 3.6).

Figure 3.5 Sawing equipment

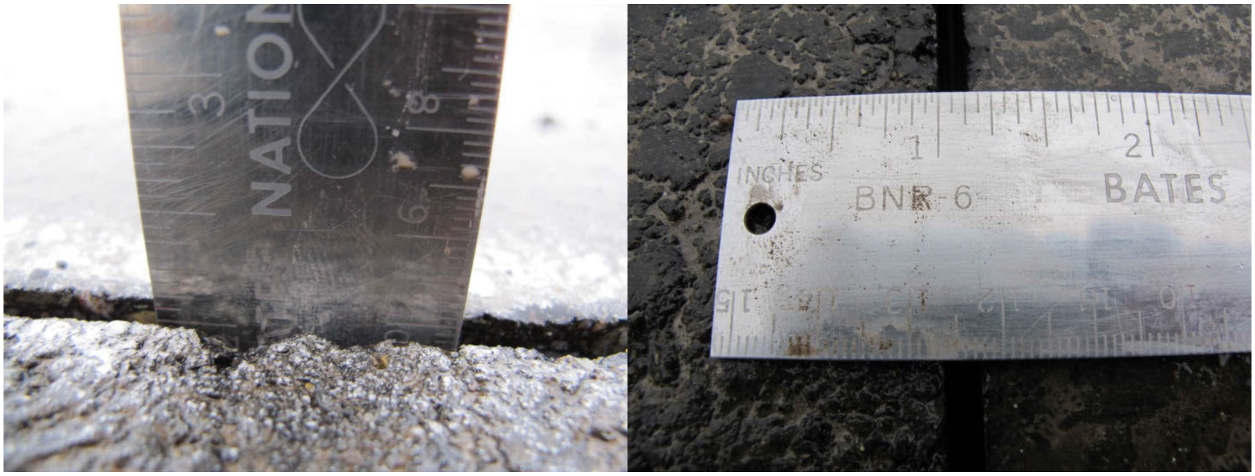


Figure 3.6 Inspection of sawn crack depth and width

The Healy experiment consisted of 16 sections, including 4 control sections. No saw cutting was done within the control sections. The total length of the experimental section was 6.7 miles, between Station 4585+00 (MP 251.9, 63°54′34″ N Lat., 149°4′35″ W Long.) and Station 4941+75 (MP 245.2, 63°49′23″ N Lat., 148°59′24″ W Long.). The cuts were made to various depths, and spacing, as indicated in Table 3.2.

Table 3.2 Design of Healy project

No.	Pavement Structure	Section	Saw Spacing (ft)	Saw Depth (in)	HMA (in)	Depth/ HMA Thickness Ratio	Total Section Length (ft)	ADOT&PF Stations
1		Precut	25	1.9	2.5	3/4	550	4585+00 to 4590+50
2	II	Control	-	-	2.5	-	570	4590+50 to 4596+20
3		Precut	35	1.9	2.5	3/4	560	4596+20 to 4601+80
4		Precut	25	1.9	2.5	3/4	700	4603+00 to 4610+00
5	III	Control	-	-	2.5	-	700	4610+00 to 4617+00
6		Precut	35	1.9	2.5	3/4	700	4617+00 to 4624+00
7	IV	Precut	25	0.6	2.5	1/4	775	4858+00 to 4865+75
8		Precut	25	1.3	2.5	1/2	775	4866+00 to 4873+75

9		Precut	25	1.9	2.5	3/4	775	4874+00 to 4881+75
10		Control	-	-	2.5	-	825	4881+75 to 4890+00
11		Precut	35	0.63	2.5	1/4	770	4890+00 to 4897+70
12		Precut	35	1.3	2.5	1/2	770	4898+05 to 4905+75
13		Precut	35	1.9	2.5	3/4	770	4906+10 to 4913+80
14		Precut	25	1.9	2.5	3/4	900	4915+00 to 4924+00
15	V	Control	-	-	2.5	-	900	4924+00 to 4933+00
16		Precut	35	1.9	2.5	3/4	875	4933+00 to 4941+75

3.4 New Pavement Structures of Test Sections

Precut sections were situated on four different newly constructed pavement structures at the Healy project. Together with one structure type for the Moose Creek sections, a total of five pavement structures were included in this study. The structures were named I through V; details are shown in Table 3.3. Materials were in conformance with the 2004 Standard Specifications for Highway Construction (ADOT&PF 2004). All precuts were installed the full width of the pavement, and saw cutting work proceeded from north to south within each pavement structure. Undefined (in this report) previously existing embankment fill materials and portions of the old pavement structures underlie the newly constructed pavement structures of all precut test sections.

Table 3.3 Pavement structures

Pavement Structure	I	II	III	IV	V
Project	Moose Creek	Healy			
Layer 1	2.0" Asphalt Concrete; Type II, Class B. PG 52-28	2.5" Asphalt Concrete; Type II, Class B. PG 52-28	2.5" Asphalt Concrete; Type II, Class B. PG 52-28	2.5" Asphalt Concrete; Type II, Class B. PG 52-28	2.5" Asphalt Concrete; Type II, Class B. PG 52-28

Layer 2	4" Crushed Asphalt Base Course	3" Asphalt Treated Base	3" Asphalt Treated Base	3" Asphalt Treated Base	3" Asphalt Treated Base
Layer 3	Previously Existing Embankment	34" Selected Material, Type A	4" Minimum Crushed Asphalt Base Course	16" Selected Material, Type A	26" Selected Material, Type A
Layer 4	"	Geotextile Reinforcement, Type I	Previously Existing Embankment	22" Selected Material, Type B	Geotextile Reinforcement, Type I
Layer 5	"	8" Selected Material, Type A	"	Previously Existing Embankment	8" Selected Material, Type A
Layer 6	"	Geotextile Reinforcement, Type I	"	"	Geotextile Reinforcement, Type I
Layer 7	"	Previously Existing Embankment	"	"	8" Selected Material, Type A
Layer 8	"	"	"	"	Geotextile Reinforcement, Type I

Figure 3.7 illustrates lane and shoulder widths associated with Moose Creek sections 1–10 described in Table 3.1. The Moose Creek resurfacing job required only surficial processing (reclaiming) of the top few inches of the pavement structure (Liu et al. 2015).

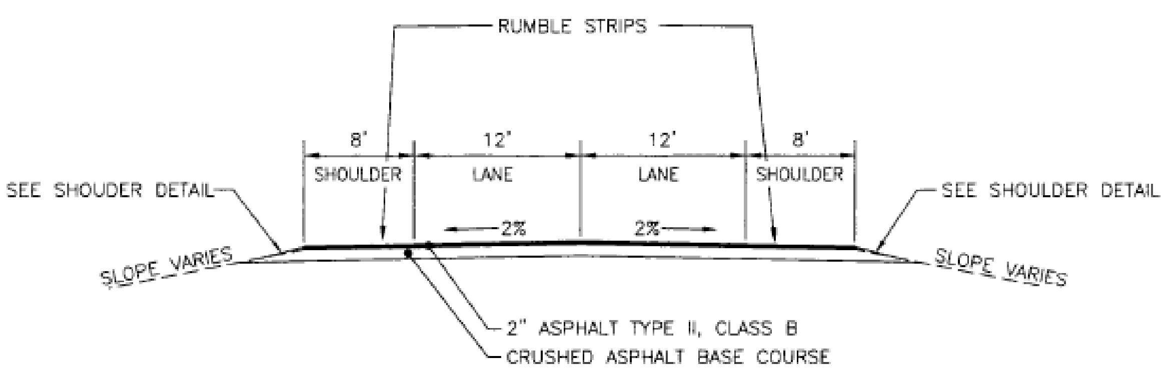


Figure 3.7 Pavement structure I (ADOT&PF)

Figures 3.8 through 3.11 illustrate lane and shoulder widths associated with Healy sections 1–16 described in Table 3.2. Pavement structure V is the most robust of the structures followed, in order or strength, by structures II, IV, III, and I. Pavement structures I and III utilize the mill-and-fill technique, in which the older pavement is reclaimed, creating crushed asphalt base course, and then shaped and compacted followed by paving.

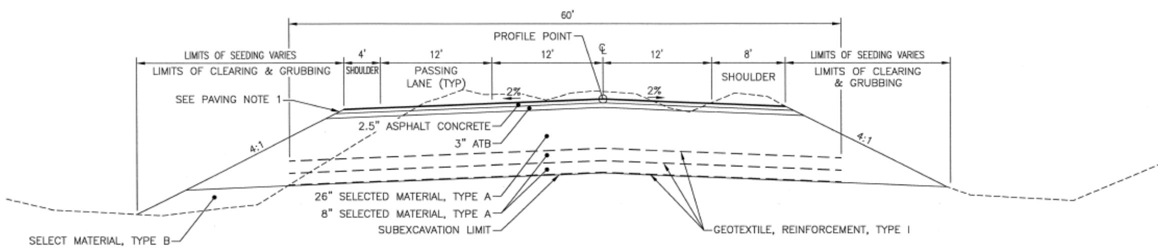


Figure 3.8 Pavement structure II (ADOT&PF)

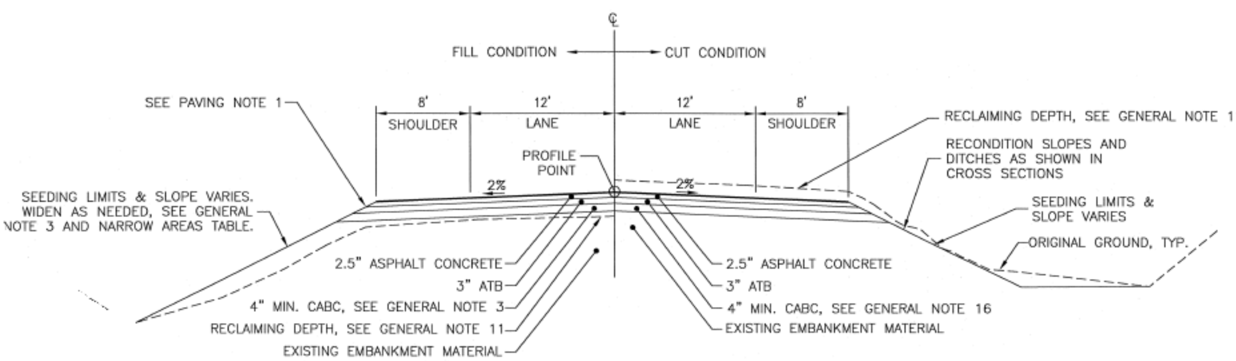


Figure 3.9 Pavement structure III (ADOT&PF)

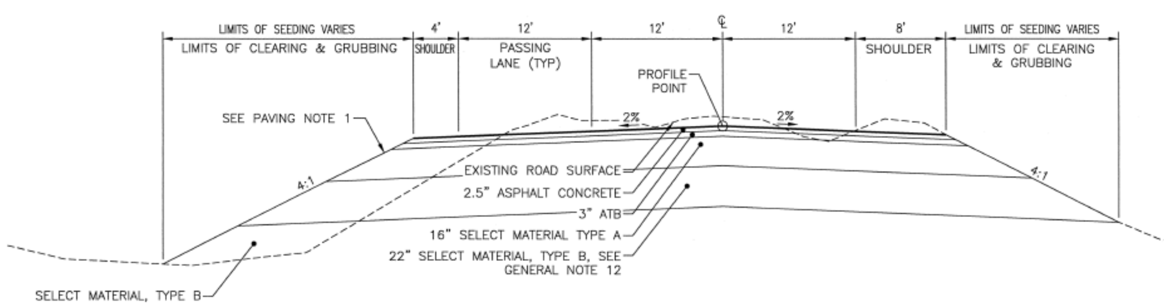


Figure 3.10 Pavement structure IV (ADOT&PF)

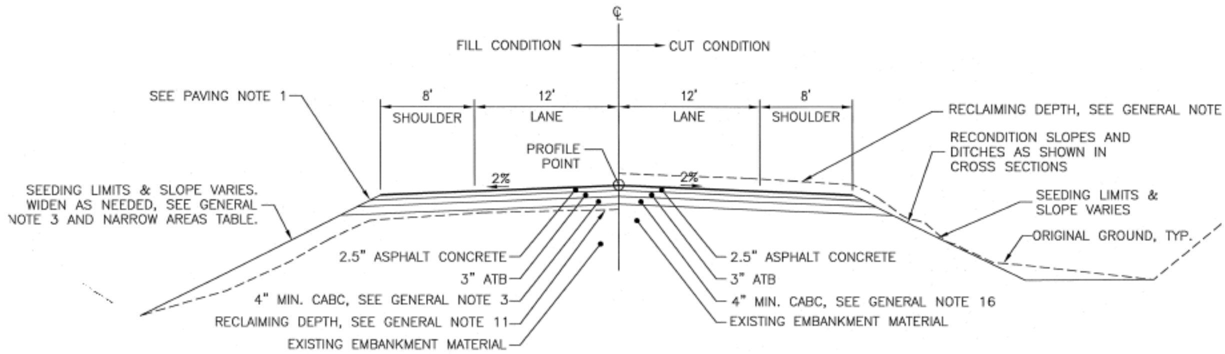


Figure 3.11 Pavement structure V (ADOT&PF)

CHAPTER 4.0 FIELD SURVEYS

4.1 Field Survey of Phillips Field Road

The Phillips Field Road test section was constructed in 1984, and precut performance was first evaluated in June 2016. A detailed survey map that includes all the cracks and other distresses observed is organized in Appendix A. All the photos taken during the field survey can be found in Appendix A. The key features observed are arranged in Figure 4.1. As no control section was available, the survey results of Phillips Field Road precut sections are presented mainly in terms of descriptive summary. After 32 years of service, many longitudinal cracks and block cracks (Figures 4.1a and 4.1b) were observed on the precut sections. Only seven natural transverse cracks (Figure 4.1c) were found on the entire 1,300-foot precut sections, including two low-severity cracks. Out of the 23 precuts installed, 13 were active (Figure 4.1e). The active precuts were identified as being significantly wider than those that did not become active. This (active versus non-active) would be most evident during the coldest part of the year.

After 32 years of service, even the active precuts showed acceptable appearance (Figure 4.1e). Better appearance of the inactive precut was also observed (Figure 4.1d). In contrast, the natural crack (Figure 4.1c) offered a broken and crooked appearance, which is unpredictable and more difficult to maintain. The driving public and state agencies would tend to prefer the "nicely designed" precuts rather than broken natural cracks. The long-term, regular appearance of pavement surfaces is considered important. For Portland cement concrete road pavements, sidewalks, etc., use of expansion joints and regularly spaced scoring has long been the standard way of controlling appearance and damage severity due to inevitable thermal cracking. Therefore, the precut technique for asphalt concrete can be considered "successful" for its effectiveness in controlling the locations of many more natural cracks that could have developed.

Several small potholes were observed where longitudinal cracks and precuts intersected (Figure 4.1f). The observation about potholes was consistent with Minnesota's experience of precutting asphalt pavement (Janisch and Turgeon 1996). Their report indicated that "a cupped depression developed approximately 5–7 years after implementation of precuts." However, the small potholes that accumulated over 30+ years on Phillips Field Road required minimal patching and did not significantly influence ride quality.

In summary, the Phillips Field Road precut site was 32 years old, but its general driving condition was found to be good. Potholes needed to be maintained, but all the cracks, including transverse cracks, active precuts, longitudinal cracks, and block cracks seemed not to deteriorate the pavement condition significantly.

It is important to emphasize the success of this precut test. Except for a few small potholes that received attention during the life of the pavement, the section made it successfully through 32 years of heavy traffic with essentially no other maintenance including the lack of routine sealing. That period represents more than 1½ times the normal 20-year pavement design life.

(a) Block cracks (b) Longitudinal crack (c) Transverse crack

(d) Non-active precut (e) Active precut (f) Pothole

Figure 4.1 Field observations of 32-year old Phillips Field Road, Fairbanks, Alaska

<u>4.2 Field Survey of Moose Creek Project</u>

The Moose Creek project was constructed in 2012. After the construction, the project was visited four times in summers/falls of 2013, 2014, 2016, and 2017. The field surveys in 2013 and 2014, first documented in a previous report (Liu et al. 2015), are summarized in this report section along with field survey information collected specifically for this report during summers of 2016 and 2017.

4.2.1 Field Surveys in 2013 and 2014 (Liu et al. 2015)

The details of the field surveys (Figure 4.2) conducted in 2013 and 2014 can be found in a previous project report (Liu et al. 2015). Figure 4.3 presents select survey photos of observed natural cracks, and both non-active precut and active precut cracks.

Figure 4.2 Field survey of Moose Creek project in 2014 (Liu et al. 2015)

(a) Natural cracks (b) Non-active precut (c) Active precut

Figure 4.3 Select field survey photos in 2013 and 2014 (Liu et al. 2015)

4.2.2 Field Survey in 2016

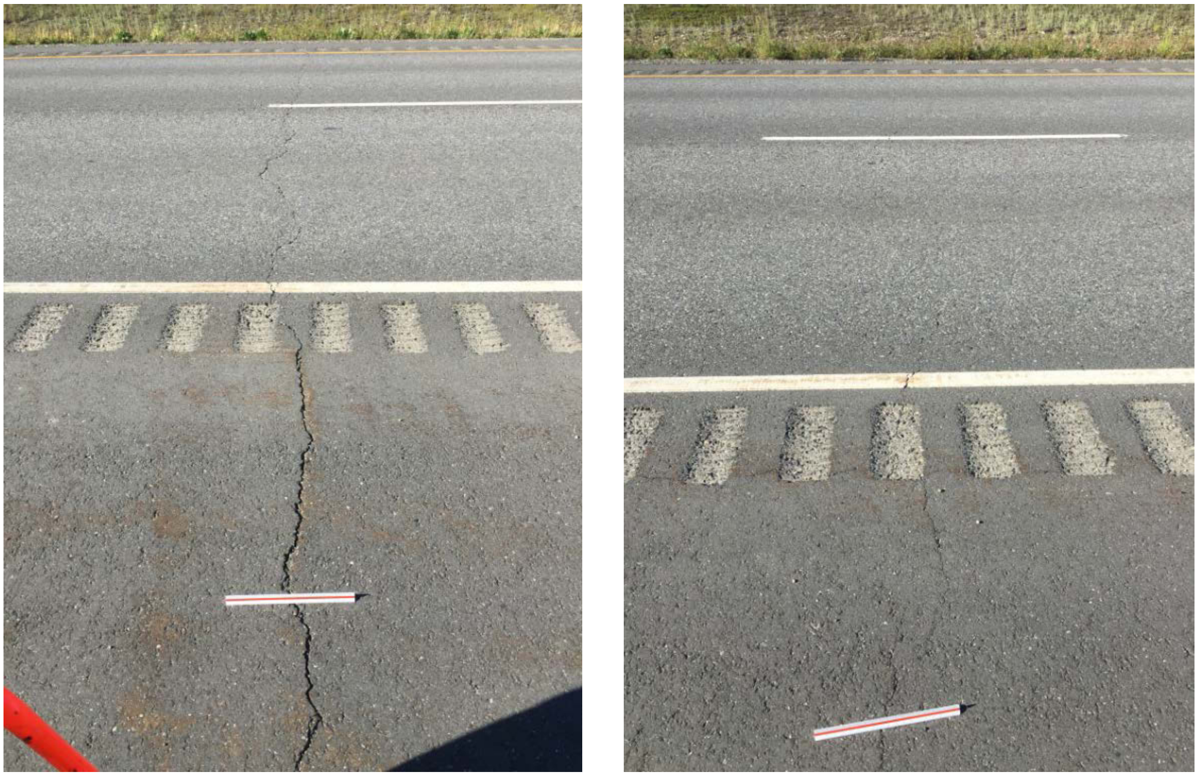
Moose Creek sections were visited as one of the tasks in this project in summer of 2016. A survey map illustrating all the cracks on the road sections and photos taken during the trip can be found in Appendix B. Some representative pictures are presented here for discussion.

Figure 4.4 presents an overview of the Moose Creek experimental sections. It can be seen that most of the Moose Creek sections are one-way two-lane highways.

(a) (b)

Figure 4.4 Overview of Moose Creek sections: (a) the control section; (b) the beginning of the precut sections

Figures 4.5 and 4.6 show observations on the control section (section No. 1 in Table 3.1). As expected, the most noticeable distress was the natural transverse cracks during the 3 years after construction. Figure 4.5 presents natural transverse cracks at different severity levels perpendicular to the road centerline. Natural transverse cracks skewed to the road centerline were also observed, as shown in Figure 4.6.



(a) (b)

Figure 4.5 Transverse cracks perpendicular to the road centerline on the control section of the Moose Creek project: (a) high severity; (b) low severity

(a) (b)

Figure 4.6 Transverse cracks skewed to the road centerline on the control section of the Moose Creek project: (a) high severity; (b) low severity

Figures 4.7 through 4.10 show observations of the precut sections with designed spacings (Moose Creek sections No. 2 to No. 7). Figure 4.7 presents the current conditions of precuts. Many precuts were non-active or closed, similar to the form of the one shown in Figure 4.7a. This means that stress concentrations sufficient to rupture the small amount of remaining pavement along the bottom of the precut slots and produce an active crack had not yet occurred. In contrast, a few active or open precuts were observed, as shown in Figure 4.7b. These open precuts are considered “nicely designed cracks,” and more are expected in a future survey. The existence of them might indicate that potential natural cracks were prevented by the precutting technique. In addition, it seems that most precuts did not require any maintenance, even if they were active.

(a) (b)

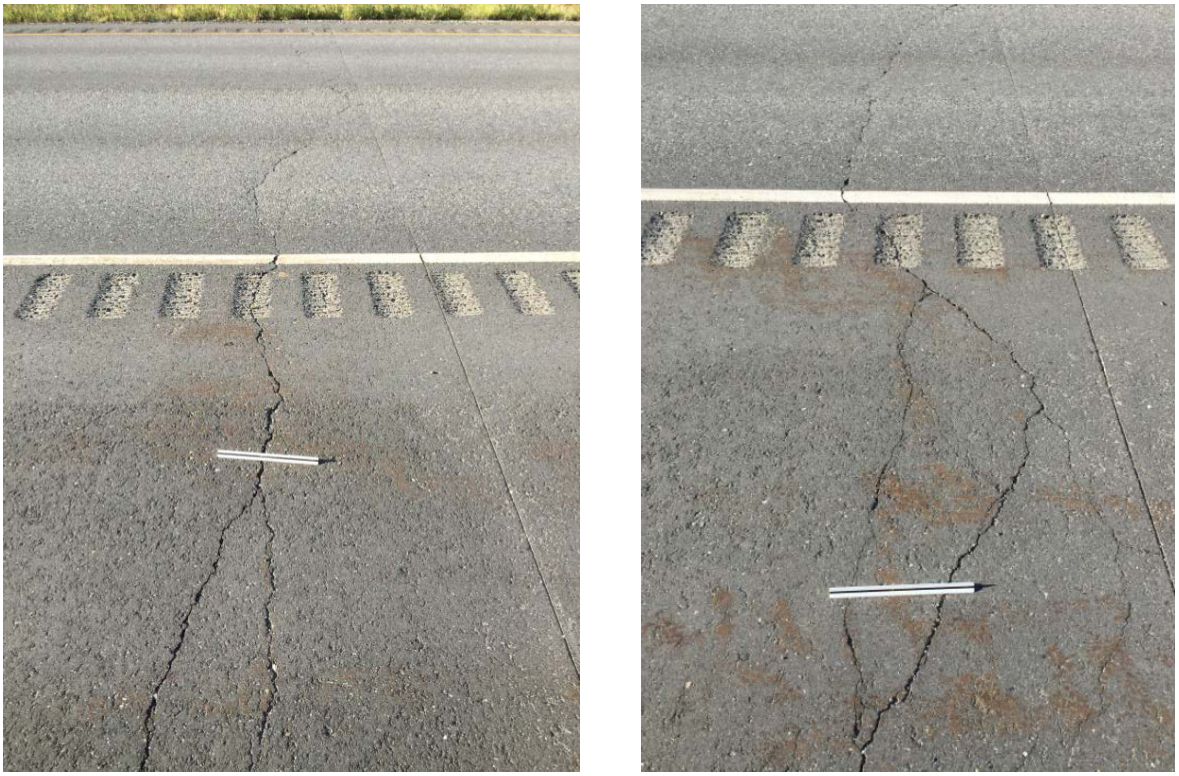
Figure 4.7 Precuts observed on the precut sections with designed spacings on the Moose Creek project: (a) non-active (closed) (section No. 7); (b) active (open) (section No. 9)

The locations of a few natural cracks were found to be at least partially controlled by precutting (Figure 4.8). Figures 4.8a and 4.8b show that the propagation of natural cracks was influenced by precutting. Both photos show natural cracks that were at least partially controlled (partially captured) by precutting. Several years of field observations during this study made it obvious that the effectiveness of precutting for controlling natural crack location can vary significantly from location to location. It is especially dependent on the thickness of the newly constructed section (the total thickness of pavement plus any other newly placed layers) that receives the precut treatment. The reader is reminded that the total thickness for new construction at the Moose Creek precut test site was only about 6 inches.

(a) (b)

Figure 4.8 Transverse cracks partially controlled by precuts on the precut sections with designed spacings on the Moose Creek project: (a) section No. 3; (b) section No. 7

A few natural cracks were observed to develop near precuts that were not active at all (Figure 4.9). These natural cracks were generally of complicated shape, which might indicate that they were reflective thermal cracks rather than new natural thermal cracks. It seems that precuts installed with designed spacings may not necessarily even partially control the location of reflective cracks.



(a) (b)

Figure 4.9 Natural cracks adjacent to precuts on the precut sections with designed spacings on the Moose Creek project: (a) section No. 6; (b) section No. 4

Figure 4.10 presents natural cracks of different severity level observed between the precuts. These cracks mean that a natural crack could still occur even with a short precut spacing of 40 feet.

(a) (b)

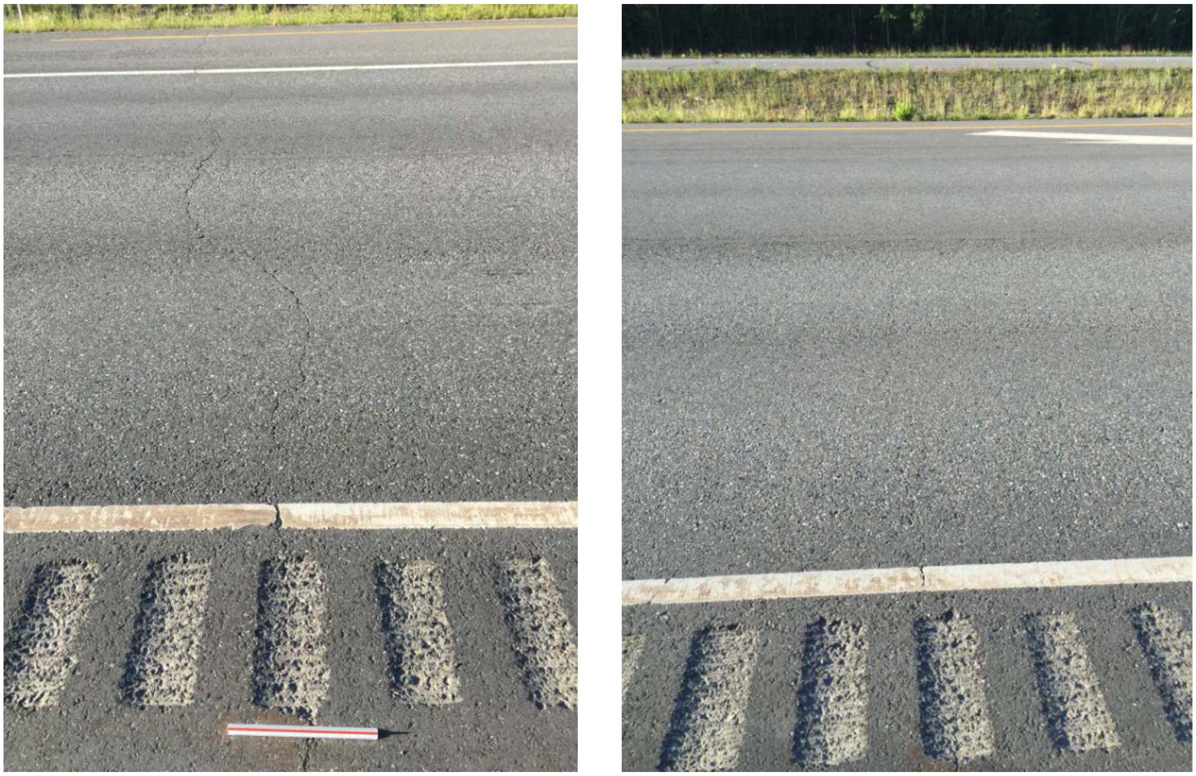
Figure 4.10 Transverse cracks in between precuts on the precut sections with designed spacings on the Moose Creek project: (a) high severity (section No. 6); (b) low severity (section No. 7)

The three sections, No. 8 to No. 10 in Table 3.1, were specially designed for the Moose Creek project. The objective was to evaluate the effectiveness of precutting on the locations of pre-existing cracks. Figures 4.11 to 4.13 present the observations that are worth some discussion. Figure 4.11 shows two cases of transverse cracks near precuts. The crack shown in Figure 4.11a was not controlled by the precut at all, but the one shown in Figure 4.11b was partially re-located (partially captured) by the precut. According to the survey maps presented in Appendix B8 to B10, a big portion of the transverse cracks occurred on or adjacent to precuts in these sections. The idea of precutting at the old thermal crack location seems reasonable, but it is still difficult to determine how effective it can be.

(a) (b)

Figure 4.11 Natural transverse cracks near precuts—where precuts are at locations of old thermal cracks on the Moose Creek project: (a) high severity (section No. 8); (b) low severity (section No. 8)

Transverse cracks that occurred between two precuts were mostly at low-severity level (Figure 4.12).



(a) **(b)**

Figure 4.12 Natural transverse cracks between precuts—where precuts are at locations of old thermal cracks on the Moose Creek project: (a) high severity (section No. 8); (b) low severity (section No. 9)

One special observation (Figure 4.13) was that the cut-on-existing-cracks section with a 1.5 inch cut depth (No. 10 in Table 3.1) was maintained with routing followed by crack sealing. It is not known why this type of expensive maintenance treatment was used at this and some nearby locations, but its effectiveness can become part of future field evaluations of the precut test sections.

(a) (b)

Figure 4.13 Crack sealing with routing observed on: (a) precut (section No. 10); (b) precut and adjacent natural crack (section No. 10)

4.2.3 Field Survey in 2017

Moose Creek sections were visited again in summer 2017. A survey map detailing all the cracks on the sections and photos taken during the trip can be found in Appendix D. Some new observations are presented below.

Figure 4.14 presents two new transverse cracks across the entire road on the control section. It can be seen that both cracks were at low- to medium-severity levels.

(a) (b)

Figure 4.14 New transverse cracks observed on the control section of Moose Creek project: (a) case 1; (b) case 2

Figure 4.15 presents two new small cracks that were perpendicular to the road centerline. The cracks had not developed to cross the entire road, but may propagate to full width in future years. The types of cracks seen in 2016 and 2017 were similar, and the 2016 survey shown in Appendix B was supplemented with the 2017 survey to become Appendix D. Most cracks and interesting spots were documented with photos that can be seen in Appendix D. Several newly taken pictures are presented below.

(a) (b)

Figure 4.15 New partial cracks observed on the control section of Moose Creek project: (a) case 1; (b) case 2

(a) (b)

Figure 4.16 Newly documented natural cracks observed on sections of Moose Creek project in summer 2017: (a) the control section; (b) section No. 6

(a) (b)

Figure 4.17 Newly documented precuts observed on sections of Moose Creek project in summer 2017: (a) section No. 9; (b) section No. 8

(a) (b)

Figure 4.18 Newly documented cracks adjacent to precuts in sections of Moose Creek project in summer 2017: (a) section No. 8; (b) section No. 9

(a) (b)

Figure 4.19 Newly documented crack sealing spots in section No. 10 of Moose Creek project in summer 2017: (a) case 1; (b) case 2

4.3 Field Survey of Healy Project

4.3.1 Field Survey in 2015 (Netardus 2016)

Rehabilitation construction and precutting on the Healy sections were performed in 2014. The first field survey was conducted in May 2015 (Netardus 2016). The measurements were done using a surveyor's "walking wheel," with a precision of about ± 2 foot over each experimental section. Figures 4.20 and 4.21 present select survey observations. Most of the natural transverse cracks were found to be skewed to the roadway centerline.

Figure 4.20 Natural transverse crack observed

Figure 4.21 Precut observed

4.3.2 Field Survey in 2016

Healy sections were visited in summer 2016. Detailed survey maps and photos showing all the distress can be found in Appendix C. Figures 4.22–4.24 show some general observations documented as survey results for Healy sections, including overview of the field site, transverse cracks, and precut status. Note that some highly active precuts (Figure 4.24c) were observed on the Healy experimental sections.

(a) (b)

Figure 4.22 Overview of Healy experimental sections: (a) section No. 15; (b) section No. 10

(a) (b)

Figure 4.23 Transverse cracks observed: (a) low-severity crack (on precut section) (section No. 6); (b) high-severity crack (on control section) (section No. 2)

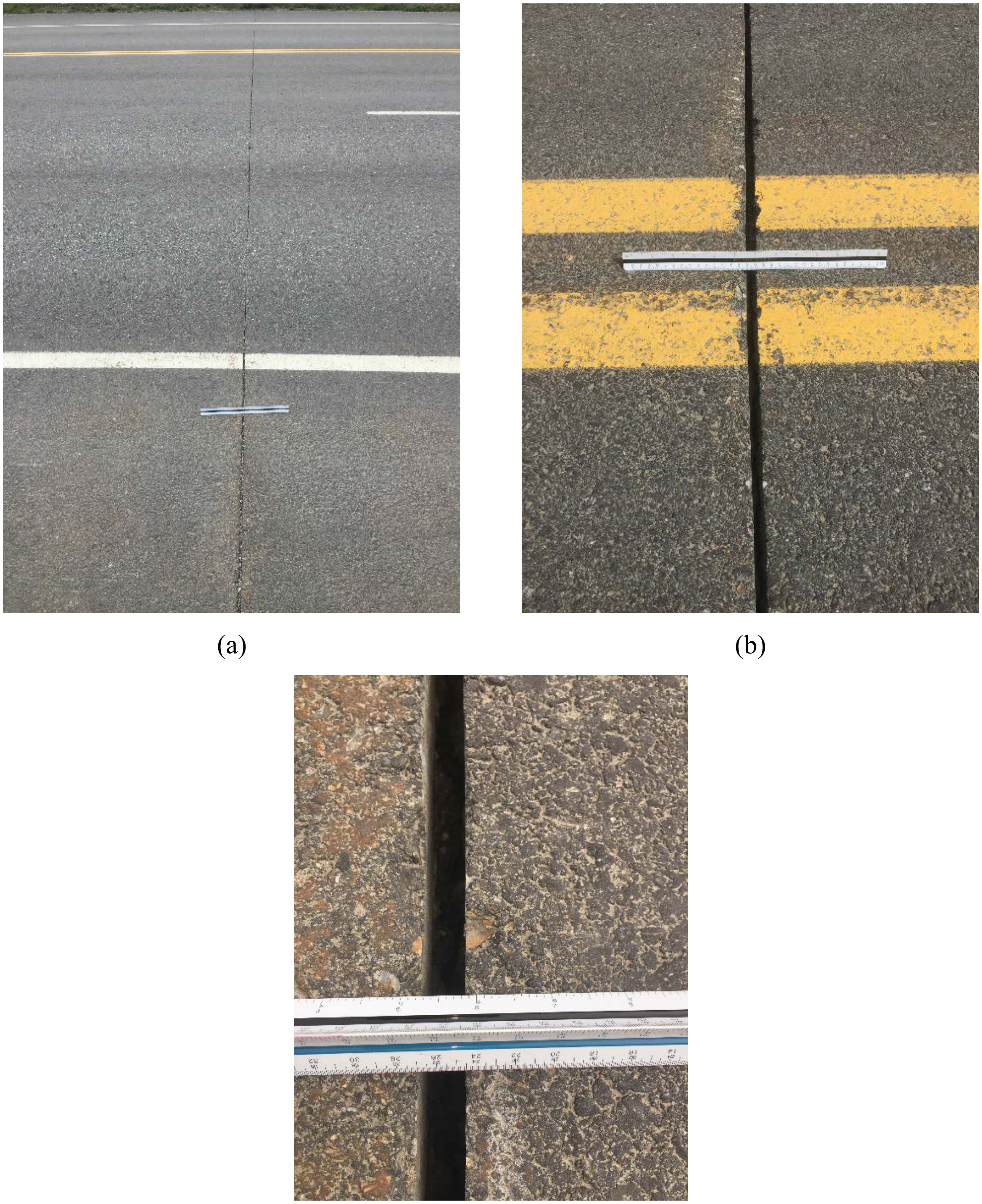


Figure 4.24 Precuts observed: (a) non-active precut (section No. 9); (b) active precut (section No. 8); (c) highly active precut (section No. 3)

4.3.3 Field Survey in 2017

Healy sections were revisited in summer 2017. Detailed survey maps and photos can be found in Appendix E. Figures 4.25–4.32 show some newly observed features worth discussion. Three forms of precuts were observed: completely closed (non-active) (Figure 4.25), partially active (Figure 4.26), and very active (Figure 4.27). Figure 4.28 presents natural transverse cracks with irregular shapes but low levels of severity. Some of the natural cracks obviously extended past the edge of the pavement and into the unpaved shoulder, as can be clearly seen in (Figure 4.29). Some natural crack paths were found to be redirected and partially captured by precuts (Figure 4.30). On the other hand, Figure 4.31 shows examples of natural transverse cracks located quite near precuts but without the apparent tendency to be captured or even influenced by precuts. Examples of low-severity bifurcating transverse cracks are shown located in a control section (Figure 4.32a) and between precuts (Figure 4.32b).

(a) (b)

Figure 4.25 Completely closed precuts observed: (a) section No. 13; (b) section No. 7

(a) (b)

Figure 4.26 Partially open precuts observed: (a) section No. 6; (b) section No. 16

(a) (b)

Figure 4.27 Very active (open) precuts observed: (a) section No. 14; (b) section No. 8

(a) (b)

Figure 4.28 Natural transverse crack examples: (a) section No. 2; (b) section No. 1

(a) (b)

Figure 4.29 Cracks extending past the paved surface: (a) section No. 9; (b) section No. 15

(a) (b)

Figure 4.30 Cracks partially captured by the precuts: (a) section No. 9; (b) section No. 8

(a) (b)

Figure 4.31 Cracks adjacent to precuts, without capture: (a) section No.9; (b) section No.12

(a) (b)

Figure 4.32 Bifurcating cracks: (a) section No. 5; (b) section No. 13

4.4 Standard Method for Describing Crack Morphology

As part of the research presented in this report, a standardized method for describing transverse thermal cracks was developed. Transverse crack morphology is described in terms of crack shape, severity, and degree of capture. Capture refers to the condition by which a natural transverse crack may become partially or completely incorporated into a precut transverse crack. The standard method for describing transverse crack morphology is outlined as follows:

- Shape of Precut and Natural Cracks
    - Precut
    - Natural Nominally Linear
    - Natural Doglegged
    - Natural Bifurcating
    - Natural Doglegged & Bifurcating

- Severity of Natural and Precut Cracks
  - Non-Broken
  - Broken
  - Spalled
- Capture of Natural Crack by Precut
  - None
  - Partial
  - Full*

  *Recognition of full capture requires field measurements to verify precut crack has become "active," that is, exhibits seasonal width variations.

A "shorthand" notation was created based on this list to simplify crack morphologic descriptions. Each notation's components (numbers and upper/lower case letters) are shown in Table 4.1. All practical combinations of these components are combined to form the designations and descriptions listed in the middle and right columns of Table 4.2. The left column of Table 4.2 indicates 18 photo examples of various designations that can be viewed in Appendix F.

Table 4.1 Transverse Thermal Crack Morphology

Shape	**Designation**
Precut	A
Natural Nominally Linear	B
Natural Doglegged	C
Natural Bifurcating	D
Natural Doglegged & Bifurcating	E
Severity	
Non-Broken	1
Broken	2
Spalled	3
Capture of Natural Crack by Precut	
None	a
Partial	b
Full	c

Table 4.2 Possible Combinations

Photo Name	Designation	Description
Moose Creek_47	A1	non-active non-broken precut
PFR_7	A2	non-active broken precut
PFR_8	A3	non-active spalled precut
PFR_17	A1c	active unbroken precut
PFR_13	A2c	active broken precut
PFR_22	A3c	active spalled precut
Moose Creek_12	B1a	natural linear non-broken non-captured
Moose Creek_48	B1b	natural linear non-broken partially captured
Moose Creek_51	B2a	natural linear broken non-captured
	B2b	natural linear broken partially captured
	B3a	natural linear spalled non-captured
	B3b	natural linear spalled partially captured
Moose Creek_28	C1a	natural doglegged non-broken non-captured
Moose Creek_39	C1b	natural doglegged non-broken partially captured
	C2a	natural doglegged broken non-captured
Moose Creek_85	C2b	natural doglegged broken partially captured
PFR_16	C3a	natural doglegged spalled non-captured
	C3b	natural doglegged spalled partially captured
Moose Creek_63	D1a	natural bifurcating non-broken non-captured
Moose Creek_70	D1b	natural bifurcating non-broken partially captured
Healy_43	D2a	natural bifurcating broken non-captured
	D2b	natural bifurcating broken partially captured
	D3a	natural bifurcating spalled non-captured
	D3b	natural bifurcating spalled partially captured
Healy_61	E1a	natural doglegged & bifurcating non-broken non-captured
Moose Creek_56	E1b	natural doglegged & bifurcating non-broken partially captured
	E2a	natural doglegged & bifurcating broken non-captured
	E2b	natural doglegged & bifurcating broken partially captured
	E3a	natural doglegged & bifurcating spalled non-captured
	E3b	natural doglegged & bifurcating spalled partially captured

CHAPTER 5.0 RESULTS AND ANALYSIS

The reader should consider the results and analyses provided in this chapter while taking into account that:

1. precuts in Section I (Moose Creek) were older than those in Sections II through V (Healy) at the time that field data were collected. In addition, because the number of natural cracks is known to increase with time, short-term direct comparison between the two sites may be somewhat uncertain.
2. at the time of this report, precuts in neither of these areas had aged enough to have exhibited a truly mature (final) pattern of thermal cracking.

Therefore, interpretation of future field observations and analyses—after long-term aging of these sites—may require reconsideration of findings presented in this chapter.

5.1 Field Survey Results

Natural crack spacing was used for quantitative analysis of the survey results, as section length was not constant for each section. Figure 5.1 presents the natural transverse crack spacing results for all ten Moose Creek sections. Data collected in 2013 and 2014 (Liu et al. 2015) were included in Figure 5.1 to show crack development with time. As expected, natural crack spacing decreased with time, which means the number of cracks increased with time. For better comparison of results obtained on the control and precut sections, data in Figure 5.1 were further processed and presented in the individual panels of Figure 5.2. It was found that all the precut sections demonstrated higher natural crack spacing compared with the control section, regardless of precut depth, precut spacing, and pavement age, which indicates that precut treatment may generally increase the thermal cracking resistance of pavement. On the other hand, this finding may simply indicate that natural thermal cracking is occurring at a rate similar to that of the control sections, but perhaps often within the precuts themselves. Either possibility provides evidence that precutting is in fact beneficial. It is difficult to tell whether installing precuts on pre-cracked locations (Moose Creek sections 8, 9, and 10) were more effective or not. Further field observations and data analysis would be needed to make more conclusive statements.

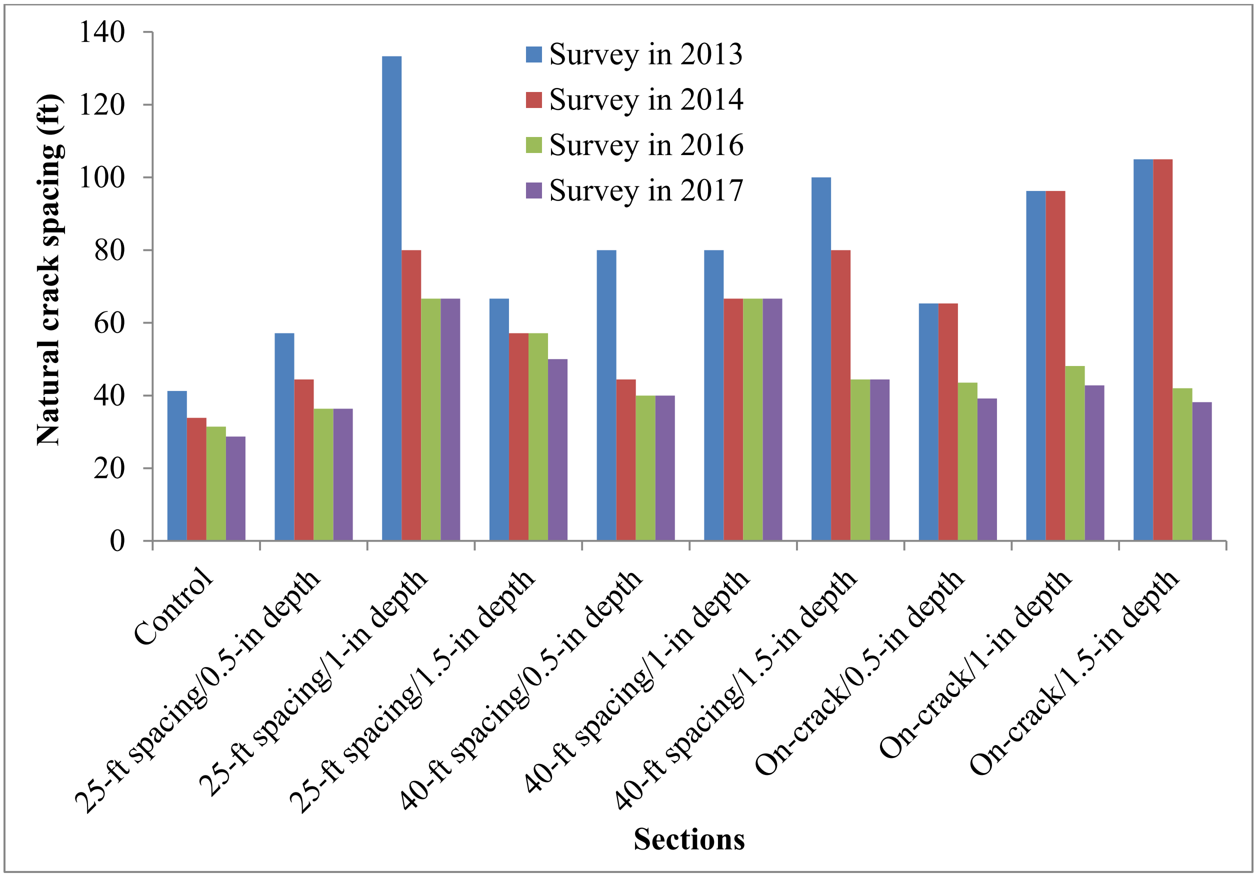
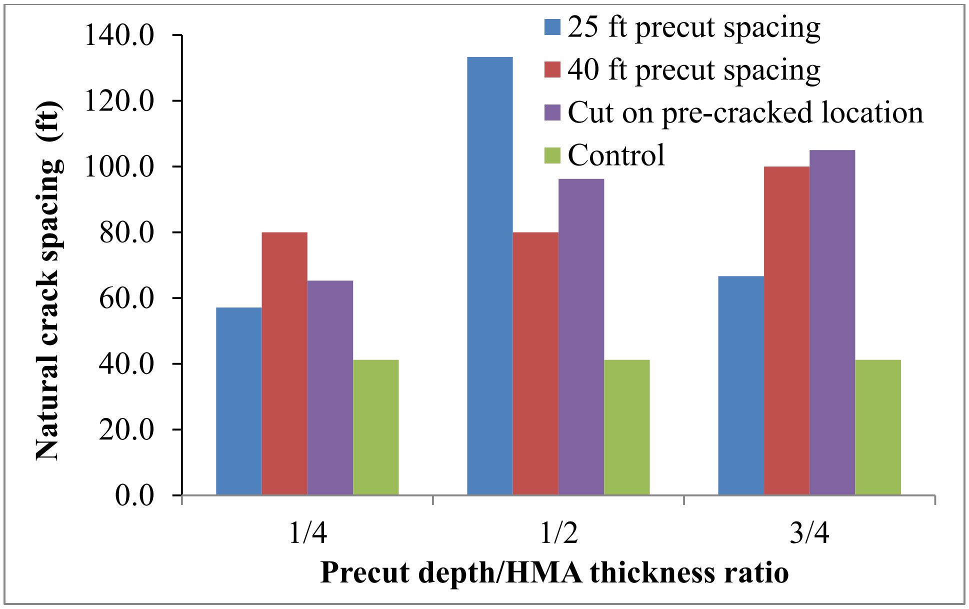
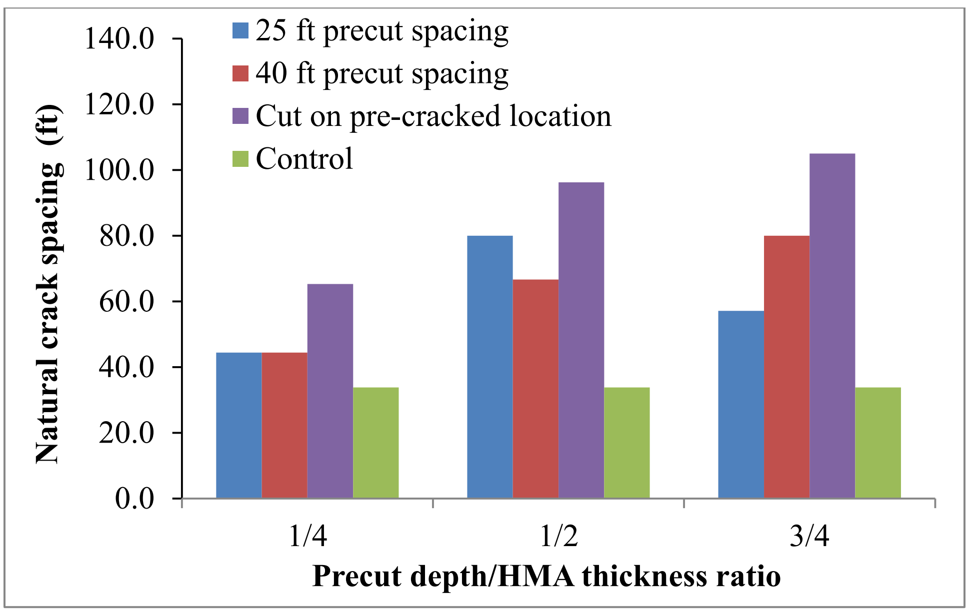


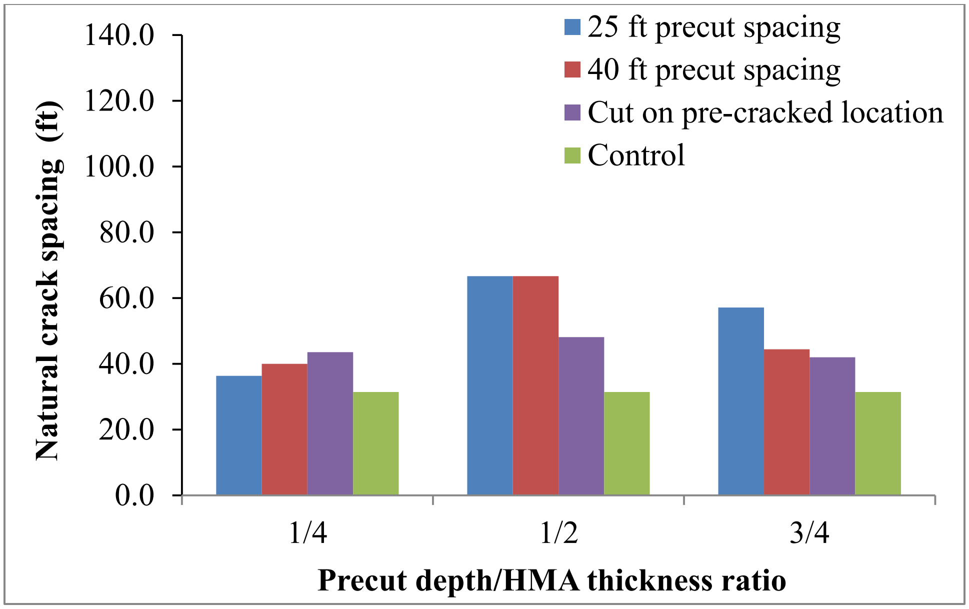
Figure 5.1 Moose Creek project survey results


25 ft precut spacing
40 ft precut spacing
Cut on pre-cracked location
Control
Natural crack spacing (ft)
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1/4
1/2
3/4
Precut depth/HMA thickness ratio

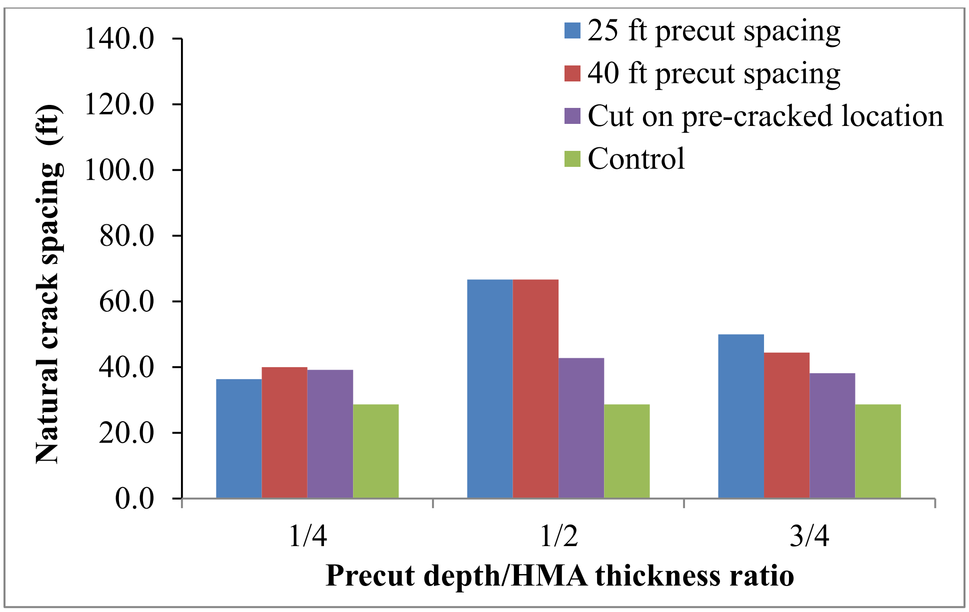
(a)


25 ft precut spacing
40 ft precut spacing
Cut on pre-cracked location
Control
Natural crack spacing (ft)
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1/4
1/2
3/4
Precut depth/HMA thickness ratio

(b)



(c)



(d)

Figure 5.2 Comparison of results: precut sections vs. the control section: (a) 2013 survey; (b) 2014 survey; (c) 2016 survey; (d) 2017 survey

Figure 5.3 presents the natural transverse crack spacing results for all the sections included in the Healy project. Data collected in 2015 were also included in Figure 5.3 to show crack development with time. As some sections demonstrated no transverse crack, the natural crack spacing of 1,000 feet was used to represent these sections for data presentation in one chart. As expected, and consistent with observations at the Moose Creek project, natural crack spacing decreased or remained the same with time, which means the number of cracks increased with time. Data comparison of the control section and precut sections can be seen in Figures 5.4–5.6. It was found that the precut sections demonstrated higher natural crack spacing compared with the control section, regardless of precut interval and pavement age for pavement structures II, III, and V. No natural transverse crack was found on the control section of pavement structure IV in 2015 and 2016, and only one crack was observed in 2017.

To make interpretation of Figures 5.3–5.6 easier, the reader should note that only one precut depth (2 inches) was used in structures II, III, and V. Multiple cut depths (0.625, 1.25, and 2 inches) were used only in structure IV. Also, each structure has its own control section, so there are 4 control sections in total for the Healy area tests. In addition, according to Figures 5.1 and 5.3, the reported natural crack spacing data of Moose Creek sections (structure I) were considerably lower than those of Healy sections (structures II, III, IV, and V). The significant difference may be due to Moose Creek pavement being older; this pavement was also the thinnest construction treatment, which perhaps facilitated faster/more reflection cracking from the previously cracked layers beneath.

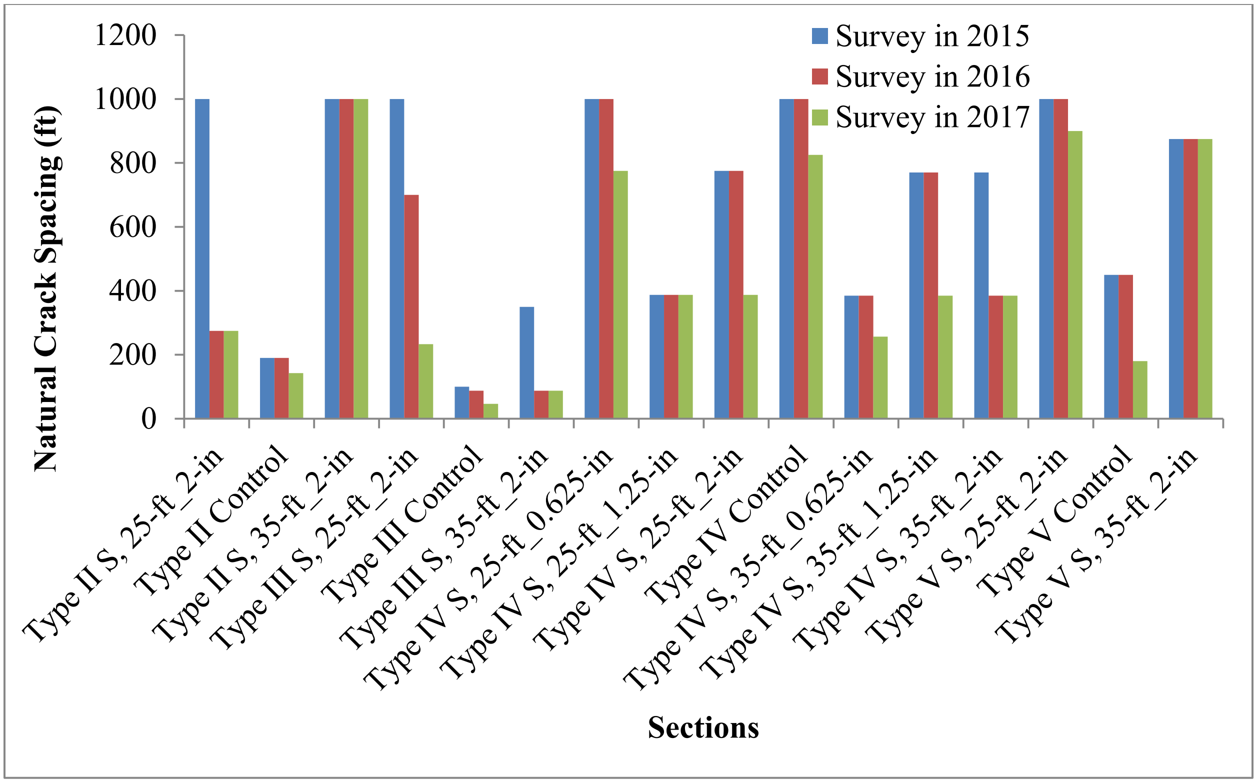
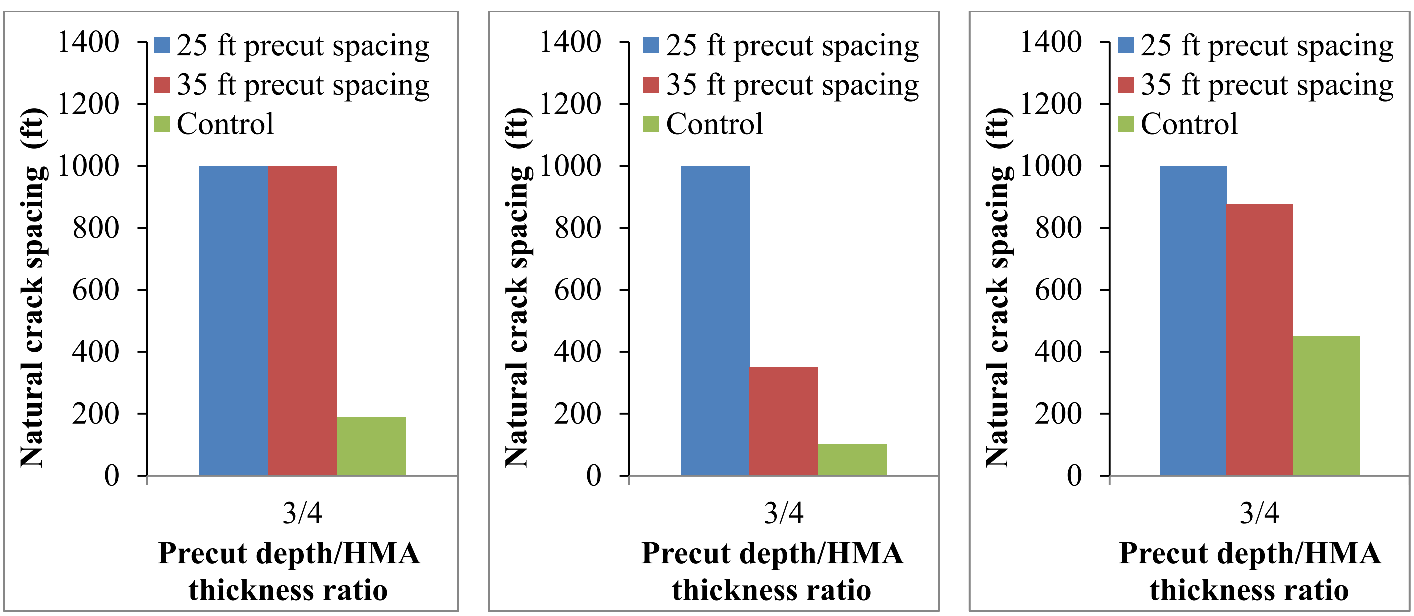
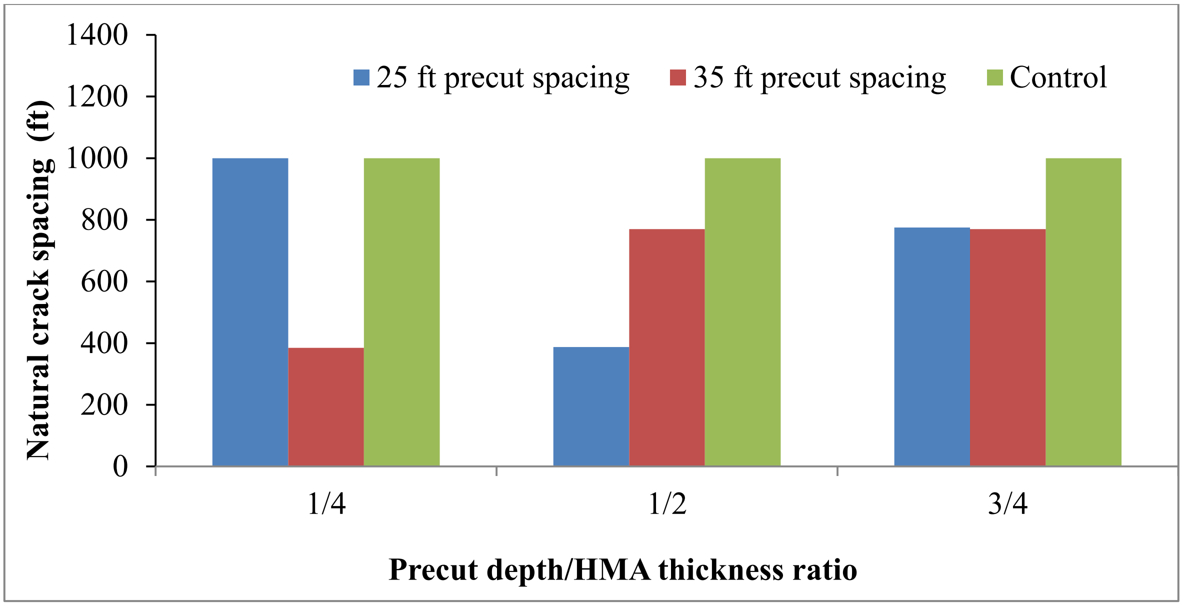


Figure 5.3 Healy project survey results

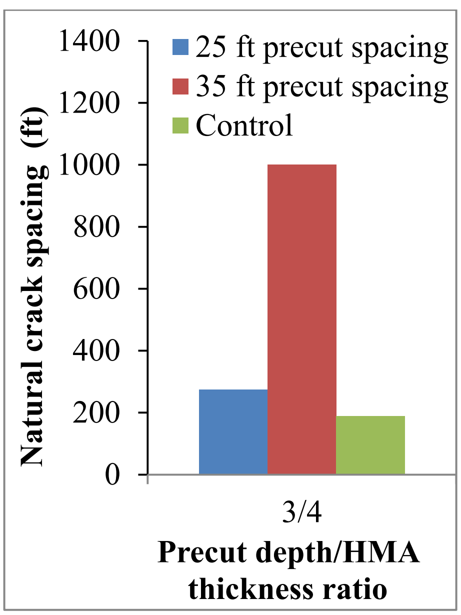


(a) (b) (c)

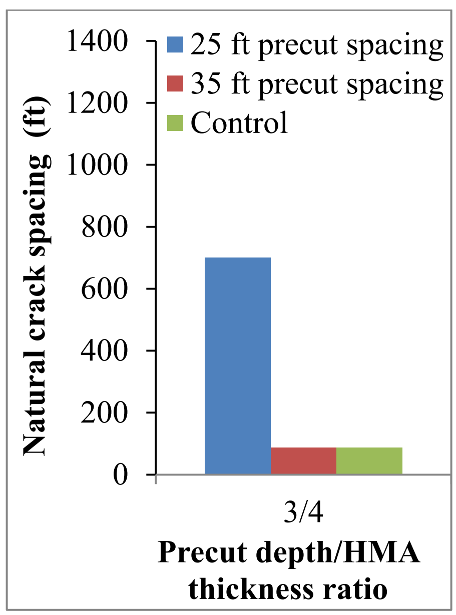


(d)

Figure 5.4 Comparison of data collected in summer 2015_precut sections vs. control section for pavement structure: (a) II; (b) III; (c) V; (d) IV



(a)



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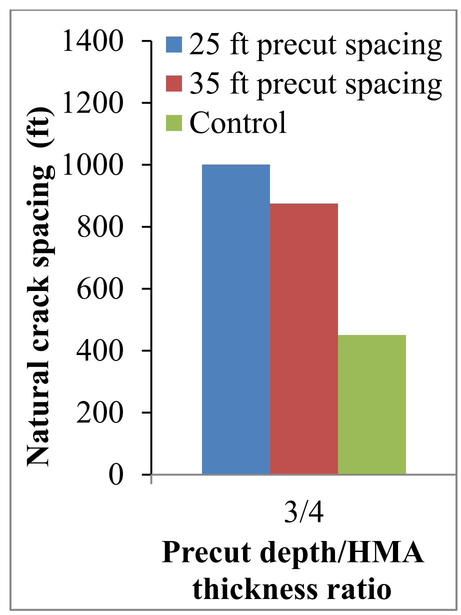

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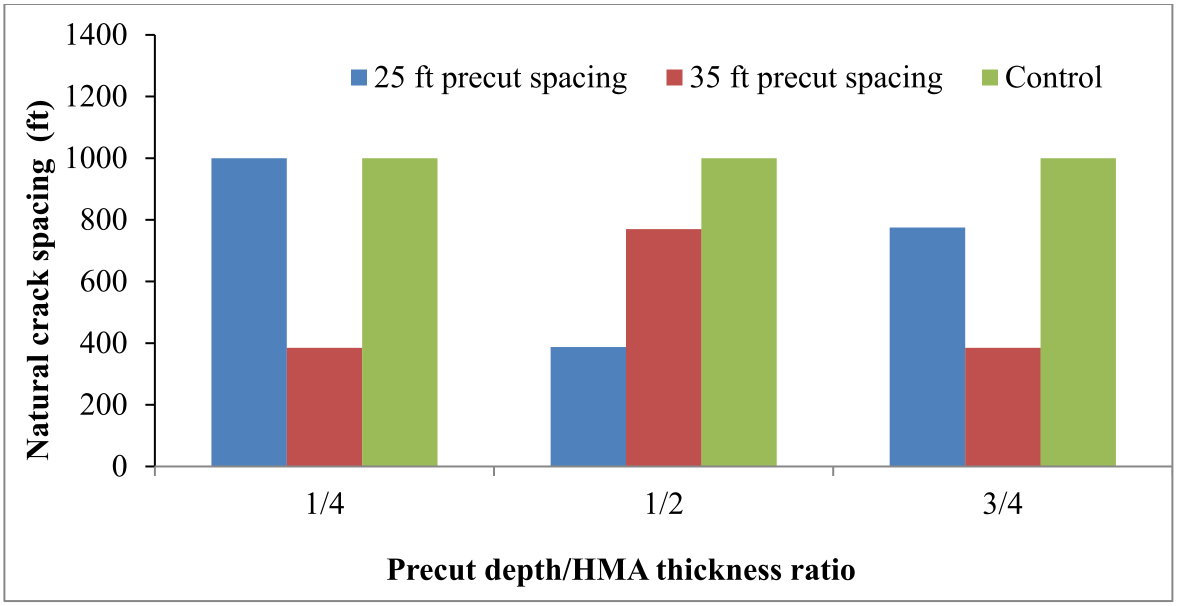
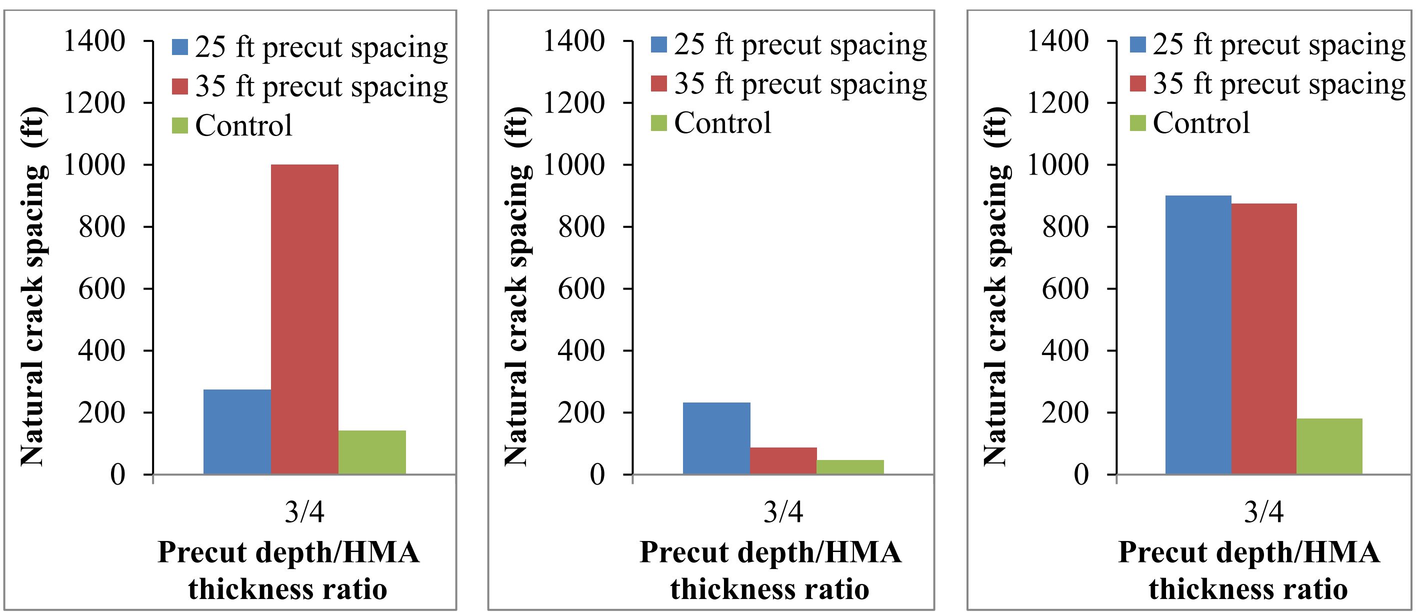
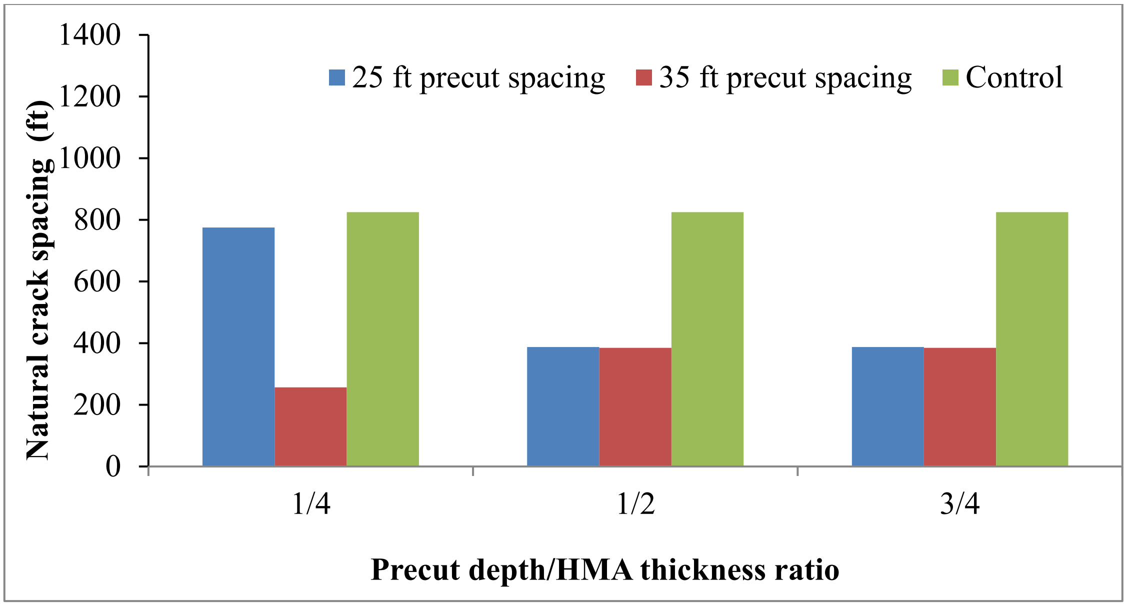


(d)

Figure 5.5 Comparison of data collected in summer 2016_precut sections vs. control section for pavement structure: (a) II; (b) III; (c) V; (d) IV



(a) (b) (c)



(d)

Figure 5.6 Comparison of data collected in summer 2017_precut sections vs. control section for pavement structure: (a) II; (b) III; (c) V; (d) IV

5.2 Effect of Precut Spacing

In order to evaluate the effect of precut spacing, the survey results collected in 2017 were used for both projects and the precut depth ratio was held at ¾. The organized results for comparison are presented in Figure 5.7. Pavement structures I, III, and V showed comparatively higher natural crack spacing when a shorter precut spacing was adopted. The two different precut spacings resulted in similar natural crack spacings for sections built on pavement structure IV. For pavement structure II, the section with the larger precut interval showed higher natural crack spacing, which is opposite of what was observed on structures I, III, and V. Most of these preliminary observations indicate that shorter precut spacing is more promising in controlling the location of natural cracks.

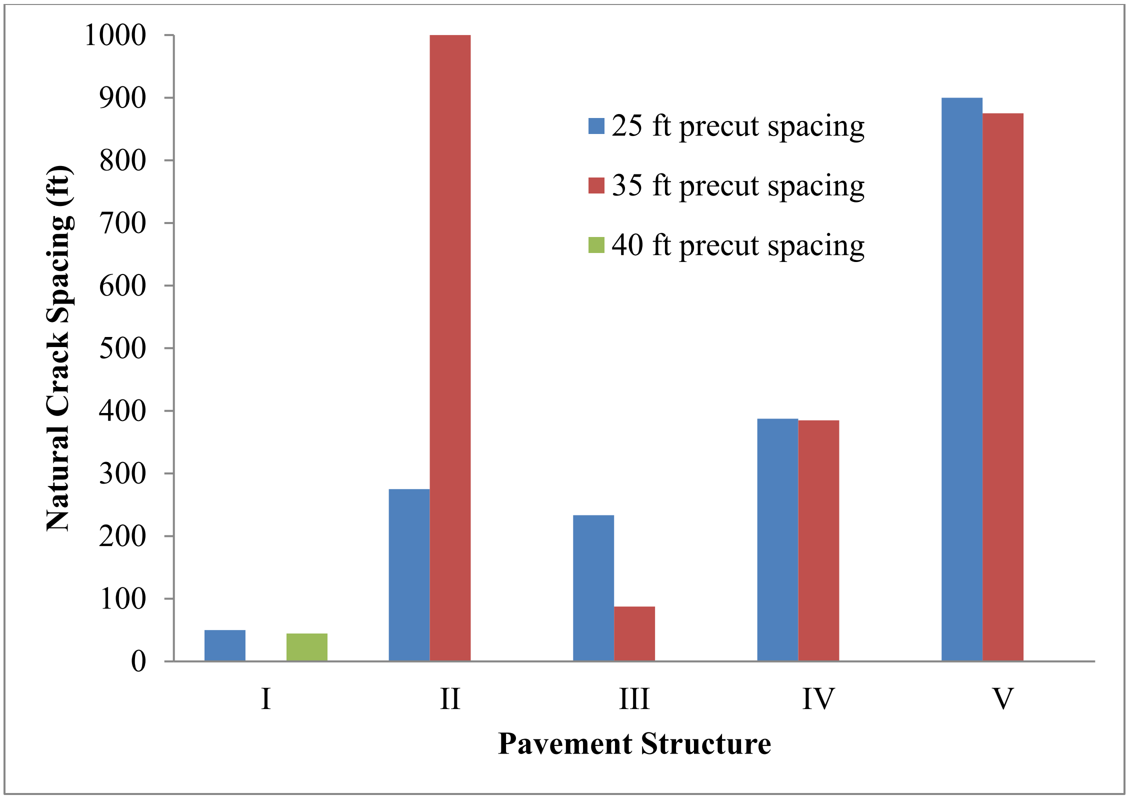


Figure 5.7 Effect of precut spacing

5.3 Effect of Precut Depth

Figure 5.8 shows the relation between precut depth and the natural cracking interval for four precut test locations. These relationships are grouped according to pavement structure and precut spacing. Each group contains natural crack spacing data at three precut depth-to-HMA thickness ratios: 1/4, 1/2, and 3/4.

Sections with a depth ratio of ½ indicated a slightly higher natural crack interval in two of the four groups, although the depth ratio of ¾ tied for greatest natural crack spacing in two groups. Is there an optimum precut depth? These observations are not conclusive. They do not strongly point to any of the three precut depths as being best or worst. However, there is a tenuous indication that more success (longer natural crack intervals) is connected to deeper precuts. Based on field data collected to date, the authors suggest using a precut ratio of ¾.

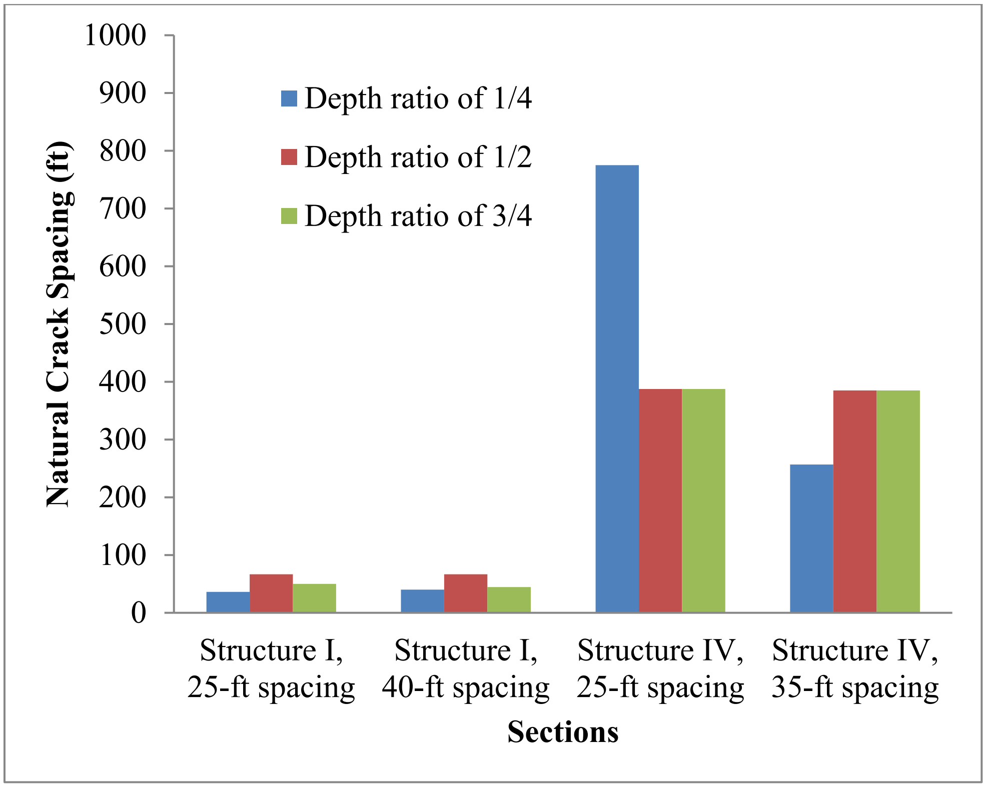


Figure 5.8 Effect of precut depth

5.4 Effect of Pavement Structure

To evaluate the effect of pavement structure, the results were organized into two groups in terms of precut spacing, as shown in Figure 5.9. The 35-foot spacing was not used in pavement structure I; thus, the data of pavement structure I were only used in groups with 25-foot spacing. Based on the results of two groups, the sections built on structure V showed the highest natural crack spacing, followed by sections on pavement structures II, IV, III, and I. Structure V was the strongest and soundest structure for the road, followed by structures II, IV, III and I. This ranking was consistent with the robustness ranking of pavement structure, as shown in Table 3.3, indicating that stronger and/or perhaps simply thicker pavement structure is likely to be more effective in controlling the locations of natural transverse cracks when the precut technique is used.

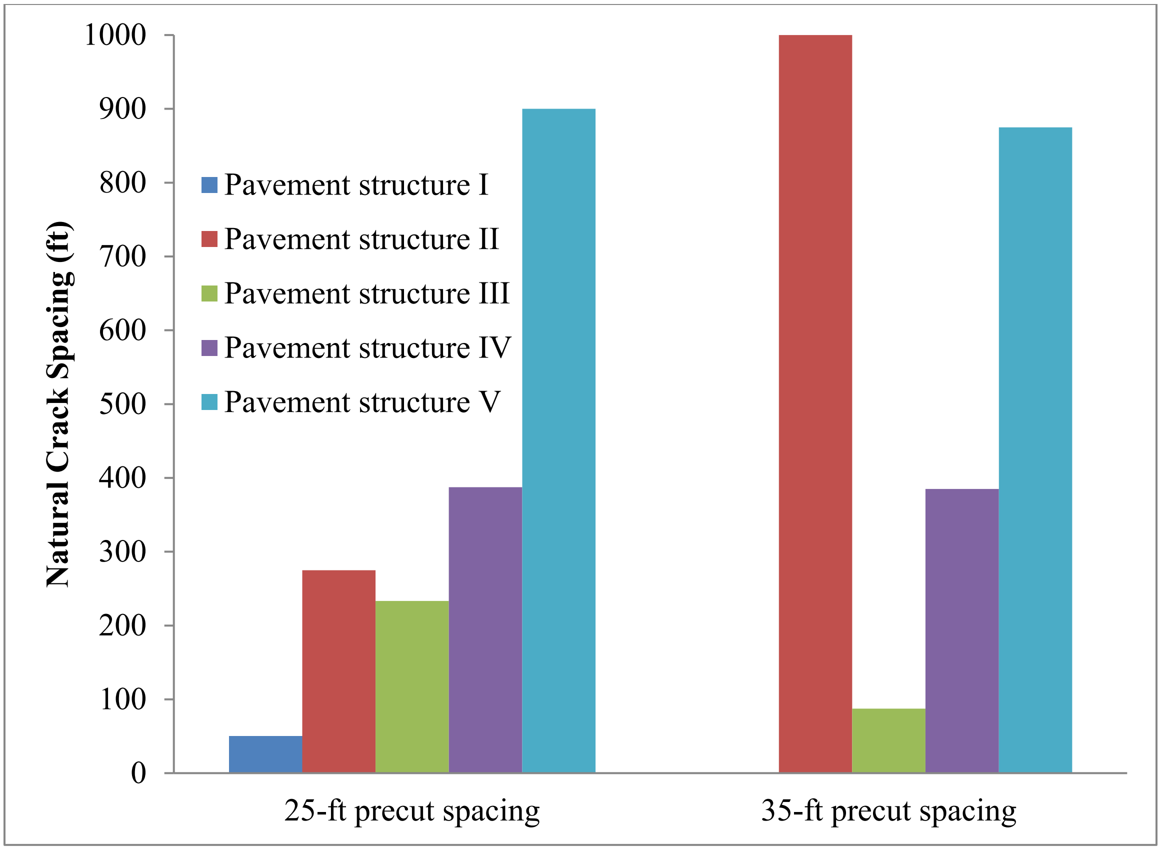


Figure 5.9 Effect of pavement structure

5.5 Effect of Environment

The Long-term Pavement Performance (LTPP) program divided the U.S. into four different environmental zones: dry freeze, dry no-freeze, wet freeze, and wet no-freeze (Perera et al. 2005). Figure 5.10 shows the geographical regions corresponding to these environmental zones. The threshold between the wet and the dry zone generally corresponds to an annual precipitation of 508 mm (20 in.), while the boundary between the freezing and nonfreezing zones generally corresponds to an annual freezing index of 89 Celsius degree-days (192.2 Fahrenheit degree-days). Although Alaska is not included in the geographical drawing shown in Figure 5.9, the environmental conditions of the locations of projects evaluated in this study can be determined based on the recommended boundary values.

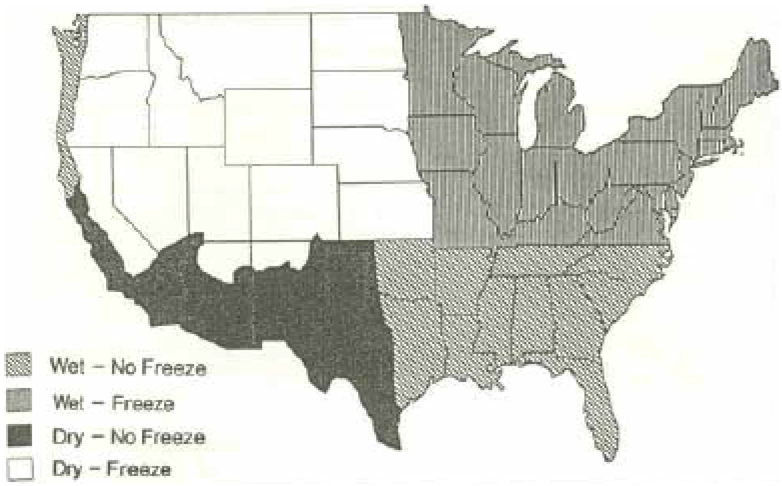


Figure 5.10 Environmental zones considered in the LTPP program (Perera et al. 2005)

In order to determine Alaska's environmental condition, the daily temperature and precipitation data of the project sites were obtained from the database of the Western Regional Climate Center (WRCC). The calculated annual freezing indices are 5322 and 3877 Fahrenheit degree-days for Moose Creek and Healy project sites, respectively. The annual precipitations are 11.839 inches and 15.442 inches for Moose Creek and Healy project sites, respectively. These data show that both projects are located in a dry-freeze zone. Moose Creek is colder and drier than Healy. However, as both project sites are in the same environmental zone, it is not possible to draw a conclusion about the effect of the environment on the effectiveness of the precut technique.

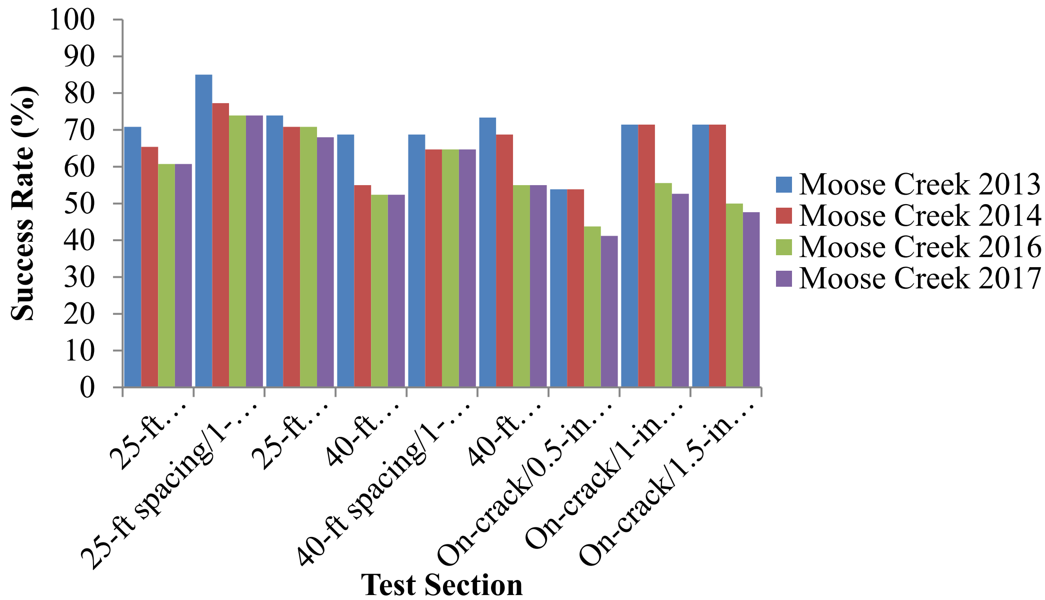
5.6 Success Rate Results

The statistic of success rate was used in the 1996 Minnesota study (Janisch and Turgeon 1996) to examine the effectiveness of the precut technique. In a specific section, the success rate is determined by the ratio of the number of the sawn joints to the sum of sawn joints plus natural transverse thermal cracks observed in that section, as shown in Eq. 5.1.

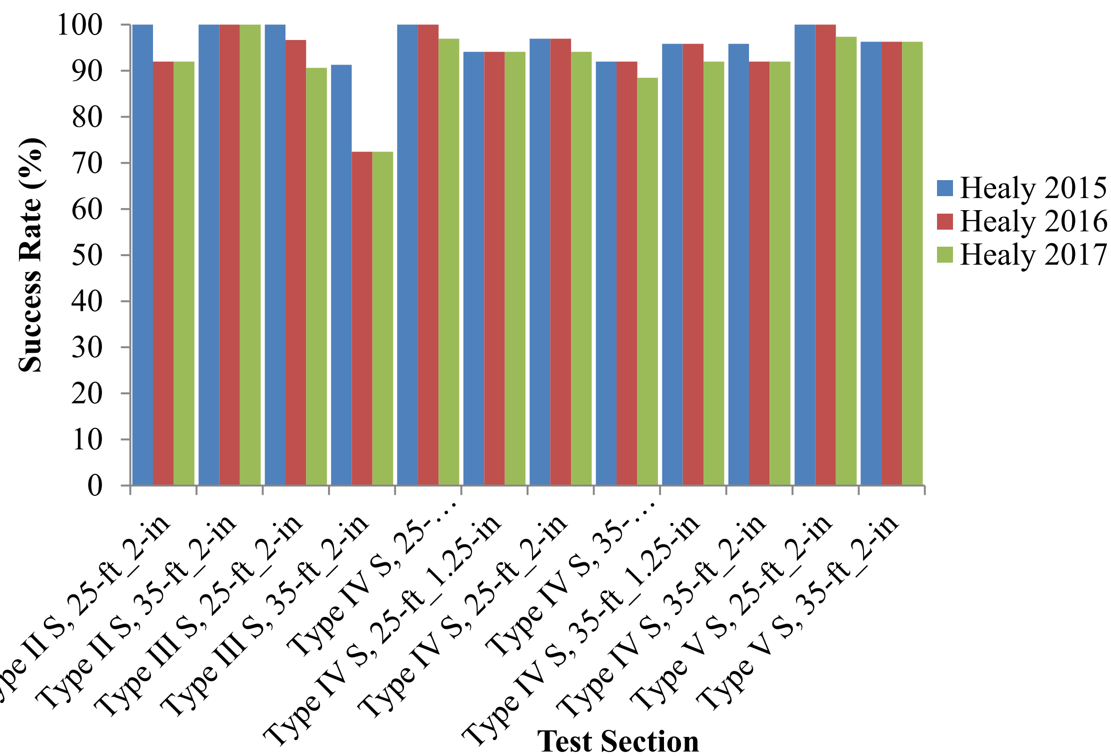
$$\frac{\#\ of\ Sawn\ Joints}{\#\ of\ Sawn\ Joints + \#\ of\ Thermal\ Cracks} \times 100 = \%\ of\ Success\ Rate \qquad (Eq. 5.1)$$

Eight-five percent (85%) success was established by the Minnesota DOT saw-and-seal advisory committee as the level at which a project was considered successful or not (Janisch and Turgeon 1996).

Figure 5.11 presents the results of success rates of all the precut sections evaluated in this study. It can be seen in this figure that the data of most Moose Creek sections are below the 85% criteria, and that those of most Healy sections are higher than 85%. Transverse cracks (even with precutting) increase with time, and the older pavement (Moose Creek sections) would be expected to show a lower score. Note that calculation of the success rate is highly dependent on the number of natural cracks—the lower the number, the higher the success rate. However, pavement with a strong structure (e.g., Healy sections) may be favored by this calculation, as cracks are rarely seen on strong pavement structure, even on a control section. This suggests that success rate may not be a good statistic for determining the effectiveness of the precut technique, especially since the precut technique is used not only to reduce natural cracks, but also to re-direct cracks to a better shape.



(a)



(b)

Figure 5.11 Results of success rates: (a) Moose Creek project; (b) Healy project

CHAPTER 6.0 COST ANALYSIS

The cost analysis conducted in this study was based on the necessary information collected from ADOT&PF Northern Region maintenance engineers and local contractors, and some reasonable assumptions. Netardus (2016) conducted closely related research and used an estimated cost of 2.33 $/ft for the precut installation, which we also used. The same crack sealing cost estimated in Netardus (2016) was used in this study, including 3.5 $/ft for the Moose Creek project and 3 $/ft for the Healy project. Below are the assumptions we used:

- Precuts are categorized as high-quality cracks that do not need to be maintained.
- Crack sealing will be done annually.
- Every new crack will be sealed when observed.
- A sealed crack will be re-sealed when sealant fails.
- Sealing maintenance will be stopped when pavement life is reached (e.g., the last sealing maintenance will be done on the 19th year after the construction of a 20-year pavement).

Three combinations of pavement design life and sealant life were used to cover different situations, including 30-year pavement life and 3-year sealant life, 30-year pavement life and 5-year sealant life, and 20-year pavement life and 5-year sealant life. The concept of net present value (NPV) was used to calculate the cost until pavement life is reached, as shown in Eq. 6.1

$$NPV = InitialCost + \sum_{k=1}^{N} FutureCost\left[\frac{1}{(1+i)^{n_k}}\right] \qquad \text{(Eq. 6.1)}$$

where

InitialCost = precut installation cost for precut sections, and none for control sections;

FutureCost = maintenance (sealing) cost;

i = discount rate, using 4% as a common number in Alaska;

n_k = the number of years after the precut installation when sealing is needed.

A calculation example is given when selecting 30-year pavement life and 5-year sealant life. The precut installation year is year 0. Assuming the number of cracks observed on the 1st, 2nd… year is n_1, n_2… for each section, the n_1 cracks will be sealed on the 1st, 6th, 11th, 16th, 21st, and 26th years, and the n_2 cracks will be sealed on the 2nd, 7th, 12th, 17th, 22nd, 27th years… . That being said, the total NPVs of control and precut sections are summarized in Table 6.1.

Table 6.1 Calculation of NPVs

Section	NPV
Control	The total cost of sealing (n_1, n_2…)
Precut	The total cost of sealing (n_1, n_2…) + precut installation cost

The calculation results are presented in Table 6.2 for the Moose Creek project and in Table 6.3 for the Healy project. For the Healy sections, only data from sections using the Type III pavement structure were used for cost analysis. Other structures—II, IV, and V—are so strong that only a few cracks have been observed so far; most sections containing only one or two cracks. Cost analysis using these small numbers so early in the life of the pavement may be very misleading.

Table 6.2 Cost calculation for Moose Creek project

No.	Section	NPV ($/1000 ft) for 30-year pavement life and 3-year sealant life	NPV ($/1000 ft) for 30-year pavement life and 5-year sealant life	NPV ($/1000 ft) for 20-year pavement life and 5-year sealant life
1	Control	26881.4	16761.2	13086.8
2	25-ft spacing & 1/4 DR	24943.5	17088.5	14234.3
3	25-ft spacing & 1/2 DR	15268.8	10995.1	9445.3
4	25-ft spacing & 3/4 DR	19232.0	13359.5	11232.3
5	40-ft spacing & 1/4 DR	21758.9	14541.5	11948.8
6	40-ft spacing & 1/2 DR	14306.3	9833.2	8248.4
7	40-ft spacing & 3/4 DR	19137.8	13095.7	10812.4
8	Precut on-crack & 1/4 DR	20606.4	13575.2	10927.5
9	Precut on-crack & 1/2 DR	19248.5	13046.1	10652.2
10	Precut on-crack & 3/4 DR	21077.9	14287.9	11634.4

The pavement life/maintenance scenarios for the Richardson Highway Moose Creek sections shown in Table 6.2 indicate the following average savings, compared with the control section, which includes the cost of precutting and maintenance sealing:

- 27% savings for 30-year pavement life w/3-year sealant life
- 21% savings for 30-year pavement life w/5-year sealant life
- 16% savings for 20-year pavement life w/5-year sealant life
- An overall average savings for all scenarios combined is 21%

Table 6.3 Cost calculation for Healy project

No.	Section	NPV ($/1000 ft) for 30-year pavement life and 3-year sealant life	NPV ($/1000 ft) for 30-year pavement life and 5-year sealant life	NPV ($/1000 ft) for 20-year pavement life and 5-year sealant life
1	Type III, 25-ft spacing & 1/4 DR	9524.4	8542.8	8157.6
2	Type III Control	14454.8	9241.2	7262.9
3	Type III, 35-ft spacing & 1/4 DR	12863.0	9857.4	8792.6

The pavement life/maintenance scenarios for the Parks Highway Healy sections shown in Table 6.3 indicate the following average savings compared with the control section, which includes the cost of precutting and maintenance sealing:

- 23% savings for 30-year pavement life w/ 3-year sealant life
- 0% savings for 30-year pavement life w/5-year sealant life
- -17% savings for 20-year pavement life w/5-year sealant life
- An overall average savings for all scenarios combined is 2%

In order to determine if a precut section is cost-effective for the designed pavement life, its life-cycle maintenance cost should be compared with the control section. Table 6.4 summarizes the comparison results, in which “Yes” means the maintenance cost of a precut section is lower than the cost of a control section with the same pavement structure and this section is cost-effective, and "No" means the opposite.

Table 6.4 The cost effectiveness of the precut section

Project	Pavement Structure	Section	30-year pavement life and 3-year sealant life	30-year pavement life and 5-year sealant life	20-year pavement life and 5-year sealant life
Moose Creek	I	25-ft spacing & 1/4 DR	Yes	No	No
		25-ft spacing & 1/2 DR	Yes	Yes	Yes
		25-ft spacing & 3/4 DR	Yes	Yes	Yes
		40-ft spacing & 1/4 DR	Yes	Yes	Yes
		40-ft spacing & 1/2 DR	Yes	Yes`	Yes
		40-ft spacing & 3/4 DR	Yes	Yes	Yes
		Precut on-crack & 1/4 DR	Yes	Yes	Yes
		Precut on-crack & 1/2 DR	Yes	Yes	Yes
		Precut on-crack & 3/4 DR	Yes	Yes	Yes
Healy	III	25-ft spacing & 3/4 DR	Yes	Yes	No
		35-ft spacing & 3/4 DR	Yes	No	No

Note that, among the three combinations, the one with a 30-year pavement life and 3-year sealant life is most advantageous to the precut technique, as most times, sealing may be done on natural cracks using this combination so that the precut installation cost carries the smallest weight during calculation. Thus, the combination of 20-year pavement life and 5-year sealant life is the least advantageous to the precut technique. In Table 6.4, it can be seen that only one section in the Moose Creek project is not cost-effective under the two combinations that are less advantageous to the precut technique. This means that the precut technique is generally cost-effective even with varying design parameters. However, for the Healy project sections with structure type III, the two sections showed "Yes" and "No" under different combinations. It is a very important fact that only 3 years of data were used in the calculation for the Healy project sections, and it is expected that the number of natural transverse thermal cracks will increase with time. It is therefore anticipated that the precut sections will demonstrate their cost-effectiveness in the future.

Note that the crack data of 5 years and 3 years have been collected so far for the Moose Creek project and Healy project. According to the current data analysis and practical expectations, three reasonable assumptions can be made: (1) natural transverse cracks will increase with time, (2) more precuts will become active with time, and (3) the number of natural cracks will increase in the control sections faster than in the precut sections. This suggests that the cost analysis presented in this study using data collected over a short period was conservative; the value of precutting should become substantially higher if the pavement sections are monitored for a long time (10–15 years).

CHAPTER 7.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

The research team conducted a comprehensive literature review regarding precutting techniques for maintaining AC pavements with thermal cracking. The review included a background of thermal cracks in AC pavement, maintenance approaches for thermal cracking, and the evolution of precut techniques for rigid and AC pavements. Application experiences with using precut techniques in northern states with severe concerns about thermal cracks in AC pavements, such as Iowa, Minnesota, Maine, North Dakota, and Alaska, were detailed.

The research team performed field surveys for three precut test sections: (1) Phillip Field Road, single evaluation (2016, 32 years after its construction); (2) Moose Creek project, four field surveys (2013, 2014, 2016, and 2017) after construction in 2012; and (3) Healy project, three field surveys (2015, 2016, and 2017) after construction in 2014. Both control and experimental sections were developed in the Moose Creek and Healy projects. Various levels of precut treatment parameters were considered in experimental sections, including pavement structure (reflecting its robustness), precut spacing, and precut depth.

As the length of each field section was not consistent, natural crack spacing was used as the key statistic for quantitative analysis of the survey results. The natural crack spacing could be used not only to compare the status of thermal cracking in a control section and an experimental section, but also to indicate the effectiveness of the precut technique using various treatment parameters. Success rate, another measurement that is determined by the ratio of the number of the sawn joints to the sum of sawn joints plus natural transverse thermal cracks observed in that section, was also used to compare the results of this study with those of other states such as Minnesota.

Precutting of major thermal cracks in AC pavements appears to function mechanically similar to the way it has consistently functioned with Portland cement pavements. The degree to which precutting works for AC pavement appears to be a function of the thickness and general structural robustness (e.g., the presence of geotextile layers, etc.) of new construction. Physical properties of construction materials that may or may not influence transverse thermal cracking were not considered in this research.

However, precutting also provides quantifiably significant advantages even for new pavement placed as part of a 4- to 6-inch rehabilitation project. Based on Alaska rehabilitation projects reconstructed since 2012 (especially at the older Moose Creek site), field data collected for this report usually indicate fewer new natural transverse thermal cracks in precut test sections versus non-precut control sections.

A preliminary cost analysis using the concept of NPV was conducted to examine the cost-effectiveness of precut treatments used in the Moose Creek and Healy projects. The precutting technique at these sections appears to be an economically promising way of controlling natural thermal cracks. There were also indications that the economic benefits of precutting will become increasingly apparent as the precut pavement ages.

The main objective of any future Alaska precutting study will be to better define that total thickness of new construction or reconstruction (or perhaps method of embankment reinforcement) that allows precutting to completely control new transverse thermal cracking. The precut experiments reported in this study did not resolve the question of optimization, that is, the "best practice" regarding precut spacing and precut depth.

7.2 Conclusions

- Conclusions regarding the Phillips Field Road precut test section were based on 32 years of casual observation and a final careful inspection and mapping of thermal cracks in 2016. The 1984 construction of this section included new pavement and 4–6 feet of new embankment. This test section received heavy traffic for the entire 32-year period. The precut treatment is considered a great success, as very few natural transverse thermal cracks developed outside of the precut locations. In this precut test section, many of the precuts became active.
- Conclusions regarding the Richardson Highway – Moose Creek and the Parks Highway – Healy precut test sections were based on preliminary results over a relatively short time. Continuing evaluation and monitoring of test sections are needed to recommend an effective design methodology and construction practice for Alaska and cold areas of other northern states. Precutting treatments at these sites indicate that precutting is an economically promising way to control natural thermal cracks. Even short-term economic benefits, evaluated after 3–5 years of service, appear to range between about 2% and 21%. For reasons previously discussed, indications are that continued field observations will increase these percentages;
- Shorter precut spacing along with stronger and/or thicker pavement structures look promising with respect to crack control according to preliminary results. Also, there may be an optimum precut depth that produces the best results;
- Crack sealing after precutting using a thin blade (1/8-inch width) may not be necessary for the life of the pavement, whether the precut becomes an active thermal crack or not.

7.3 Recommendations for Future Construction

- For all new construction that includes new AC pavement and at least 4 feet of new embankment, use the precutting technique with the expectation of achieving nearly complete control of transverse thermal crack locations. The long-term economics should be highly beneficial. It is anticipated that little or no sealing/filling of transverse thermal cracks will be required for the design life of the pavement.
- For all new construction that includes new AC pavement and less than 4 feet of new embankment, use the precutting technique with the expectation of achieving significant control of transverse thermal crack locations. Long-term economics are predicted to be very positive and, in terms of required crack sealing, may provide a 20% cost advantage compared with no precutting.
- Recommended precutting interval = 35 feet.
- Recommended precut depth = ¾ of total asphalt concrete pavement thickness.

7.4 Ideas for Future Research

The following are suggestions for further research based on concerns, problems, and questions raised during the transverse thermal crack precut study reported herein.

- Continue periodic monitoring of the Richardson and Parks Highway precut test sites for an additional 10 years.
- Commence testing to determine optimal precut spacing and depth. This can be done by including small precut test areas on any new construction project that includes a new (not overlay) pavement layer.

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APPENDIX A. LITERATURE REVIEW

Thermal Cracks in Asphalt Pavement

Thermal cracking is a common form of distress in asphalt concrete (AC) pavement in the northern United States and Canada; it generally occurs transversely across the width of the pavement (Anderson 2001). Specifically, in Interior Alaska, road-width thermal cracks (major transverse cracks) are possibly the most noticeable form of damage on AC pavements.

Thermal cracks in AC pavement form when the internal thermal-induced stress exceeds its fracture or tensile strength. Two major contributors to thermal cracking are low temperatures and large diurnal temperature differentials (Netardus 2016). As asphalt pavement cools, it contracts at a rate governed by the coefficient of thermal expansion, leading to thermal stress. The top layers of pavement are usually exposed to larger temperature fluctuations than the layer below it. This difference in temperature between the top and bottom AC layers creates a temperature gradient, with the thermally induced stress being largest at the top surface and decreasing towards the bottom of the asphalt layer. If the thermally induced stress is greater than the tensile strength of the asphalt, an initial crack develops on the surface and propagates downwards. Thermal cracks that develop perpendicular to traffic (major transverse thermal cracks) are thought to form in a top-down manner. This form of crack commonly penetrates a foot to several feet into the sub-pavement layers.

Contrary to normal thermal cracking, diurnal temperatures apply constant cyclical stress to pavement, leading to a combination of thermal and fatigue cracking. Thermal fatigue cracking occurs during the diurnal cycle of a typical winter day when the temperature reaches the pavement's "fracture point" (Lytton et al. 1983). Thermal fatigue cracks may serve as a stress concentrator for the propagation of normal thermal cracking under low winter temperatures with great daily temperature differentials. Other factors related to the development of thermal cracks include rate of temperature change, coefficient of thermal contraction, pavement slab geometry, constraint, aging, stiffness, fracture toughness, fracture energy, polymer additives, reclaimed asphalt content, air voids, and mixture aggregate (Netardus 2016).

In addition to cracking distress itself, other types of degradation of the pavement structure can be caused by the existence of transverse cracks (Marasteanu et al. 2007). The pavement base and subbase can be weakened by water that enters the pavement through the cracks. Water and fine materials are pumped out under moving loads, resulting in progressive deterioration of the AC layer. Frost heaves may be generated during the winter in the presence of water in any pavement layer.

The latest edition of the distress identification manual for the Long-term Pavement Performance (LTPP) program, published by the Federal Highway Administration (FHWA) (Miller and Bellinger 2014), categorizes thermal cracking (transverse cracking) into three severity levels:

1. thermal cracking of low severity is defined as an unsealed crack with a mean width mean width ≤ 6 mm or a sealed crack with sealant material in good condition and with a width that cannot be determined;
2. moderate thermal cracking indicates any crack with a mean width > 6 mm and ≤ 19 mm or any crack with a mean width ≤ 19 mm and adjacent low-severity random cracking; and
3. high-severity thermal cracking represents any crack with a mean width > 19 mm or any crack with a mean width ≤ 19 mm and adjacent moderate to high-severity random cracking.

Figure A1 illustrates how thermal cracking should be documented during a field survey. The number and length of thermal cracks at each severity level should be recorded (Miller and Bellinger 2014). One crack should be rated at the highest severity level present for at least 10% of the total length of the crack. Cracks less than 0.3 m in length are not recorded.

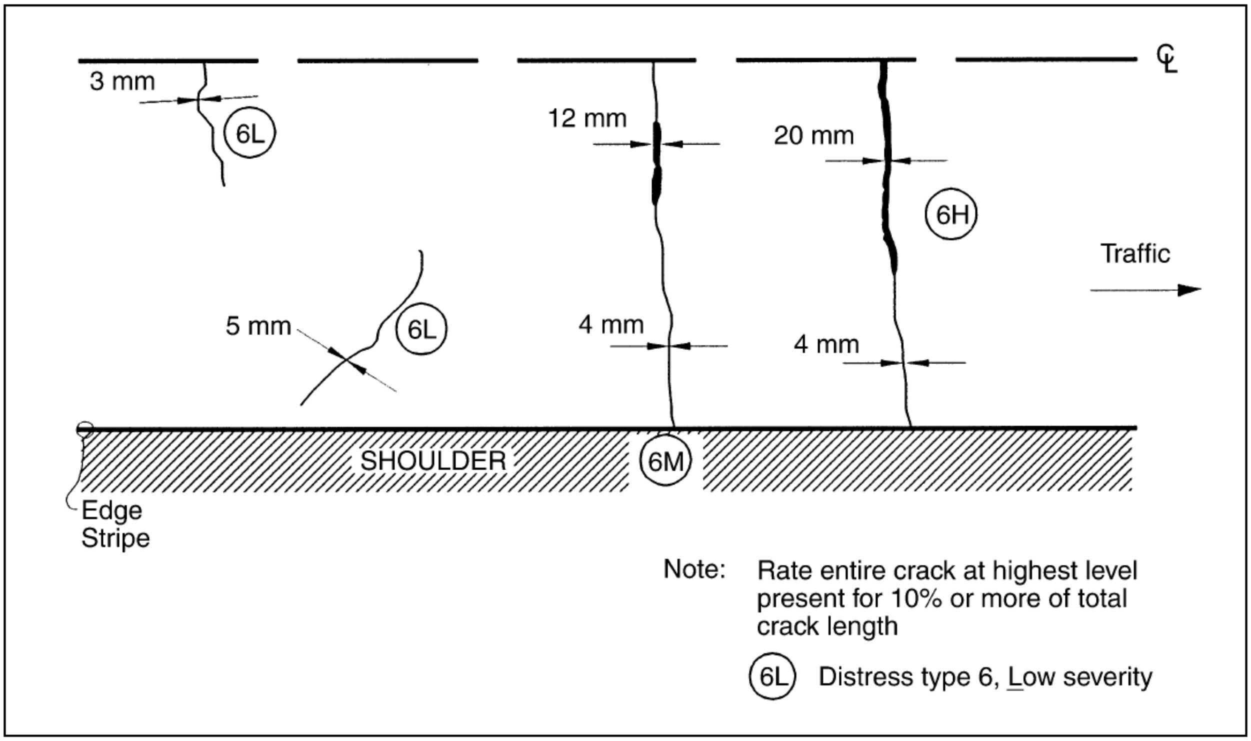

Figure A1. Field survey example for thermal cracking in LTPP manual (Miller and Bellinger 2014)

Maintenance Approaches for Thermal Cracking

Conventional treatment of thermal cracking is by periodic sealing or replacement of damaged sections, which increases road maintenance costs and negatively impacts roadway usage in the form of delays during repairs. Low-severity cracks are less than ½ inch wide and occur infrequently along the pavement (Roberts et al. 1996). Typically, low-severity thermal cracks are sealed to prevent moisture from getting into the crack and further wearing down the edges of the crack. If moisture gets into a crack, freeze–thaw cycles can cause an increase in the crack size and severity. High-severity cracks are greater than ½ inch wide and occur frequently along the pavement. Typically, high-severity cracks are treated by removal and replacement of the cracked pavement (Roberts et. al. 1996). Common treatments for thermal cracking are both expensive and time consuming.

Thermal cracking can also be minimized through AC pavement design. Techniques such as using softer asphalt binders, aggregate interlayers, thicker overlays, fabrics, stress absorbing membranes, and stress absorbing membrane interlayers can reduce crack occurrence (Janisch and Turgeon 1996). The frequency of these thermal cracks primarily depends on asphalt stiffness, but is influenced by subgrade soil type, pavement thickness, traffic loading, asphalt content, air voids, and other variables (Janisch and Turgeon 1996). Researchers in Iowa conducted a project to investigate if transverse cracking would be affected by changing the asphalt content of the asphalt treated base (ATB) (Marks 1985). It was found that natural cracks occurred every 528 feet instead of every 170 feet by just increasing the asphalt content of ATB by 1%. This was partially attributed to the reduction of the void space in the ATB layer from 11.1% to 6.7% due to the increase of the asphalt content.

In the same study conducted in Iowa (Marks 1985), another means, using different asphalts in separate test sections, was tried to reduce the number of transverse cracks. The penetration-viscosity (pen-vis) system was still in use for asphalt classification. Using the pen-vis system, asphalts from two separate source locations were used in different test sections. The test section with a higher pen-vis number meant that the asphalt had low-temperature susceptibility, and the test section with the lower pen-vis number had high-temperature susceptibility. The research data showed that the low-temperature susceptible asphalt exhibited natural crack spacing of 170 feet, while the high-temperature susceptible asphalt exhibited natural crack spacing of only 35 feet. This means that asphalt property could have a tremendous impact on the occurrence of transverse cracking and that this method of reducing the number of transverse cracks warrants future studies. The performance grade system of asphalt classification used today replaced older systems including the one that the Iowa project utilized, which included the penetration-viscosity (pen-vis) number, a method of describing asphalt grade.

Last but not least is the precut technique that can also be used to reduce transverse thermal cracking in asphalt pavement, which will be further described in the following sections.

Precut Techniques in Pavement

Precut Techniques in Rigid Pavement

The practice of joints or pre-sawing started from, and is still commonly used, in concrete in rigid pavements. Concrete pavement is brittle and naturally cracks from various factors including drying shrinkage, thermal contraction, internal or external restraint, subgrade settlement, and applied loads. Joint sawing creates a weakened plane that forces a crack to develop below the saw cut; this prevents random or uncontrolled cracking and helps accommodate slab movement in response to temperature and moisture fluctuations (Krstulovich et al. 2011). Various methods of reducing the occurrence of cracking in concrete include reinforcement, and early entry or conventional sawing followed by the sealing of concrete and rigid pavement joints. According to Morian and Stoffels (1998), the two primary purposes for sealing rigid pavement are (1) to prevent or reduce water infiltration of the pavement structure and resultant slab erosion and loss of support; and (2) to minimize the incompressible material entering the joint reservoir resulting in point loading when slabs experience thermal expansion and subsequent joint damage. Several agencies have adopted or are considering using a single unfilled 1/8 inch joint for rigid pavement. In areas with positive drainage features, this practice may be acceptable. However, in wet climates with fine subgrade materials, slab-support erosion has resulted in acceleration of jointed rigid pavements (Morian and Stoffels 1998).

Conventional joint sawing is usually performed as the concrete reaches final set, which generally occurs 4 to 12 hours after paving. Early entry sawing can cut joints soon after final finishing, reducing random cracking and requisite depth of cuts (McGovern 2002). Sawing too early can result in the concrete joint crumbling or raveling, while sawing too late results in initiation of cracking ahead of the sawing operations. Careful consideration of material properties (strength, elastic modulus, moisture migration, heat capacity), environmental conditions (relative humidity and wind speed), and geometric factors (pavement thickness and crack depth) must be performed to determine the optimal saw timing and depth (Raoufi et al. 2008). As illustrated in Figure A2, excessive raveling and/or tearing of the pavement surface are incurred if sawing operation commences too early. However, internal stresses develop in the slab, if sawing is done too late, which could lead to random cracking (Okamoto et al. 1994).

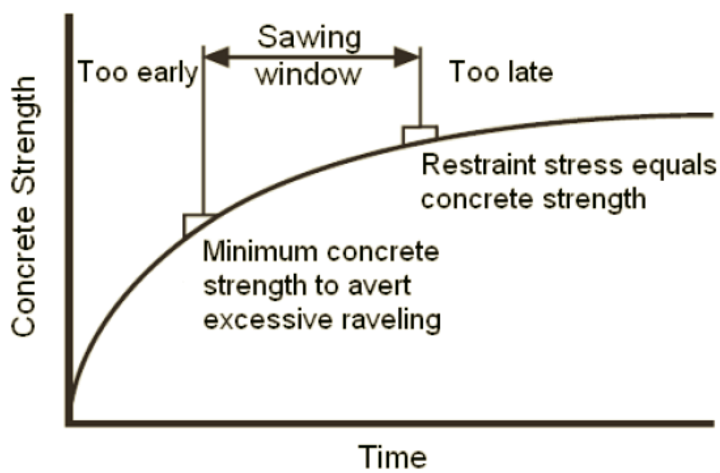

Figure A2 Concrete sawing timing in terms of time vs. strength (Okamoto et al. 1994; Krstulovich et al. 2011)

A potential concern with precut concrete is the possibility for decreased durability and longevity. The Illinois Department of Transportation preformed a study on the durability of joints using early entry sawing (Krstulovich et al. 2011), during which cores were retrieved throughout the test sections and petrographic analysis, freeze–thaw testing, and resistance to salt scaling were used to assess the durability of Portland cement concrete (PCC). The 3-, 7- and 28-day tests indicated the long term durability and longevity using early-entry sawing are not compromised (Krstulovich et al. 2011).

Precut Techniques in AC Pavement

For AC pavement, the precutting technique was first attempted and recommended by Bone and Crump (1956) in 1956. The concept of sawing and sealing joints in an AC overlay was proposed then as a method of controlling the location and severity of reflective cracks starting from the old PCC pavements (Figure A3). Many states, particularly in the northeastern United States, have developed procedures for the design and construction of the saw-and-seal technique for asphalt overlays over PCC pavements (Kilareski and Bionda 1990).

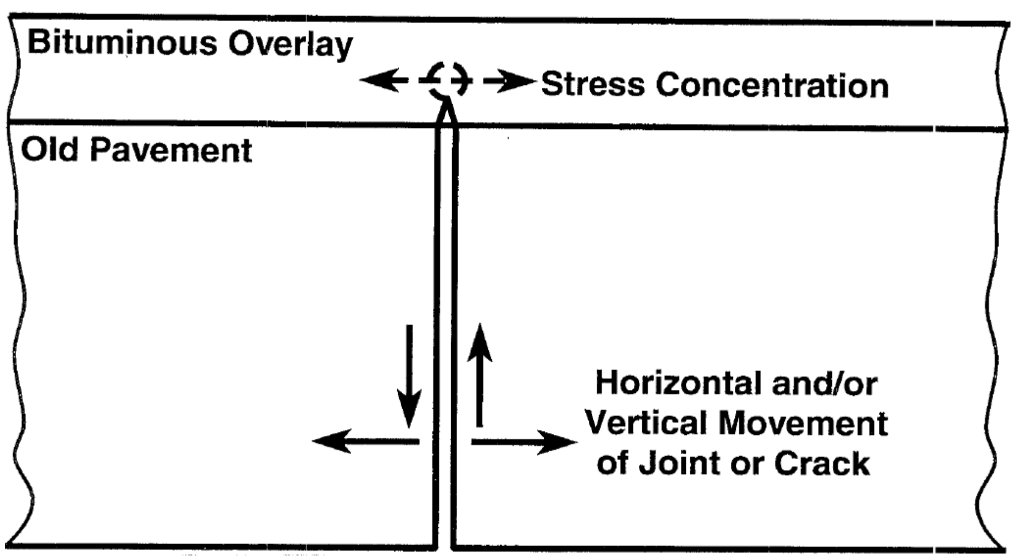

Figure A3 How reflective cracking starts from the old PCC pavement (Janisch and Turgeon 1996)

The saw-and-seal technique was soon adopted in construction of new bituminous pavements. Unlike overlay construction, sawing precuts in new bituminous pavement was motivated by an assumption that uniformly spaced sawed joints could be sealed more efficiently than the random, crooked thermal cracks that formed naturally (Morchinek 1974). According to the explanation by Janisch and Turgeon (1996), a weakened plane is produced due to the pavement's reduced cross section when a saw cut is installed in AC pavement. When thermal stresses develop, the weakened plane cannot withstand the same thermal stresses as the unsawed portion without cracking, thus the pavement will crack at the sawed joint. For asphalt overlay on pre-cracked asphalt pavement, both reflective and thermal cracking should be considered.

Early Studies – AC Overlay on PCC Pavement

The sawing-and-sealing technique was first attempted in Connecticut in 1958 (Wilson 1962). Two sections, US-7 in Norwalk and US-1 in East Haven, were established to determine whether sawing and sealing joints would extend the maintenance-free life of the overlay sufficiently to justify the additional cost. Based on field survey results collected 3 years later, the author concluded that substantial extension of the maintenance-free life of the overlay could be achieved. Therefore, a consequent reduction in the annual cost per square yard of bituminous concrete overlays could be expected. However, the adhesion failure of the sealant was reported to be a problem.

The New York DOT started to investigate sawing and sealing of joints in AC overlays around 1980 (Noonan and McCullagh 1980; Vyce 1983). This was done to control reflection cracking on AC overlays over PPC pavement after poor or inconsistent results from other methods such as reinforcing mesh and fabrics, bond breakers, etc. Note that the methods less successful in New York State had been previously considered successful by other agencies. Several factors unique to New York State were presented by Vyce (1983) that could account for the discrepancy, including crack initiation due solely to horizontal movement, slab length, and temperature change. This indicates that the success of the precutting technique can also depend on the location of the project. The New York studies finally claimed that a properly designed sawing-and-sealing technique offers a solution to the widespread occurrence of deterioration in bituminous resurfacings over transverse joints in rigid pavements.

A comprehensive study was conducted later covering 10 projects with a total of 15 overlays in the northeastern United States, including Connecticut, Maine, New Jersey, New York, Ohio, and Pennsylvania (Kilareski and Bionda 1990). Pavements with up to 10 years of service life were evaluated through condition surveys, roughness measurements, and deflection measurements. The authors claimed that properly locating the saw cut above the existing joint is an important step in the construction process. Saw-and-seal sections with thick overlays performed better than sections with thin overlays. The study concluded that saw-and-seal joints in an AC overlay on jointed PCC can reduce the adverse effects of reflection cracking; thus, this technique can extend pavement life (Kilareski and Bionda 1990).

Janisch and Turgeon (1996) summarized Minnesota's experience of sawing and sealing joints in bituminous pavements including bituminous overlays of jointed concrete pavement. Saw and seal can be extremely effective in eliminating maintenance costs associated with transverse reflective cracks. It was claimed that saw cuts must be made within 1 inch longitudinally of the joints below or the cracks will form near, but not at, the sawed joint in the overlay. It was recommended that saw cuts be made above every PCC joint, as observations showed that simply using short joint spacing produced many non-working joints and would not be promising in reducing cracks.

Minnesota Research (Morchinek 1974)

The first documented project conducted to evaluate the effects of the precut technique on new asphalt pavement (non-overlay) was a study in Minnesota completed in 1974 (Morchinek 1974). The purpose of the study was to determine if sawing control joints would reduce or eliminate uncontrolled cracking of flexible pavements. To achieve this, joints were sawed to a depth of 3 inches at 40-, 60-, and 100-foot spacings in November 1969, and were alternately sealed with hot-rubber and neoprene seals.

The key findings of the 1974 Minnesota Research can be summarized as follows:

- Transverse cracking developed on control sections with no joints after two winters of service.
- After five winters, numerous cracks formed in the control sections; a few random cracks formed on sections with 100-foot precut spacings; complete arresting of uncontrolled cracking was accomplished on sections with 40- and 60-foot precut spacings.
- The sidewalls of neoprene-sealed joints were softening and random swelling was visible on the day after seal installation; laboratory analysis showed that the lubricant used for installing the neoprene seals contained a high percentage of volatiles, which probably caused softening of the materials.
- The hot-rubber asphalt sealed joints failed in adhesion after one winter of service, which was attributed to the joint shape factor such as the ratio of width to depth.
- After five winters, some spalling or raveling of the wearing course was observed within the wheel tracks at the sawed joints; a theory was proposed that neoprene compression seals would exert pressure on the joint sidewalls.
- Based on some reasonable assumptions, costs for sawing and sealing with neoprene would be approximately the same as for the maintenance practice of crack filling at the

time, while the cost for sawing and sealing with hot-rubber-asphalt was considerably higher.

Iowa Research (Marks 1985)

Another study was conducted by the Iowa Department of Transportation to investigate eight test sections to determine three questions (Marks 1985), one of which was about precut spacing. The project placed precuts at intervals of 40, 60, 80, and 100 feet and sealed them. Each precut was 1/4-inch wide by 3 inches deep. The pavement structure was 3 inches of asphalt surface course over 8 inches of asphalt-treated base. After 3.5 years, all of the seals had failed, but no detrimental effects had occurred at the precut locations, which may indicate that sealing cracks is not necessary for precuts. No natural cracking (at non-precut locations) was recorded in the first 3.5 years, which the authors said was not a surprise considering that the control section natural crack interval was 170 feet. This means precuts were effective in preventing natural transverse cracks from forming except at the precut locations.

Minnesota Research (Janisch and Turgeon 1996)

One of the most important studies to evaluate precut technique is the 1996 Minnesota study (Janisch and Turgeon 1996). This project evaluated over 50 sections of road including new hot mix asphalt construction, bituminous overlays on PCC, and bituminous overlays on bituminous pavements.

The success rate equation was introduced in this study to examine the success of the saw-and-seal technique. In a specific section, the success rate is determined by the ratio of the number of the sawn joints to the sum of sawn joints plus natural transverse thermal cracks observed in that section, as shown in Eq. A1.

$$\frac{\#\ of\ Sawn\ Joints}{\#\ of\ Sawn\ Joints + \#\ of\ Thermal\ Cracks} \times 100 = \%\ of\ Success\ Rate \qquad (Eq. A1)$$

Eight-five percent (85%) success was established by Minnesota DOT's saw-and-seal advisory committee as the level at which a project was considered successful or not (Janisch and Turgeon 1996). The success rate ranged from 47 to 100% for a total of 50 test sections reviewed in the study, more than 75% of which had a success rate above 85%.

The Minnesota experiment showed promising results and gave recommendations for where to use the technique and what to avoid. For new bituminous pavements, they evaluated the effect of precut spacing and it was determined that cracks cut between 30 and 50 feet would control thermal and random cracking, while cuts spaced at 60 feet would not. Saw cut depth was evaluated, but no conclusive evidence was determined for new bituminous pavements, and only a suggestion of cutting at least one-third of the pavement depth was made. Bituminous pavements overlaid on concrete should be cut to a depth of 2 inches or one-third the pavement thickness, whichever is greater. Lastly, bituminous overlays of bituminous pavement should be cut very deeply, at least one-third of the total pavement thickness, or the underlying cracks may meander away from the new precut location.

Maine (Marquis 2004)

In Maine, construction was completed on two projects that included saw-and-seal technology in the fall of 1997. The project description can be found in Table A1. One project was a highway reconstruction project with 9.5 inches of HMA base and wearing surface. The wearing surface consisted of a 0.5-inch stone C-mix with AC-20 grade asphalt binder. The second project was a highway pavement rehabilitation project that included grinding and stockpiling of the existing 3-inch wearing surface, full depth reclamation of the remaining 8 inches of existing HMA, then surfacing with 4.5 inches of HMA. The wearing surface was a 0.5-inch stone Superpave mix with an AC-20 grade asphalt binder.

Table A1 Maine study (new AC pavement) (summarized from Marquis 2004)

Project	Section	Saw Spacing (ft)	Joint Information			HMA Course Thickness (in)	Total Section Length (ft)
			Depth (in)	Depth Ratio (%)	Width (in)		
1	Test	30	2.5	26.3	1/8 to 1/2	9.5	1000
		40	2.5	26.3	1/8 to 1/2	9.5	1000
	Control	-	-	-	-	9.5	1000
2	Test	30	2.5	55.6	1/8 to 1/2	4.5	2000
	Control	-	-	-	-	4.5	2000

For the first project, “wet cut,” which was not allowed in Special Provision 419, was allowed by the resident engineer, as the contractor brought the “wet cut” saw only. Details of joints can be seen in Figure A4. No natural transverse cracks developed in the Sherman project test sections, but did develop in the control section of this experiment. Neither project precut on the shoulders, and it was mentioned that cracks formed out of the ends of the precut through the shoulders, so using the precut technique across the full width of the pavement is preferred. The authors (Marquis 2004) also mentioned that some of the precut sealants failed due to not including bond breaker tape on the Sherman project.

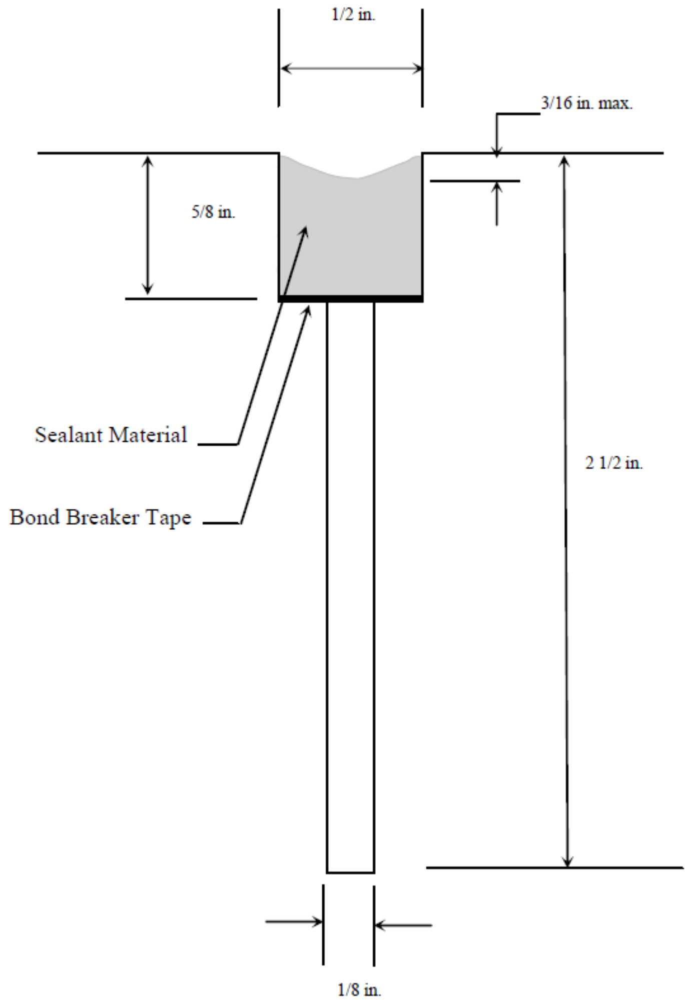

Figure A4 Joint details in Maine study

North Dakota (Evert and Richter 2007)

The details of the North Dakota project are presented in Table A2. All the sections were constructed in 1998. Field evaluation data obtained in 2003, 2004, 2005, and 2007 were presented. The pavements in the test sections were in good condition after 10 years of service. Random cracks were controlled by the saw-and-seal joints. Few random transverse cracks were found next to intersections, approaches, and pipe. Longitudinal cracks were observed to develop on the test sections but not related to the saw and seal.

Table A2 North Dakota study (new AC pavement) (summarized from Evert and Richter 2007)

No.	Section	Saw Spacing (ft)	Joint Information			HMA Course Thickness (in)	Total Section Length (mile)
			Depth (in.)	Depth Ratio (%)	Width (in.)		
1	Test	30	3/8	7.5	3/4	5	0.5
2		40	3/8	7.5	3/4	5	0.5
3		80	3/8	7.5	3/4	5	0.5
4		40	5/8	12.5	3/4	5	0.5
5		80	3/4	0.15	3/4	5	0.5
6	Control	-	-	-	-	5	9

The statistic of success rate was also adopted in the North Dakota study (Evert and Richter 2007), and a success rate of 85% or greater was pursued. It was found that, after 4 years of monitoring, all five test sections showed success rates greater than 85%, ranging from 89 to 100%. The test section with 89% success had a crack spacing of 80 feet. Many sealants failed due to adhesion after 4 years. The reservoir type will determine the effectiveness of the sealant adhesion. The joints may need to be resealed after 7 to 10 years.

Alaska Research

Alaska has a few test sections in roads near Fairbanks and at the Fairbanks International Airport (Griffith 2011). One test section in Fairbanks is over 30 years old, constructed in October 1984; it is located on Phillips Field Road. Precuts on Phillips Field Road remained in very satisfactory condition during the long life of the pavement with minimal spalling and little to no settlement. Unfortunately, no formal study or continuous monitoring was conducted on Phillips Field Road, but the test section that remained, prior to 2016 rehabilitation, provided excellent informal positive reinforcement to the ideas tested on the two new projects investigated in this study. This section provided a promising look at the longevity and potential success of the precut technique. The project was examined and documented in 2016, just prior to its destruction as part of a new construction project. Observations regarding this old test site are presented in Chapter 4.

Recently, the saw-and-seal technique was included in the “Fairbanks International Airport FIA Apron Improvements” project constructed in 2013 (Griffith 2011). A grid of precuts was installed to alleviate thermal cracking in the massive airport tarmac. This grid also helps channel water off the tarmac while avoiding potentially dangerous sheet flow that could lead to hydroplaning. These cracks have not been evaluated for success, but were installed with a design similar to what other airports in the contiguous United States have successfully used, and also similar to that used for Minnesota and Maine research projects.

A more recent project was completed during the 2012 construction season within a 1-mile section of ADOT&PF’s Richardson Highway Mile 340 to 346 project (Liu et al. 2015). Details of this project are presented in Chapter 4.

Summary

Generally, the saw-and-seal method worked well for newest pavement construction, and worked on bituminous overlays of concrete when the cuts were aligned with the concrete joints. Bituminous overlays of bituminous materials sections seemed not very effective, but sections had been reported to perform well where precuts were aligned over existing cracks that were straight.

All of the states that evaluated precutting, excluding Alaska, evaluated the saw-and-seal technique to control transverse thermal cracking. Alaska’s experiments involved precutting without sealing. In general, precut spacing of 40 feet or less was most effective in preventing thermal cracking. The test sections in Iowa experienced complete sealant failure within the joints without detriment to the pre-sawn joints. Other states experienced varying rates of sealant adhesion with promising results pertaining to thermal crack mitigation by precut joints.

Significant documentation of precutting effectiveness was published in the older literature. However, in recent years, little information regarding the implementation and the results of the saw-and-seal technique has been published. As such, information was not available in print; key authors of the 1996 Minnesota study were contacted via phone and email.

In a phone communication with Turgeon, we learned that the saw-and-seal technique was very effective at combatting transverse thermal cracking. However, deterioration in the asphalt as a result of the saw-and-seal technique was observed. A cupped depression developed approximately 5–7 years after implementation. It was observed also that in areas of lower vehicular traffic, these distresses developed much later in the pavement's life. Turgeon speculated that the damage was due to a combination of high traffic volumes and heavy truck traffic. As a result, saw-and-seal is no longer employed as standard practice by Minnesota DOT. PG 58-34 binder has replaced the saw-and-seal technique for standard practice in preventing thermal cracking. The modified binder seems to be effective in preventing thermal cracking in most situations. However, many cities and towns in Minnesota still use saw-and-seal as standard practice.

Much of the information provided by Janisch agreed with Turgeon's conclusions. The cupped depressions extended approximately 6 to 12 inches on each side of the joint, with a depth of up to an inch. Janisch speculated that the cupped depressions at the joint formed through a combination of traffic and climate (precipitation and temperature). The repeated traffic loading pounded the edge down while rainwater infiltration weakened the material below the asphalt.

Janisch also provided additional information regarding current implementation of saw-and-seal. In pavement with protrusions such as manhole and utility access covers, saw and seal is still the preferred method for thermal crack prevention. In addition, it was noticed that sections of asphalt bounded by curb and gutter with sawn and sealed joints did not exhibit the cupped depressions. Janisch speculated that the curb and gutter provided a boundary that provided support for the pavement structure.

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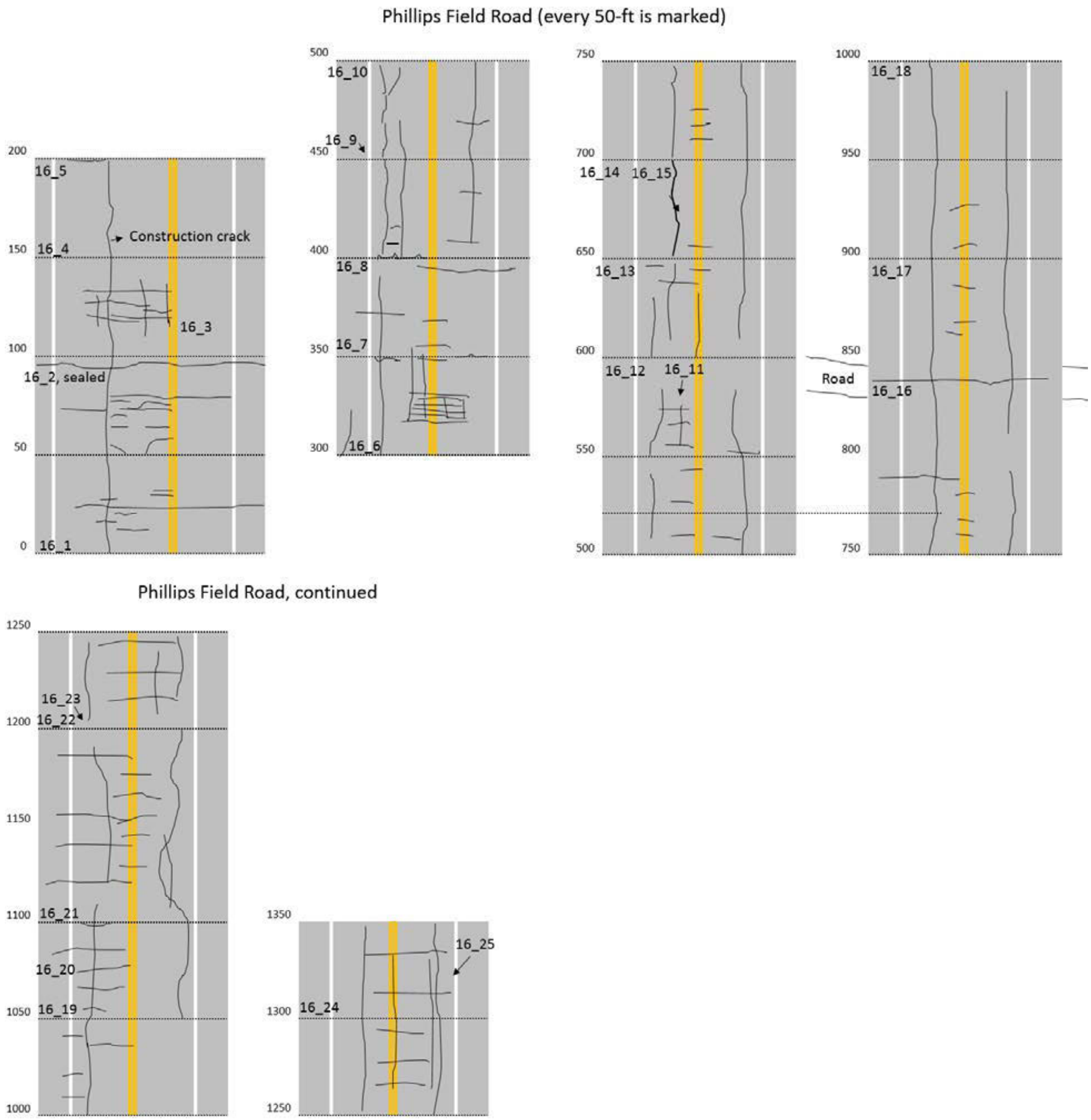
APPENDIX B 2016 FIELD SURVEY SUMMARY_PHILLIPS FIELD ROAD



Appendix B1. Phillips Field Road Survey Map

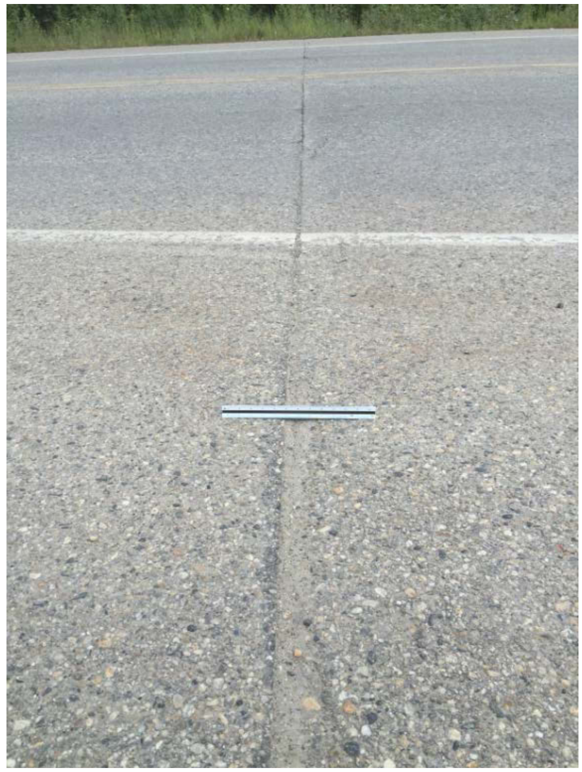
Appendix B2. Phillips Field Road 16_1

Appendix B3. Phillips Field Road 16_2

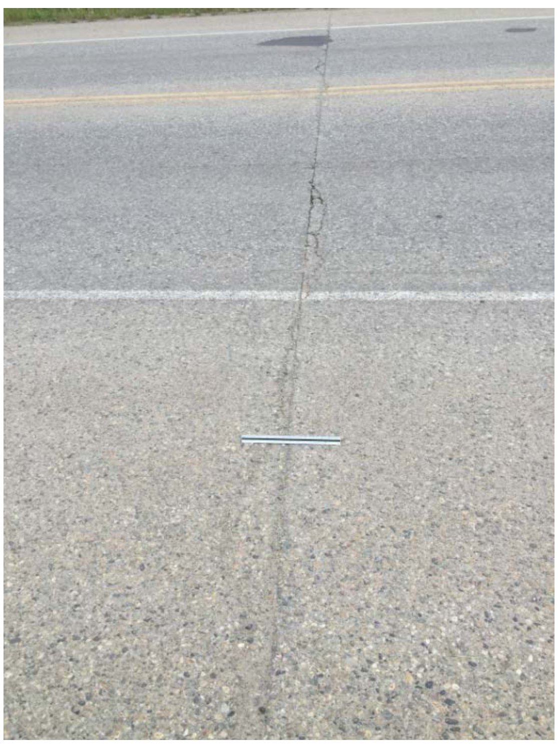
Appendix B4. Phillips Field Road 16_3

Appendix B5. Phillips Field Road 16_4

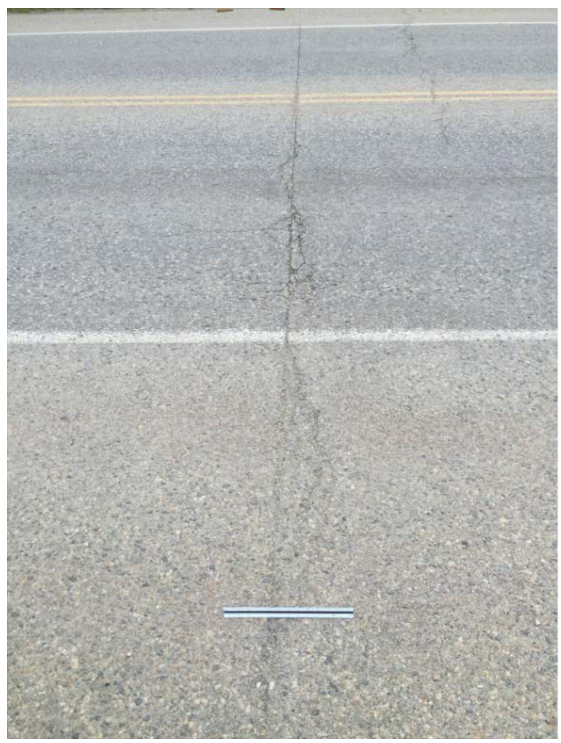
Appendix B6. Phillips Field Road 16_5



Appendix B7. Phillips Field Road 16_6



Appendix B8. Phillips Field Road 16_7



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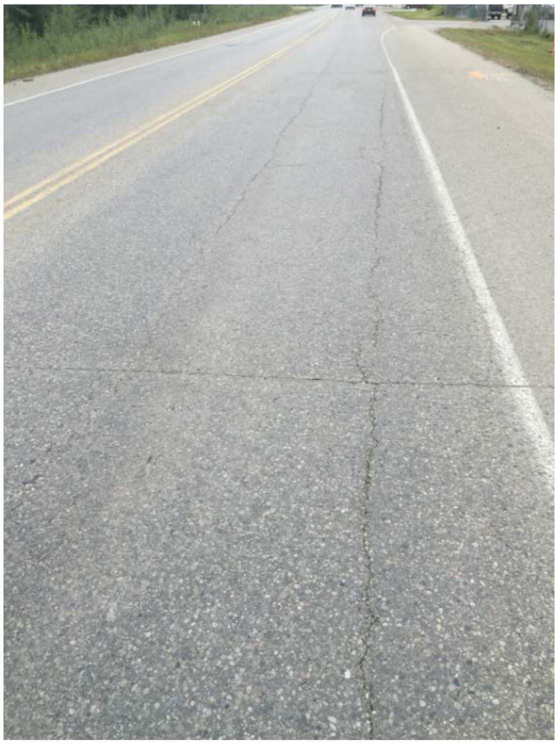

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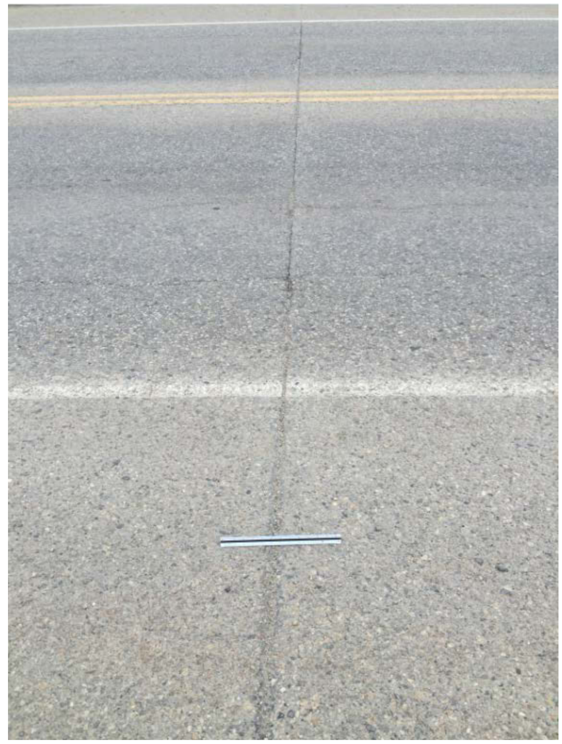
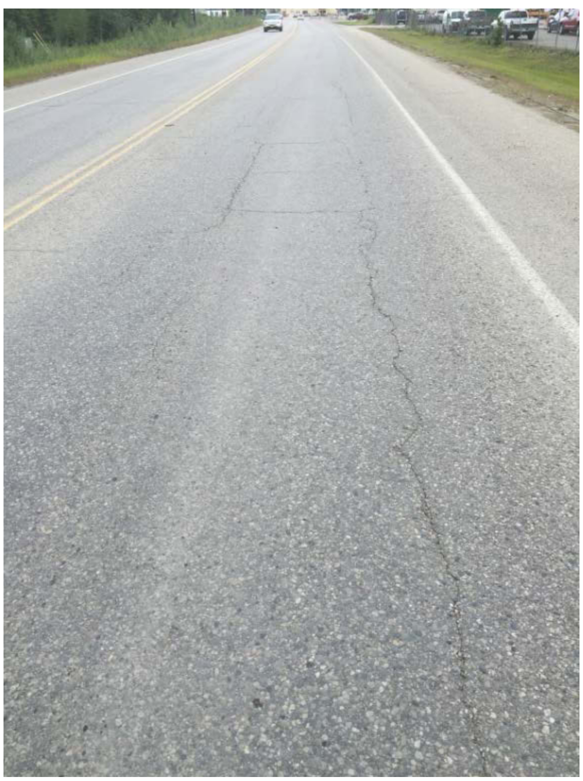
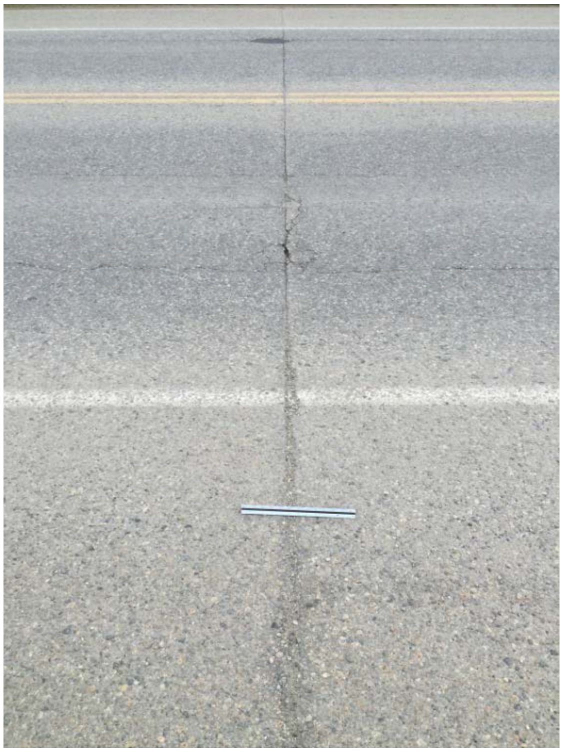


Appendix B11. Phillips Field Road 16_10

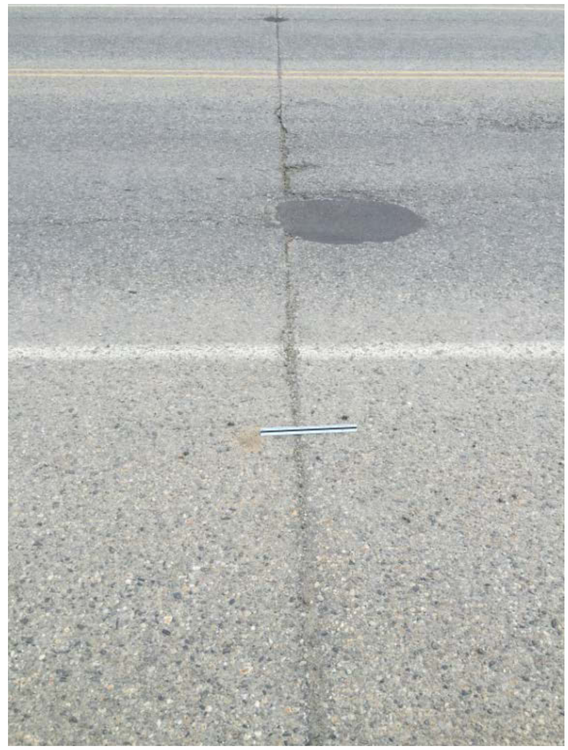


Appendix B12. Phillips Field Road 16_11

Appendix B13. Phillips Field Road 16_12



Appendix B14. Phillips Field Road 16_13

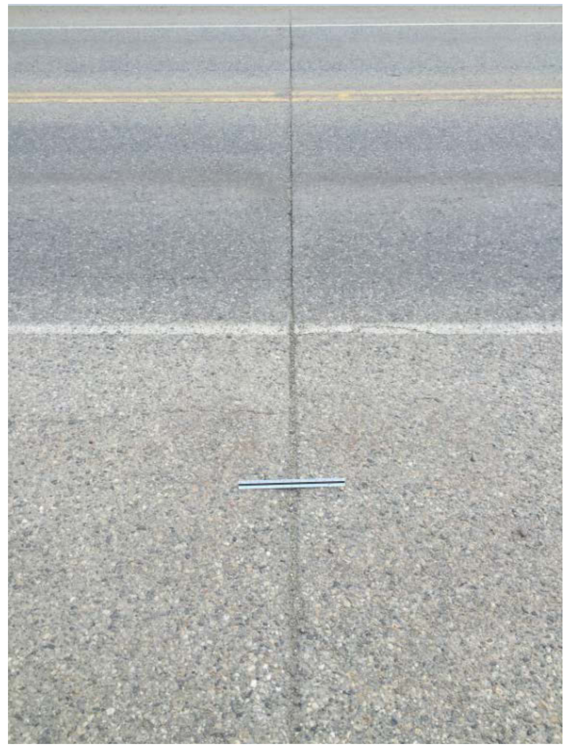


Appendix B15. Phillips Field Road 16_14

Appendix B16. Phillips Field Road 16_15

Appendix B17. Phillips Field Road 16_16

Appendix B18. Phillips Field Road 16_17

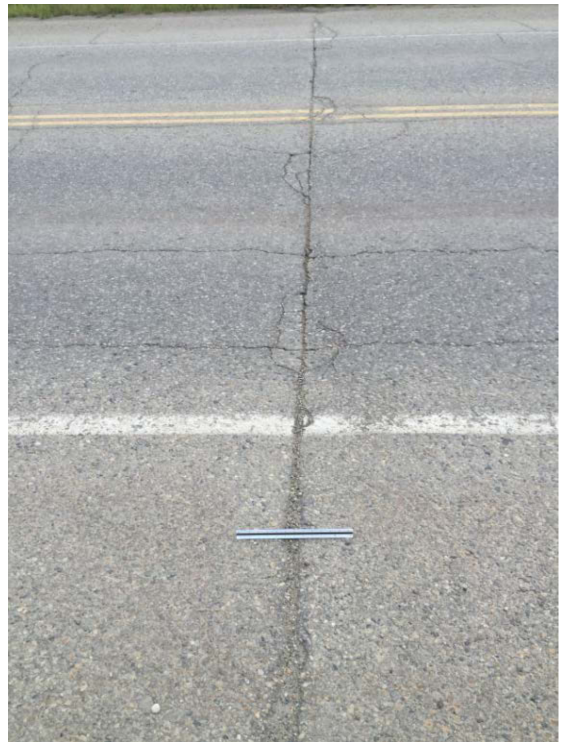


Appendix B19. Phillips Field Road 16_18

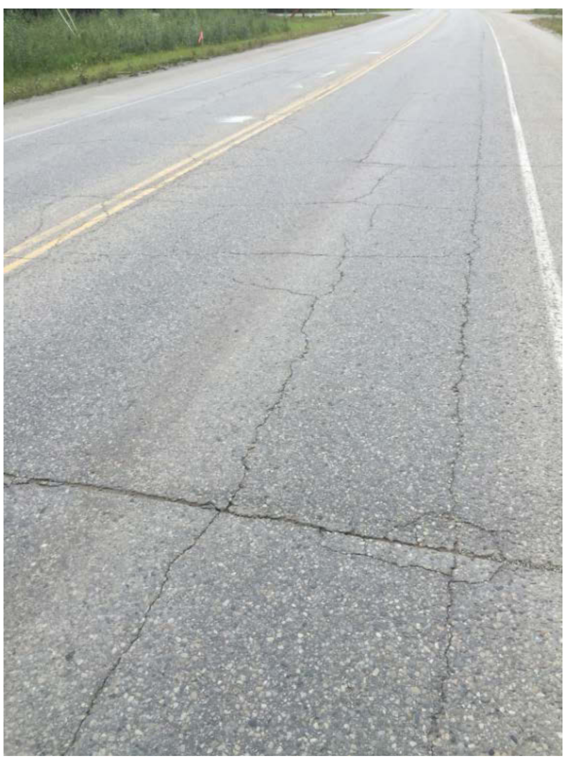
Appendix B20. Phillips Field Road 16_19

Appendix B21. Phillips Field Road 16_20

Appendix B22. Phillips Field Road 16_21



Appendix B23. Phillips Field Road 16_22

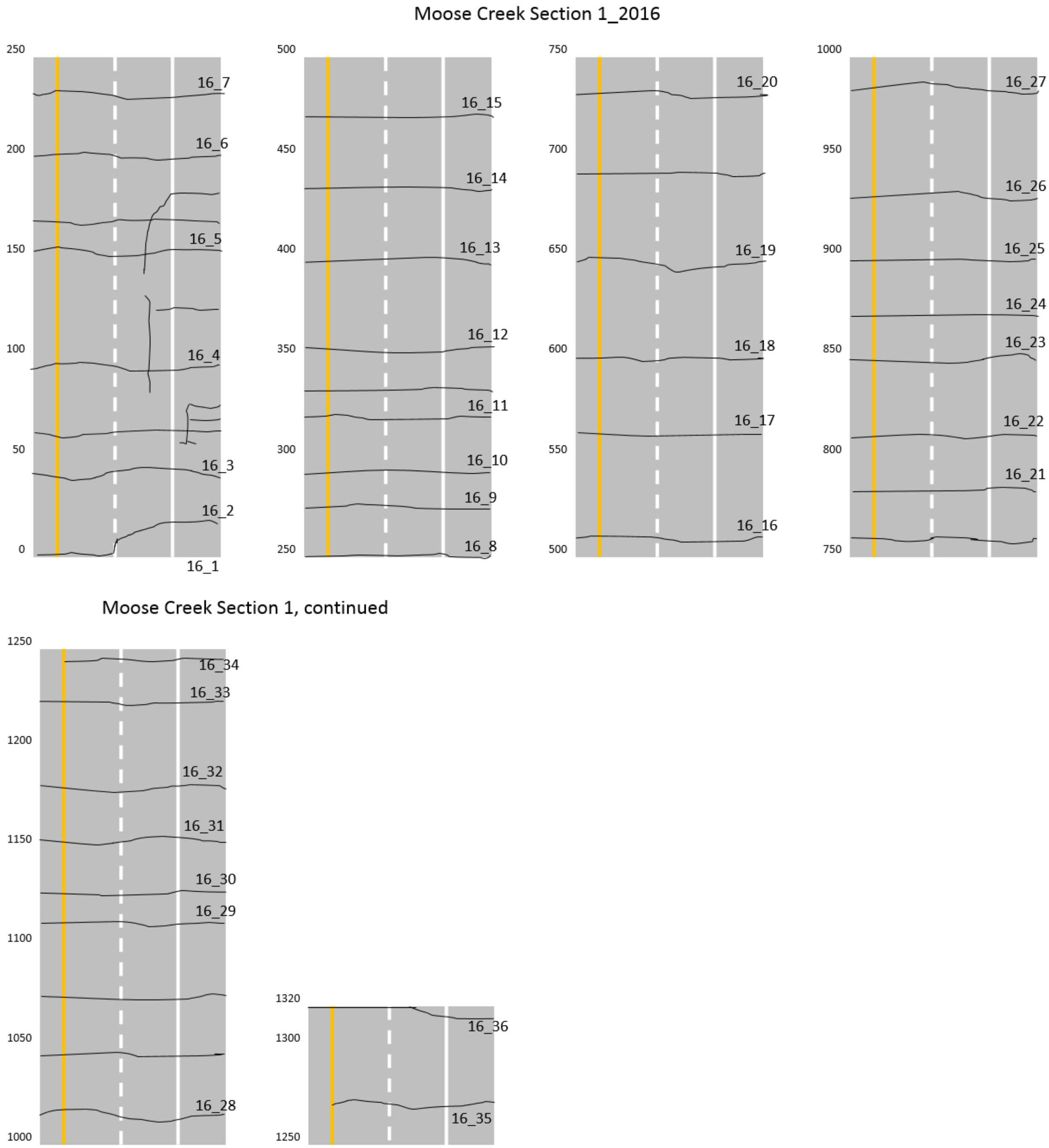


Appendix B24. Phillips Field Road 16_23

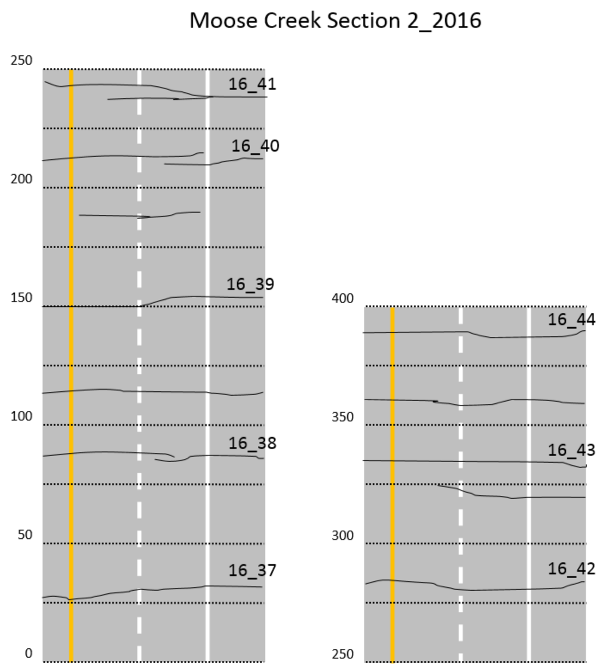
Appendix B25. Phillips Field Road 16_24

Appendix B26. Phillips Field Road 16_25

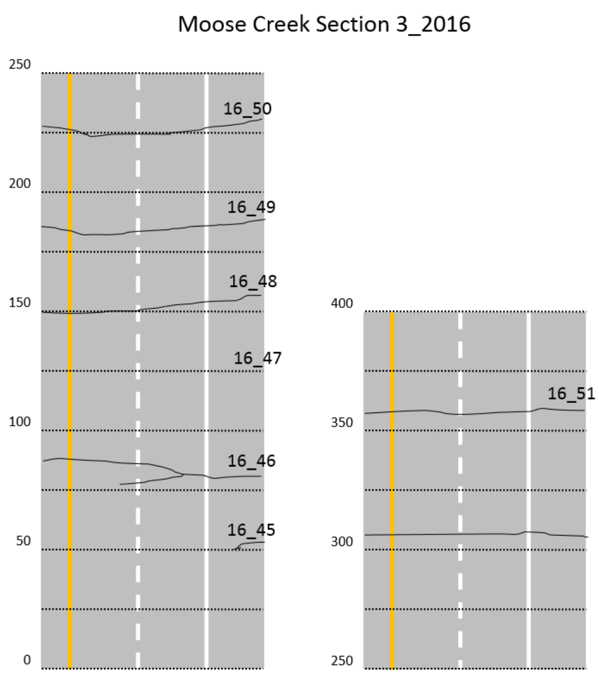
APPENDIX C 2016 FIELD SURVEY SUMMARY_MOOSE CREEK PROJECT



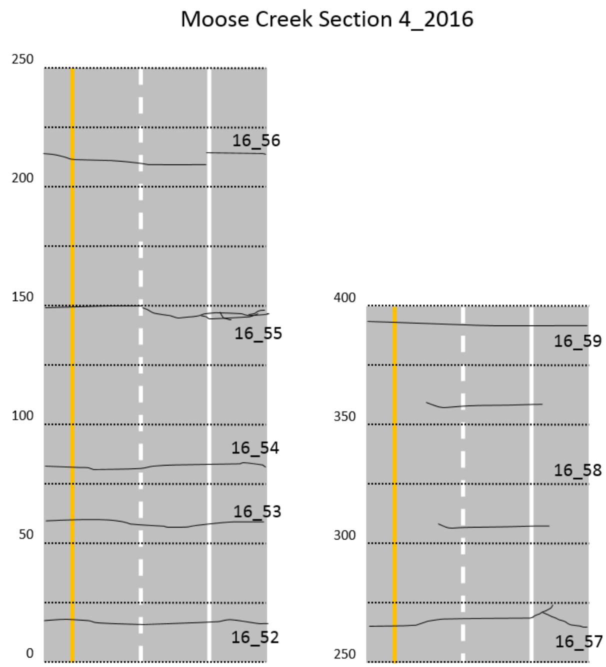
Appendix C1. Moose Creek section 1



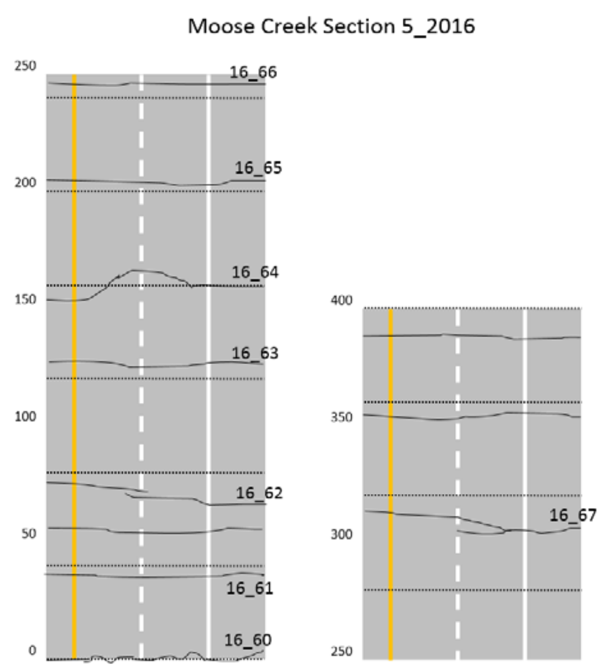
Appendix C2. Moose Creek section 2



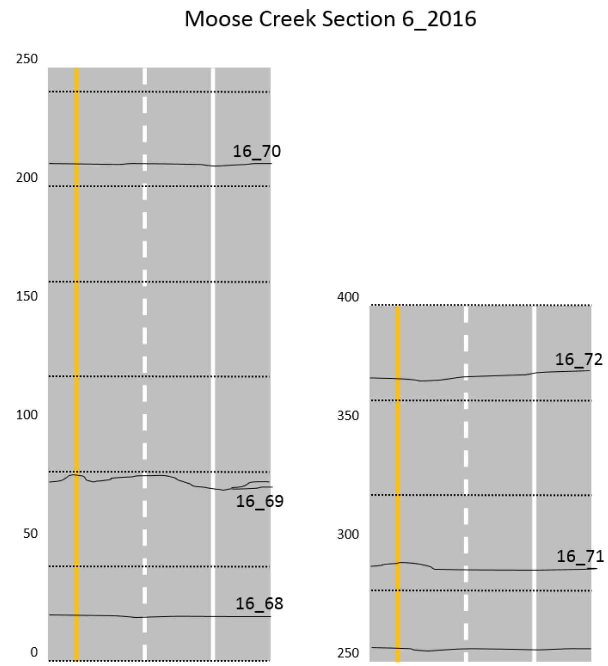
Appendix C3. Moose Creek section 3



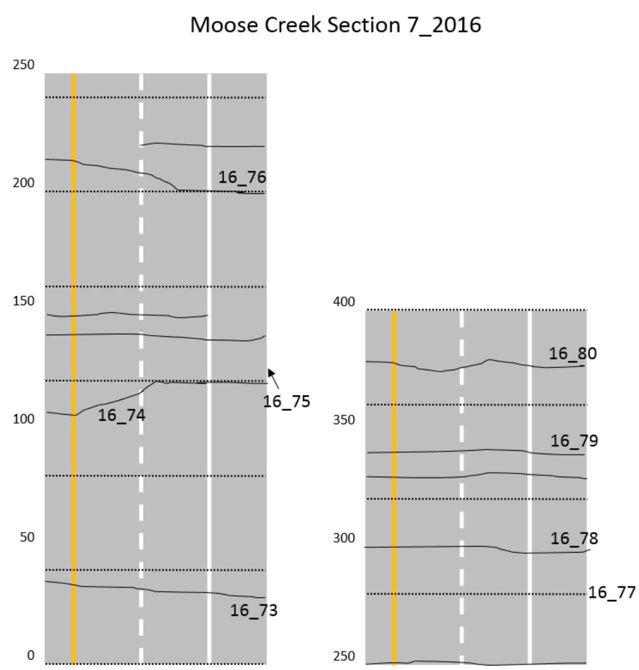
Appendix C4. Moose Creek section 4



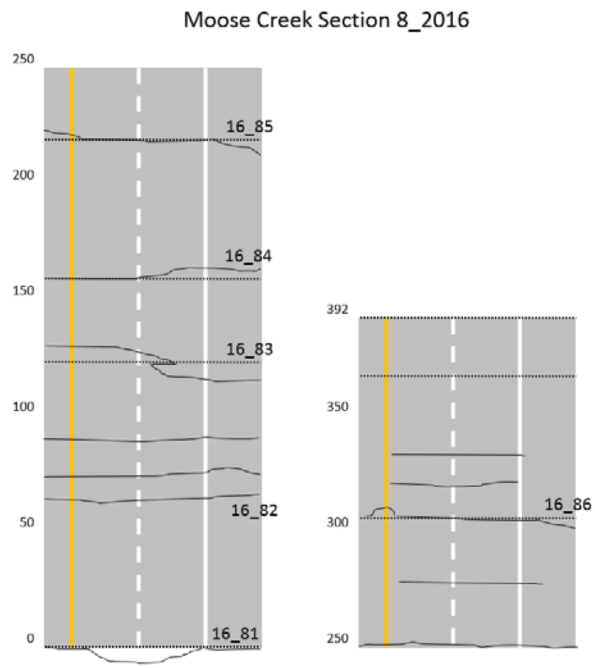
Appendix C5. Moose Creek section 5



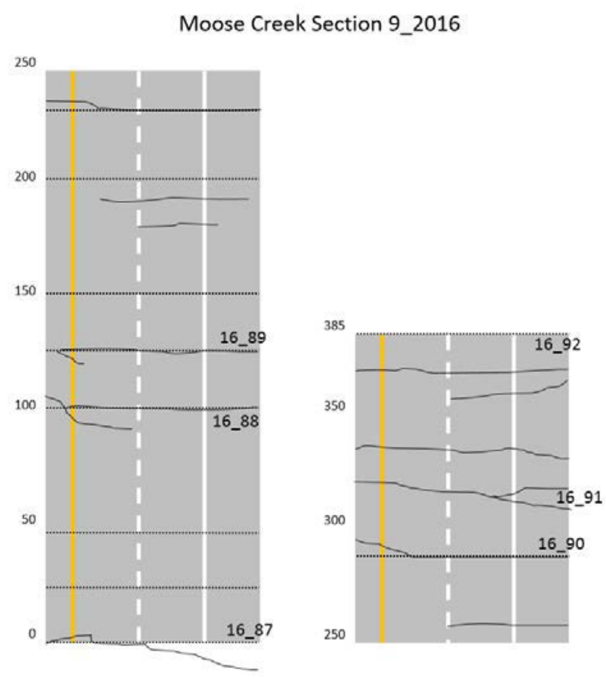
Appendix C6. Moose Creek section 6



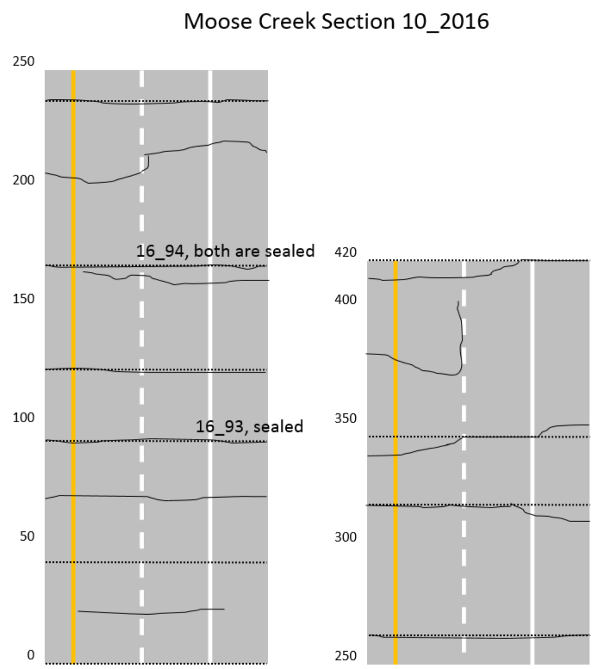
Appendix C7. Moose Creek section 7



Appendix C8. Moose Creek section 8

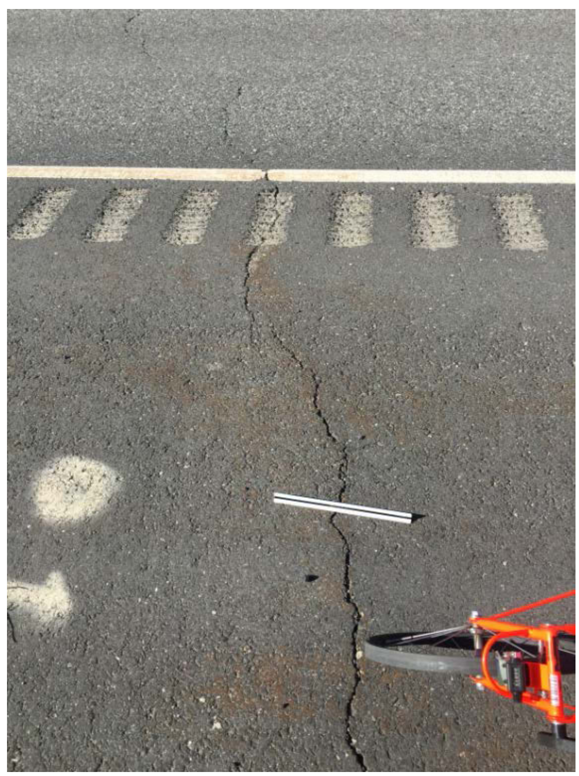


Appendix C9. Moose Creek section 9



Appendix C10. Moose Creek section 10

Appendix C11. Moose Creek 16_1



Appendix C12. Moose Creek 16_2

Appendix C13. Moose Creek 16_3

Appendix C14. Moose Creek 16_4

Appendix C15. Moose Creek 16_5

Appendix C16. Moose Creek 16_6

Appendix C17. Moose Creek 16_7

Appendix C18. Moose Creek 16_8

Appendix C19. Moose Creek 16_9

Appendix C20. Moose Creek 16_10

Appendix C21. Moose Creek 16_11

Appendix C22. Moose Creek 16_12

Appendix C23. Moose Creek 16_13

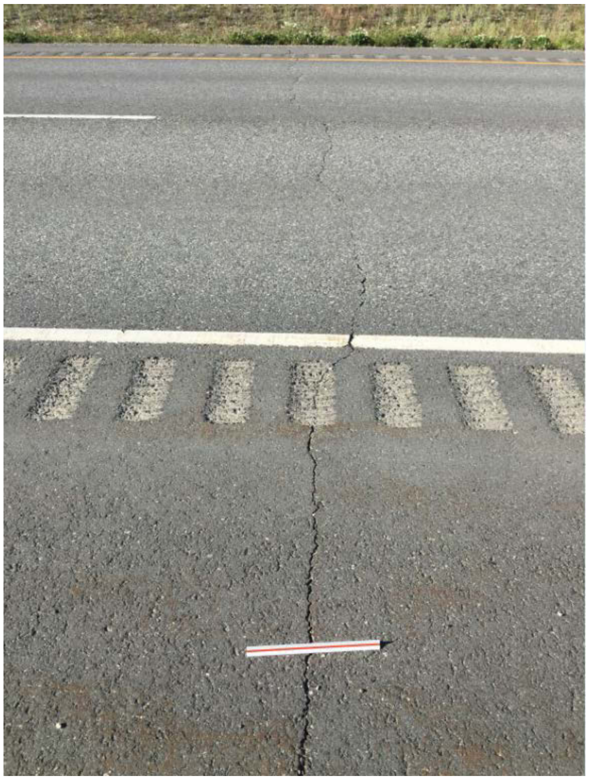
Appendix C24. Moose Creek 16_14

Appendix C25. Moose Creek 16_15

Appendix C26. Moose Creek 16_16

Appendix C27. Moose Creek 16_17

Appendix C28. Moose Creek 16_18



Appendix C29. Moose Creek 16_19

Appendix C30. Moose Creek 16_20

Appendix C31. Moose Creek 16_21

Appendix C32. Moose Creek 16_22

Appendix C33. Moose Creek 16_23

Appendix C34. Moose Creek 16_24

Appendix C35. Moose Creek 16_25

Appendix C36. Moose Creek 16_26

Appendix C37. Moose Creek 16_27

Appendix C38. Moose Creek 16_28

Appendix C39. Moose Creek 16_29

Appendix C40. Moose Creek 16_30

Appendix C41. Moose Creek 16_31

Appendix C42. Moose Creek 16_32

Appendix C43. Moose Creek 16_33

Appendix C44. Moose Creek 16_34

Appendix C45. Moose Creek 16_35

Appendix C46. Moose Creek 16_36

Appendix C47. Moose Creek 16_37

Appendix C48. Moose Creek 16_38

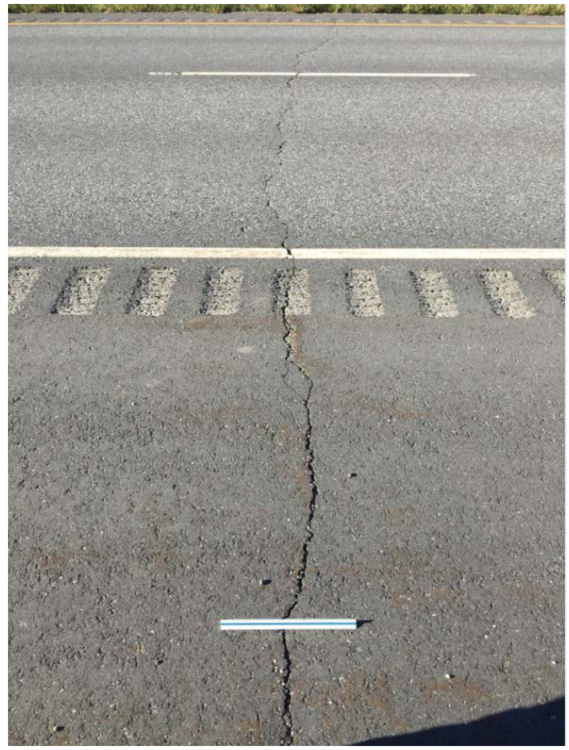
Appendix C49. Moose Creek 16_39

Appendix C50. Moose Creek 16_40

Appendix C51. Moose Creek 16_41

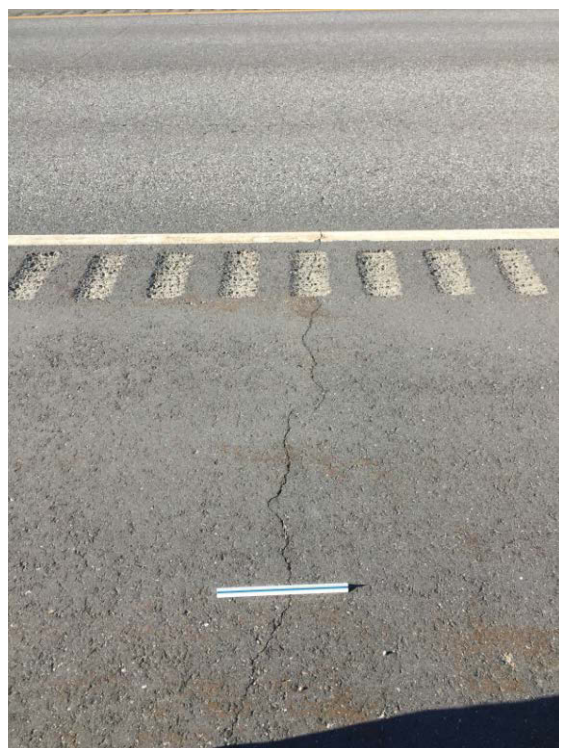
Appendix C52. Moose Creek 16_42

Appendix C53. Moose Creek 16_43

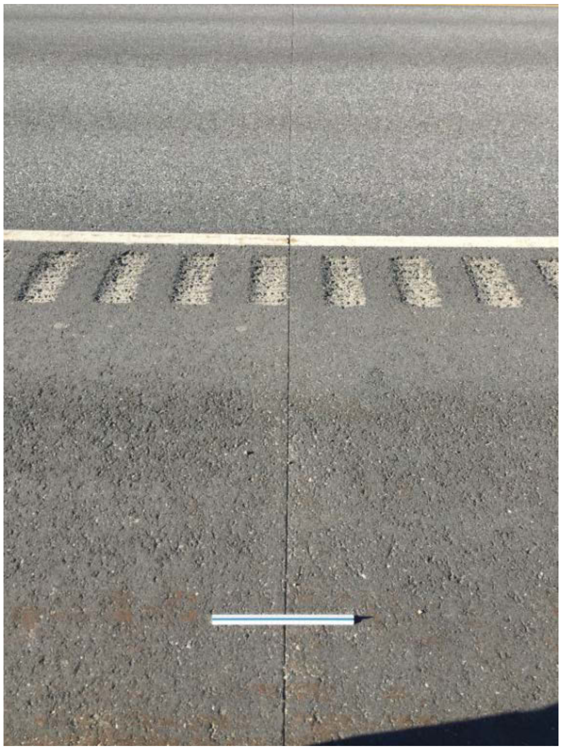


Appendix C54. Moose Creek 16_44

Appendix C55. Moose Creek 16_45



Appendix C56. Moose Creek 16_46



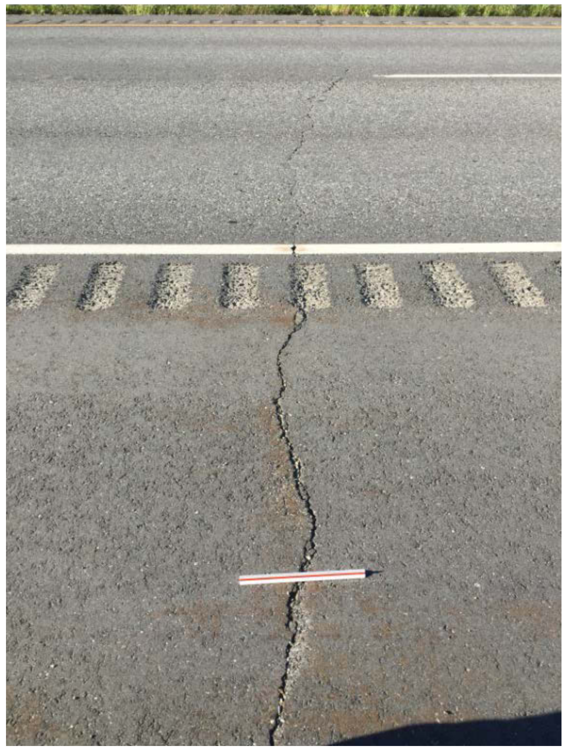
Appendix C57. Moose Creek 16_47

Appendix C58. Moose Creek 16_48

Appendix C59. Moose Creek 16_49

Appendix C60. Moose Creek 16_50

Appendix C61. Moose Creek 16_51



Appendix C62. Moose Creek 16_52

Appendix C63. Moose Creek 16_53

Appendix C64. Moose Creek 16_54

Appendix C65. Moose Creek 16_55

Appendix C66. Moose Creek 16_56

Appendix C67. Moose Creek 16_57

Appendix C68. Moose Creek 16_58

Appendix C69. Moose Creek 16_59

Appendix C70. Moose Creek 16_60

Appendix C71. Moose Creek 16_61

Appendix C72. Moose Creek 16_62

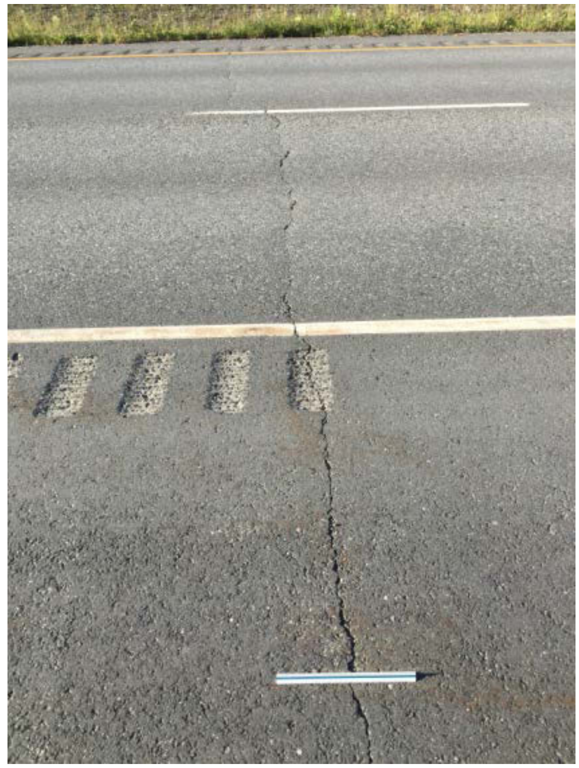
Appendix C73. Moose Creek 16_63

Appendix C74. Moose Creek 16_64

Appendix C75. Moose Creek 16_65

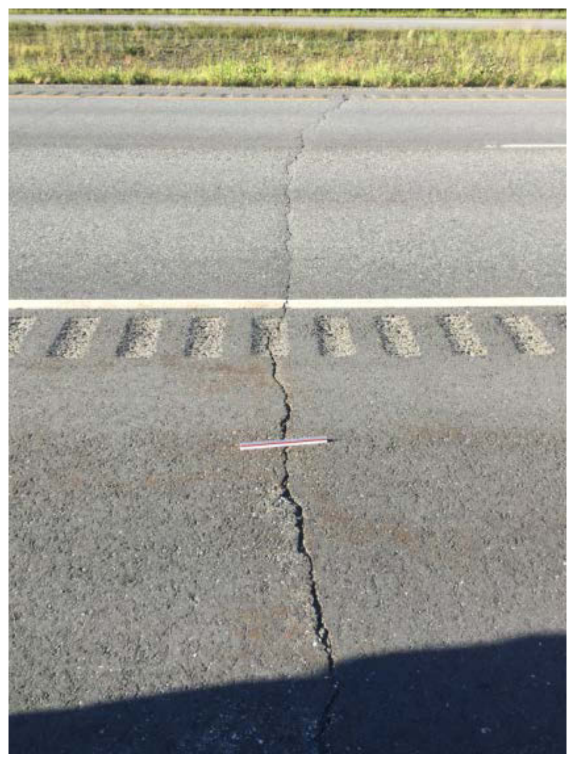
Appendix C76. Moose Creek 16_66

Appendix C77. Moose Creek 16_67



Appendix C78. Moose Creek 16_68

Appendix C79. Moose Creek 16_69



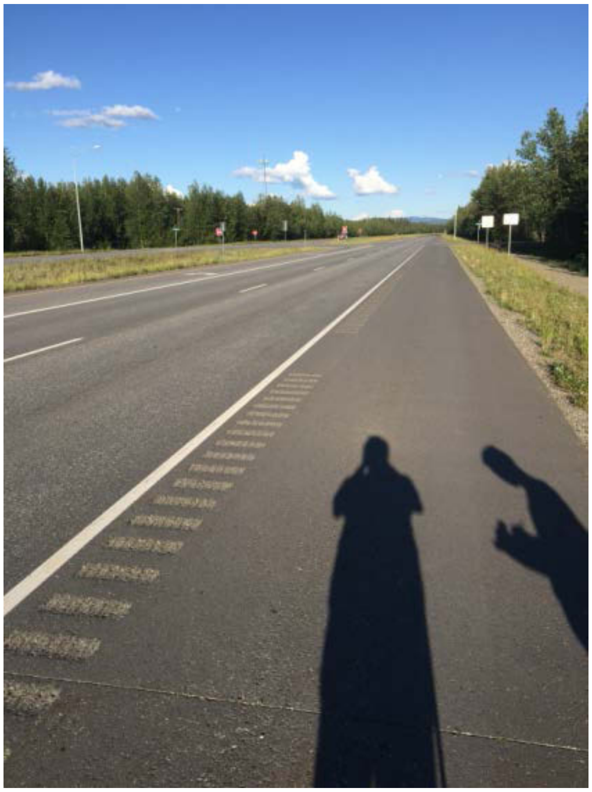
Appendix C80. Moose Creek 16_70

Appendix C81. Moose Creek 16_71

Appendix C82. Moose Creek 16_72

Appendix C83. Moose Creek 16_73

Appendix C84. Moose Creek 16_74



Appendix C85. Moose Creek 16_75

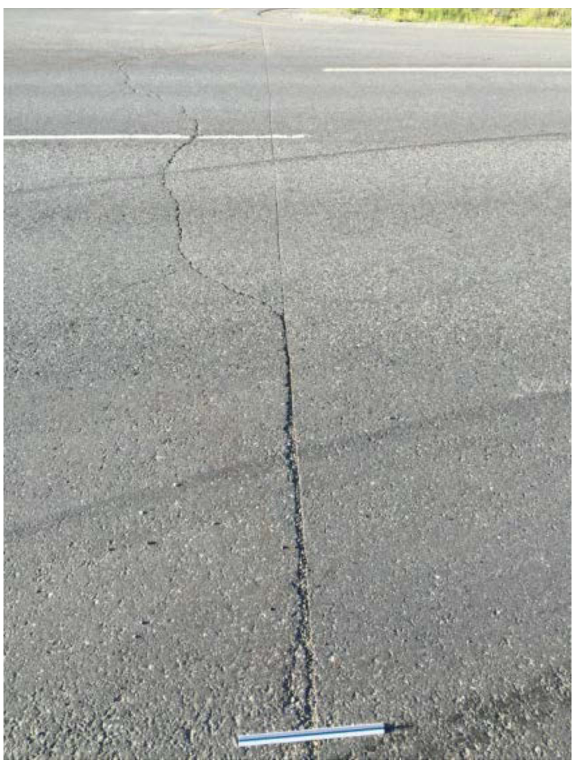
Appendix C86. Moose Creek 16_76

Appendix C87. Moose Creek 16_77

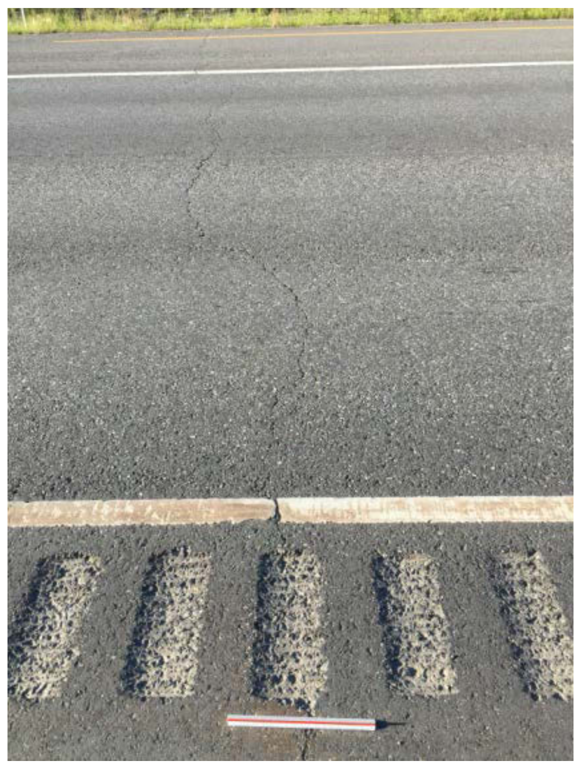
Appendix C88. Moose Creek 16_78

Appendix C89. Moose Creek 16_79

Appendix C90. Moose Creek 16_80

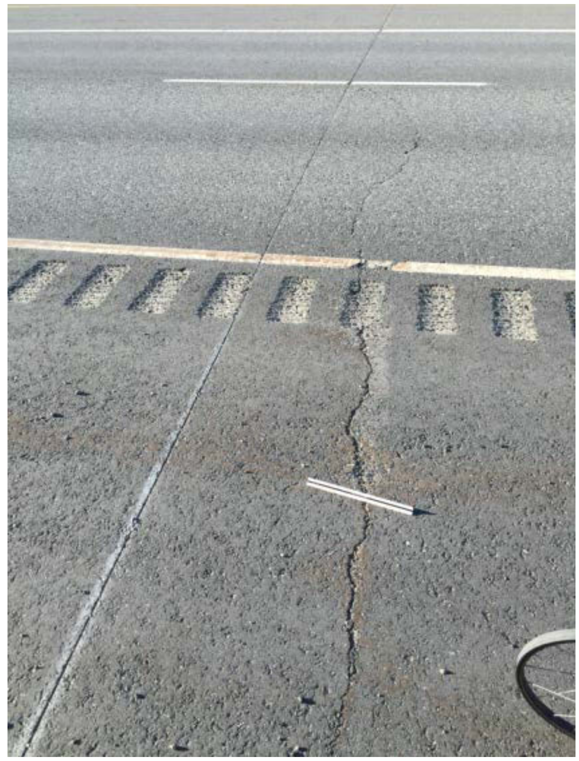


Appendix C91. Moose Creek 16_81



Appendix C92. Moose Creek 16_82

Appendix C93. Moose Creek 16_83



Appendix C94. Moose Creek 16_84

Appendix C95. Moose Creek 16_85

Appendix C96. Moose Creek 16_86

Appendix C97. Moose Creek 16_87

Appendix C98. Moose Creek 16_88

Appendix C99. Moose Creek 16_89

Appendix C100. Moose Creek 16_90

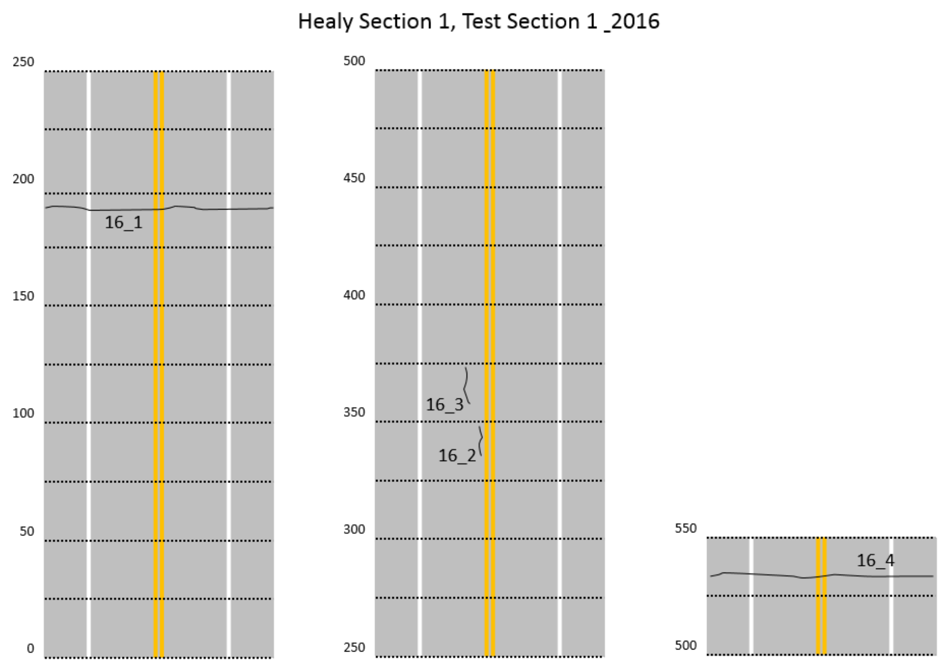
Appendix C101. Moose Creek 16_91

Appendix C102. Moose Creek 16_92

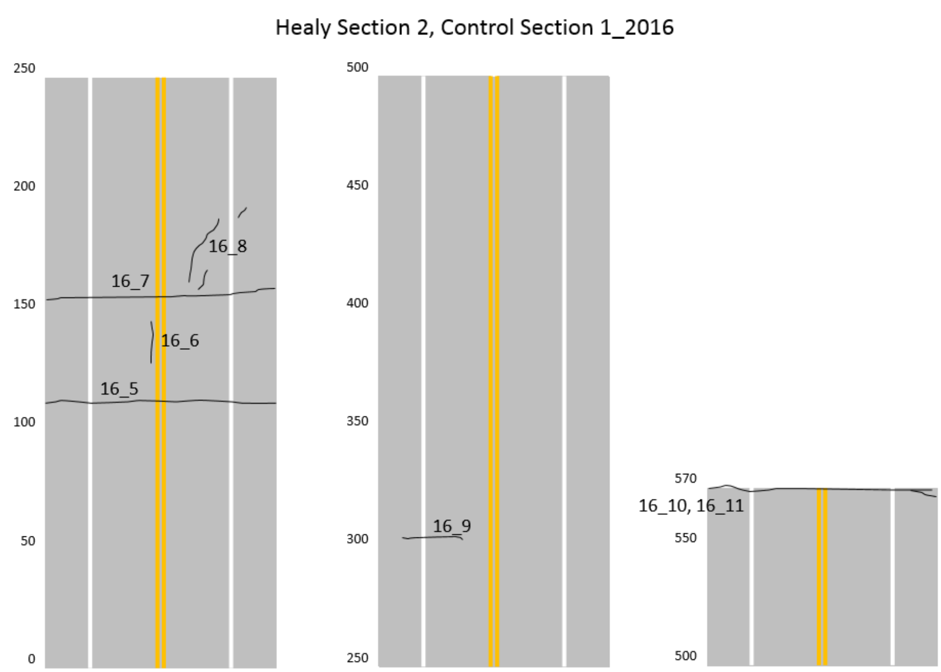
Appendix C103. Moose Creek 16_93

Appendix C104. Moose Creek 16_94

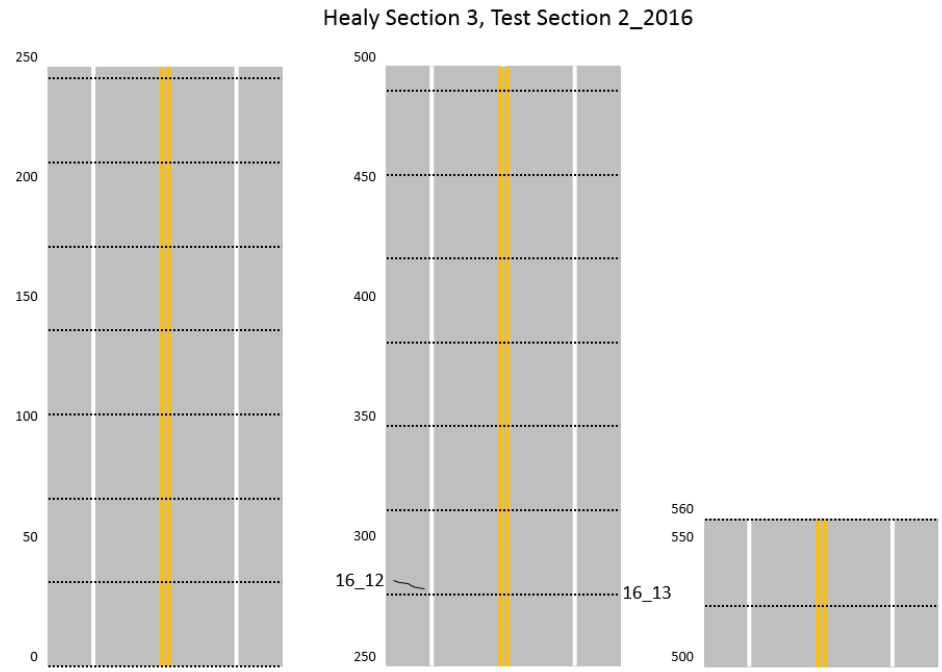
APPENDIX D 2016 FIELD SURVEY SUMMARY_HEALY PROJECT



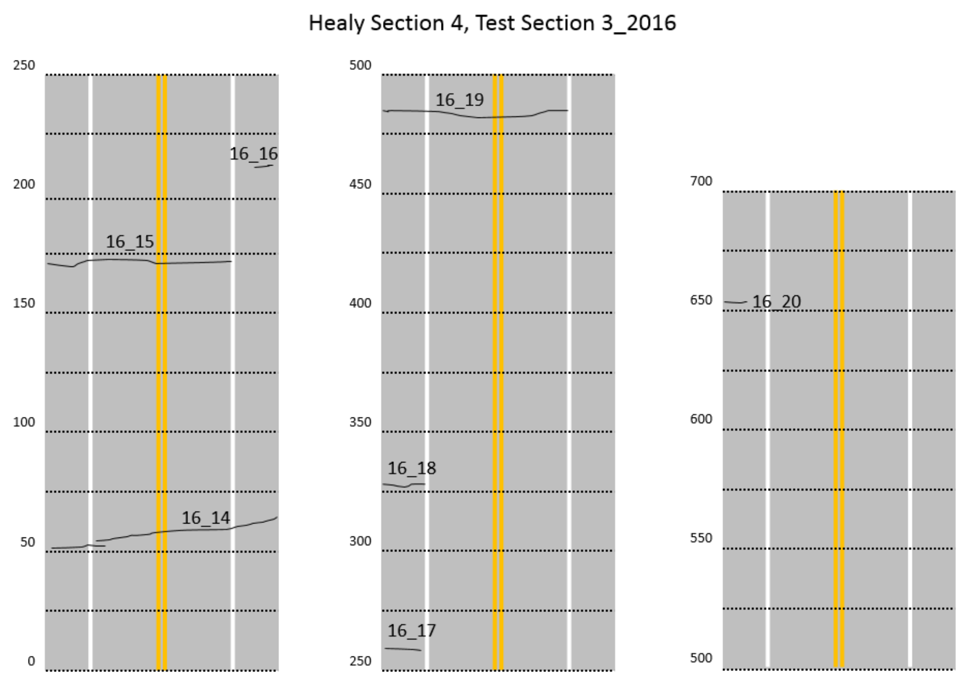
Appendix D1. Healy section 1



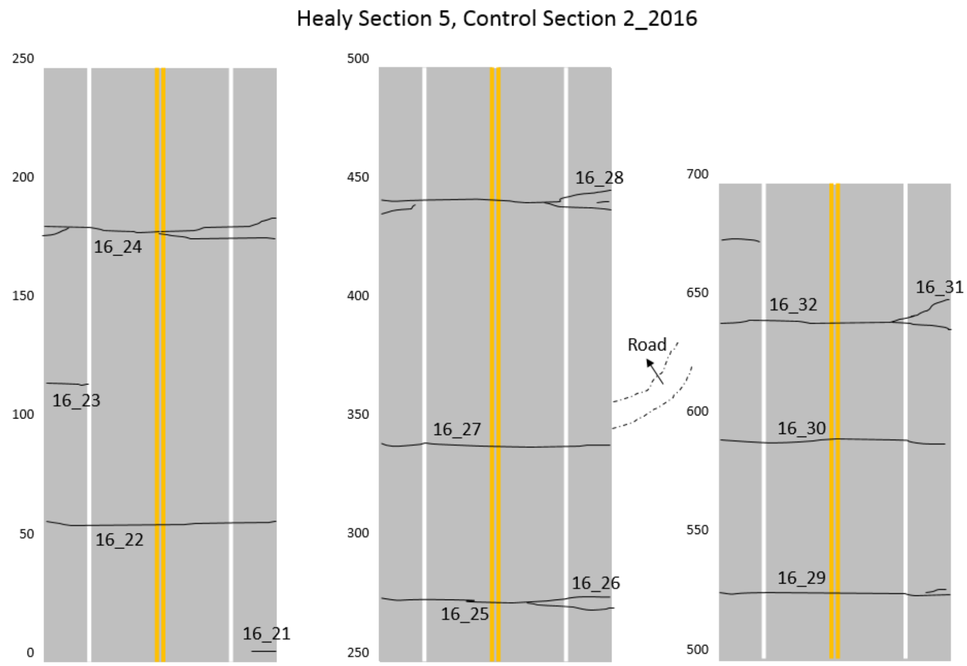
Appendix D2. Healy section 2



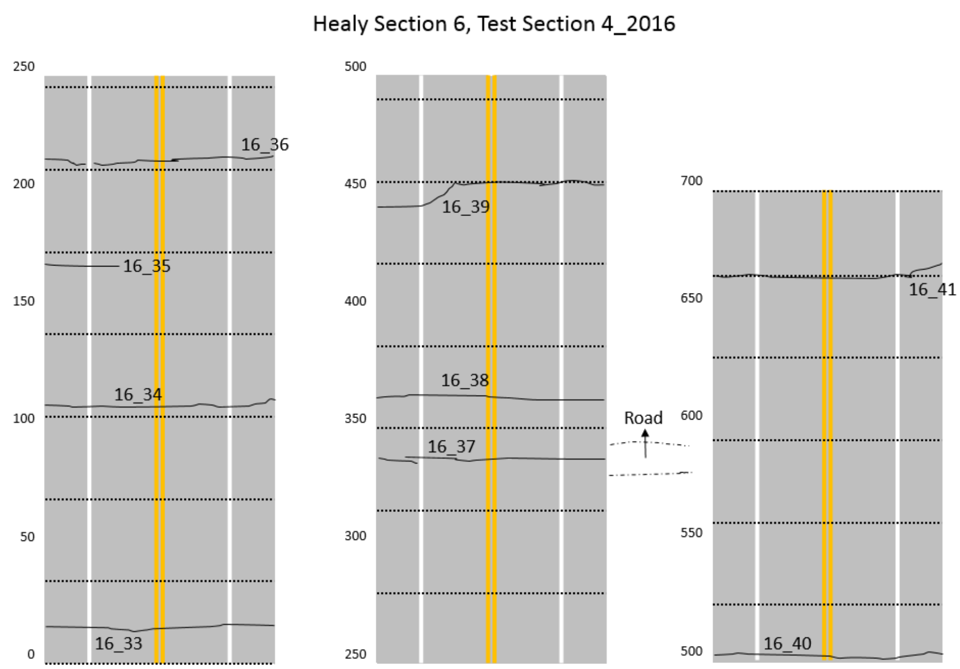
Appendix D3. Healy section 3



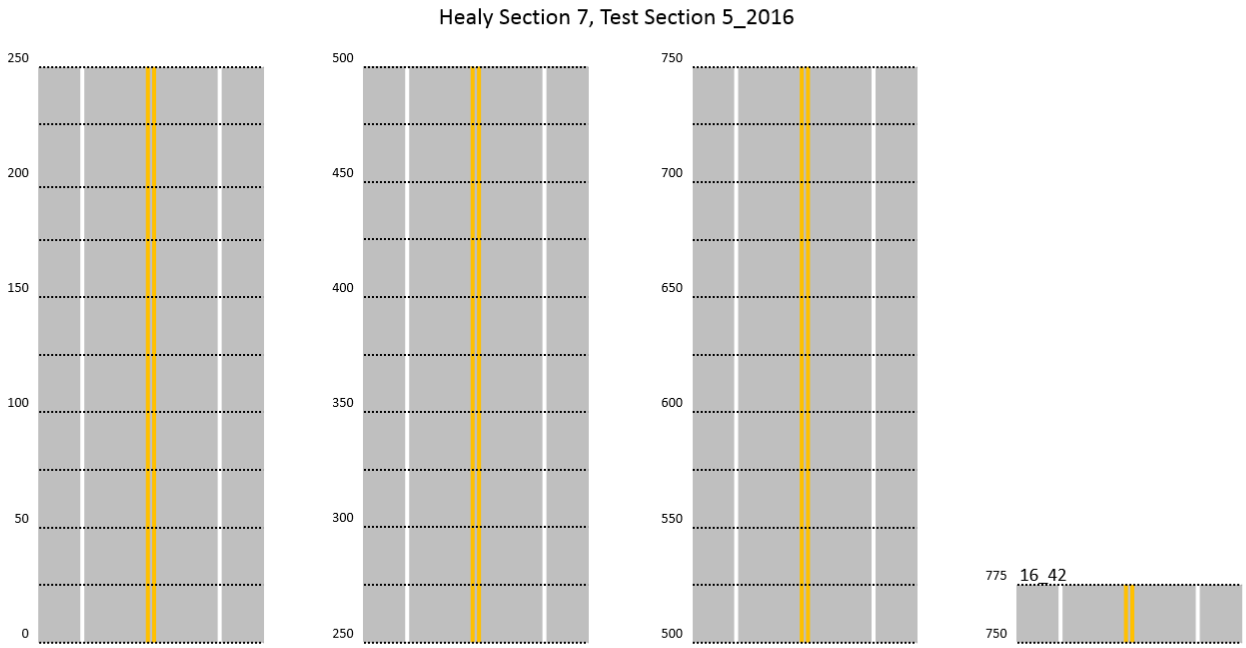
Appendix D4. Healy section 4



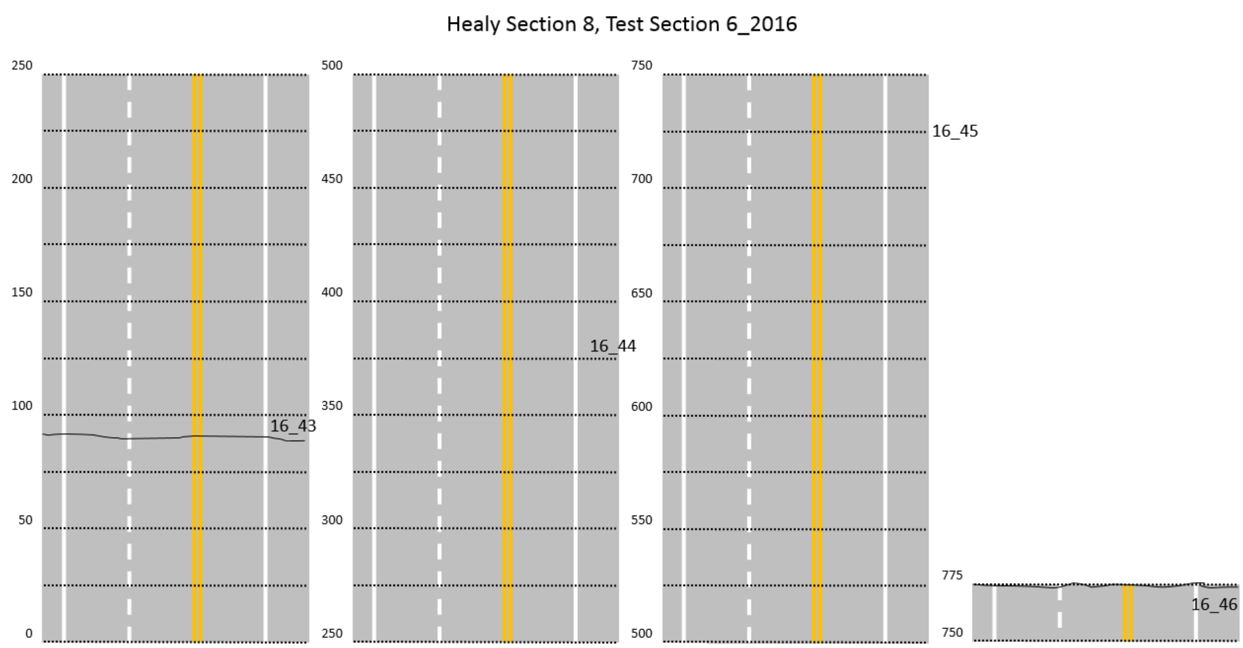
Appendix D5. Healy section 5



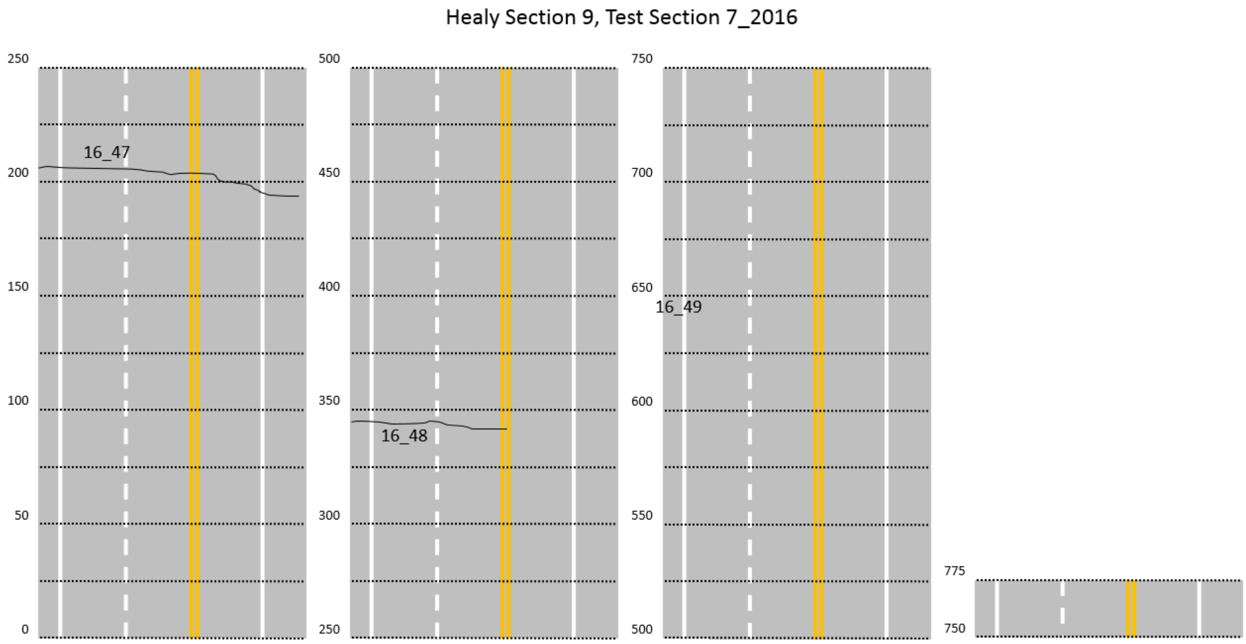
Appendix D6. Healy section 6



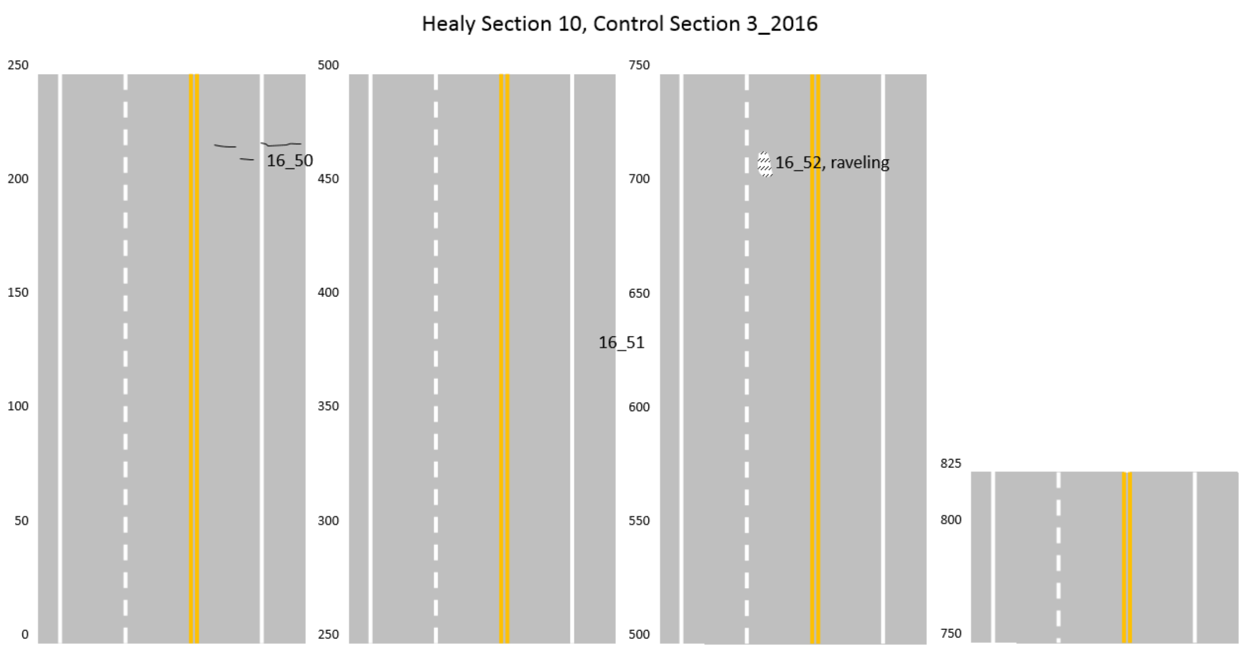
Appendix D7. Healy section 7



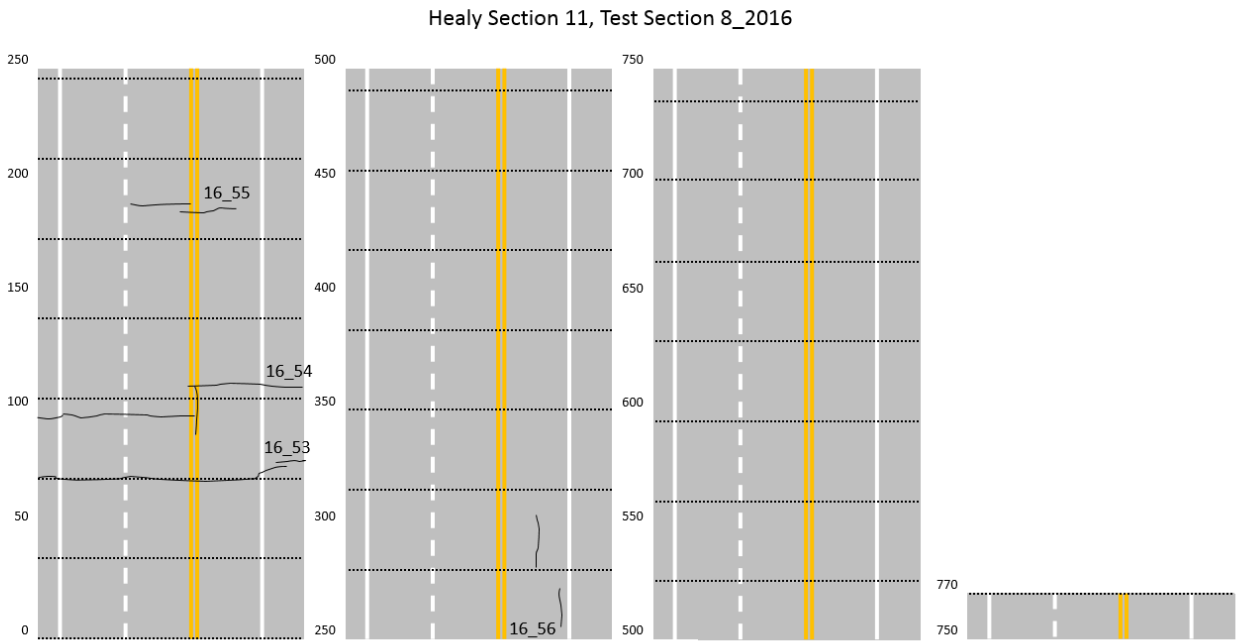
Appendix D8. Healy section 8



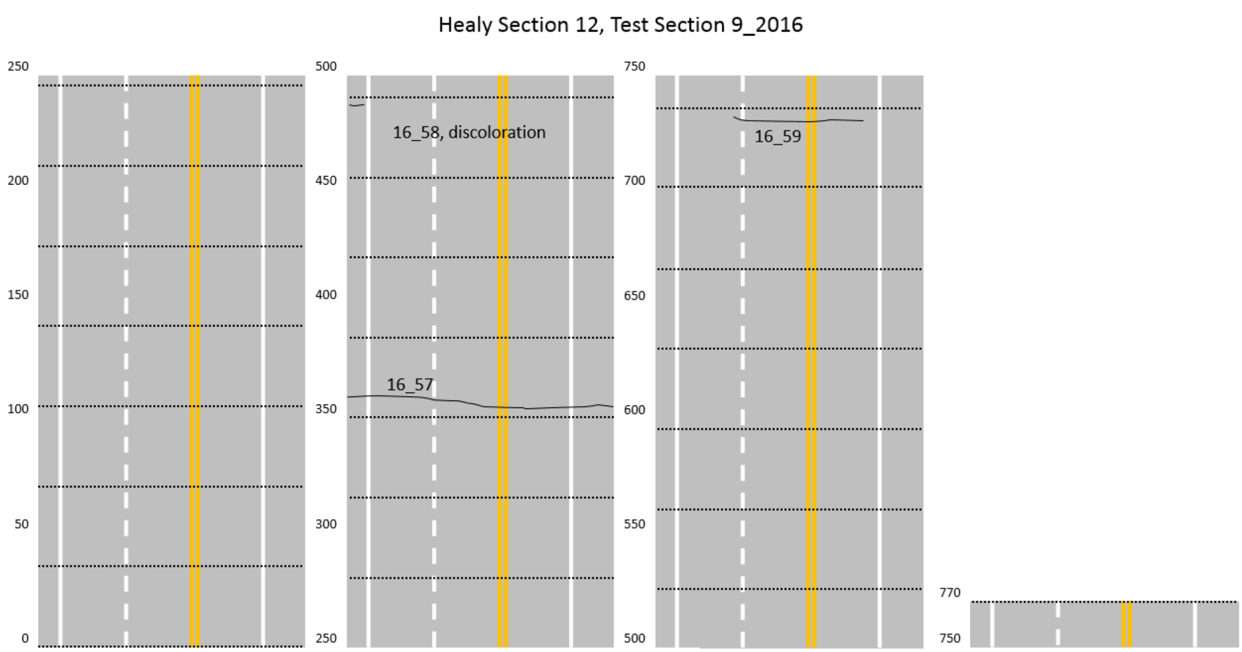
Appendix D9. Healy section 9



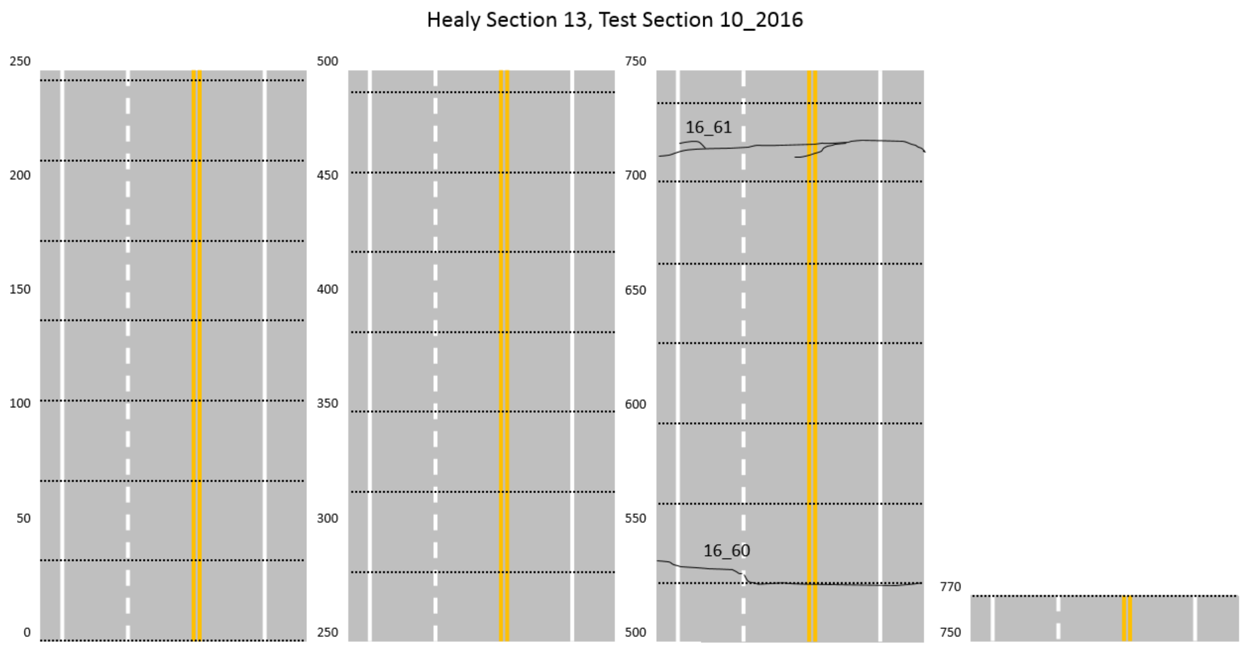
Appendix D10. Healy section 10



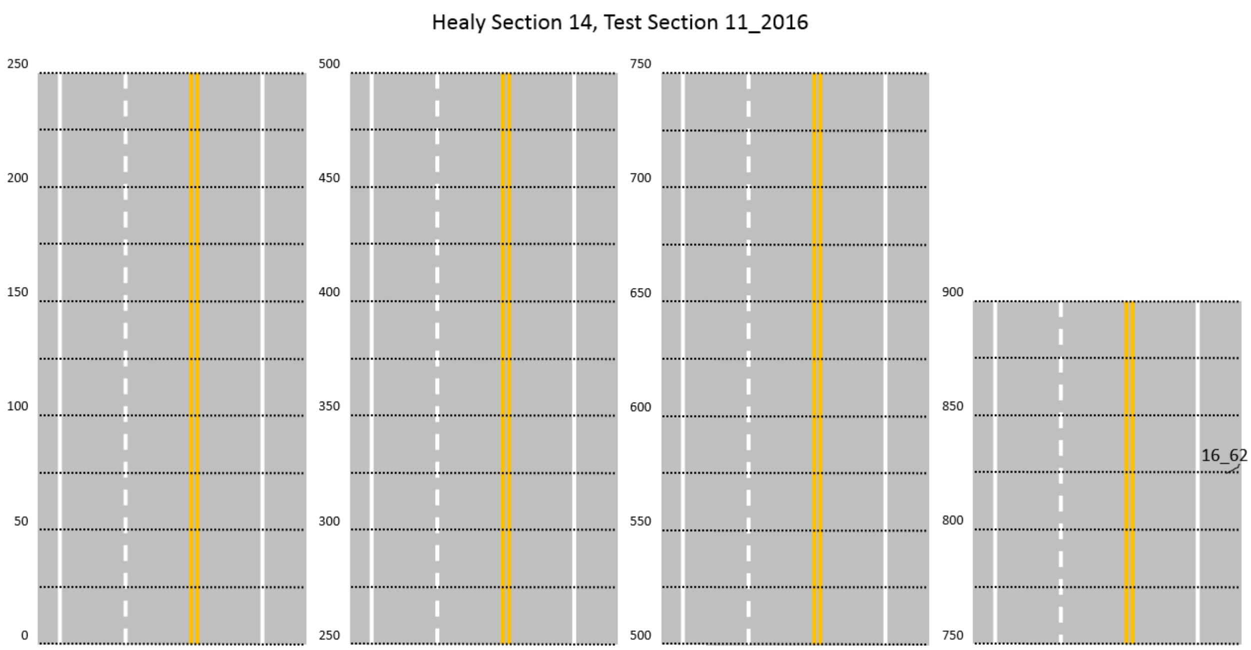
Appendix D11. Healy section 11



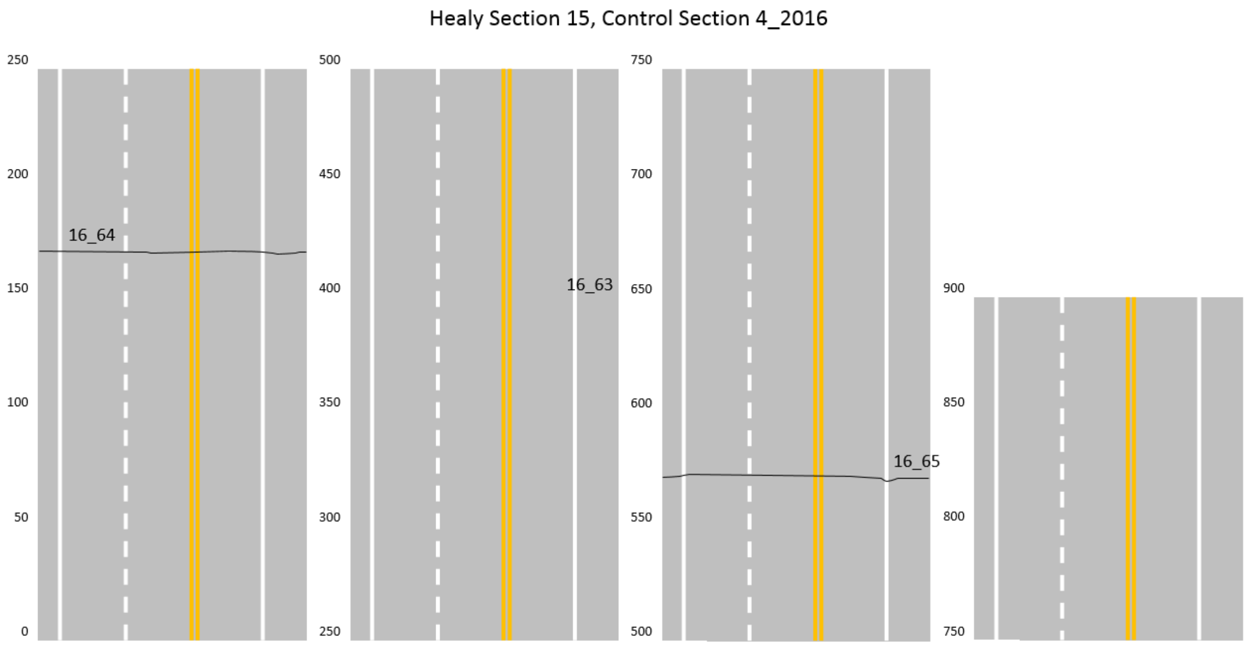
Appendix D12. Healy section 12



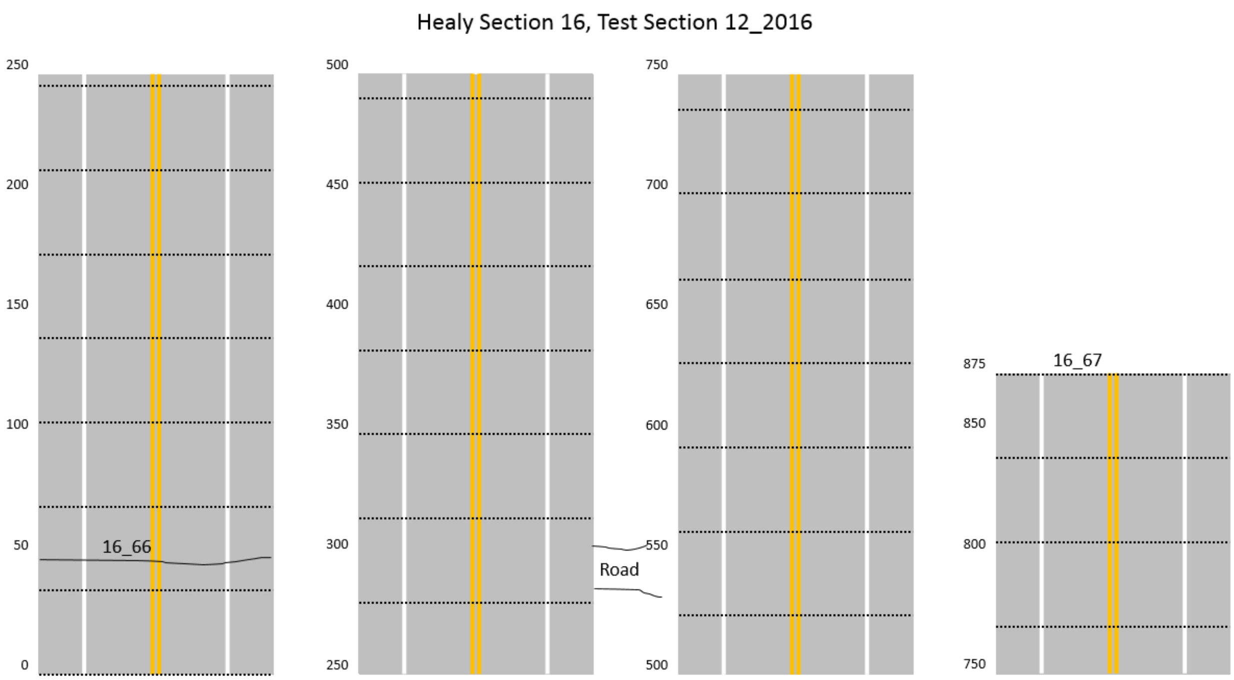
Appendix D13. Healy section 13



Appendix D14. Healy section 14



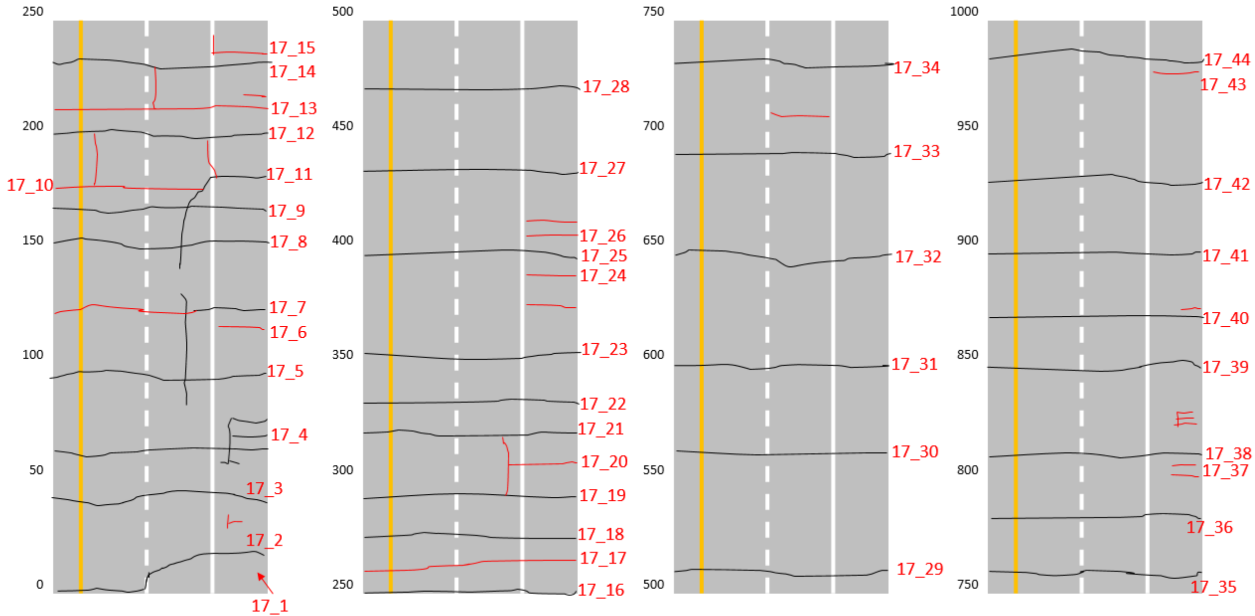
Appendix D15. Healy section 15



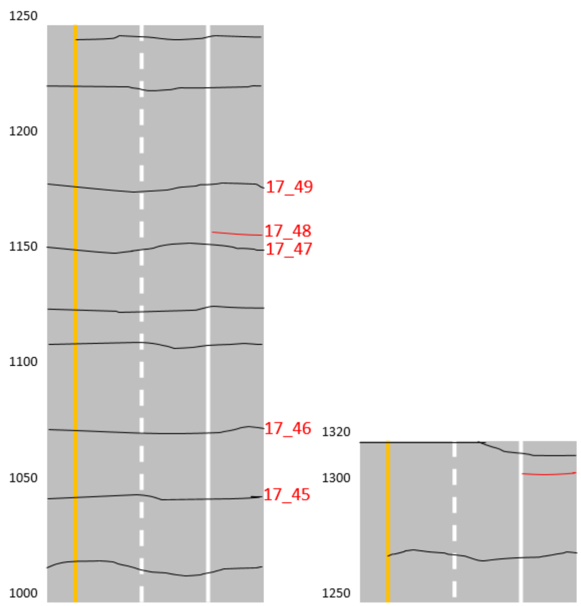
Appendix D16. Healy section 16

APPENDIX E 2017 FIELD SURVEY SUMMARY_MOOSE CREEK PROJECT

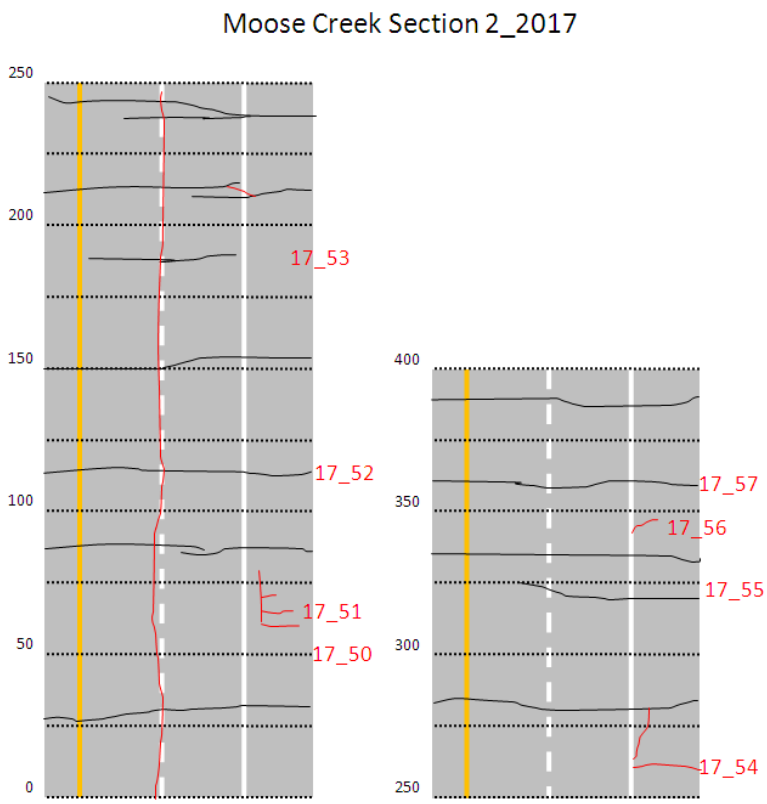
Moose Creek Section 1_2017 (new crack marked in red)



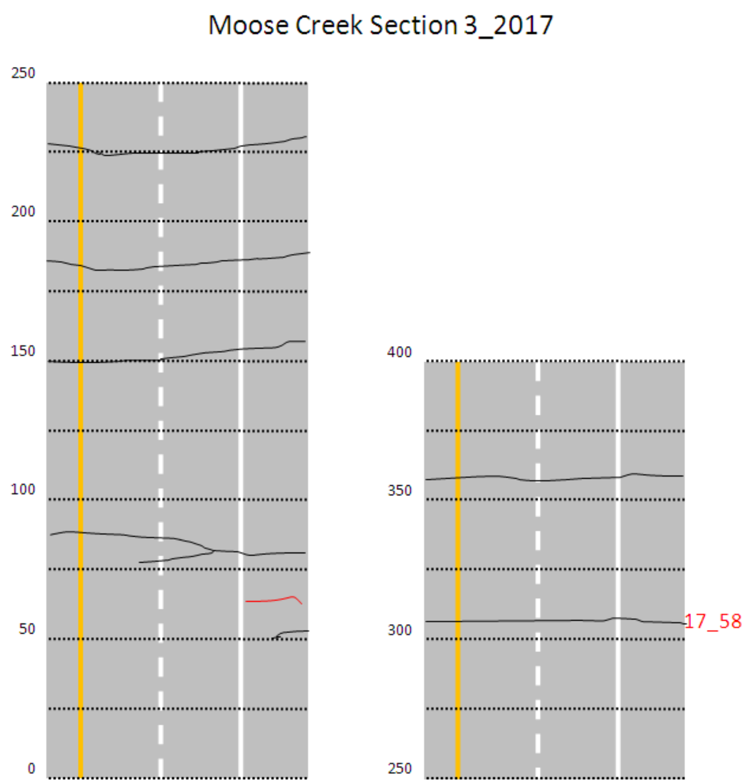
Moose Creek Section 1, continued



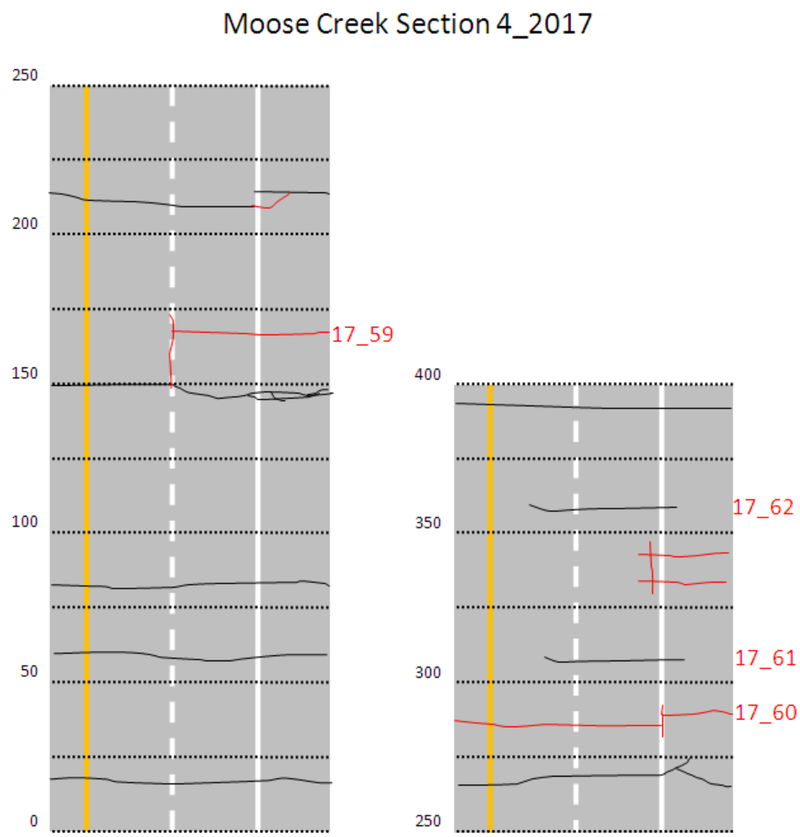
Appendix E1. Moose Creek section 1



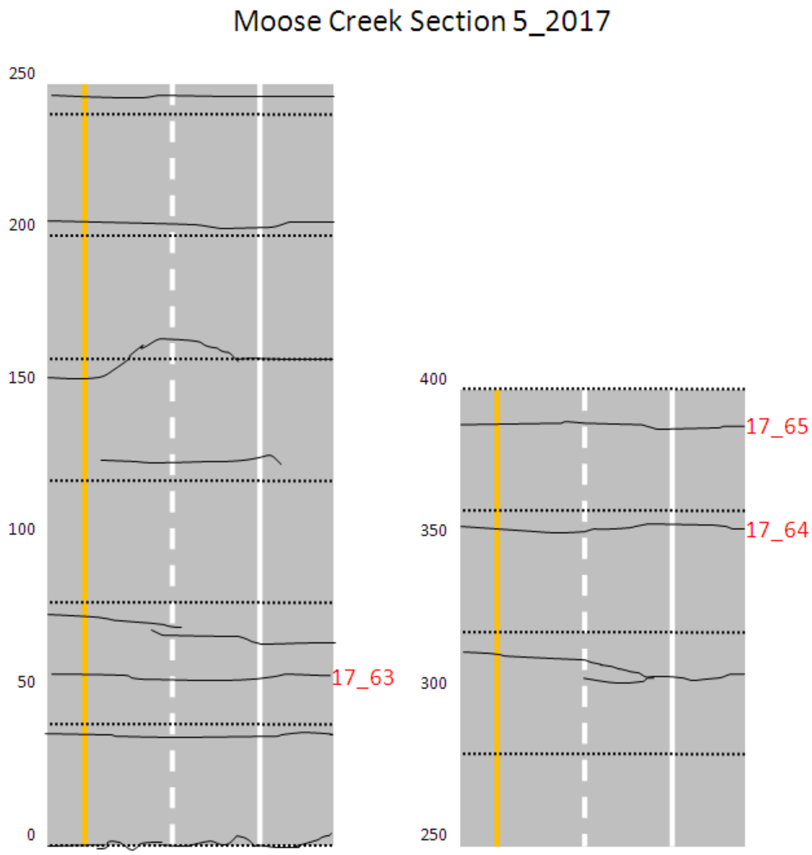
Appendix E2. Moose Creek section 2



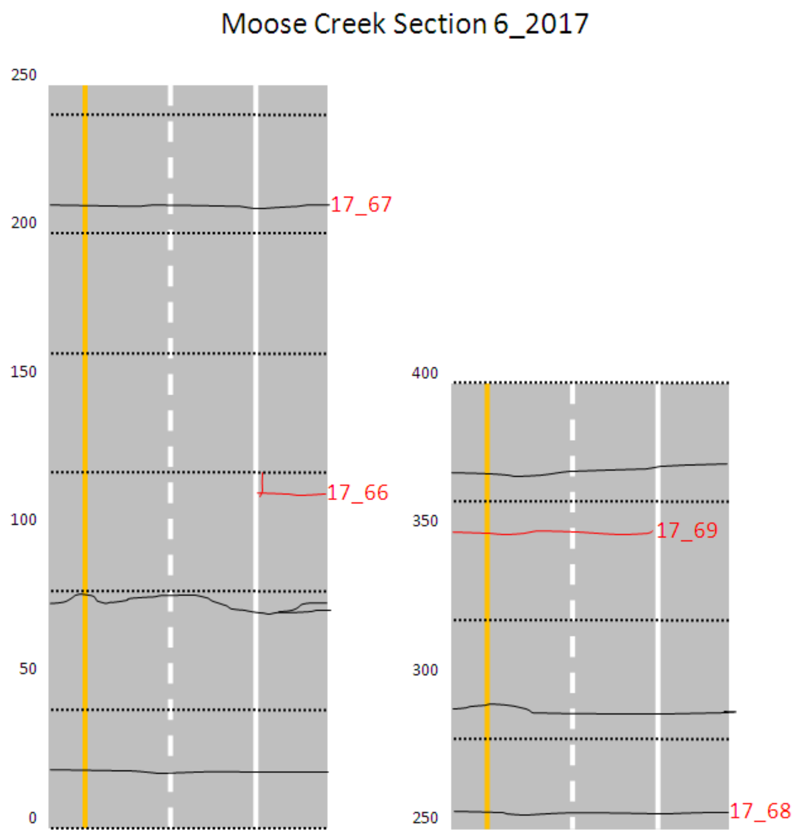
Appendix E3. Moose Creek section 3



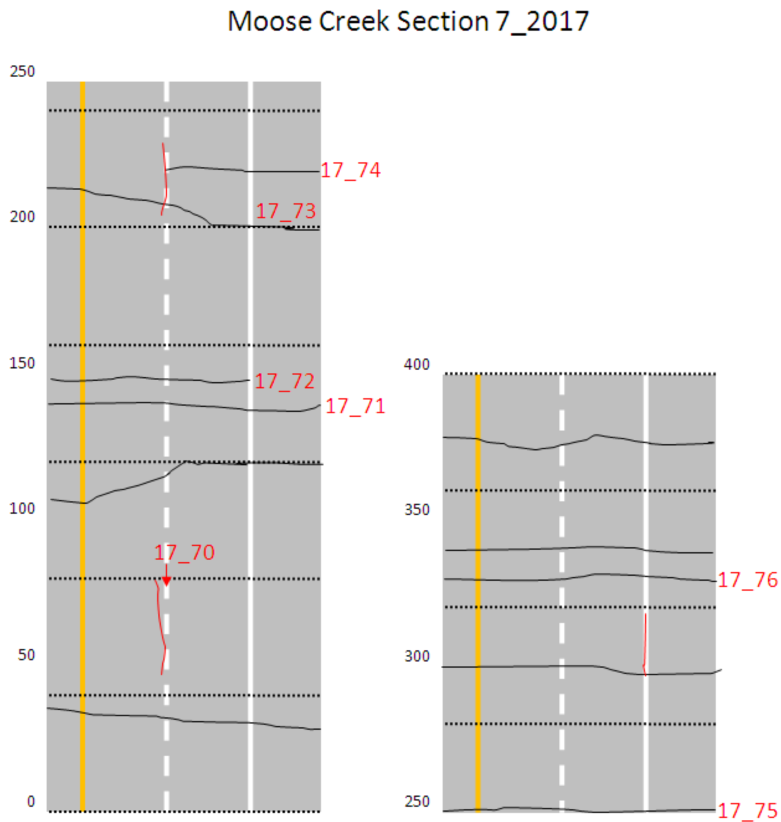
Appendix E4. Moose Creek section 4



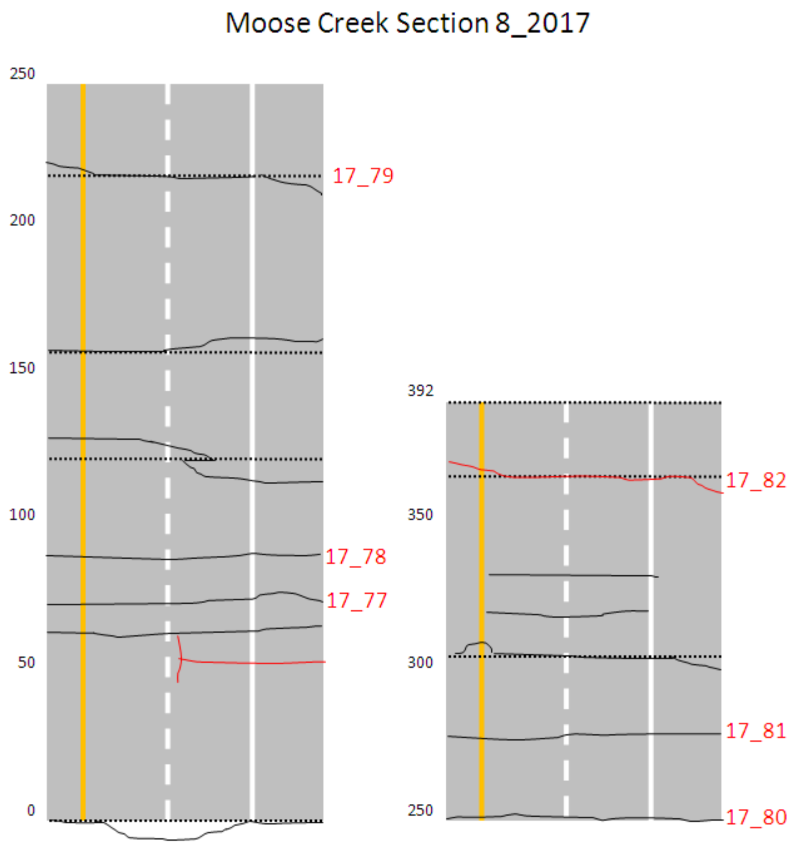
Appendix E5. Moose Creek section 5



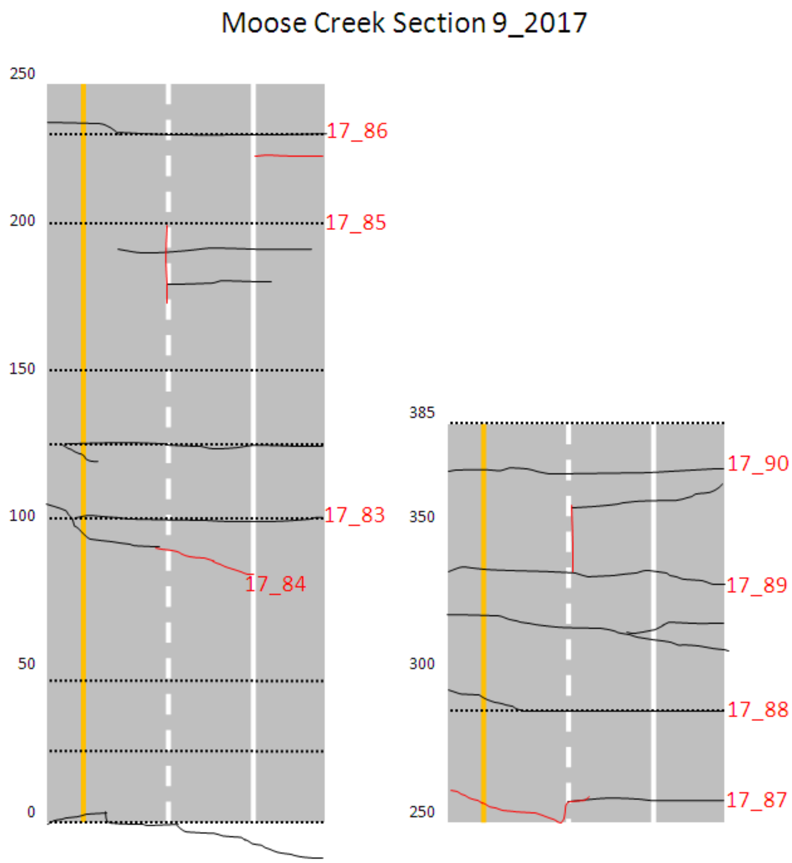
Appendix E6. Moose Creek section 6



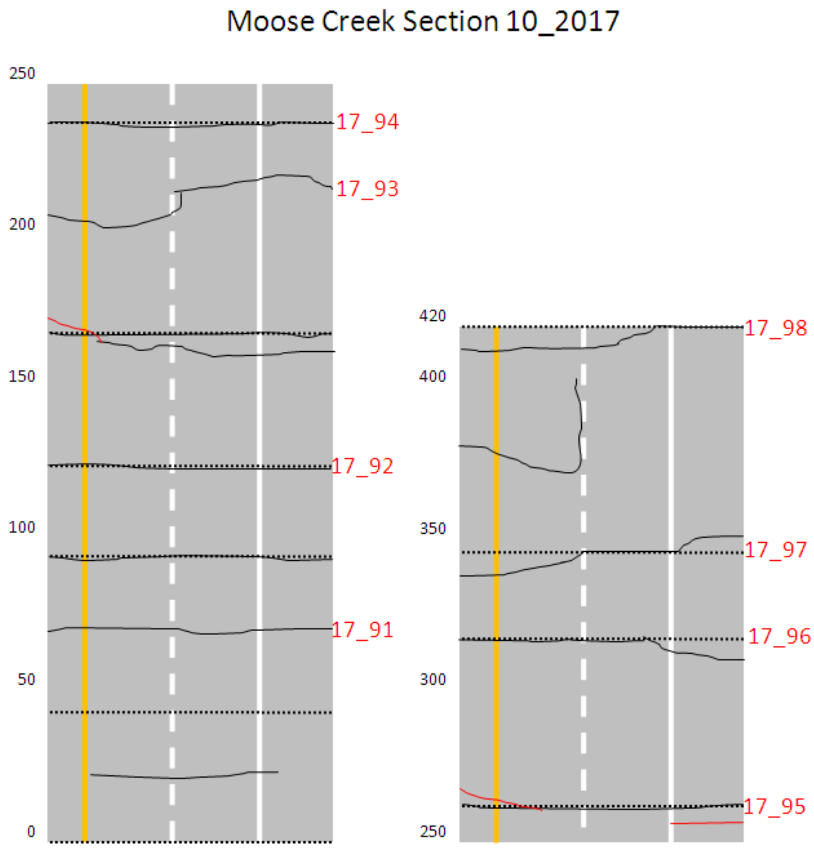
Appendix E7. Moose Creek section 7



Appendix E8. Moose Creek section 8

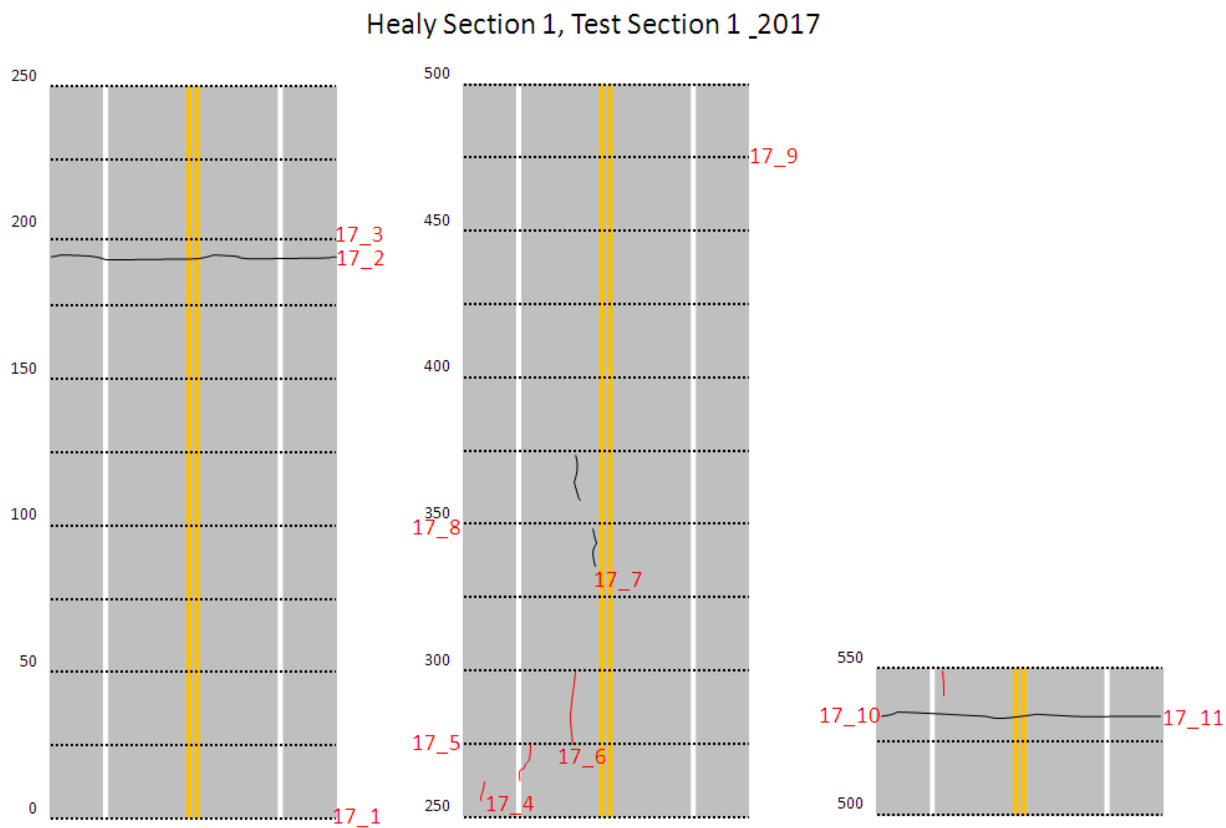


Appendix E9. Moose Creek section 9

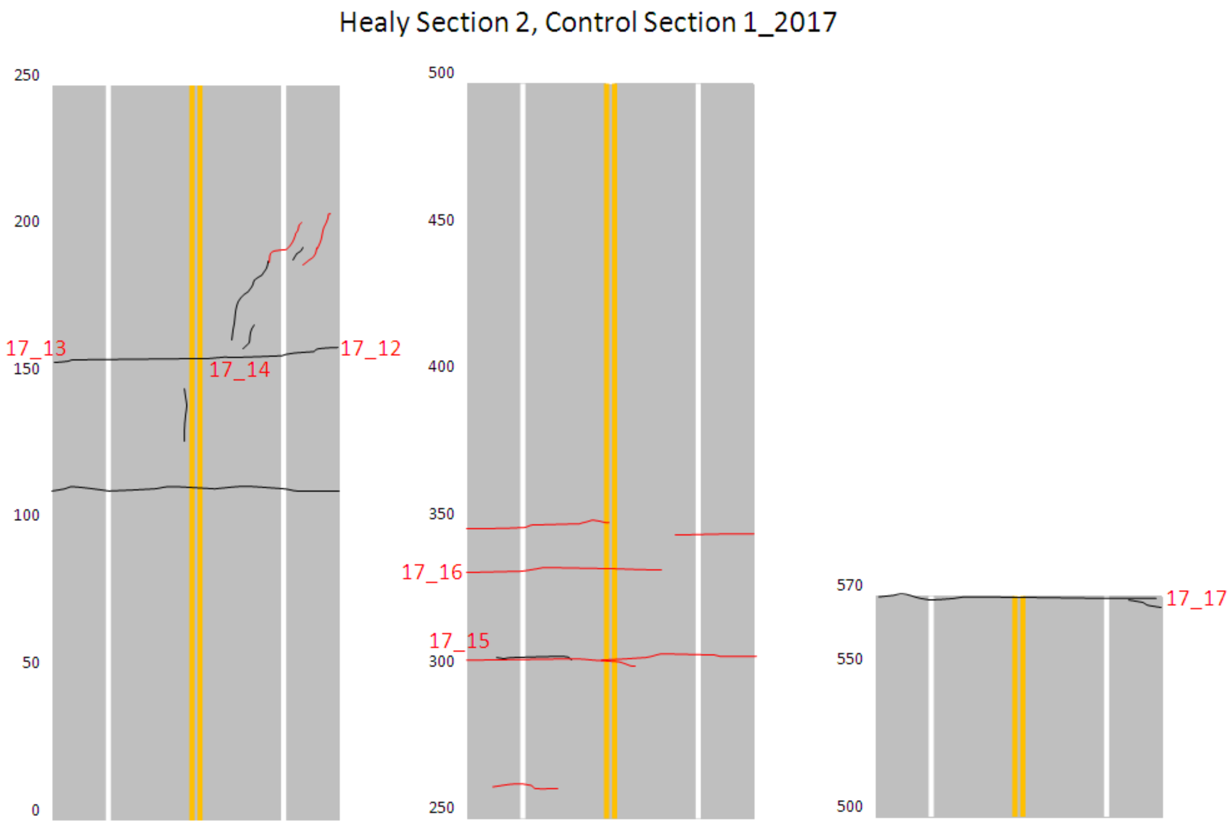


Appendix E10. Moose Creek section 10

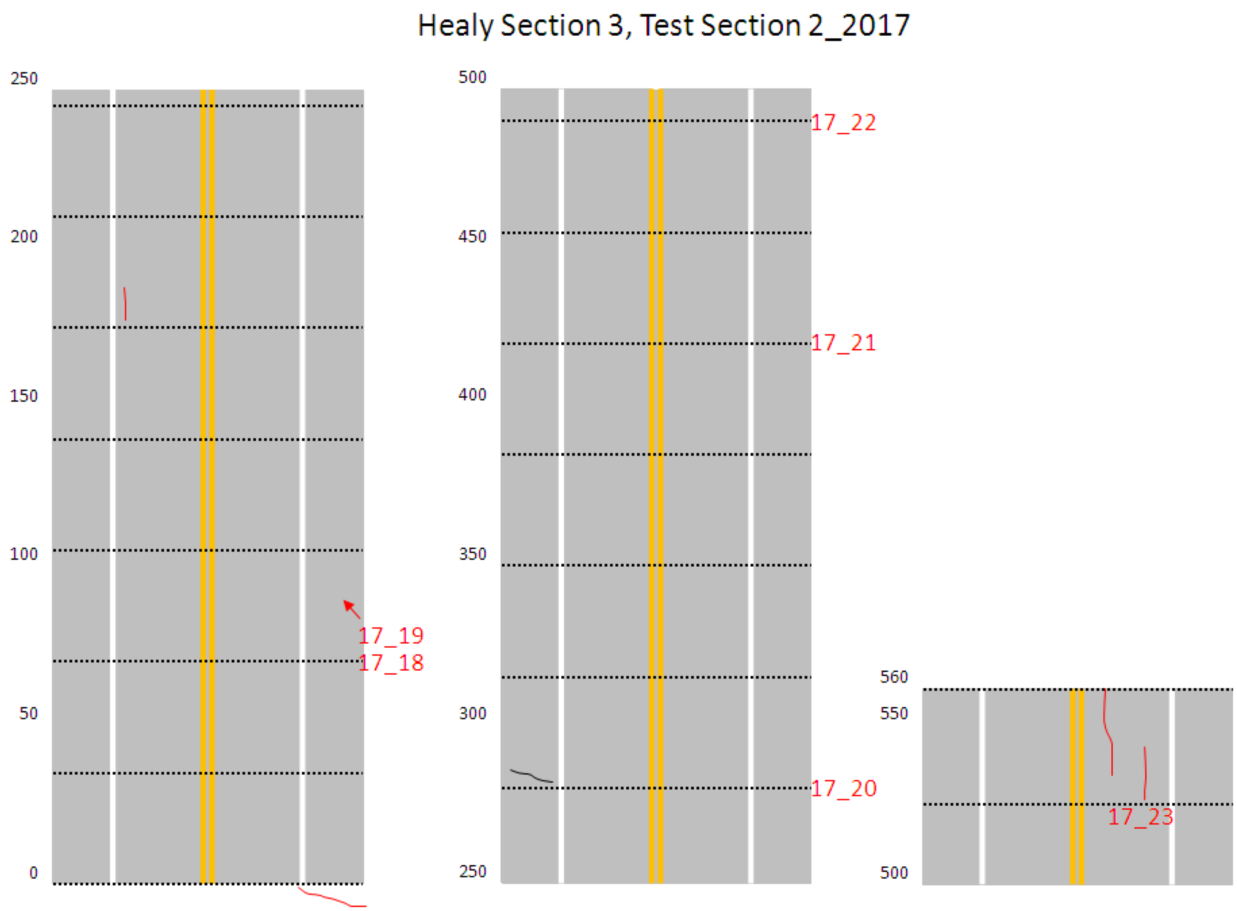
APPENDIX F 2017 FIELD SURVEY SUMMARY_HEALY PROJECT



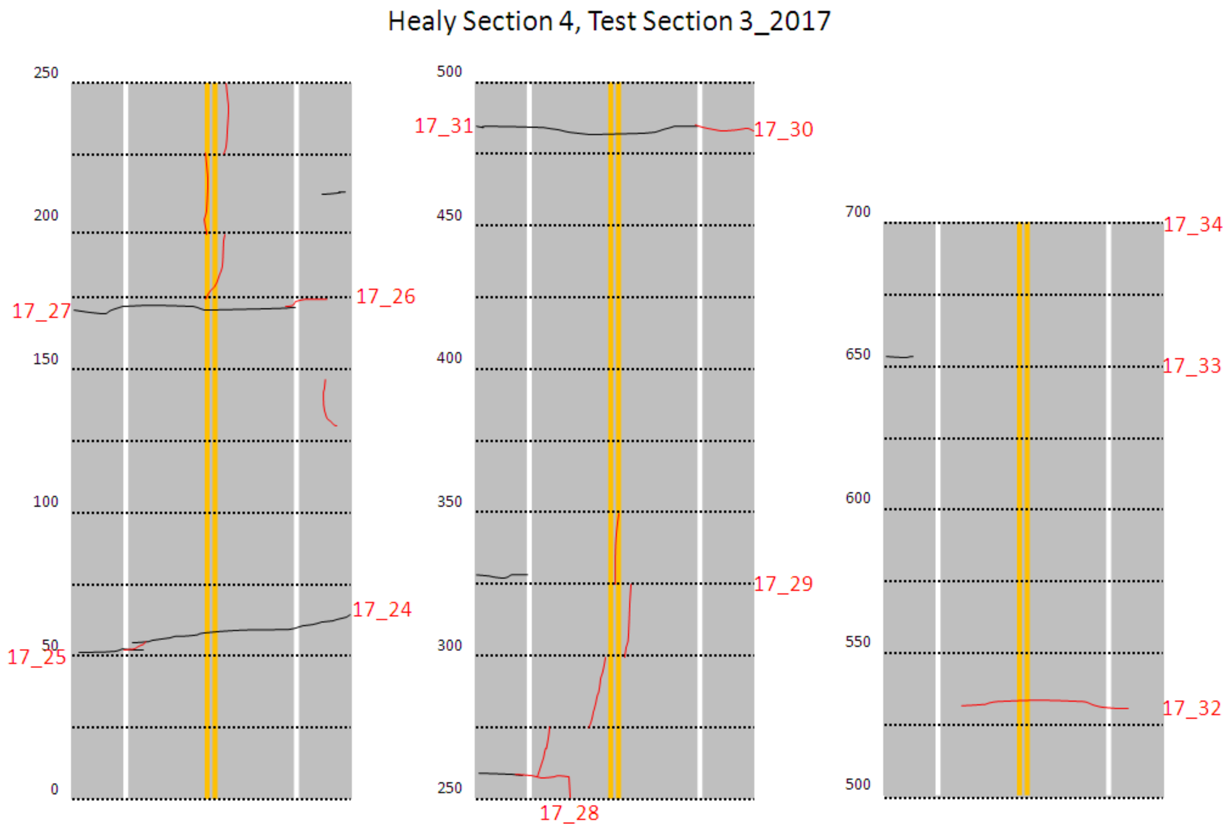
Appendix F1. Healy section 1



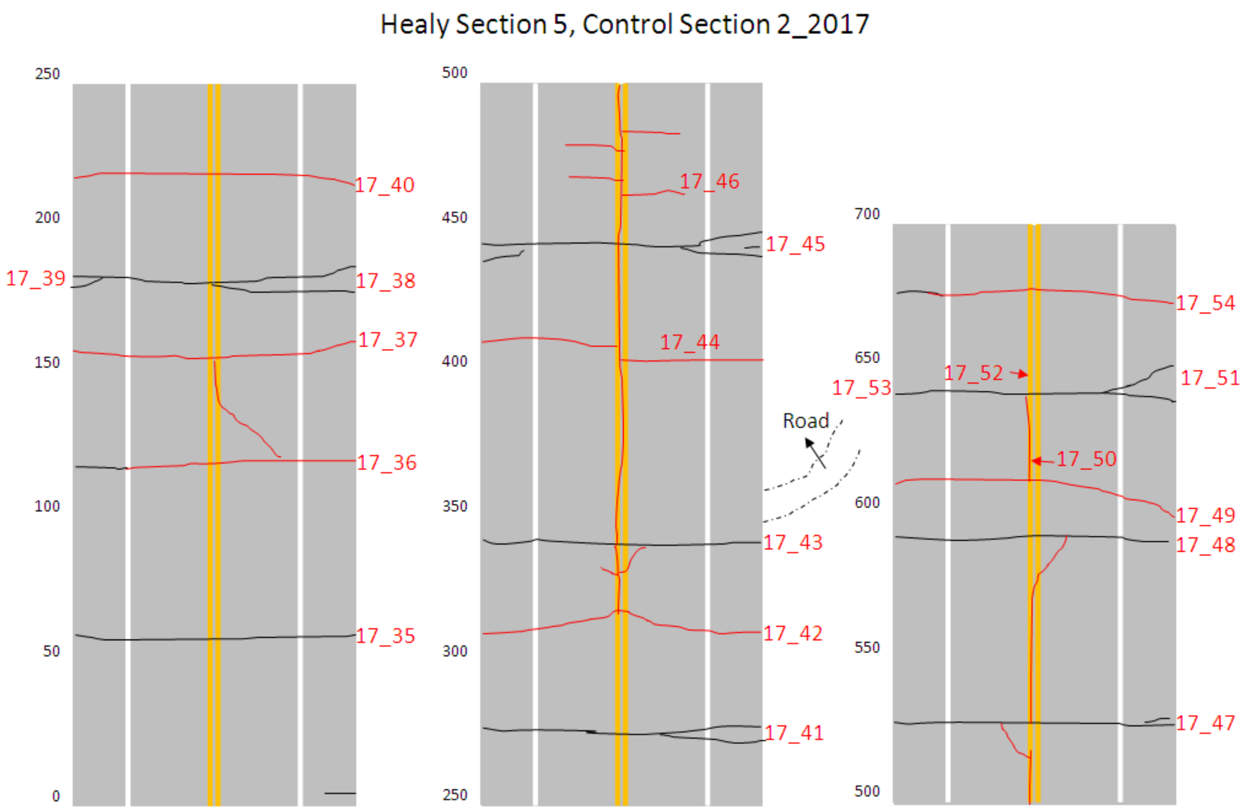
Appendix F2. Healy section 2



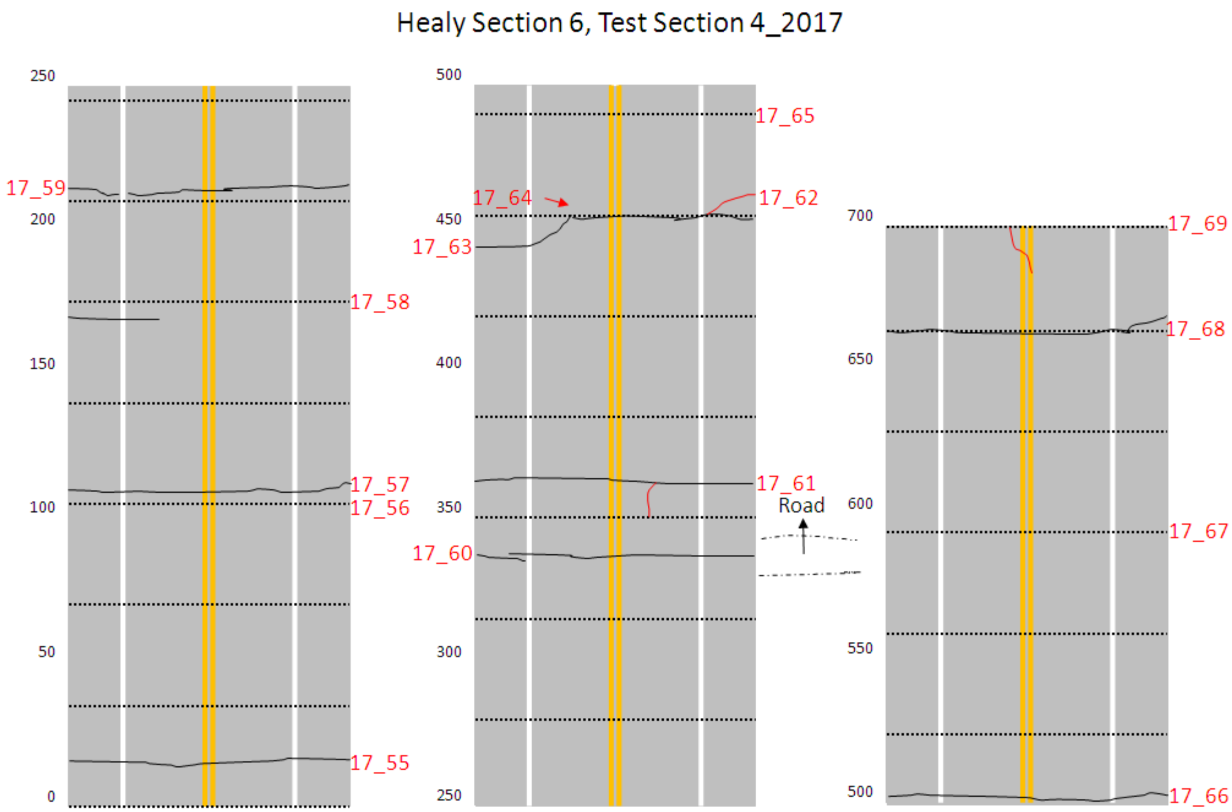
Appendix F3. Healy section 3



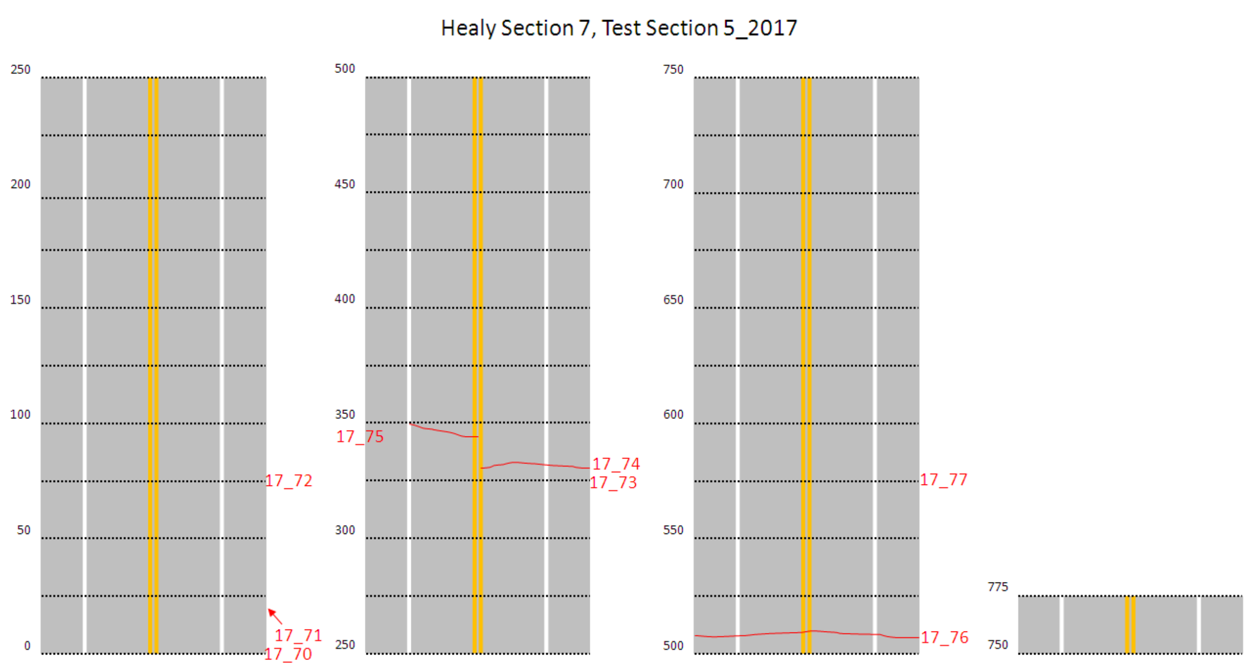
Appendix F4. Healy section 4



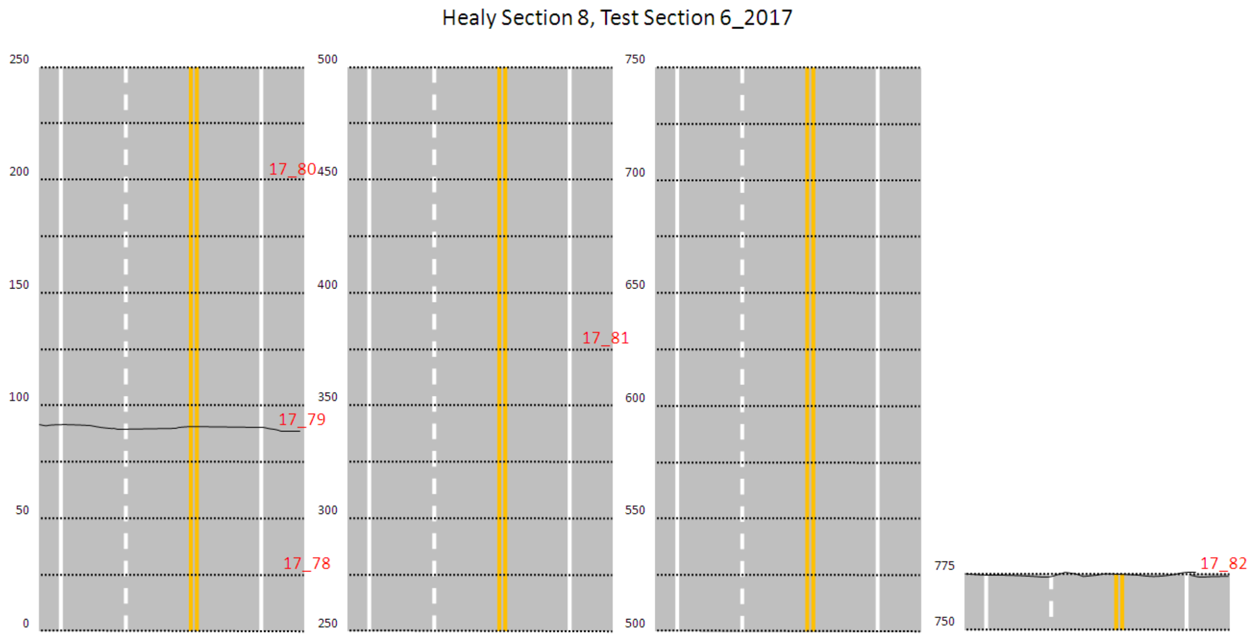
Appendix F5. Healy section 5



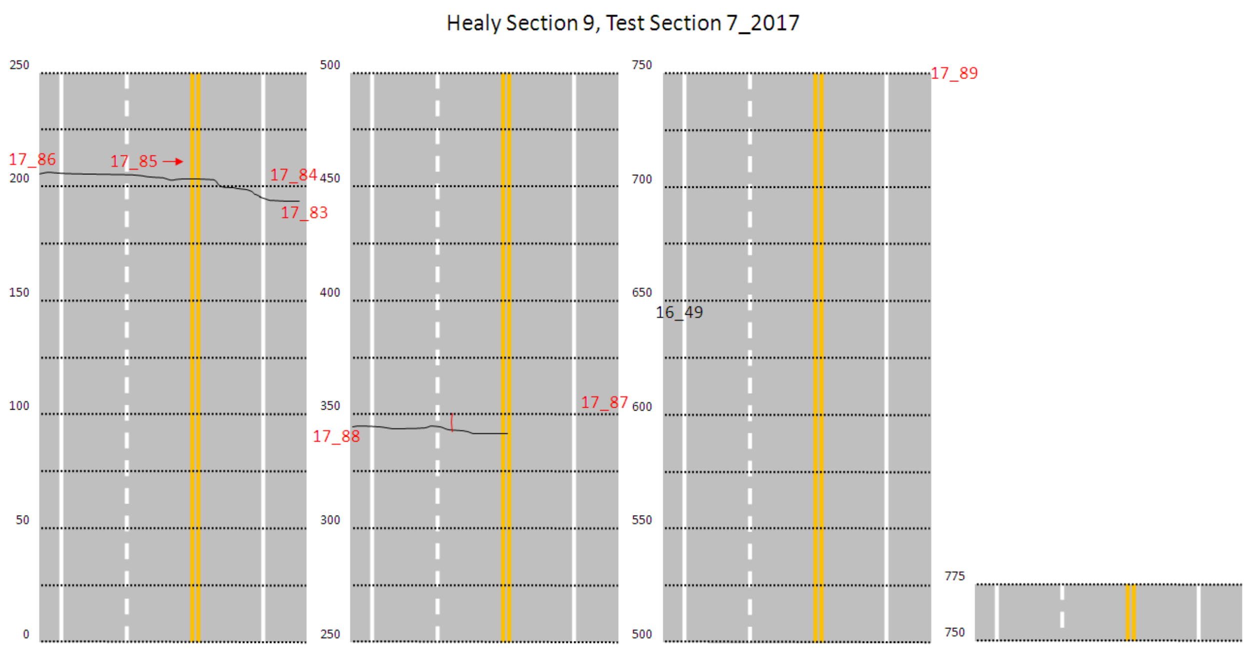
Appendix F6. Healy section 6



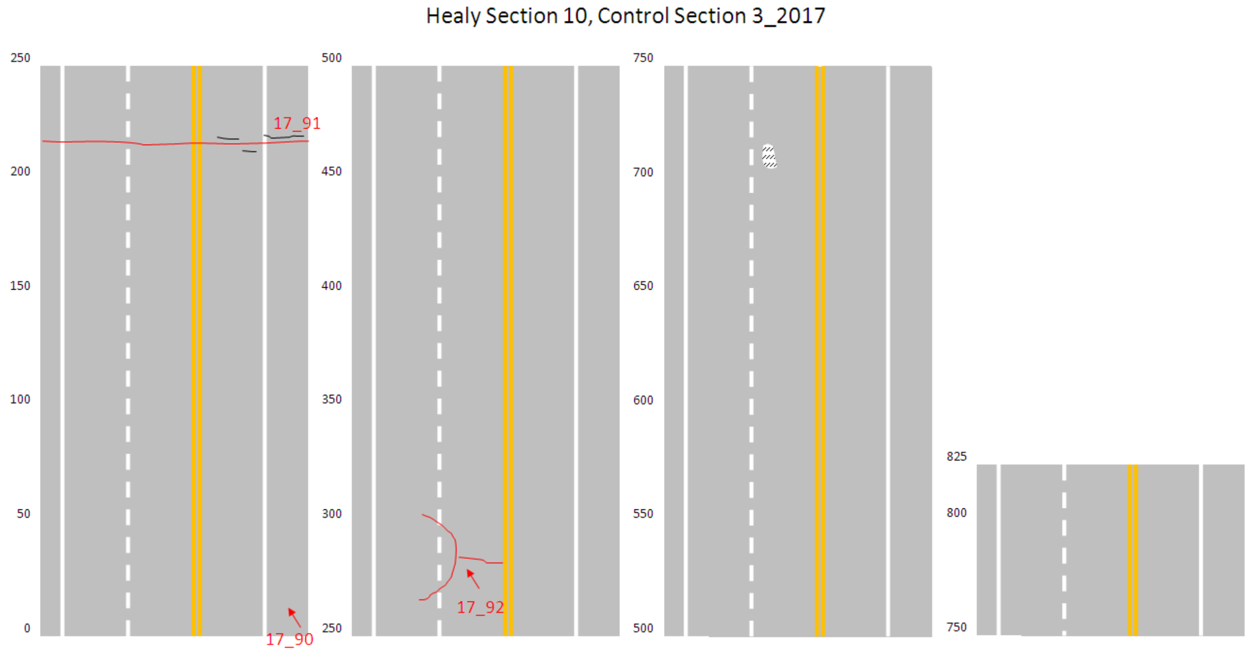
Appendix F7. Healy section 7



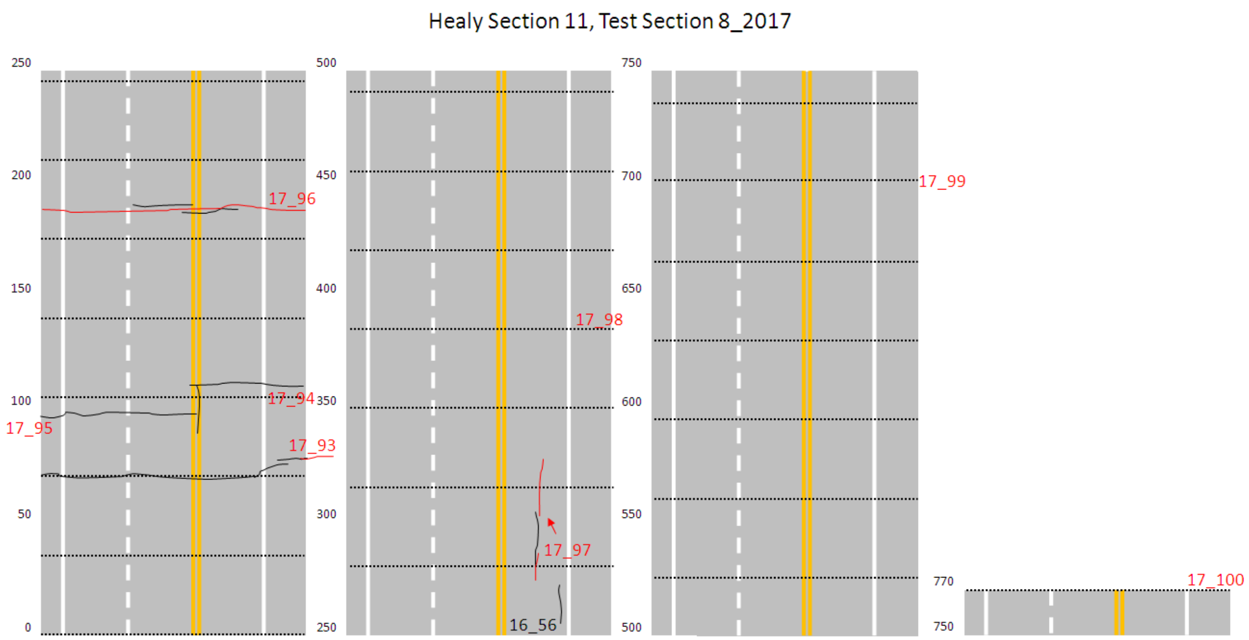
Appendix F8. Healy section 8



Appendix F9. Healy section 9

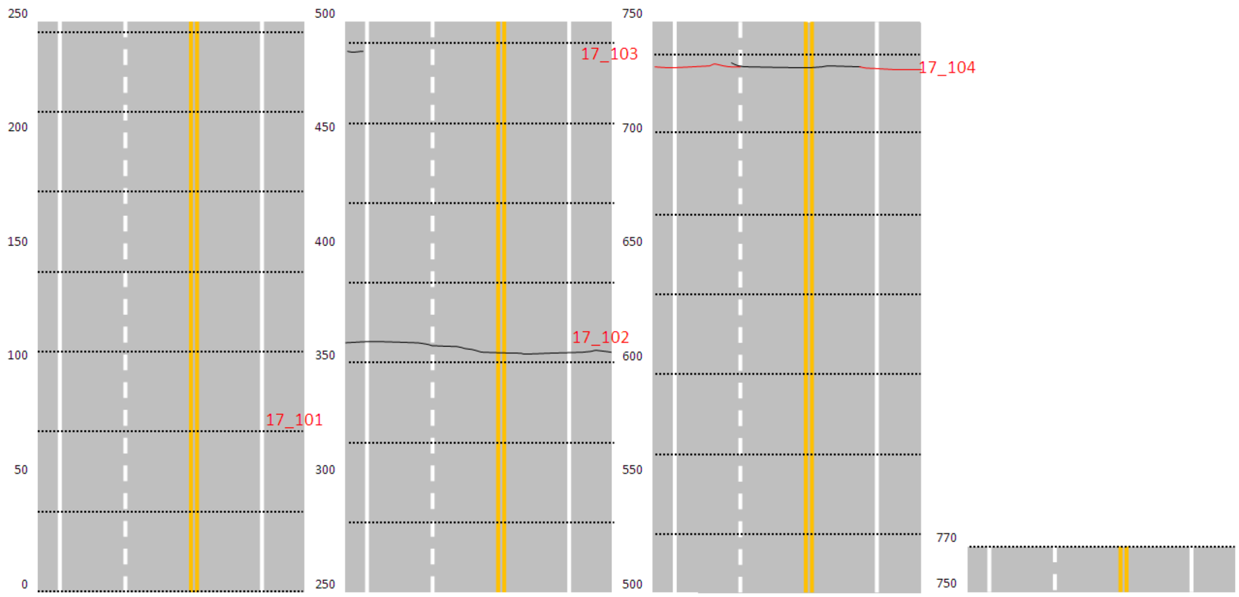


Appendix F10. Healy section 10



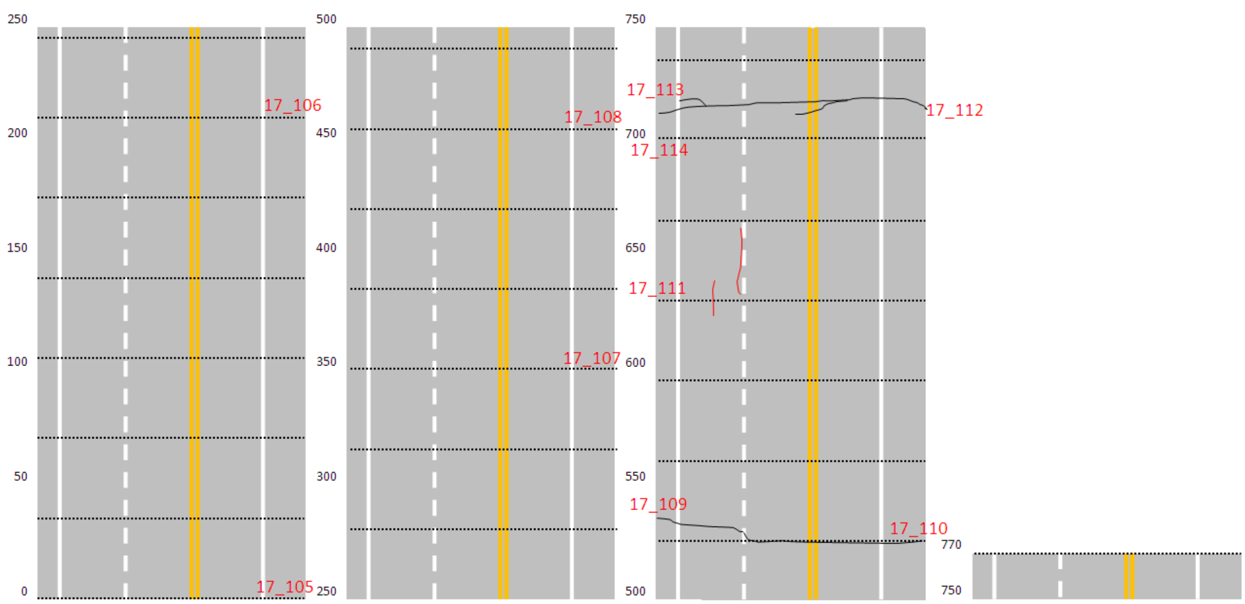
Appendix F11. Healy section 11

Healy Section 12, Test Section 9_2017

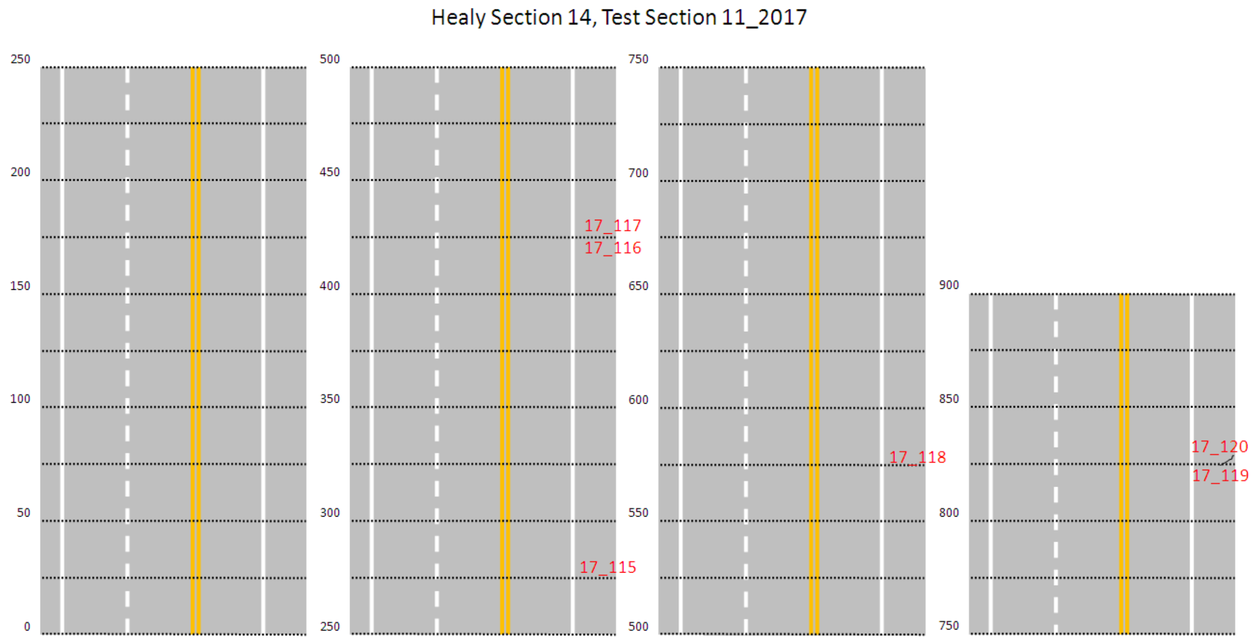


Appendix F12. Healy section 12

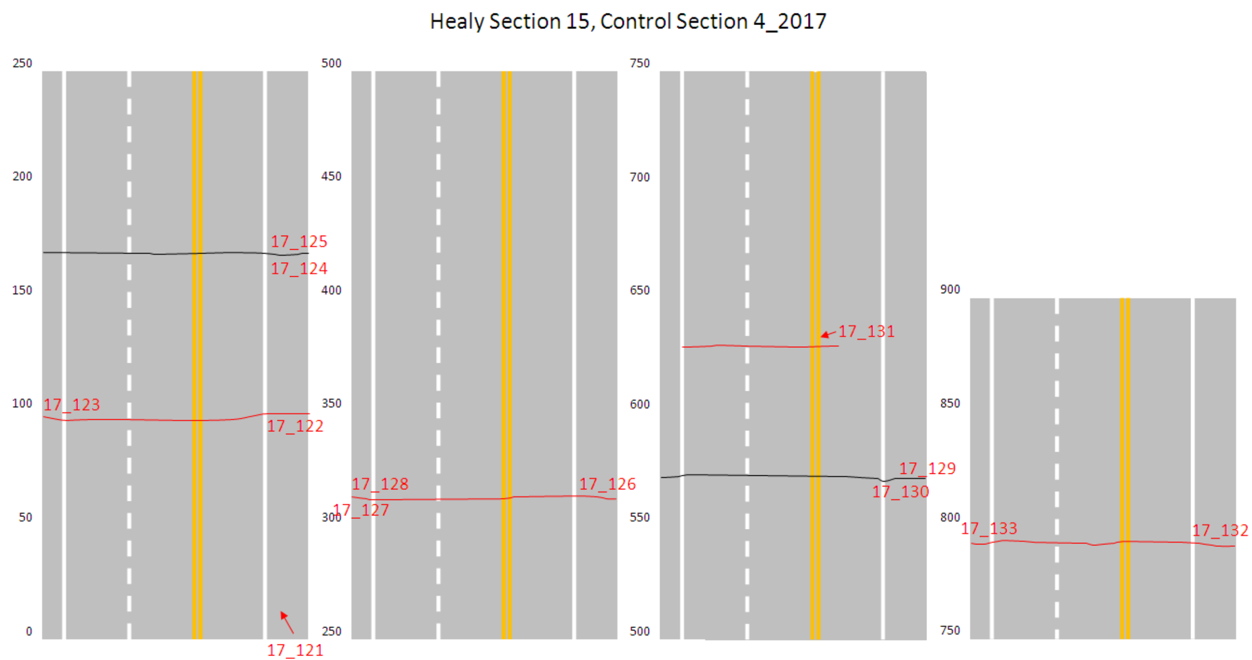
Healy Section 13, Test Section 10_2017



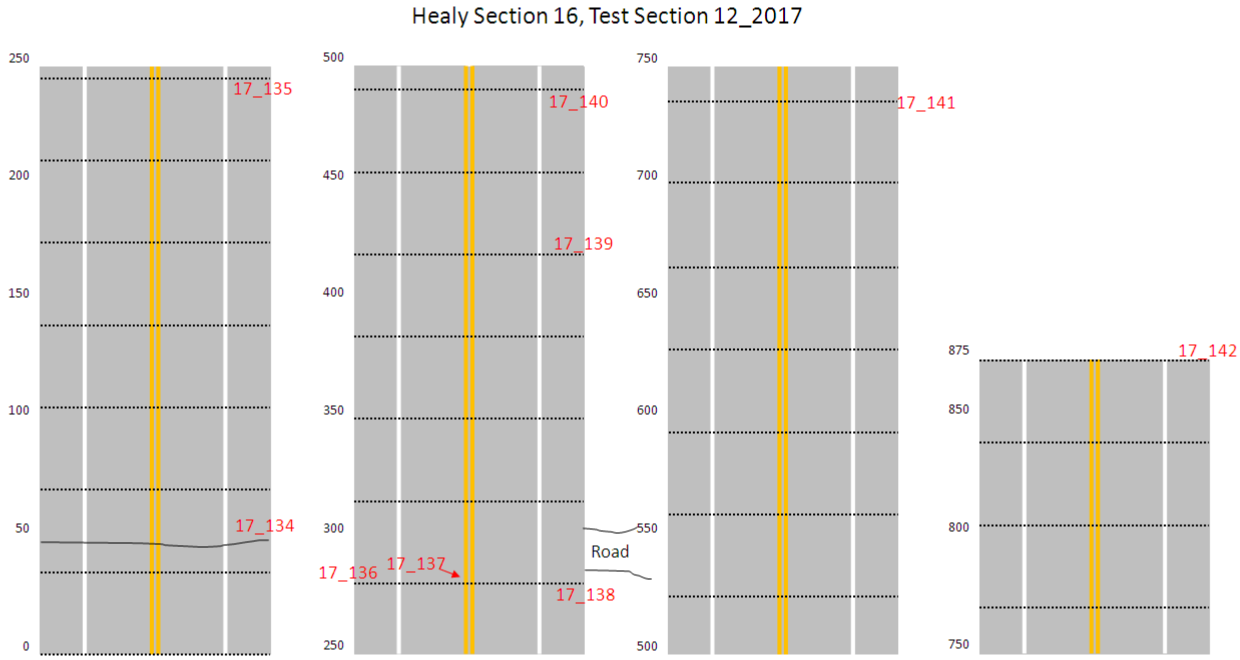
Appendix F13. Healy section 13



Appendix F14. Healy section 14



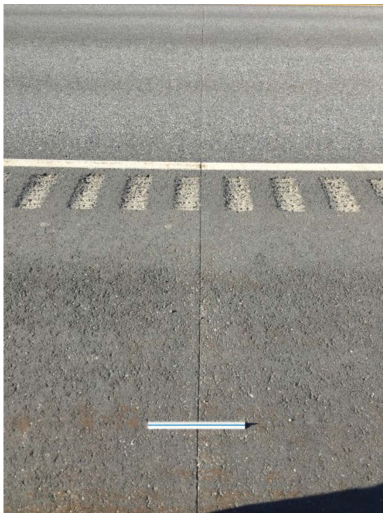
Appendix F15. Healy section 15



Appendix F16. Healy section 16

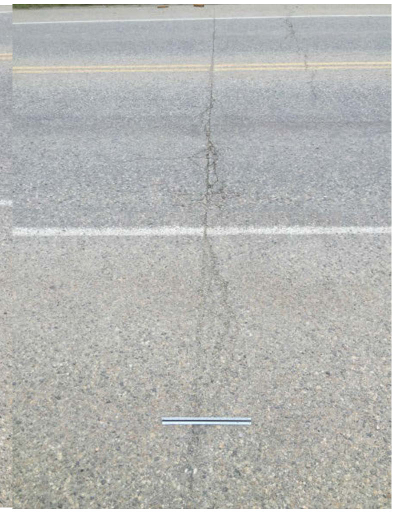
APPENDIX G PHOTO EXAMPLES OF TRANSVERSE CRACK MORPHOLOGIC DESCRIPTIONS

Photo examples are shown in the order listed in Table 3.2.



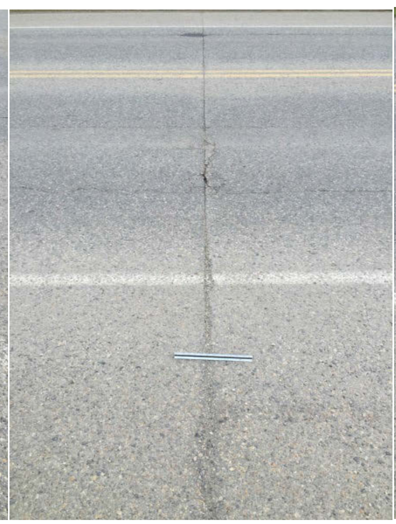
Moose Creek 4

PFR 7

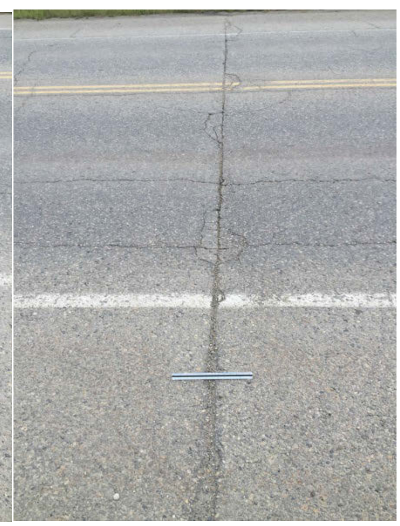


PFR 8

PFR 17



PFR 13



PFR 22

Moose Creek 12

Moose Creek 48

Moose Creek 51

Moose Creek 28

Moose Creek 39

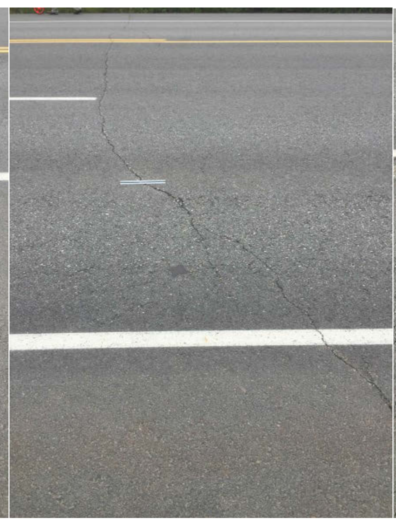
Moose Creek 85

PFR 16

Moose Creek 63

Moose Creek 70

Healy 43



Healy 61

Moose Creek 56