



NATIONAL CENTER FOR TRANSPORTATION SYSTEMS PRODUCTIVITY AND MANAGEMENT

Next Generation Crack Sealing Planning Tool for Pavement Preservation

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Principal Investigator: Yichang (James) Tsai, Ph.D.



National Center for Transportation Systems Productivity and Management

O. Lamar Allen Sustainable Education Building
788 Atlantic Drive, Atlanta, GA 30332-0355

P: 404-894-2236

F: 404-894-2278

nctspm@ce.gatech.edu

nctspm.gatech.edu



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16. Abstract: As one of the most popular preventive maintenance methods, crack sealing and filling (CS/CF) has been widely used by state highway agencies. Due to stringent highway budgets and the lack of work forces in state highway agencies, it is urgent that CS/CF, as well as other types of pavement preservation methods, be incorporated in a pavement management system (PMS). For this purpose, this research project proposed a systematic framework to study the cost-effectiveness of CS/CF and incorporate CS/CF planning in a PMS. Three key research objectives have been investigated: 1) to propose an accurate workload estimation method using 3D laser data and automatic crack detection and crack width measurement method, 2) to propose a quantitative methodology to objectively evaluate CS/CF effectiveness, and 3) to propose a Fisher-clustering-algorithms-based pavement segmentation method to partition a pavement network into individual CS/CF projects. The proposed methodology has been evaluated using different case studies and has demonstrated promising results. It is hoped this research project will advance the state-of-good-repair practices for asphalt pavement crack sealing into the next generation to prolong the life of pavements.			
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**NEXT GENERATION CRACK SEALING PLANNING TOOL FOR
PAVEMENT PRESERVATION**

By

Yichang (James) Tsai, Ph.D., P.E.

Zhaohua Wang, Ph.D., P.E.

Georgia Institute of Technology

Contract with

Georgia Department of Transportation

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Executive Summary

As one of the most popular preventive maintenance methods, crack sealing and filling (CS/CF) has been widely used in state highway agencies. In the past, it was normally considered as routine maintenance and performed by agencies' internal manpower resources. Nowadays, due to stringent highway budgets and the lack of work forces in state highway agencies, CS/CF is considered as one of the most efficient preventive maintenance methods in the pavement preservation toolbox. To maximize the return on investment, it is urged that CS/CF, as well as other types of pavement preservation methods, be incorporated in a pavement management system. To do this, the cost and effectiveness of CS/CF need to be determined. This research project aimed at proposing a systematic framework to facilitate the cost-effectiveness study of CS/CF by using emerging 3D laser technology and computer-vision-based automatic crack detection and classification algorithms. It is hoped that the state-of-good-repair practices for asphalt pavement crack sealing into the next generation will be advanced to prolong the life of pavements. The research outcomes and major findings are presented below.

For each CS/CF project, a reliable cost estimation is needed for two purposes. First, it is needed in a pavement management system (PMS) when competing projects are to be selected within given budget constraints. Second, it is crucial when outsourcing, which has become a hurdle for state highway agencies, is required. The traditional survey method is very time-consuming, subjective, and inaccurate when crack lengths and crack widths need to be manually measured in the field. To address the above challenge, an automatic approach, which uses 3D laser technology and automatic algorithms for crack detection and crack width measurement, was proposed. Based on the crack maps and the associated crack characteristics (i.e. crack widths), a pavement's cracks can be classified in terms of their CS/CF treatment specification. Finally, accurate costs can be computed according to the crack length in each category of cracks using different CS/CF methods. Besides cost estimation, the detected crack maps and the crack classification information can also be used as a means for construction contractors and agencies to conduct construction quality checking. The case study, performed on a runway shoulder at Atlanta's airport, shows that the proposed method is very promising in its ability to

provide an automatic approach that cost-effectively and reliably generates categorized crack maps and accurately estimates crack sealing costs. Due to the use of sensing vehicle for field data collection and automatic computer programs for data processing, it is practical to conduct large-scale, e.g. network level, analysis in considering time and effort needed. The tested case can be easily extended to other highway agencies' practice.

Quantitative effectiveness of CS/CF is the key to incorporating it into a PMS. When the effectiveness and cost of CS/CF projects are known, their planning at the network level could be done using an optimization model or a simple prioritization framework to determine the optimal project selection within a given budget. However, the past study of CS/CF effectiveness is still very limited. Traditionally, a composite pavement condition measure is used to quantify the effectiveness of CS/CF, which contains both relative and irrelative pavement condition measures and is normally subjectively defined. Thus, there is a need to objectively quantify the effectiveness of CS/CF. For this purpose, an objective method was proposed in this research project to accurately evaluate the effectiveness of CS/CF. To eliminate the subjectivity of the definition of a crack index that is often used in a protocol of pavement distress identification, the measures of fundamental crack characteristics, such as total crack length, CS/CF patched density, and crack width of the initial cracks, were recommends. In addition, because different types of cracks at different locations might have different benefits from a CS/CF, the effectiveness relative to different types of cracks at different locations was also analyzed. To obtain the detailed, fundamental crack characteristics, emerging 3D laser technology, automatic crack detection, and the CFE model were employed in the proposed methodology; this overcame the problems with the visual inspection method, which has been extremely difficult or often infeasible in the past. A case study using real-world 3D pavement data collected on State Route 26 near Savannah, Georgia, at different times, validated the feasibility of using 3D pavement data and the proposed methodology to objectively evaluate the effectiveness of CS/CF.

For CS/CF project planning at the network level, pavement segmentation, which divides the entire pavement network into individual pavement sections, i.e. projects, is

indispensable. The pavement conditions in each CS/CF project should be statistically identical in terms of CS/CF effectiveness. Thus, the selected CS/CF projects at the network level could be more cost-effective. In this research project, the Fisher clustering algorithms were used to perform a spatially sequential segmentation of pavement network. The CS/CF-effectiveness-related crack characteristics, i.e. the total transverse crack length, total wheel-path longitudinal crack length, total non-wheel-path longitudinal crack length, and the 85-percentile of crack width in each 5-m 3D pavement image, were used as clustering factors. The case study, conducted on a 5.5-mile pavement section on State Route 26 near Savannah, Georgia, showed that the automatic segmentation results comply with visual identification.

In summary, this research project proposed a systematic framework to study the cost-effectiveness of CS/CF and incorporate CS/CF planning in a PMS. Three key research activities were conducted: 1) to propose an accurate workload estimation method using 3D laser data and automatic crack detection and crack width measurement method, 2) to propose a quantitative methodology to objectively evaluate CS/CF effectiveness, and 3) to propose a Fisher-clustering-algorithms-based pavement segmentation method to partition pavement networks into individual CS/CF projects. The proposed methodology has been evaluated using different case studies and has demonstrated promising results.

Chapter 1 Introduction

1. Research Background and Research Need

Crack sealing and filling (CS/CF) of asphalt pavements are two of the most commonly used pavement preventive maintenance methods. These two methods are used to prevent water from entering pavements, bases, and subbases, which could cause pavement deterioration very quickly. Results of CS/CF repairs show that every \$1.00 spent on proper pavement preservation could save \$6.00 to \$10.00 or more in future rehabilitation or reconstruction costs (<http://www.fp2.org/why-pavement-preservation/>). To promote the use of cost-effective pavement preservation methods, federal funds can be used under the new federal surface transportation law MAP-21 (the Moving Ahead for Progress in the 21st Century Act). However, to achieve improved pavement performance, treatments should be applied properly and at the right time. If a treatment is applied too soon, only a little benefit can be added; if it is applied too late, it becomes ineffective (Peshkin, et al., 2004). A study by Morian (Morian, et al., 1997) showed that proper use of CS/CF could extend pavement life by three to five years. Ponniah and Kennepohl (1996) reported at least a 2-year pavement life extension from CS/CF, and the Michigan DOT reports that CS/CF can provide up to a 3-year life extension (Bausano, et al., 2004). The annual cost of CS/CF is estimated at more than \$10 million dollars for the Georgia Department of Transportation (GDOT).

To determine the right timing for CS/CF, several state DOTs use a decision tree or pavement condition index (ADOT, 2011; Caltrans, 2008; George, 2012; IDOT, 2010; Jusang, 2010; PennDOT, 2010; SDDOT, 2010). For example, GDOT uses the criteria for selecting candidate pavements (i.e. at the right timing) for CS/CF as follows: a) a Computerized Pavement Condition Evaluation System (COPACES) rating of between 80 and 85 (that means crack development is at an early stage); b) crack width is greater than 1/8 in.; and c) transverse/block cracking caused by weathering and early stages of longitudinal cracking caused by loading. Though the criteria for identifying the candidates (e.g. 5,000 miles out of 18,000 miles) for CS/CF at the network level are clearly based on the aggregated information in a Pavement Management System (PMS), they must be further evaluated and prioritized to achieve the highest return on investment (that is, maintaining the pavements in good repair) based on the

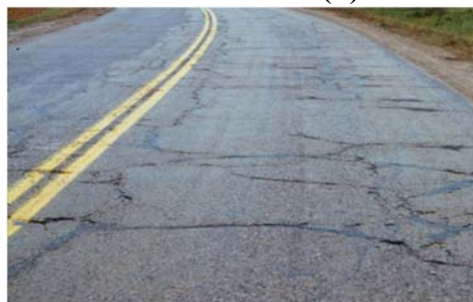
detailed crack characteristics. There is currently no method a) to further evaluate the adequacy of these candidates at the detailed level using the full coverage crack map data and to categorize/prioritize them based on the treatment cost-effectiveness, and b) to reliably compute the workload and cost of the actual CS/CF and routing needed for internal maintenance forces and outsourcing. Under stringent budget conditions, it is especially important to achieve the highest cost-effectiveness and maximize the return on investment. A fair and reliable quantitative estimation of workload and cost is especially important when it is outsourced. Inaccurate cost estimation has been found to be detrimental to treatment performance, according to GDOT engineers, when it is outsourced to contractors. If “dollar per gallon” is used for pricing, pavement cracks are normally overtreated. As shown in Figure 1.1 (a), excessive sealing would degrade the skid resistance of pavement surface. In addition, the raised and bumpy sealing caused by excessive sealing materials has a negative impact on driving comfort and safety. In contrast, if “dollar per mile” is used, it is normally undertreated (Figure 1.1 (c)).



(a) Overtreated Cracks



(b) Raised and Bumpy Sealing



(c) Undertreated Cracks

Figure 1.1: Problematic CS/CF

Full coverage, detailed-level crack characteristics data, including crack length, width, location, orientation, etc., are needed to support the evaluation of the selected pavement candidates at the network level so their effectiveness in relation to return on investment of a CS/CF project can be

determined. Based on that, these pavement candidates can be effectively prioritized and, finally, programmed in terms of available funds. This is a data-driven planning and programming decision-making process. However, the pavement condition survey methods currently used only record aggregated crack information (e.g. score and percentage), which is insufficient to support the data-driven decision-making process. In a conventional manual survey, it is virtually impossible to obtain a full-coverage, detailed-level crack characteristics data, including length, width, location, and orientation of cracks. Therefore, there is a need to develop methods by leveraging automatic crack detection and classification methods a) to evaluate these candidates so the effectiveness of a CS/CF project can be determined, b) to categorize and prioritize these pavement candidates based on their return on investment to provide transportation agencies a tool for making data-driven, cost-effective CS/CF planning and programming decisions, and c) to reliably compute the CS/CF workload and cost. The proposed method will employ advanced 3D laser technology and automatic crack detection methods to advance the state-of-good-repair, especially on pavement preservation planning and programming, into the next generation.

2. Research Objectives

Based on the above-mentioned need, the objective of this research project is to develop a next generation, data-driven CS/CF planning tool that advances the existing state-of-good-repair practices to achieve the highest return on investment for pavement preservation and better utilizes existing infrastructure by prolonging its life. The tool is especially important because outsourcing has become a trend for CS/CF, and transportation agencies' budgets are stringently constrained. The following are the major tasks:

- Develop a procedure to compute and estimate the cost of each CS/CF project using full-coverage, detailed crack characteristics data. This will help establish accurate CS/CF workload estimation and planning.
- Develop a quantitative method to objectively evaluate the effectiveness of CS/CF. The relative crack characteristics, instead of the traditionally used composite rating, will be used to quantify the effectiveness.

- Develop a systematic pavement segmentation method to partition a pavement network into individual CS/CF projects in which the relative crack characteristics of each should be statistically identical.

3. Report Organization

This report is organized into six chapters. Chapter 1 introduces the research background, need, research objective, and major tasks. Chapter 2 is a literature review that summarizes highway agencies' practices on CS/CF and performance studies. Chapter 3 presents the proposed methodology for automatic CS/CF workload estimation. Chapter 4 presents the quantitative methodology for objectively evaluating CS/CF effectiveness. Chapter 5 presents the methodology for CS/CF project segmentation. Chapter 6 summarizes the project, presents conclusions, and offers recommendations for future research and implementation.

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Chapter 2 Literature Review

When cracks develop in pavements, they need to be treated because the penetration of moisture and incompressible fines into pavement layers leads to accelerated pavement deterioration (Yildirim, et al, 2010). Crack sealing and crack filling are two commonly used crack treatment methods that are generally on a routine basis (Thomas, et al., 1994). Defined by the Strategic Highway Research Program (SHRP) (Thomas, et al., 1994), crack sealing is the placement of specialized materials into working cracks using unique configurations to prevent the intrusion of water and incompressible fines into the crack. Crack filling is the placement of materials into nonworking cracks to reduce infiltration of water and to reinforce the adjacent pavement. A working crack will open and close with the change of temperature. Normally, it can be identified by the amount of horizontal movement. Different agencies may use different criteria. The Federal Highway Administration (FHWA) defines a working crack as having annual horizontal movement equal to or greater than 3 mm (Smith, et al., 2001). In the California Department of Transportation (Caltrans) (Caltrans, 2003), it is 6 mm.

Though crack sealing and crack filling are two different types of crack treatments, many highway agencies make no distinction between them. According to a recent survey of 28 state departments of transportation (DOTs), 106 counties, and 9 other highway agencies (Decker, 2014), 62% of the 157 responses make no distinction between them. In GDOT, there is also no difference between crack sealing and crack filling. In this case, we use CS/CF to represent these two treatments as a whole. Table 2.1 lists the advantages and disadvantage of CS/CF.

1. CS/CF Materials and Construction Practice

1.1 CS/CF Materials

Three major categories of CS/CF materials are listed in Table 2.2. According to the Caltrans guide (Caltrans, 2003), hot application ensures a good adhesive bond to the crack walls. These materials have excellent abrasion resistance and are useful for trafficked surfaces. In contrast, cold-pour materials for crack sealing are usually silicone-based and often used prior to paving. An advantage of the cold pour-asphalt emulsion treatment in comparison with the hot-pour rubberized material is its ability to seep in and fill much smaller cracks due to its much lower

viscosity. These materials cure either by exposure to moisture in the air or by mixture of a hardening agent with the base silicone. These materials often have poor abrasion resistance and should not be used in trafficked areas. Other materials, such as epoxies and polyurethanes, are usually cured by addition of a second chemical.

Table 2.1: CS/CF Characteristics

Advantages	Disadvantages
<ul style="list-style-type: none"> • Reduces water infiltration • Decreases further crack deterioration (e.g., spalling at crack) • Reduces or delays moisture damage • Slows pavement deterioration (roughness increases, potholes and depression formation) • Performs well in all climate conditions • Performance is not significantly affected by varying ADT or truck levels • Quick opening to traffic • Substantial life-cycle cost savings 	<ul style="list-style-type: none"> • Over application can cause a reduction in skid resistance • Poor appearance and visibility • No structural improvement

Table 2.2: CS/CF Material Types

	Cold-Applied Thermoplastic	Hot-Applied Thermoplastic	Chemically cured thermosetting materials
Michigan (Gesford)	Set by release of solvents (cutbacks) or breaking of emulsions	Soft upon heating Hard on cooling No change in chemical composition	Cure through chemical reaction
SHRP (Thomas, et al., 1994)	Asphalt emulsion Polymer-modified liquid asphalt	Asphalt cement Mineral-filled asphalt cement Fiberized asphalt Asphalt rubber Rubberized asphalt Low-modulus rubberized asphalt	Self-leveling silicone

Table 2.3 lists the properties of some commonly used CS/CF materials.

Table 2.3: Properties of Some CS/CF Materials (Smith, et al., 2001)

Property	Material Type*							
	Asphalt Emulsion	Polymer-Modified Emulsion	Asphalt Cement	Fiberized Asphalt	Asphalt Rubber	Rubberized Asphalt	Low-Modulus Rubberized Asphalt	Self-Leveling Silicone
Short Preparation	✓	✓						✓✓
Quick & Easy to Place	✓	✓	✓✓	✓✓	✓✓	✓✓	✓✓	
Short Cure Time			✓✓	✓✓	✓✓	✓✓	✓✓	✓
Adhesiveness	✓✓	✓	✓✓	✓	✓	✓	✓	✓
Cohesiveness					✓	✓	✓✓	✓
Resistance to Softening and Flow (cured state)		✓			✓	✓	✓✓	✓✓
Flexibility		✓			✓	✓	✓✓	✓✓
Elasticity		✓			✓	✓	✓	✓✓
Resistance to Aging and Weathering						✓	✓	✓✓
Resistance to Tracking and Abrasion					✓	✓✓	✓	

✓ Applicable; ✓✓ Very Applicable

The site-specific climatic conditions during treatment operations could influence which procedures or materials should be used. For instance, in areas where moisture or cold temperatures present scheduling problems, the use of a heat lance may help expedite operations (Smith, et al., 2001). The general climatic conditions must also be considered in deciding which materials and procedures to use. Hot climates necessitate the use of materials that will not significantly soften and track at high temperatures. Very cold climates, on the other hand, will generally require materials that retain good flexibility at low temperatures (Smith, et al., 2001). Based on the study by Masson et al. (Masson, 1997), sealant material selection is a critical issue in areas with extreme climates, such as in cities that experience arctic and subarctic climates (e.g., most Canadian cities and those of the northern United States). Selected sealants in these places must be able to endure unusual stresses. The low temperatures during a typical Canadian winter can make a sealant inelastic so that it can no longer adapt to the temperature-induced changes in the dimensions of a crack. The sealant then no longer rests tightly against the walls of the crack. Consequently, water, salt, and can dust enter it. At this point, the function of the sealant has been irreversibly compromised. Materials designed for low-stress elongation, especially at low temperature, are preferred for treating working cracks because materials for working cracks must adhere to the crack sidewalls and flex as the crack opens and closes (Thomas, et al., 1994). Generally, stiffer and more heat-resistant materials are used in hot

environments, and softer materials are used in mountainous cold-weather areas. Also, softer and more flexible materials are used with blow and fill; slightly stiffer materials are used for routing and filling techniques (NMDOT, 2007).

1.2 Construction Procedures

This subsection presents some key factors that need to be considered for CS/CF construction.

- Seasonality and Temperature

Seasonality is an issue that must be considered when deciding the time to apply CS/CF. In regions where seasonal temperature difference is large, crack treatment usually occurs in the fall. This decision is made mainly based on two considerations. First, a crack tends to open up in cold weather and close in hot weather. As shown in Figure 2.1(c), when CS/CF is applied in the fall, the material contraction in winter and expansion in summer could be balanced. Second, as Masson et al. (Masson, 1997) observed, crack sealant performance is heavily dependent upon proper and consistent workmanship during both crack preparation and sealing operations. Good workmanship is most likely to be achieved during good working conditions; therefore, crack sealing should be conducted at a time of year when temperatures are moderately cool, when working conditions are pleasant, and cracks have dried out.

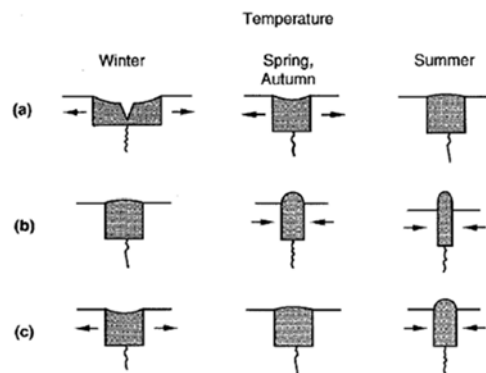


Figure 2.1: Effects of Seasonality (Masson, et al., 2003)

Ambient temperature should be considered when CS/CF is applied. Table 2.4 lists the ambient temperatures suggested by some highway agencies.

Table 2.4: Ambient Temperature Suitable for CS/CF Application

	Sealing	Filling
SHRP (Thomas, et al., 1994)	45 to 65 F, spring or fall	Can be conducted year-round, but often during cool or moderately cool weather (35 to 55 F)
Michigan (Gesford)	40-90	
Indiana (INDOT)	45-65, Spring and fall	Any time of the year
Ohio (OPE, 2001)	Above 40 F	
New Mexico (NMDOT, 2007)	Above 40 -70 F	

- Surface Preparation

Pavement surfaces need to be clean and dry before CS/CF is applied. An adequate bond will not form when the surface is wet, especially when using hot-poured sealants. The four typical methods used for cleaning and/or drying cracks are air blasting, hot air blasting, sandblasting, and wire brushing (Smith, et al., 2001).

- Routing/Cutting

In the process of CS/CF, one of the most important steps is crack preparation, which usually includes crack routing. Routing removes the deteriorated edges of crack, the dust or existing sealant from the crack, facilitating the placement of sealant and improves the adhesion between the sealants and the crack walls. With routing, the treated crack is cut into the same size; therefore, a thin crack will be widened to meet the geometry of the routers. As we will discuss later, the routing geometry has been found to influence the effectiveness of crack sealing. The advantages and disadvantages of routing (MTU, et al., 1999) are listed in Table 2.5. According to a SHRP study (Thomas, et al., 1994), there is almost a 40% greater chance of sealant success if cracks are routed prior to sealing (Johanns, et al., 2002). Table 2.6 lists the cutting configuration suggested in different literature.

Figure 2.2 shows a crack after cutting. However, whether to cut the crack prior to the treatment is a controversial subject. In Decker's survey (Decker, 2014), only less than half of

respondents routinely rout cracks (recessed routed 35%, flush routed 48%, and over-band routed 43%). Routing is a process that should be evaluated by agencies in more detail.

Table 2.5: Advantages and Disadvantages of Routing

Advantages	Disadvantages
Opens small cracks to allow greater penetration	Very labor intensive, thus extra cost
Provides a reservoir for sealant	Can be difficult to follow meandering crack
Produces uniform edges for better adhesion	May damage older or thin asphalt pavements
	Longer exposure

Table 2.6: Cutting Configuration

	Width (inch)	Depth (inch)
NCHRP (Decker, 2014)	1/2 - 1-1/2	3/4
New Mexico (NMDOT, 2007)	1/2-3/4	3/4-1
Michigan (Gesford)		1/3 of asphalt thickness or 2-1/2
Indiana (INDOT)	Max 0.75	Min 0.75
South Dakota (SDDOT, 2010)	5/8	5/8



Figure 2.2: Crack after cutting

- **Material Installation**

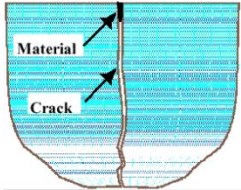
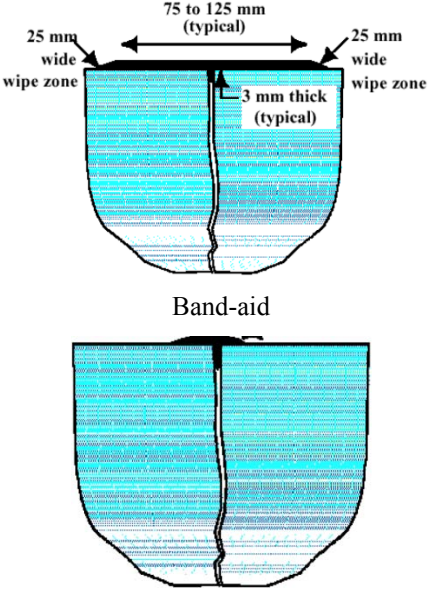
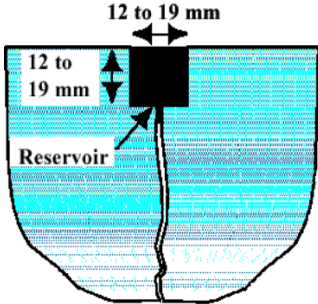
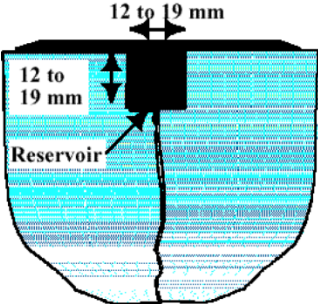
Material placement methods vary according to the nature of the distress. Material placement configuration includes flush fill, over-band, reservoir, combination, and backer rod. The characteristics of each method are shown in Table 2.7. If sealant is placed too deeply into the crack, the potential for cohesive failure is high (Decker, 2014). Therefore, a crack with a

depth greater than 5/8'' should have a backer rod inserted to a depth to provide a sealant depth equal to the sealant width (SDDOT, 2010), as shown in Figure 2.3.



Figure 2.3: Application of Backer Rod

Table 2.7: Characteristics of CS/CF Material Installation

	Flush fill	Over-band	Reservoir	Combination
	Uncut	Uncut	Cut	Cut
Excess material	Struck off	Shaped into a band using a squeegee or left unshaped	Placed either flush with or slightly below the pavement surface	A squeegee is used to shape the material into a band
disadvantages	Fail rapidly	Not ride comfortable	Cost more	Noise and cost more
advantage	Speed and cost	Speed, cost, and a little more durability over flush filling	Better coherence between sealant and surface	More stability
Figure	 <p>Material Crack</p>	 <p>25 mm wide wipe zone 75 to 125 mm (typical) 25 mm wide wipe zone 3 mm thick (typical) Band-aid capped</p>	 <p>12 to 19 mm 12 to 19 mm Reservoir</p>	 <p>12 to 19 mm 12 to 19 mm Reservoir</p>

- Finishing/Shaping

After routing and placement of sealants, finishing is the final step of CS/CF. As described in the Caltrans' guide, a poor finish could cause quick re-cracking, a bumpy surface, adhesion loss, and many other effectiveness issues. In some cases, a preformed plate on a hand lance assists in making the required flush result (Figure 2.4). Figure 2.5 shows typical flat finishing techniques. All sealant left on the surface shall be squeegeed to prevent a rough ride.



Figure 2.4: Preformed plate



Figure 2.5: Typical flat finishing techniques
(<http://www.battseal.com/residential.php>)

- Material Blotting

Cure time after CS/CF is usually less than 1 hour (OPE, 2001). Sometimes, it is beneficial to apply a sufficient amount of blotter material to protect the uncured crack treatment material from tracking. Fine sand (the most commonly used blotter), toilet

paper, talcum powder, limestone dust, and commercial products are often used. These blotters should be applied immediately after finishing so that they can stick to the material and serve as temporary covers. Care must be taken not to over-apply dust and powder materials. Sand is used primarily as a blotter for emulsion materials and occasionally for asphalt cement (see Figure 2.6 and Figure 2.7). It should be applied in a thin layer and should fully cover the exposed treatment material.



Figure 2.6: Sand as blotting material



Figure 2.7: Toilet paper as blotting material(<http://www.whartonasphalt.com/crack.asp>)

2. Criteria for CS/CF Project Selection

The criteria for CS/CF project selection define the best timing for CS/CF when the best cost-effectiveness can be achieved. However, our extensive literature review shows that highway agencies often define the treatment timing based on their experience or rules of thumb.

Inconsistency among different agencies is not rare. This subsection summarizes the major factors that need to be considered for CS/CF projection selection.

2.1 Pavement Conditions

Current practices tend to put the overall pavement condition in the dominant place instead of the characteristics of cracking in the crack treatment decision-making, as evidenced by several agencies that use either decision trees or pavement condition indexes to identify when to perform crack treatment.

The best candidates for CS/CF are newer pavements that are just beginning to form cracks. In contrast, CS/CF may not be suitable for older, aged asphalt pavements (e.g. above 6 years old) and thin asphalt pavements (less than 2") (Gesford). If asphalt overlay has been done before, CS/CF should be done within 2 years (Johanns, et al., 2002).

CS/CF are pavement preservation technologies; they cannot provide additional load carrying capacity. Thus, the drainage conditions should be sound and no structural damage is allowed in pavements. Since different pavement distress protocols are used in different highway agencies, the pavement conditions specified for CS/CF are normally nontransferable among different highway agencies though they can be mapped to some extent. This situation also causes the inconsistency of CS/CF treatment criteria among different agencies. For example, in SHRP's report, pavement condition index (PCI) should be 70 or more when using CS/CF. Based on the FHWA study (Wu, et al., 2010), the Michigan DOT requires "a minimum remaining service life of ten years, Distress Index < 15, Ride Quality Index < 54 and Rut < 3 mm" for flexible pavement and for composite pavement "Distress Index < 15" is required instead. Based on Li et al. (Li, et al., 2014), Washington DOT has adopted crack sealing as a life-cycle maintenance method and determines timing of crack sealing programs based on the condition index deduction, age of

pavements, and stages of the pavement overall condition (initiation, propagation, acceleration, due, past due, and fail).

2.2 Crack Characteristics

Other than the overall pavement conditions, crack characteristics, such as crack type, width, orientation, etc., are also important factors affecting CS/CF project selection.

- **Crack Type and/or Orientation**

According to the characteristics, cracks are classified into many types: transverse cracking, longitudinal cracking, block cracking, alligator cracking, reflective cracking, etc. According to Eaton et al. (Eaton, et al., 1992) and Rouen et al. (Caltrans, 2003), it is a consensus that alligator cracking is not suitable for CS/CF because it indicates the failure of the pavement base, and reconstruction is the only cure to base failure.

- **Crack width**

It is a common sense that cracks should not be too tight or too wide open for CS/CF. However, different threshold values are used by different agencies; there is no sufficient research to support the selection of different threshold values. Caltrans (Caltrans, 2008) recommended that cracks should be greater than 1/4 inch in width before applying CS/CF. The FHWA (Smith, et al., 2001) recommended that crack widths of 0.2 inch or greater should be sealed or filled. In the report by Eaton and Ashcroft (Eaton, et al., 1992), cracks with widths greater than 1/8 inch should be treated. The upper limit of crack width is normally defined as 1 inch for highway agencies, such as South Dakota, Indiana, Michigan and Nebraska, etc. (Johanns, et al., 2002; Gesford; INDOT; SDDOT, 2010).

- **Crack Density**

If a pavement has high-density cracking (covering more than 25% of surface area), CS/CF should not be applied because pavement skid safety will be seriously diminished (Decker, 2014). In this case, resurfacing might be more suitable. Table 2.8 is the guide provided by SHRP to determine the type of maintenance for cracks based on crack density (Thomas, et al., 1994). However, there is no quantitative definition of crack density defined in the manual because “experienced personnel can usually make reasonable assessments of density”

(Thomas, et al., 1994). Nevertheless, MDOT (MTU, et al., 1999) used 10-m and 130-m linear crack length per 100-m pavement section as the threshold values for low to moderate and moderate to high crack density. Again, these criteria can be considered as rules of thumb lacking sufficient support of research.

Edge deterioration, like cupping, lipping, or faulting, is not good for crack sealing/filling performance. If the amount and the severity of these deficiencies are too high, patching or milling are more appropriate.

Table 2.8: Guide for Determining Type of Maintenance

Crack density	Average level of edge deterioration (percent of crack length)		
	Low (0 to 25)	Moderate (26 to 50)	High (51 to 100)
Low	Nothing	Crack treatment	Crack repair
Moderate	Crack treatment	Crack treatment	Crack repair
High	Surface treatment	Surface treatment	Rehabilitation

Note: Crack treatment indicates crack sealing and filling; surface treatments indicates chip seal and slurry seal; Crack repair indicates partial-depth patching and spot patching; pavement rehabilitation indicates resurfacing.

2.3 Selection of CS and CF

Though many states highway agencies do not distinguish between crack sealing and filling, in general, there are some differences between them. Therefore, some types of cracking can be treated by crack filling, but others can be better treated by crack sealing, as shown in Table 2.9 (Thomas, et al., 1994). The advantage of using crack filling is that it is less expensive. Crack sealing, on the other hand, requires thorough crack preparation and more expensive materials, but it is generally considered a more long-term treatment. Both crack sealing and crack filling can be performed at the same time in different areas of a given project (Decker, 2014).

However, if existing cracks are both working and non-working, using a material appropriate for the most demanding crack type may be desirable.

Table 2.9: Criteria for Determining whether to Seal or Fill

	Crack sealing	Crack filling
Crack types	Working cracks	Non-working cracks
Routing	YES	NO
Crack width, in.	0.2-0.75	0.2-1.0
Edge deterioration (i.e., spalls, secondary cracks)	Minimal to none (<25% percent of crack length)	Moderate to none (<50% percent of crack length)
Materials	Low-quality thermoplastic sealant materials like crumb rubber (asphalt rubber sealant)	Low-quality thermoplastic sealant materials like Emulsion
Performance	Long term	Short term

Note: The materials used in crack sealing and filling are not always the same in different places, and the width criteria vary in different guides.

3. CS/CF Performance Study

As mentioned above, the criteria for CS/CF project selection mainly rely on highway agencies' experience and rules of thumb. However, to cost-effectively apply CS/CF, the quantitative performance study is very crucial. This section will briefly review the study of CS/CF performance. Additional review can also be found in Chapter 4.

3.1 Methods for CS/CF Performance Assessment

This subsection presents two commonly used methods for assessing CS/CF performance.

- **Composite Pavement Condition Rating**

Pavement life extension resulting from CS/CF is the most commonly used performance measure to quantify the benefit of CS/CF. Depending on how pavement end of service life is defined, different pavement condition ratings/indexes were used in literature, such as PCI (Ponniah, et al., 1996), pavement condition rating (PCR) (Rajagopal, et al., 2011), Pavement Distress Index (PDI) (Shober, 1997), COPACES Rating used by GDOT (GDOT, 2007), or CSI used by the Wisconsin DOT (Fang, 2003). All these indexes are composite ratings that count for various types of distresses. Figure 2.8 illustrates how a pavement condition index is used to evaluate the performance of CS/CF. In comparison with the control section, the

extended service life in test section, ΔT , is used to represent the extension of service life that is considered as the benefit from CS/CF.

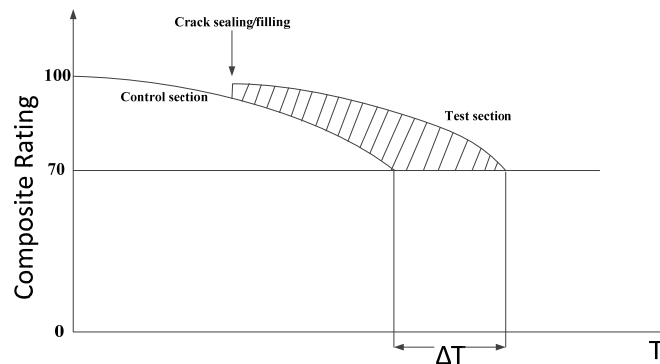


Figure 2.8: Pavement Life Extension of CS/CF

The advantage of using life extension to measure the performance of CS/CF is that it is easy to be understood and incorporated in PMS. However, the use of composite rating cannot exclude the contributions of unrelated distresses, e.g. rutting, which should not be improved by CS/CF, and thus, should not be considered in a performance study. In addition, due to the use of different composite ratings and different definitions of end of service lives, it is difficult to directly compare the CS/CF performance among different highway agencies.

- Individual Crack Performance

Pavement life extension and all the measures used above have not assessed how the sealed cracks develop; instead, they focus on the overall condition of the pavement. This method is valid from the perspective that crack sealing should slow down the deterioration rates of the pavements. However, this is based on the assumption that the intrusion of moisture from unsealed crack leads to the rapid deterioration of pavements. If the deterioration of pavements were caused by other factors, such as poor construction quality, it would be unreasonable to claim that crack sealing failed to prevent the deterioration of pavements if the sealants still functions well to protect pavements from water intrusion. For this reason, the percentage of effectiveness was proposed by a study from FHWA (Yildirim, et al., 2002) to objectively evaluate the crack sealing itself instead of the overall pavement conditions. The treatment effectiveness was defined as a percentage of fully functioning crack sealing after a certain period. Treatment condition is often evaluated by visual inspections and the

percentage is defined based on the identification of several types of crack-sealing failures, full-depth adhesion or cohesion loss, complete pullout, spalls and secondary cracks, and potholes. During a survey, the total length of failed crack sealing is measured and the failure of cracking is evaluated by the rate of failure (e.g., 50 indicate future maintenance should be performed) (Smith, et al., 2001). The calculation of percent failure and percent effectiveness can be found in equations 3-1 and 3-2.

$$\text{Percent Failure} = 100 \times (\text{failed length}/\text{total length}) \quad 3-1$$

$$\text{Percent Effectiveness} = 100 - \text{failure}/\text{total} \quad 3-2$$

Percentage failure and percent effectiveness were used to study the impact of different factors on CS/CF performance or cost effectiveness (Smith, et al., 2001). As shown in Figure 2.9, the treatment effectiveness can also be used to calculate the service life of the crack sealing treatment by specifying a threshold of failure. Johnson (Johnson et al., 2000) and Cuelho (Cuelho, et al., 2004) from Montana, Ponniah from Canada (Ponniah, et al., 1996), Eacker from Michigan (Eacker, et al., 1998), Zinke from Connecticut (Zinke, et al., 2006), Yildirim from Texas (Yildirim, et al., 2006) and many other researchers have used the percentage of failure/percentage effectiveness to study the performance of crack sealing/filling.

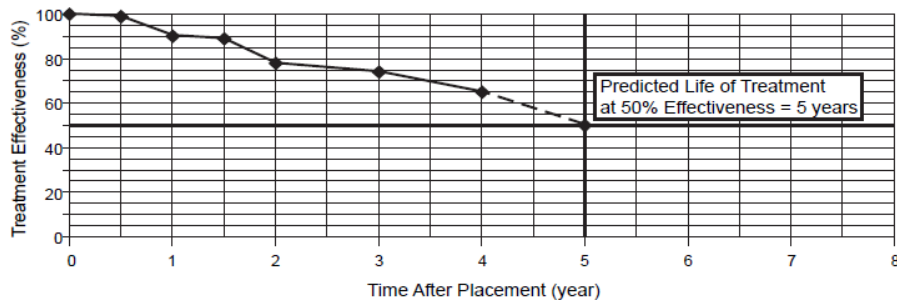


Figure 2.9: CS/CF Service Life Identified by Treatment Effectiveness

There are also some other indexes used to evaluate the individual sealed crack performance, like the coin test (Johnson, et al., 2000) to provide an indication of how the sealant stiffness and resilience change over time. In addition, pavement movement is also monitored by measuring the distance between masonry nails, which are installed at one crack per test section. Because CS/CF is a localized crack treatment, it makes sense to use the individual

sealed crack condition to evaluate its performance. However, there are some limitations if only individual sealed crack conditions are used.

- If the overall pavement condition is poor or bad because of other distresses unrelated to cracks, the pavement has to be treated even if the sealed cracks are still in good conditions. Thus, the lives of the sealed cracks are ended, regardless of their actual sealing conditions.
- CS/CF can reduce water infiltration; it has the benefit of slowing down crack deterioration and decreasing secondary cracks, but the individual sealed crack condition cannot reflect the crack deterioration after crack sealing/filling.

Therefore, the individual sealed crack performance is mostly used in evaluating CS/CF materials; it is not suitable for evaluating the overall performance of CS/CF.

3.2 Cost Effectiveness of CS/CF

The cost-effectiveness of crack sealing has been studied by researchers since the 1980s. Hand (Hand, et al., 2000) reviewed over 100 references after searching several databases on the topic and found that only 18 reports specifically addressed the cost-effectiveness and the bulk of the literature focused on sealing materials and procedures. Chong (Fang, 2003) designed experimental tests to study the CS/CF performance and concluded that rout and seal treatment of cracks did not appear to have significant influence on crack development, since there was no discernible difference in crack development between the sealed test sections and the unsealed control sections. However, crack deterioration (lipping and cupping) data showed that the performance of the rout and seal cracks remained static with time, whereas the cracks in the control sections showed significant increase in lipping/cupping deterioration after three winters.

The Utah DOT has found 75% to 80% of unsealed cracks developed additional distresses compared to only 1% of the sealed cracks (Eaton, et al., 1992) in a project. A recent study by Wang (Wang, et al., 2011) reported results of a survey among 29 state DOTs. It was reported that crack sealing has the lowest service life-extension among the most common preventive pavement treatments, including thin HMA overlay, micro-surfacing, chip seal and slurry seal. For crack sealing, it is shown that the expected life extension ranges from one to eight years, and

the median value is three years. The expected life extension of crack filling ranges from 1 to 10 years, and the median value is 4 years. This study also investigated the LTPP SPS data and found that crack sealing reduces IRI with statistical significance. Compared with a pseudo control section based on pooled data from all SPS control sections, it was found that CS/CF provides an approximate 1.7-year life extension.

Studies from Ponniah and Kennepohl (Ponniah, et al., 1996) aimed at determining the cost-effectiveness of crack sealing through a life-cycle cost analysis. With proper crack preparation (including correct size, equipment, and cleaning) and sealant materials, results from 37 test sites in Canada showed that pavement life could be extended by at least 2 years, depending on the initial condition, environment, and traffic volume. Life-cycle cost analysis showed that crack sealing provides a 48% increase in cost-effectiveness over more elaborate maintenance alternatives.

As the performance of crack sealing/filling is affected by many factors and the threshold of the end of service life and composite rating indexes are all different, the performance of CS/CF varies in different projects. Some examples are shown in Table 2.10.

Table 2.10: Extension of Service Life of CS/CF

Resource	Agency	Service life extension
(Eaton, et al., 1992)	U.S. Army Corps	average of 3 years
(Ponniah, et al., 1996); (Thomas, et al., 1994)		2-5 years
(Wu, et al., 2010)	FHWA based on 11 projects from 4 states: Kansas, Michigan, Minnesota, and Texas	0-4 years
(Bausano, et al., 2004)	Michigan DOT	up to 3 years
(Eltahan, et al., 1999)	The LTPP SPS-3 experiment	average of 2.5 years
(Johanns, et al., 2002)	Nebraska	3-5 years
(OPE, 2001)	Ohio	1-4 yrs

4. Summary

Based on the literature review, experience and rules of thumb are normally used in highway agencies to determine the optimal timing of CS/CF, which is insufficient when they are

incorporated in existing PMS. Thus, there is a need to quantitatively and accurately assess the cost effectiveness of CS/CF. However, the existing study of CS/CF effectiveness was mainly based on the extension of service life. A composite pavement condition rating was used to define a pavement's end of service life. As discussed above, this method cannot exclude the unrelated pavement distresses and lacks the comparability among different highway agencies. In addition, due to the use of visual inspection of pavement surface distresses, the surveyed pavement condition ratings were often subjective and suffered from great variability. The above shortcomings might cause the variable and, sometimes, conflict results in literature. With the advancement of 3D laser technology, it becomes feasible to accurately detect, classify, and measure pavement cracks. This detailed crack characteristic data can then be used to objectively study the performance of CS/CF, which will be presented in Chapter 4.

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Chapter 3 Automatic Crack Sealing/Filling Workload Estimation

When outsourcing of crack sealing is required, a cost estimation for contracting is needed, which can only be based on the total crack length categorized by the associated crack width. Crack filling refers to the placement of material in an uncut crack. Crack sealing, on the other hand, usually refers to routing cracks and placing sealing material on the routed channel. Normally, crack width is an important factor for routing depth. Wider cracks need deeper routing. Table 3.1 shows the criteria used by Hartsfield-Jackson Atlanta International Airport (the Atlanta airport) (from section P-608 – Asphalt Pavement Joint and Crack Seal in Airfield Pavement Repair and Maintenance 2004) to determine routing depth. Table 2.6 also shows the route depth criteria, but they vary from agency to agency, and not consistent with the ones used by Atlanta airport.

Table 3.1: Crack Routing Criteria

Initial Crack Width	Depth for Routing
0 – 4.8 mm (0 – 3/16")	No routing or sealing required
4.8 – 12.7 mm (3/16" – 1/2")	25.4 mm (1")
12.7 mm – 19.1 mm (1/2" – 3/4")	38.1 mm (1-1/2")
19.1 – 25.4 mm (3/4" – 1")	50.8 mm (2")
Greater than 25.4 mm (1")	50.8 mm (2")

Since different routing depths are needed for different cracks of different widths, the accuracy of the workload and the cost estimation will mainly rely on the accuracy of a crack survey. A manual, visual survey of cracks for estimating crack-sealing work is currently used by most highway and airport agencies, e.g. the Atlanta airport, which is the world's busiest airport. However, this process is very time-consuming, subjective, and inaccurate when crack lengths and crack widths need to be manually measured in the field. Based on our discussion with GDOT pavement maintenance engineers, cost estimation is a big hurdle for outsourcing CS/CF projects, which is the reason that GDOT still performs all the major CS/CF work using internal manpower resources.

To address the above challenge, this chapter proposes an automatic approach that uses 3D laser technology and automatic crack detection and crack-width measurement algorithms. The high-accuracy 3D laser device scans pavement surfaces while mounted on a vehicle moving at speeds up to 100 km/hr. Then, crack detection algorithms are used to automatically generate crack maps and measure the crack widths. Based on the crack maps and the associated crack widths, all the cracks can be categorized in terms of their crack sealing treatments and different routing depths. Finally, accurate cost estimation can be made according to the crack length in each category of cracks using different crack sealing methods. Other than the cost estimation, the detected crack maps and the crack classification information can also be used to guide construction contractors and provide a means for agencies' quality checking and making more accurate estimation of CS/CF performance. Without loss of generality, a case study will be conducted on the asphalt pavement runway shoulders at Atlanta airport. In highway agencies, the CS/CF construction specification, e.g. routing configurations, is normally simpler. Nevertheless, the proposed methodology can be easily extended to any type of CS/CF projects when a construction specification is determined.

1. Automatic Crack Detection and Classification

In recent years, 3D laser technology that employs a laser triangulation principle has gained widespread interest from researchers, industry, and highway agencies, and has been successfully used for collecting pavement surface distresses, such as pavement cracking, rutting, and textures. In comparison to 2-dimensional (2D) digital image data, 3D laser data has an intrinsic advantage for pavement crack detection. Figure 3.1 shows an example 2D pavement image (left) and the corresponding 3D laser data (right). A 2D image shows the optical intensity of a pavement surface under natural or artificial lighting conditions. Cracks are often darker than the surrounding area due to the reduced amount of reflecting light. The difference in color is used for crack map detection by employing proper signal processing algorithms. Therefore, the performance of crack detection using 2D images is largely impacted by lighting conditions and color changes on the pavement surface (e.g. oil marks). On the other hand, cracks revealed in 3D laser data are more distinct than the cracks of the surrounding area due to their lower elevations. After rectification, the pixels with lower elevations are shown in the dark color (shown in Figure 3.1(b)). It can be seen that the noise on 3D laser data is much less than the on

2D image, and a crack can be more accurately detected. Our previous study has comprehensively validated that 3D laser data is much more robust in crack detection (Tsai, et al., 2012a).

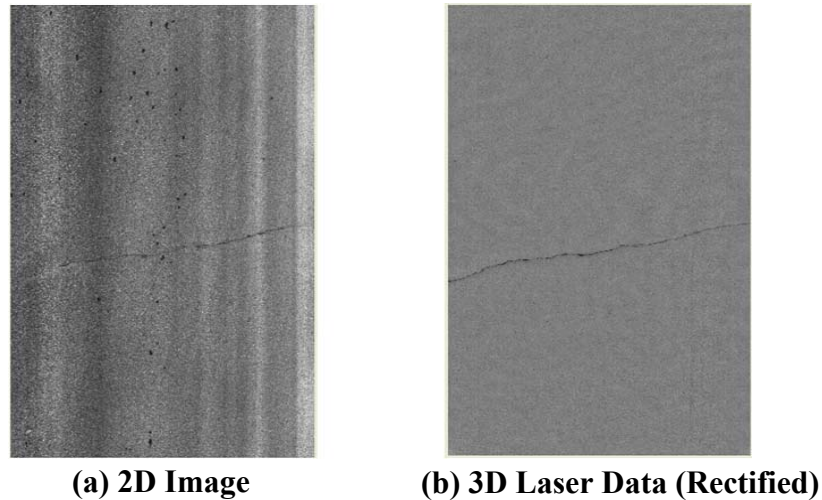


Figure 3.1: Sensing Data for Crack Map Detection.

To extract the fundamental crack characteristics (i.e. crack density, total length, and mean crack width) for different types of cracks, the first step is to detect crack maps. The detection accuracy determines the quality of the final crack characteristics. In the proposed methodology, crack maps are detected using the algorithm developed in our previous study (Kaul, et al., 2012).

After crack maps are detected, the next step is to generate fundamental crack characteristics for different types of cracks. In the proposed methodology, three types of cracks are considered: transverse cracks, non-wheel-path longitudinal crack, and wheel-path longitudinal crack. Tsai, et al. (Tsai, et al., 2012b) proposed a multi-scale crack fundamental element (CFE) model to not only topologically represent crack patterns, but also to provide rich crack properties at three different scales (fundamental crack properties, aggregated crack properties, and CFE cluster geometrical properties) to support the crack condition analysis. Figure 3.2 briefly illustrates the concept of multi-scale crack properties extraction. Fundamental crack properties focus on each crack curve and describe the fundamental and physical properties of cracks; aggregated crack properties focus more on crack patterns inside the clustered CFE and represent how cracks interact with each other, including crack intersection, crack piece, and crack network; clustered CFE geometrical properties treat each CFE as a whole and describe its overall properties. The

required fundamental crack characteristics, such as crack type, length, and width, can be extracted from different levels of CFE.

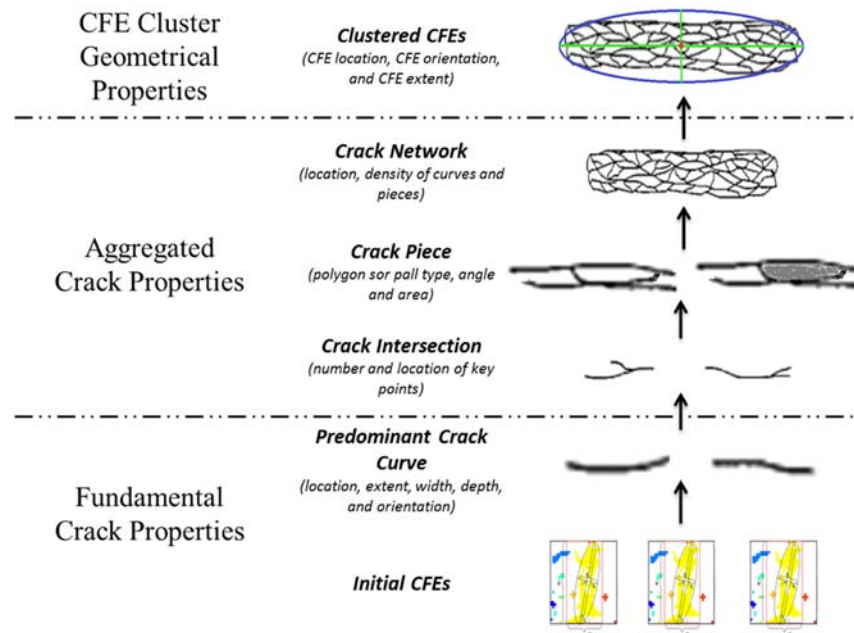


Figure 3.2: Multi-scale crack properties extraction (Tsai, et al., 2012b).

2. Proposed Methodology

Figure 3.3 shows the procedures of the proposed methodology that is applied to automatically estimate crack-sealing costs. Four steps are taken: 1) collect 3D pavement laser data; 2) conduct automatic crack detection and crack width measurement; 3) calculate crack-sealing workload based on crack length and the associated crack width; and 4) estimate crack-sealing costs. The key component is the automatic crack detection and crack width measurement. As long as cracks can be reliably detected and their widths accurately measured, the workload of routing and crack sealing can be determined. Then, the total construction cost can be estimated based on the workload and the unit price.

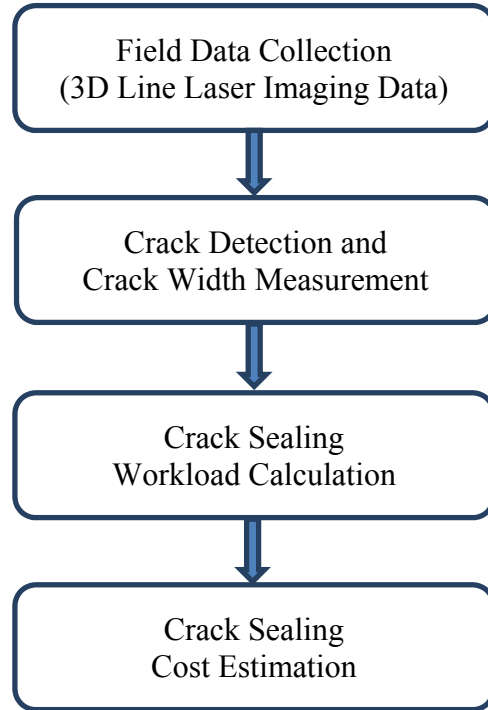


Figure 3.3: Procedures of automatic crack sealing cost estimation.

Instead of using a manual field crack survey, the proposed methodology employs 3D line laser imaging data and image processing algorithms to achieve automatic crack detection and determine crack width measurements.

Crack width is critical information for determining routing depth. After cracks are detected, their widths can be automatically measured and categorized based on different routing criteria. Figure 3.4 shows an example of 3D line laser imaging data with detected cracks and measured widths. Based on the Atlanta airport's criteria (see Table 3.1), cracks are classified into five categories (less than 4.8 mm; 4.8 mm to 12.7 mm; 12.7 mm to 19.1 mm; 19.1 mm to 25.4 mm; and greater than 25.4 mm) using different colors. After all cracks are categorized, the total length in each category can be automatically calculated, which represents the workload for the corresponding routing and crack sealing. Then, the total workload and cost estimation can be made when the unit price for each crack-sealing category is known.

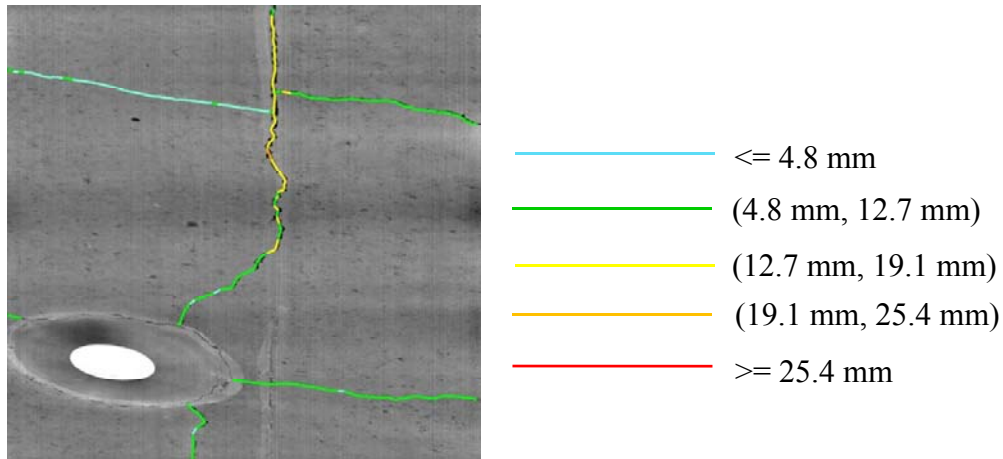


Figure 3.4: Crack width measurements.

3. Experimental Study

To validate the proposed methodology, a preliminary field test was conducted at the Atlanta airport. The Atlanta airport is the world's busiest airport in number of passengers and number of flights. There are five runways. The field test site is located beside the runway 8L-26R, which is mainly used as a landing runway (Boudreau, et al., 2006). As shown in Figure 3.5, the loop surrounded by the red rectangle was chosen as the test site. The total shoulder length is about 950 meters, and the width is about 9 meters.



Figure 3.5: Testing site in Hartsfield-Jackson Atlanta International Airport (courtesy of Google Map).

3.1 Field Data Collection

3D pavement laser data was collected on the shoulder of the selected test site using the Georgia Tech Sensing Vehicle (GTSV) equipped with a 3D laser system, a mobile LiDAR system, and a digital video logging system (shown in Figure 3.6). The GTSV was developed and integrated by our research team at the Georgia Institute of Technology (Tsai et al., 2013). As shown in the rear view of Figure 3.6, two laser sensors are installed on each side of the roof at the back of the GTSV. The Field of View (FOV) of the two sensors covers a full-lane width, i.e. 4 meters. To avoid overlooking transverse cracks in the pavement, both sensors are configured at approximately 15 degrees clockwise to the transverse direction. During data collection, each laser sensor uses a high-powered laser line projector with a customized filter to generate a fine infrared laser line illuminating a strip of the pavement. The corresponding spatial high intensity camera captures the deformed laser line on the pavement. From the captured image, range measurements are extracted. With a two-sensor setup, the 3D line laser produces 4,160 3D data points per profile (2,080 pixels per sensor) covering a 4-m pavement width. Therefore, the resolution in the transverse direction is less than 1 mm. The resolution is 0.5 mm in the depth direction. The highest resolution in the driving direction depends on the vehicle speed. The interval between two 3D transverse profiles can be less than 1 mm at a low speed of 30 km/h. However, the system is typically configured to collect transverse profiles at 5-mm intervals at a speed of 100 km/h. Since a 5-mm interval would make the transverse crack width measurement is inaccurate, the data used in this case study was collected at a low speed (30 km/h) with a 1 mm interval.



Figure 3.6: Georgia Tech Sensing Vehicle (GTSV).

The shoulder of the selected loop is about 9 meters in width, which cannot be covered by the 4-m laser coverage. Thus, three parallel data collection runs were conducted on the loop. Every two runs were overlapped to make sure the entire shoulder width was covered. Figure 3.7 shows an example video log image (left) and the corresponding pavement 3D line laser imaging data (right). It can be seen that cracks can be more easily identified in the 3D line laser imaging data, since they appear as the surface depth changes; the complicated surrounding color change can be removed.

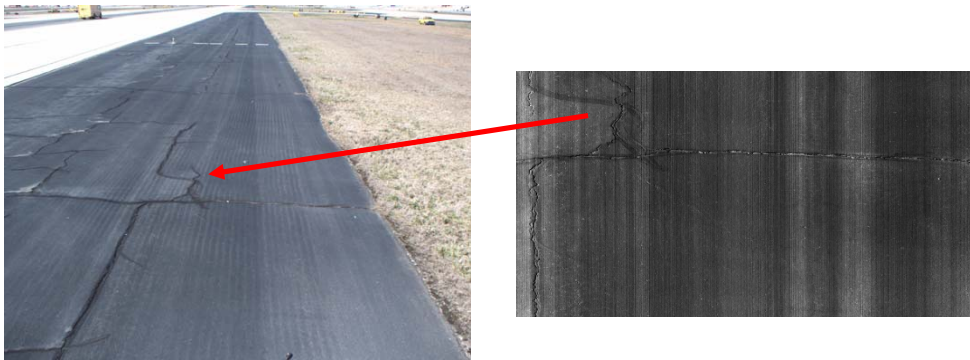


Figure 3.7: Example video log image and 3D line laser imaging data.

3.2 Crack Detection and Width Measurement

In this field test, only the data from a 30.5-m (100-ft) test section was processed with crack detection and width measurement. The width of the selected test section is about 4.0 m (13 ft). Thus, the total area is 120.8 m² (1,300 ft²). In Figure 3.8, the left figure shows the range data of the selected 30.5-m (100-ft) test section. The figure on the right in Figure 3.8 shows the detected cracks. All the detected cracks are categorized using the different colors shown in Figure 3.8; categorization is based on the crack widths, which delineate the corresponding routing depths when crack sealing is performed. For example, red indicates cracks with widths greater than or equal to 25.4 mm (1 inch) and indicates that 50.8-mm (2-in) routing is needed.

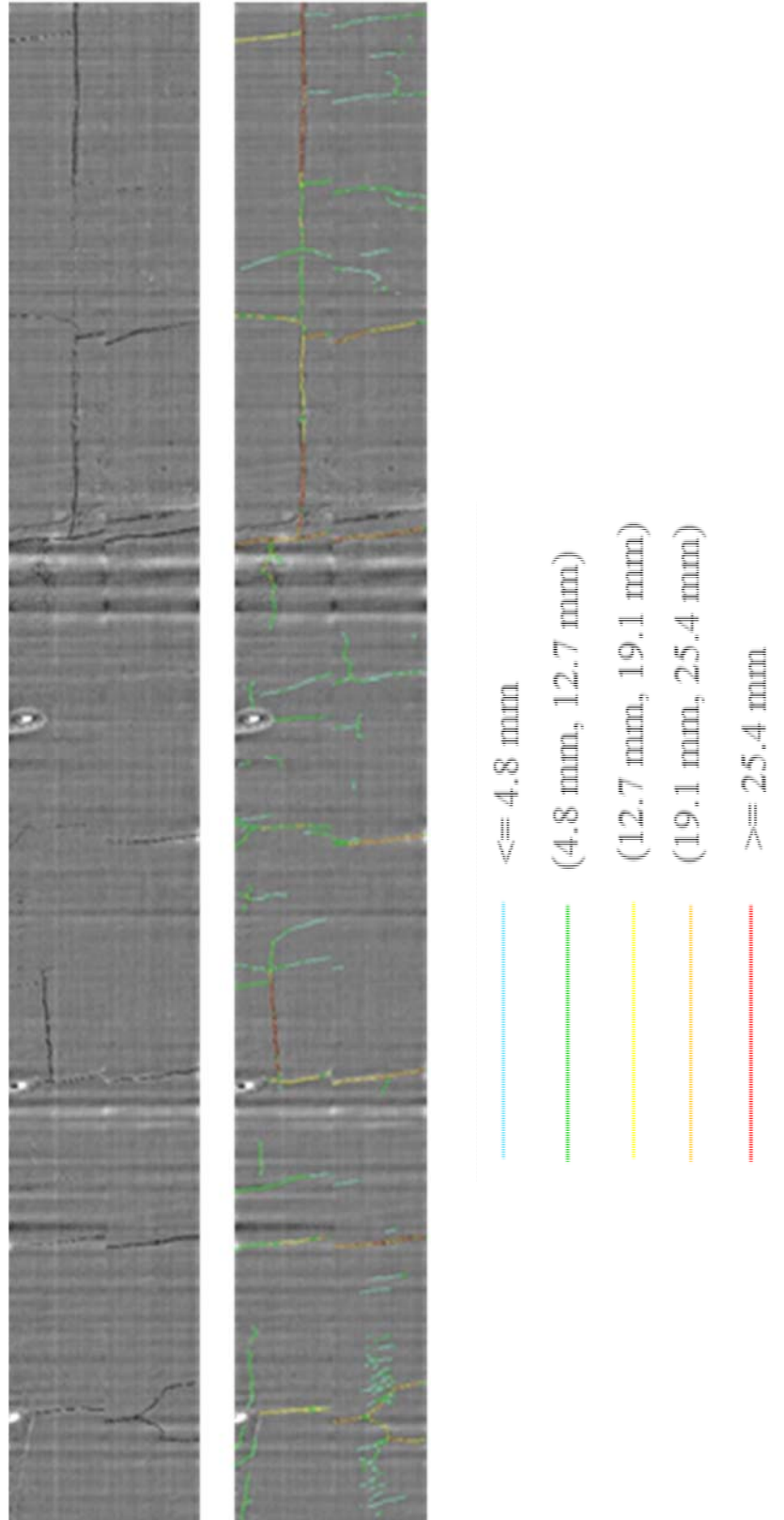


Figure 3.8: Crack detection and width measurement in 100-ft test section.

With the detailed crack maps and the crack width information, the total length of crack sealing in each category can be calculated and used for contracting, pricing, construction, and quality checking. As shown in Table 3.2, in this 30.5-m (100-ft) test section, there are total 97.8-m (321 linear-ft) cracks, among which 31.7-m (104 linear-ft) cracks need no routing or sealing; 32-m (105-ft) cracks need routing of 25.4 mm (1 in) depth; 14.3-m (47-ft) cracks need routing of 38.1 mm (1-1/2 inch) in depth; and 19.8-m (65-ft) cracks need routing of 50.8 mm (2 in) in depth. If the unit price for each category of routing and cracking is known, the total construction cost can be easily calculated.

Table 3.2: Length of Cracks in Each Category of Crack Sealing

Depth for Routing (in.)	Crack Length (m/ft.)
No routing or sealing required	31.7/104
1	32/105
1-1/2	14.3/47
2	19.8/65
Total	97.8/321

The information shown in Figure 3.8 and Table 3.2 could be very useful in the following two aspects:

- The detailed crack length in each crack sealing category can be used to accurately calculate the workload and further estimate the total needed budget. Thus, the shortcoming of tonnage-based and linear-foot-based workload estimation can be overcome. Thus, the cost estimate for crack sealing is improved and the construction quality can be improved.
- The detailed crack maps with different routing categories can be used by contractors to plan and guide the field work of crack sealing. They can also be used by airport engineers to conduct quality checking.

4. Summary

A cost estimation for CS/CF is critical when outsourcing is required and can be calculated based on the crack maps and crack width information. Since different routing depths are needed for

different crack widths, the accuracy of cost estimation will be significantly affected by the crack survey results. A manual survey of cracks for estimating crack sealing work is currently used by most highway and airport agencies, which is very time-consuming, subjective, and inaccurate when crack lengths and crack widths need to be manually measured in the field.

To address the above challenge, this chapter proposed an automatic approach that uses 3D laser technology and automatic crack detection algorithms. The high-accuracy 3D laser device scans pavement surfaces while mounted on a moving vehicle moving at speeds up to 100 km/hr. Then, crack detection algorithms are used to automatically generate crack maps and measure crack widths. Based on the crack maps and the associated crack characteristics (i.e. crack widths), all the cracks can be classified in terms of their crack sealing treatments and different routing depths. Finally, accurate cost estimation can be made according to the crack length in each category of cracks using different crack sealing methods. Besides cost estimation, the detected crack maps and the crack classification information can be used as a guide for construction contractors and can provide a means for agencies' quality checking. The case study, performed on a runway shoulder at Atlanta's airport, shows that the proposed method is very promising for providing an automatic approach that cost-effectively and reliably generates categorized crack maps (used for determining appropriate crack sealing methods) and accurately estimates crack sealing costs.

Due to the use of sensing vehicle for field data collection and automatic computer programs for data processing, it is practical to conduct large-scale, e.g. network level, analysis in considering time and effort needed. For example, the sensing vehicle used in this study can run at 60 mph for field data collection. By using eight GPUs in a parallel computing, one pavement image that cover 5-meter pavement section can be automatically processed to extract all the crack-characteristics-related data in about 8 seconds. Thus, one-mile data can be processed in about 43 minutes, which could be further reduced if larger computer clusters and more computing threads are used. More importantly, a computer can run 24 hours a day, 7 days a week.

Since the crack sealing specification at Atlanta airport is more complicated than the ones used in highway agencies, the proposed methodology can be easily extended to highway pavements.

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Chapter 4 Performance Study using 3D Laser Data

CS/CF performance is the most critical information in applying CS/CF in pavement preventive maintenance, especially when budget is insufficient. Given a certain budget, the most cost-effective treatment and pavement projects should be selected to maximize the return on investment. To achieve this goal, accurate performance of CS/CF needs to be studied. However, the traditionally used service life extension and individual crack performance, as discussed in Chapter 2, have limitations to address the true performance of CS/CF. To solve this problem, this chapter propose a methodology to objectively evaluate effectiveness of CS/CF using emerging 3D laser technology and crack characteristics.

1. Introduction

Based on the survey conducted by Decker (Decker, 2014), organizations of different sizes in the U.S. spent various annual budgets, ranging from \$100,000 to \$10,000,000, on CS/CF.

According to a report in 2003 (Fang, et al., 2003), the Indiana DOT spent approximately \$4,000,000 annually on CS/CF. The Alaska DOT spends more than \$1,000,000 per year (Mullin, et al., 2014). Highway agencies spend significant highway budgets on CS/CF because they think CS/CF should be cost-effective in comparison to other pavement surface treatment methods. However, a survey conducted by Hand, et al. (2000) indicated that 53% of 42 state DOTs made CS/CF decisions based on long-standing policy, or they were unsure of the reason for sealing, which means that many states have not justified the cost-effectiveness of CS/CF. Zimmerman also pointed out that there is very little evidence to identify when and what to treat, although there is a lot experience using preventive maintenance methods (Zimmerman, et al., 2004). Thus, the need of studying the cost-effectiveness of CS/CF is obvious for the following reasons:

- 1) Though CS/CF is considered cost-effective in general, there exists some cases to the contrary. For example, several studies conducted by the Wisconsin DOT revealed that joint sealing on jointed PCC pavements didn't improve pavement performance (Dunn, 1987; Rutkowski, 1990; Shober, 1997). The study conducted by Mullin, et al. (2014) recommended that lessor thermal cracking receive no maintenance except on delaminating

pavements, and the treatment of major transverse thermal cracks can be greatly reduced. Thus, a highway agency needs to justify the cost-effectiveness of CS/CF.

- 2) Due to stringent highway budgets, state DOTs need to prioritize the pavement maintenance and preservation projects. That means, within the given budget, the selected CS/CF projects should yield the maximum return on investment. To achieve this goal, the cost-effectiveness of CS/CF for each candidate project needs to be known. In a broad sense, it requires the integration of pavement management and preventive maintenance in which the effectiveness of CS/CF, and, of course, all other candidate preventive maintenance methods, should be known. Thus, under the framework of a pavement management system (PMS), when, where, and how to treat a pavement can be optimally determined (Zimmerman, et al., 2004).
- 3) The quantitative study of cost-effectiveness of CS/CF is very limited in comparison to the large volumes of publications related to CS/CF materials, designs, and construction techniques. Hand, et al. (2000) searched over 100 potential references and only 4 included useful quantitative data. In the past more than 10 years, have been very few related studies. However, the performance of the materials is not the same thing as the performance of crack sealing/filling. Thus, quantitative study of cost-effectiveness of CS/CF is needed to demonstrate whether crack sealing/filling is beneficial for pavement or cracks.
- 4) In previous studies, a composite rating, e.g. pavement condition index (PCI), pavement distress index (PDI), or pavement serviceability index (PSI) was often used to evaluate the performance of CS/CF and estimate the extension of service life based on the agency-specified threshold for end of service life. However, the composite rating and threshold for end of service life are normally subjectively defined and vary from one agency to another. It is hard to compare the effectiveness of CS/CF among different agencies if different composite ratings are used. Thus, further study is needed by using more objective pavement performance measure, which will also align with the requirements of the Moving Ahead for Progress in the 21st Century Act (MAP 21).

Therefore, a new methodology that can objectively quantify the effectiveness of CS/CF using fundamental crack characteristics, such as crack total length, crack density, and crack width, which are directly related to CS/CF effectiveness is needed. The objective of this chapter is to develop a methodology that can objectively quantify the effectiveness of CS/CF using

fundamental crack characteristics, including crack type, crack length, and crack density, which are directly related to CS/CF effectiveness. The methodology is composed of 1) 3D pavement laser data collection, 2) automatic crack detection, 3) automatic extraction of crack fundamental elements and determination of crack characteristics, and 4) computation of the effectiveness of CS/CF with statistical analysis.

2. Measurement of CS/CF Effectiveness

1.1 Evaluation Measurement

To study the effectiveness of CS/CF, a performance measure needs to be determined first. The commonly used performance measures for pavements can be categorized into three types: structural index, functional index, and composite index (Prozzi, 2001). Cracking, pavement deformation (e.g. rutting), pavement layer moduli, and subgrade resilient modulus can be used as structural indexes. Functional indexes normally represent riding quality and safety. Many indexes can be used, such as the present serviceability rating (PSR), riding comfortable index (RCI), international roughness index (IRI), skid resistance, etc. A composite index combines the structural index and function index, such as PCI, which was developed by the U.S. Army Corps of Engineers.

It should be noted that not all these indexes are suitable for evaluating the effectiveness of CS/CF because CS/CF is neither to increase structural integrity, nor to improve riding quality. Instead, the objectives of CS/CF are 1) to reduce the amount of moisture that infiltrate pavement structure and subgrade, and 2) to prevent the intrusion of incompressible fines from being accumulated in a crack. Since moisture in pavement structure and subgrade could cause stripping and weakening of foundation, it would result in the loss of pavement structural integrity and loading capacity. If a CS/CF is in effect, it should retard the deterioration of pavement structure integrity and loading capacity. Thus, a structural index is a good performance measure to evaluate the effectiveness of CS/CF.

In the past study, pavement cracking condition is normally represented by some form of cracking index that is calculated by deducting it from a maximum score, e.g. 100. Visual inspection is normally used to rate the severity level and extent of each type of crack, which are subjective and

inaccurate, and, more importantly, cannot reveal the detailed crack characteristics of each individual crack, such as crack location, orientation, length, width, etc. Based on a literature review, it was found that the effectiveness of CS/CF varies for different cracks with different characteristics. Thus, a lump sum crack index is not good for studying the effectiveness of CS/CF. With the advancement of sensing technology, pavement cracks can be accurately detected, and their fundamental characteristics can be derived, which provides a unique opportunity for us to investigate the effectiveness of CS/CF. We proposed to use cracking to study the effectiveness of CS/CF because cracking data can be accurately obtained in full coverage using up-to-date 3D laser technology. CS/CF is not beneficial to pavement riding quality; i.e., it will increase pavement roughness and decrease skid resistance. Functional indexes such as IRI and skid resistance can be used for treatment criteria.

1.2 Evaluation Analysis

Labi and Sinha (Labi, et al., 2003) summarized three ways to measure the effectiveness of a maintenance treatment using field monitoring data (deterioration reduction level, performance jump, and deterioration rate reduction) based on the past studies in literature. These three types of measurements are considered as short-term performance measures because only one treatment is evaluated at a time.

- 1) Deterioration reduction level uses two condition measurements before and after maintenance. These two measurements are normally considered as scheduled pavement condition surveys by a highway agency, and they may be 1 year apart. The difference between these two measurements is called the deterioration reduction level if it is used to measure the effectiveness of a maintenance treatment. Apparently, this method could underestimate the effectiveness because, after the first measurement and before the treatment, pavement condition continuously deteriorates, which is not counted in the performance gain. Similarly, after maintenance treatment and before the second measurement, pavement continuously deteriorates, which would underestimate the performance gain after treatment.
- 2) Performance jump uses the pavement condition measurements right before and after a maintenance treatment to calculate the treatment effectiveness. This method is straightforward for those treatments that can improve pavement functions. For example, thin

overly can seal pavement surface cracks and improve pavement smoothness. If IRI or cracking is used as to indicate pavement conditions, a drop in IRI or jump in pavement condition index can be used to measure the treatment effectiveness. However, since CS/CF doesn't increase structural integrity or loading capacity, some highway agencies, e.g. Georgia DOT, don't count its effect in a pavement condition survey. In this case, there is no performance jump after CS/CF that can be observed in a performance curve.

- 3) Deterioration rate reduction measures the effectiveness of a treatment based on the assumption that the treatment will slow down the pavement deterioration with respect to time or cumulative loading. The objective of CS/CF is to prevent the intrusion of moisture and incompressible fines into the cracks, and, therefore, to reduce the moisture and stress induced cracks. A rational assumption can then be made that a CS/CF could slow down the cracking-related pavement deterioration. To measure the deterioration rate reduction, a control section can be used to compare with the test section. The control section and test section should have the same initial pavement conditions and other characteristics, e.g., traffic, location, pavement structure, etc., which is important and yet may be difficult to ensure the similarity, especially for long sections.

Service life extension is another commonly used method for evaluating the effectiveness of CS/CF, which is also widely used in a survey and “estimated” by experienced engineers (Eaton, et al., 1992; Wu, et al., 2010; Wang, et al., 2011). Rajagopal (2011) has adopted a service life extension to evaluate the effectiveness of CS/CF. PCR, a composite rating based on pavement surface distresses, was used to forecast the pavement life with a terminal PCR being 60. The difference of estimated service lives between the test section and control section was the extended service life of the applied CS/CF. One obvious drawback of this method is that the service life is normally monitored by using a composite pavement condition index that includes the impact of all types of pavement distresses. However, CS/CF is a “local” treatment, as pointed by Rajagopal (2011), which may not have influence on other distresses. Thus, the “extended” service life cannot be attributed to CS/CF only. In addition, CS/CF is normally applied when pavement condition is good. To estimate the service life, an extrapolation is needed to forecast the time when pavement condition reaches its terminal point. This estimation needs good knowledge on pavement deterioration and may cause significant errors.

Based on the above discussion, the method of deterioration rate reduction is suggested to assess the CS/CF effectiveness as shown in Figure 4.1. Instead of using a crack index or deduct that is subjective and varies from one agency to another, the measurement of crack characteristics, e.g. crack length, width, density, will be used as performance measures, which will be discussed in the following section. As shown in Figure 4.1, before CS/CF, $t_{CS/CF}$, the deterioration rates (i.e., the increasing rate of crack measurement such as length, width, or density) are the same on both the test section and the control section. After that, the deterioration rate on the control section is s_1 , and it is s_2 on test section. If CS/CF is effective with regard to the selected crack characteristics, s_2 should be less than s_1 . Statistical analysis can be performed to justify whether or not CS/CF is effective with regard to the selected crack characteristics.

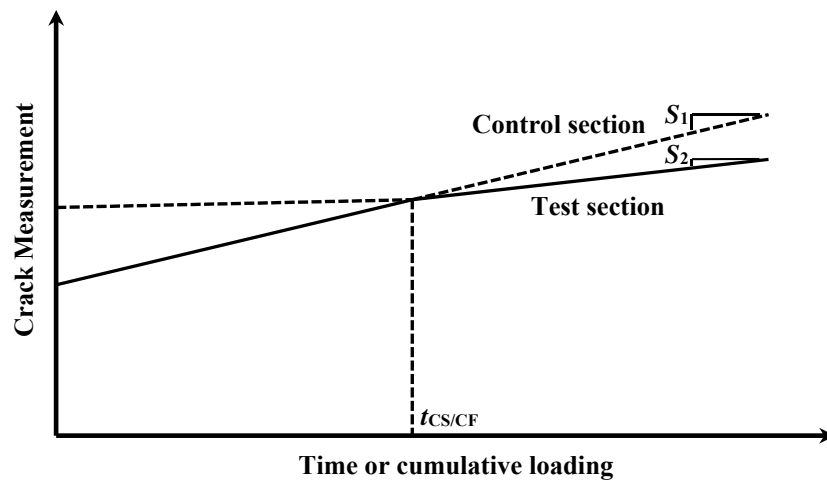


Figure 4.1: Illustration of Deterioration Rate Reduction

3. Crack Characteristics Impacting CS/CF Effectiveness

To study the effectiveness of CS/CF, it is critical to identify the potential crack characteristics that could be impacted. It should be noted that many other factors also impact CS/CF effectiveness, such as pavement type, initial pavement condition, traffic, climate, sealant materials, design, and construction process (Yildirim, et al., 2006; Johnson, et al., 2000). If the effectiveness of CS/CF is considered as a function, the impacted crack characteristics should be the response variable (or dependent variable) and all other factors are predictor (or independent variable). Equation 4-1 illustrates this relationship.

$$(Crack)_i = f(PavType, PavCon_{ini}, Traffic, Climate, Material, Design, Construction ; t) \quad (4-1)$$

In which, $(Crack)_i$ is the i^{th} crack characteristics; $PavType$ is the pavement type, such as full-depth AC pavement and composite AC pavement; $PavCon_{ini}$ is the initial pavement conditions when CS/CF is applied; t is elapsed time counted since CS/CF is applied. The following will identify the potential crack characteristics, $(Crack)_i$, that are response variables based on literature review. The predictor variables are important in experimental design, which will be discussed later.

It is well recognized that CS/CF should be applied when overall pavement condition is good. Though there is lack of quantitative evidence of CS/CF effectiveness, rules of thumb for CS/CF treatment criteria or decision tree were defined in highway agencies (Zimmerman, et al., 2004). Based on an FHWA study (Wu, et al., 2010), the Michigan DOT requires “a minimum remaining service life of ten years, Distress Index < 15, Ride Quality Index < 54 and Rut < 3mm” for flexible pavement; and for composite pavement “Distress Index < 15” is required. The Washington DOT determines timing of crack sealing programs based on the condition index deduction, age of the pavements, and stage of the pavement overall condition (initiation, propagation, acceleration, due, past due, and fail) (Li, et al., 2014). Thus, to study the effectiveness of CS/CF, it is critical to consider the initial pavement conditions as a whole, which is a predictor variable.

Other than the overall pavement conditions, crack characteristics are considered the direct factors that determine if a pavement a good candidate for CS/CF. Based on Decker’s survey (Decker, 2014), approximately 80% of total 157 survey respondents consider the following three crack characteristics are key factors: 1) crack type, 2) crack width, and 3) crack density.

3.1 Crack type

Since CS/CF is a preventive maintenance and considered not effective for correcting structure-related cracks, most highway agencies recommend not performing CS/CF on fatigue cracking (also known as alligator cracking) (Decker, 2014, MTAG, 2009). Alligator cracking typically has wide cracks and high density, and it indicates the structural failure in the pavement system. As aforementioned, though many highway agencies make no distinction between crack sealing

(CS) and crack filling (CF), they do have clear definitions (Smith, et al., 1999). CS is “the placement of specialized treatment materials above or into working cracks.” while CF is “the placement of ordinary treatment materials into non-working cracks...” There are three major differences between CS and CF. First, the material used in CS has higher adhesive and cohesive strength; thus it is more expensive than the materials used in CF. Second, along with CS, crack routing is often needed to cut a crack and make a rectangular cross section. The depth-to-width ratio of the cross section is the so-called shape factor. Many studies have been done to design the best shape factor for CS routing. Third, CS is used on working cracks, while CF is used on non-working cracks. A working crack will open and close with the change of temperature. Normally, it can be identified by the amount of horizontal movement, while different agencies may use different criteria. FHWA defines a working crack as the annual horizontal movement equal to or greater than 3 mm (Smith, et al., 1999). In the California Department of Transportation (Caltrans), it is 6 mm. Because the horizontal movement is caused by the thermal expansion and contraction of AC materials, transverse thermal cracks and transverse reflective cracks are often working cracks and need CS, while longitudinal cracks and distantly spaced block crack are non-working and can be treated using CF (Smith, et al., 1999).

Based on the above discussion, it can be concluded that crack type is an important crack characteristic that impacts the effectiveness of CS/CF. CS/CF effectiveness may be different on different types of cracks. In the proposed methodology, three types of cracks are suggested to be separately analyzed: transverse crack, non-wheel-path longitudinal crack, and wheel-path longitudinal crack. Longitudinal cracks are distinguished by being in the wheel path or not because traffic loading is another factor that could affect CS/CF effectiveness.

3.2 Crack width

Crack width is normally considered in terms of workability and effectiveness. A crack that is too tight makes it difficult for sufficient sealant to enter it; a wide crack indicates structural failure and needs crack repair instead of sealing. Normally, a crack should be wider than 5 mm and narrower than 25 mm to be sealed (Smith, et al., 1999). However, different agencies may have slightly different criteria. One question may be raised: is there any difference on effectiveness of CS/CF when it is applied on cracks with different widths? Though there is no previous study, a

wider crack may indicate worse pavement conditions. Thus, different crack widths might result in different effectiveness of CS/CF.

In the proposed methodology, 3D pavement laser data is used to detect and measure cracks. After the cracks are sealed, their width change cannot be obtained through 3D laser data. However, the initial crack width distribution before CS/CF can be considered as a predictor variable. That means different initial crack width distributions might indicate different effectiveness of CS/CF.

3.3 Crack density/total length

Crack density or total crack length can be used as a response variable to directly measure the effectiveness of CS/CF. Studies have shown that CS/CF can retard the growth of new cracks. For example, Yildirim et al. (2010) reported that the Utah DOT has found that 75 to 80% of unsealed cracks develop additional distresses compared to only 1% of the sealed cracks in a project. One advantage of using crack density or total crack length as response variable is that the measure, combined with crack type and/or crack width, can be easily converted to an agency-specified cracking index. Therefore, the extension of service life, which depends on an agency's policy, can be further evaluated.

Though crack density and total length are equivalent to some extent, they do have some difference. Crack total length can be used to measure crack extent in a larger area, e.g., every 100 ft. (30.5 m); crack density can be used to measure the localized crack characteristics. A large number of cracks in a small area indicate a severely deteriorated pavement where CS/CF is uneconomical because it cannot or is hard to slow down the pavement deterioration rate. Another consideration is that sealing or filling dense cracks would cover a significant area of pavement surface and decrease skid resistance. Some highway agencies don't do CS/CF if it covers more than 25% of surface area (Decker, 2014). Though FHWA defined three severity levels for crack density, low, moderate, and high (Smith, et al., 1999), it gave no clear definition and calculation, and asked engineers to judge it. The Michigan DOT defines crack density based on the linear crack length per 100 m pavement section: < 10 m (Low), 10 m to 135 m (Moderate), and > 135 m (High) (Reay, et al., 1999). In the proposed methodology, crack density is defined as *CS/CF patched density* to consider the reduction of skid resistance, which

will be calculated every 5 m in 3 regions (left and right wheel paths and the area between two wheel paths); the total crack length is calculated every 100 ft. (30.5 m). As shown in Figure 4.2, CS/CF patched density, D_c , is calculated every 5 m for each three 3 regions as the area ratio between the sealed area and the total area. The sealed area can be estimated by the total crack length multiplied by the average sealed width, e.g. 2 inches plus crack width. Equation 4-2 shows the calculation.

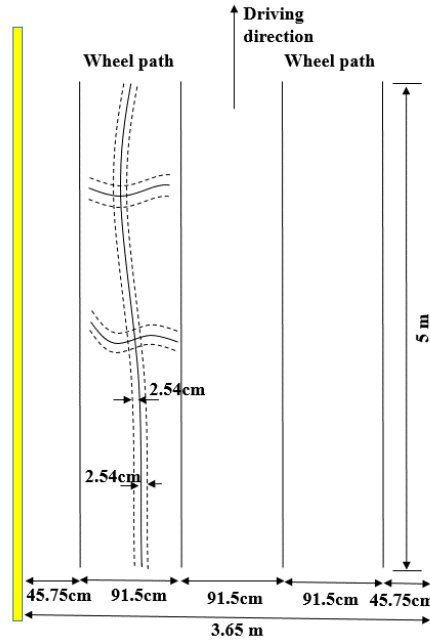


Figure 4.2: Calculation of CS/CF Patched Density

$$D_c = \left(\sum_i l_i \cdot (\bar{C}_{wi} + S_w) \right) / Area \quad (4-2)$$

In which l_i is the i^{th} crack length and \bar{C}_{wi} is the average crack width of the i^{th} crack; S_w is the sealing width, which is dependent on the construction process, i.e. flush fill or overbanding, and design configuration (Decker, 2014); and $Area$ is the total area in one of three regions. Unlike the total crack length, CS/CF patched density, D_c , is defined as the ratio of total crack sealing area to a pre-defined reference area. It can be used to consider the safety issue that is caused by the reduction of skid resistance. If it is greater than a threshold, CS/CF is considered infeasible, and thus, ineffective. In this sense, CS/CF patched density can be considered as a supplement to total crack length in studying CS/CF effectiveness.

In summary, three major categories of crack characteristics, crack type, crack width, and CS/CF patched density determine the applicability of CS/CF based on the past research and highway agencies' practices. On the other hand, these crack characteristics would be affected by CS/CF and can be used to evaluate its effectiveness. In Equation 4-1, the crack-related response variables can be defined as the total crack length and CS/CF patched density. The increase of total crack length and CS/CF patched density will reflect how CS/CF is effective in retarding the generation of new cracks. The effectiveness of CS/CF on three types of cracks need to be studies, i.e. transverse crack, non-wheel-path longitudinal crack, and wheel-path longitudinal crack. To study the optimal timing of CS/CF application, different experimental tests should be conducted with different initial pavement conditions, such as different overall pavement conditions, different mean crack widths, and different crack densities. Unlike the commonly used crack index or deduct values that are subjectively defined by various highway agencies and/or researchers, the above performance measures are fundamental crack characteristics and can be objectively and accurately measured using the emerging 3D pavement laser data and computer vision algorithms. Thus, the measured effectiveness can be compared among different agencies. In addition, the fundamental crack characteristics are ready to be converted to any agency-specified crack index. So, the traditional extension of service life of CS/CF can be analyzed given the threshold of end of service life.

4. Methodology to objectively assess CS/CF effectiveness

In the past, the study of CS/CF effectiveness usually employed pavement condition index, e.g. PCI, to track its change over time. Based on the gain of the selected pavement condition index (performance jump or deterioration rate reduction) or the extended service life (in this case, a terminal value needs to be defined), the CS/CF effectiveness is measured. This type of performance measure made an assumption that the selected pavement condition index is the sole response variable and it is the direct consequence of CS/CF. This assumption might not be true. As aforementioned, a PCI is normally a composite rating considering all the major types of pavement distresses, including cracking, rutting, raveling, roughness, etc. The definition and calculation of this composite rating is also subjective. On the other hand, the objective of CS/CF is to prevent or reduce the intrusion of moisture and incompressible fines into cracks and, thus, to assist to retard the deterioration of pavement structural integrity and loading capacity.

Apparently, CS/CF is not beneficial to ride quality since it would increase surface roughness and decrease skid resistance. Thus, it is irrational to include riding quality in the response variable to measure the effectiveness of CS/CF. The most direct way is to measure the response of crack characteristics, i.e. total crack length and CS/CF patched density, as proposed in the above section. It should be noted that data is more detailed often results in more sensitivity to the variation of subgrade, pavement structure, construction quality, etc. For example, two adjacent cracks of the same type might deteriorate differently, which could be considered as normal variation if the difference is small. However, if the difference is very significant, further investigation, e.g. coring, is also needed to reveal the cause. The uncommon crack deterioration should be excluded from the performance study.

The direct measurement of crack characteristics needs an accurate crack map and measurement of crack width. This has been difficult to achieve in the past, and almost all studies employed visual inspection and an agency-specified distress identification protocol (Hand, et al., 2000). With the advance of data acquisition technology, like emerging 3D laser technology, and crack detection method, it has become feasible to extract detailed, accurate crack characteristics data, including crack length, width, density, etc. Thus, the objective of this chapter is to develop a methodology that can objectively quantify the effectiveness of CS/CF using the fundamental crack characteristics that are detected and measured using 3D laser data.

The following subsections will briefly introduced the authors' previous work in automatic detection of pavement cracks and a crack fundamental element model. After that, a complete methodology using 3D pavement laser data and automatic crack detection will be proposed to study the effectiveness of CS/CF.

Proposed Methodology for Studying Effectiveness of CS/CF

To study the effectiveness of CS/CF, a comprehensive experimental test is needed. The first thing is to determine the predictor variables. As shown in Equation 4-1, the predictor variables for effectiveness of CS/CF include pavement type (full-depth AC pavements and composite pavements, including different AC mix types), initial pavement condition when CS/CF is applied, traffic, climate, sealant materials, cross profile design, and construction process.

Though lots of past research has been done to study the sealant materials, cross profile design,

and construction process, each highway agency often has its prevailing specifications. Thus, there is no need to change these variables. If climate changes dramatically in an area (e.g. California or other states with elongated geography), different test sites should be selected in areas where climates are different. Otherwise, this variable can be considered as a constant in an agency. Traffic is an important variable that affects the effectiveness of CS/CF, especially when it is applied on the cracks in wheel paths. Thus, test sites should be selected in different categories of traffic conditions. Initial pavement conditions determine the timing of CS/CF applications. To compare the effectiveness of different projects and seek the optimal timing of CS/CF application, different test sections with different pavement conditions should be selected. Another way is to select test sections with the similar conditions. However, CS/CF applied on these sections at different times (Rajagopal, 2011) can also be used to directly assess the different of effectiveness due to treatment delay. Finally, pavement types and AC mixes should be considered when select experimental test sites. In each test site, several test sections should be laid out, each of which can be 100 ft. (30.5 m) long. Also, at least one control section, where no treatment is applied and initial pavement conditions are the same, should be selected.

After test sites are selected and test sections are laid out, the study of CS/CF effectiveness can be carried out as follows:

- 1) **Step 1: Collect 3D pavement laser data.** The first data collection should be conducted right before CS/CF. If some other sections are selected for delayed treatment, 3D laser data should also be collected on these test sections, as well as on the control section. After CS/CF, 3D laser data should be collected at least once a year. Because a thermal crack opens and closes with changes of temperature, it is recommended that data be collected at the same time each year. To obtain the full trend of performance change, it is recommended that data be collected at least for the following 5 years.
- 2) **Step 2: Conduct automatic crack detection.** After 3D laser data is collected, automatic crack detection will be performed using the method introduced in the previous sub-section. To trace the change of the selected fundamental crack characteristics, the detected crack maps should be aligned/registered over time.
- 3) **Step 3: Generate crack fundamental elements and calculate selected crack**

characteristics. Following the concept of CFE, the fundamental crack characteristics will be calculated. To study the effectiveness of CS/CF, the following crack characteristics will be generated: crack types (transverse cracks, non-wheel-path longitudinal crack, and wheel-path longitudinal crack), total crack length of each type of crack, and CS/CF patched density.

- 4) **Step 4: Analyze effectiveness of CS/CF on selected crack characteristics.** When the selected crack characteristics are calculated at each time when 3D pavement laser data is collected, a performance curve can be drawn. After that, the effectiveness based on the deterioration rate reduction can be evaluated by comparing the deterioration rates between the test section and the control section (shown in Figure 4.1).

5. Case study

In this section, a case study, using 3D pavement data collected on State Route 26 / U.S. 80 near Savannah, Georgia, is presented to evaluate the feasibility of the proposed methodology for studying the effectiveness of CF/CS using fundamental crack characteristics. Though no CS/CF was actually applied on the selected test road, the purpose of the case study is to evaluate if the proposed methodology can be applied to extract fundamental crack characteristics over time and to analyze the deterioration rate. Next, we will work with Georgia DOT to select test sites and conduct field experimental tests.

Figure 4.3 shows the selected test road for this case study, which is between milepost 5.5 and milepost 11.5. According to the 2013 traffic data in the Georgia DOT, the annual average daily traffic (AADT) is about 24,020, and the truck percentage is about 12%. This road was resurfaced in 2004, but constant deterioration has been observed since then. To monitor the pavement condition change, we have continuously collected 3D pavement data since December, 2011. The dates for all data collection are December 6, 2011; March 21, 2012; July 13, 2012; March 20, 2013; December 7, 2013; July 18, 2014; and June 15, 2015.

Following the proposed methodology, the following presents the change of fundamental crack characteristics for each type of crack over time. The deteriorate rate is also analyzed.

5.1 Total Crack Length

Total crack length is a direct measure of crack extent. Its change over time can be used to measure the deterioration of pavement condition. Similarly, it can also be used to quantify the effectiveness of CS/CF in comparison to the control section. As mentioned previously, the effectiveness of CS/CF might be different on different types of cracks. It is proposed three types of cracks, transverse crack, non-wheel-path longitudinal crack, and wheel-path longitudinal crack, be considered.

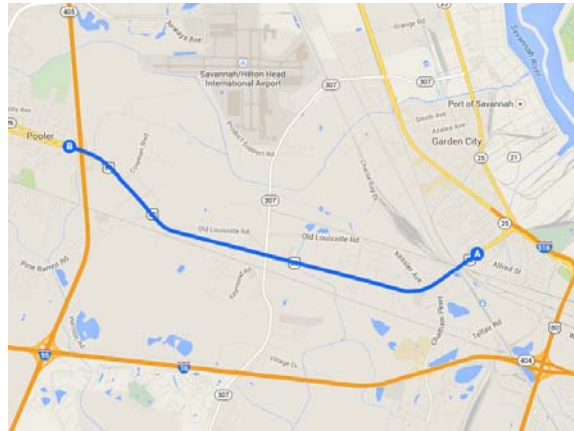


Figure 4.3: Test Road on State Route 26 in Georgia

Without loss of generality, a 100 ft. (30.5 m) test section was chosen starting from milepost 8. Figure 4.4 shows the change of total crack length over time for three types of cracks. Please note that the data collected on July 13, 2012, and July 18, 2014, was excluded after data quality checking because it was found that vehicle wandering during data collection made some cracks close to the edge marking to be missed, which would underestimate the total crack length. Thus, it is very important to keep a vehicle running in the middle of a lane when data is being collected. As shown in Figure 4.4, the total length of each type of crack increased over time. In the selected test section, wheel path longitudinal cracks and transverse cracks are much more severe than non-wheel-path longitudinal cracks. However, all of them show a good trend of linear growth. Table 4.1 lists the R^2 of each linear regression and the annual average growth rate of total crack length, i.e. deterioration rate, s_1 , as shown in Figure 4.1. However, in this case, the increasing trend indicates pavement condition deterioration. It can be that different types of cracks experiences different regression rates. Transverse cracks have the largest growth rate,

16.0 m/year; wheel-path longitudinal cracks have only 2.3 m/year of growth rate. If a test section with CS/CF can be compared, the difference in the total crack length growth rate can be used to quantify the effectiveness of CS/CF, i.e. $\Delta s = s_2 - s_1$. If $\Delta s < 0$, it indicates CS/CF is effective and retards the growth of total crack length.

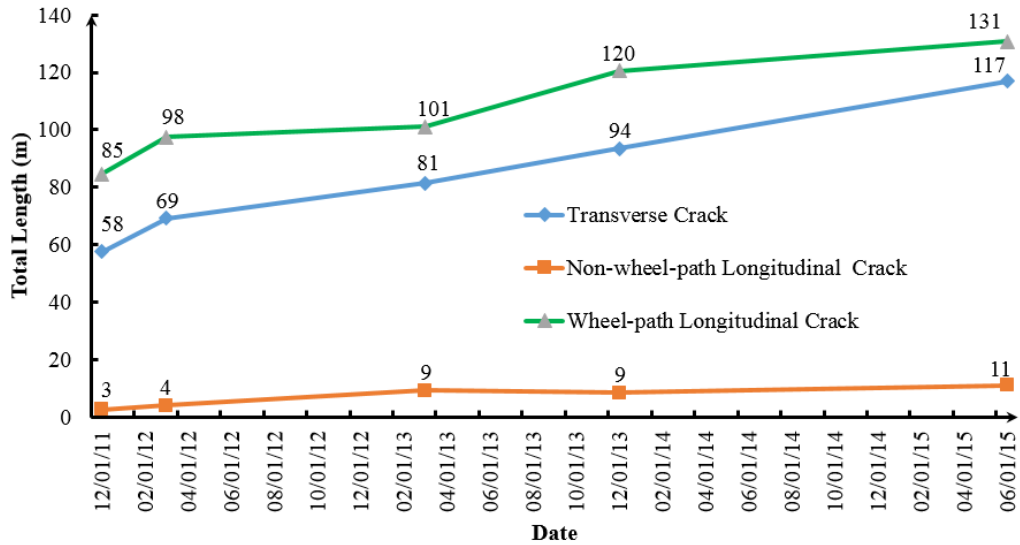


Figure 4.4: Change of Total Crack Length Over Time

Table 4.1: Deterioration Rate in Terms of Total Crack Length

Crack Type	R^2 of Linear Regression	Deterioration Rate, s_1 (m/year)
Transverse	0.99	16.0
Non-wheel-path Longitudinal	0.83	2.3
Wheel-path Longitudinal	0.92	12.5

5.2 CS/CF Patched Density

As discussed above, though CS/CF patched density and total length are equivalent to some extent, they do have some difference. Crack total length can be used to directly measure crack extent in a larger area, e.g., every 100 ft. (30.5 m); CS/CF patched density can also be used to measure the localized crack characteristics and determine if CS/CF is feasible in terms of skid resistance. High-density cracks in a wheel path normally indicate the occurrence of more severe cracking, such as alligator cracking, which can be used as a crack classification feature. Since CS/CF patched density is defined as the percent of total sealed area, the correlation between

CS/CF patched density and crack type (e.g. alligator cracking) is also related to how crack is sealed in practice. In addition, higher density means more use of sealing materials, which could potentially raise safety issues due to the decrease of skid resistance. Thus, CS/CF patched density can be used to determine if CS/CF is feasible, i.e. effective, in considering driving safety.

In the proposed methodology, CS/CF patched density, D_c , is calculated as the ratio between the sealed area and the area of each of three regions, i.e. left wheel path, middle of lane, and right wheel path, every 5-m pavement section. Equation 4-2 is used for calculating CS/CF patched density. To demonstrate the feasibility of the proposed methodology, a 5-m pavement section was selected. Based on the 3D pavement data collected at different times, they are aligned/registered after cracks are detected. Figure 4.5 shows the detected crack maps of the selected pavement section at different times. It can be clearly seen that fatigue cracking in the left and right wheel paths grew over time. In the right wheel path, the initial cracking on December 6, 2011, forms some polygons, which indicates the early stage of alligator cracking. Over time, the size of polygons became smaller, and the severity of cracking increased. In the left wheel path, the initial condition was better than the one in the right wheel path. There was only one longitudinal crack with some short branches. On March 20, 2013, small polygons became apparent. The latest data (on June 15, 2015) clearly showed alligator cracking in the left wheel path.

Figure 4.6 shows the change of CS/CF patched density in three regions over time. Similar to the observation on crack maps, the CS/CF patched density in the right wheel path is greater than the ones in other two regions. Initially, the density in the right wheel path is almost twice the one in the left wheel path, 15.9% vs. 8.1%. Over the time, cracks in the left wheel path grew faster than the ones in the right wheel path. The latest data showed that the density in the right wheel path is 1.4 times of the one in the left wheel path. As observed in Figure 4.5, cracks in the middle of the lane are not significant. The density increased also very slowly. Table 4.2 summarizes the results of regression and the deterioration rates. It can be seen that linear regression might not be good to fit in with the change of CS/CF patched density. The R^2 for middle of lane is only 0.59. After 2nd order polynomial regression is used, the goodness of fit improves greatly. In Table 4.2, the deterioration rate is represented by percentage per year, which is estimated by using linear regression. It further confirms that cracks in the left wheel path grew faster than the ones in the

other two regions.

Table 4.2: Deterioration Rate in Terms of Total Crack Length

Region	R^2 of Linear Regression	R^2 of 2 nd Order Polynomial Regression	Deterioration Rate, s_1 (%/year)
Right Wheel Path	0.83	0.98	1.2
Middle of Lane	0.59	0.86	0.6
Left Wheel Path	0.89	0.94	1.8

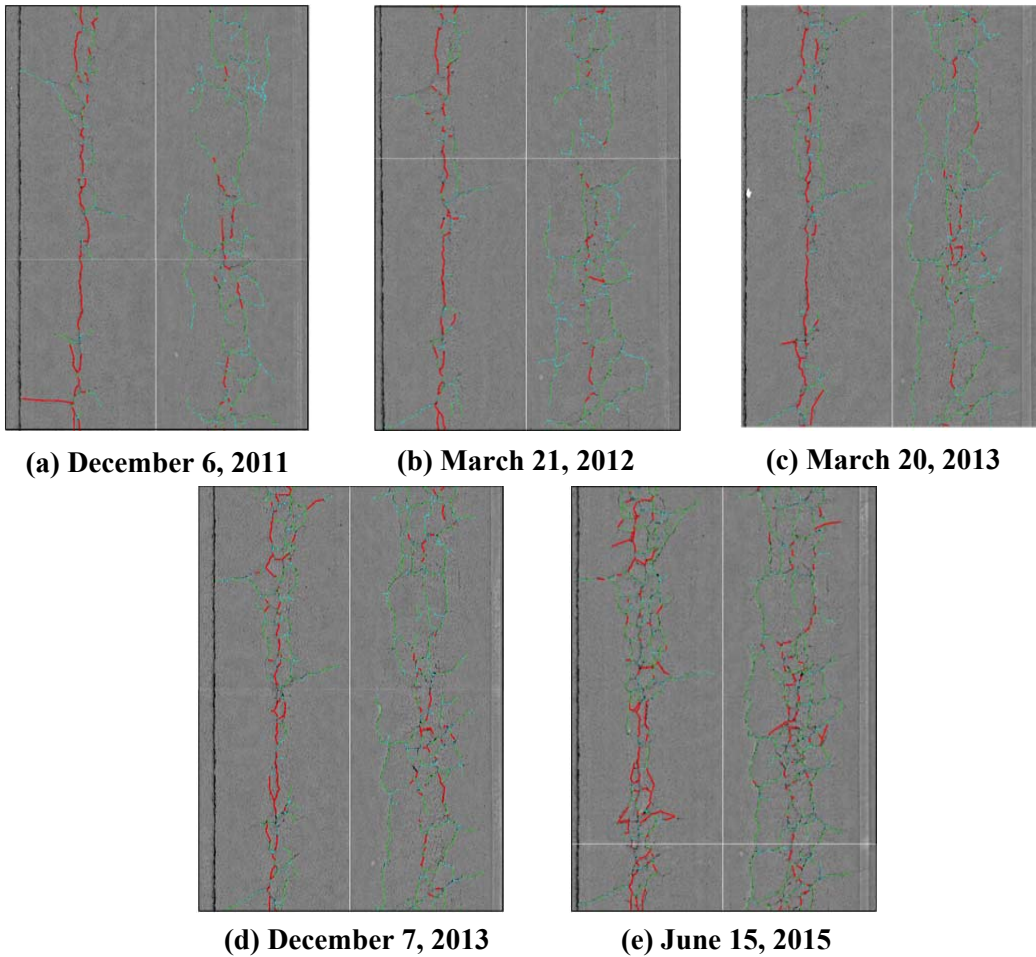


Figure 4.5: Crack Maps of 5-m Pavement Section

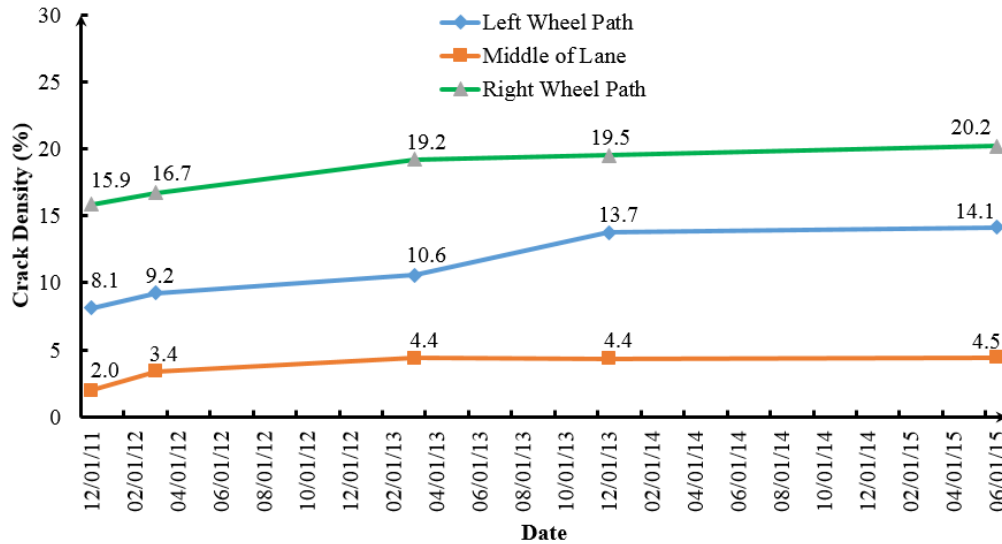


Figure 4.6: Change of CS/CF Patched Density Over Time

5.3 Crack Width

Like total crack length and CS/CF patched density, crack width is also one measure of pavement conditions. Wider cracks mean worse conditions. However, after cracks are sealed, it is difficult to measure their widths over time though a sealed crack can still be detected using 3D laser data (note: intensity images can be used to detect sealed cracks). Thus, in the proposed methodology, crack width is considered as a predictor variable and included in the initial pavement conditions (see Equation 4-1). In addition, the initial total crack length and CS/CF patched density are also predictor variables representing the initial pavement conditions.

Figure 4.7 shows the initial crack width distribution in the 100-ft test section that was also used to analyze the total crack length as discussed above. Apparently, the crack width distribution is right-skewed. Different statistics can be employed to represent the overall crack width, such as length-weighted mean, median, 75th percentile, and 85th percentile, which are 8 mm, 6.5 mm, 10 mm, and 14 mm, respectively.

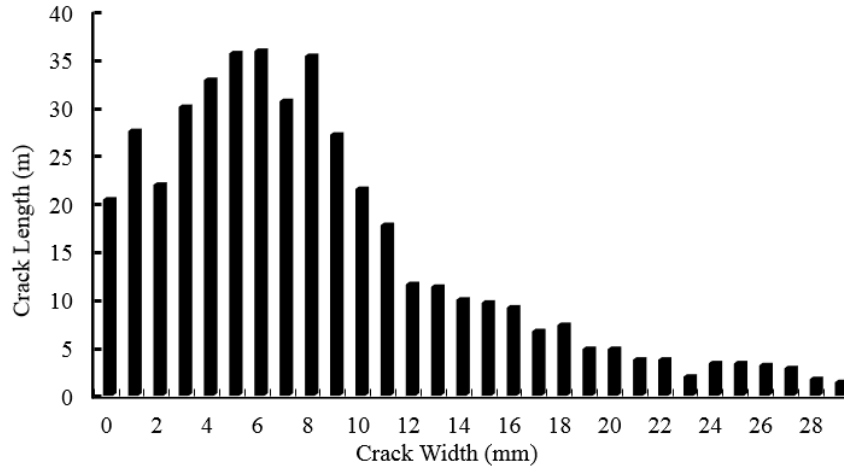


Figure 4.7: Initial Crack Width Distribution on December 6, 2011

6. Summary

It has become a consensus among highway agencies and researchers that pavement preservation is a viable, cost-effective strategy to proactively maintain highway pavements. Though highway agencies have been using preventive maintenance treatments for a long time, the study of their effectiveness is still very limited, which makes it difficult to determine when, where, and how to treat a pavement, and also makes it difficult to integrate pavement preservation into a PMS. The current proliferation of preventive maintenance techniques make this situation even worse, as it is hard for a highway agency to adopt a new method without knowing its cost-effectiveness.

As one of the most common preventive maintenance treatments, CS/CF has been widely used in different highway agencies. However, the study of its cost-effectiveness is still very limited. Traditionally, a composite pavement condition measure is used to quantify the effectiveness of CS/CF, which contains both relative and irrelative pavement condition measures and is normally subjectively defined. Thus, there is an urgent need to objectively quantify the effectiveness of CS/CF, which is comparable among different agencies. For this purpose, this chapter proposed an objective method to accurately evaluate the effectiveness of CS/CF. To eliminate the subjectivity of the definition of a crack index that is often used in a visual pavement distress identification protocol, this chapter recommends using the measures of fundamental crack characteristics, such as total crack length, CS/CF patched density, and crack width of the initial cracks. Also, because different type of cracks at different locations might have different benefits

from a CS/CF, the effectiveness relative to different types of cracks at different locations are also analyzed. To obtain the detailed, fundamental crack characteristics, the emerging 3D pavement laser technology, automatic crack detection, and the CFE model were employed in the proposed methodology. Gathering this information has been very hard or, even, infeasible in the past because the visual inspection method was inadequate.

The case study, using real-world 3D pavement data collected on the State Route 26 near Savannah, Georgia, at different times, validated the feasibility of using 3D pavement data and the proposed methodology to objectively evaluate the effectiveness of CS/CF. The advantages of the proposed methods are as follows:

- 1) The selected response variables in the experimental tests are objective, direct measurements of fundamental crack characteristics without the involvement of traditionally used, subjective crack indexes and/or composite pavement condition indexes. The benefits are twofold. First, the research results found in different agencies or areas are more comparable due to the use of same response variables; second, the results can be easily converted to agency-specified crack indexes or composite pavement condition indexes, which is especially useful if the extension of service life needs to be estimated.
- 2) The proposed method divided cracks into different types and locations. The study of CS/CF effectiveness for each type of crack at a location can help reveal the fundamental characteristics of CS/CF when it is applied to different cracks. For example, it can help answer the following questions: a) is CS/CF effective on transverse crack and longitudinal crack? b) does traffic affect the effectiveness of CS/CF? c) can CS/CF prevent the generation of new cracks? d) can CS/CF retard the deterioration of sealed crack? e) can CS/CF prevent the generation of secondary cracks?
- 3) After the effectiveness of CS/CF for each type of crack at different locations is obtained, the overall effectiveness using a crack index or composite pavement condition index can be more accurately predicted by combining the effectiveness of all types of cracks. Then, a life cycle cost analysis (LCCA) can be performed to obtain the cost-effectiveness, which can be used in treatment selection and network-level project selection. Moreover, it makes it possible to integrate CS/CF into a PMS.

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Chapter 5 Crack Sealing/Filling Project Segmentation

The ultimate goal for pavement preservation is to select the right treatment on the right pavement at the right time. If CS/CF is to be applied at the network level, the goal becomes selecting the right pavements, constrained by given budgets, to achieve the highest return on investment. For this purpose, the pavement network needs to be segmented into individual pavement sections. Thus, CS/CF can be applied to those pavement sections that can achieve the highest return. In each pavement section, CS/CF should perform uniformly. In other words, the crack characteristics directly related to CS/CF effectiveness should be statistically similar. Chapter 4 discussed the CS/CF-effectiveness-related crack characteristics. After a pavement network is segmented, the CS/CF effectiveness can be determined for each pavement section. In the meantime, the workload and cost can be estimated using the methodology proposed in Chapter 3. Combining CS/CF effectiveness and cost, we can further incorporate CS/CF planning into an optimization model or a simple prioritization framework to determine the optimal CS/CF projects within a given budget. In this chapter, a systematic segmentation method will be proposed to divide a pavement network into pavement sections with statistically similar crack characteristics that are directly related to CS/CF effectiveness.

1. Pavement Segmentation Methods

Previous studies have proposed a variety of methods to solve segmentation problems. The majority of existing methods handle the segmentation problem as a one-dimensional clustering problem. The existing one-dimensional clustering methods that have been developed in the context of pavement condition assessment are presented below.

The first and most popular method is the cumulative difference approach (CDA) specified in AASHTO (1993). It detects the points where the sign of the slope of the cumulative difference between the input data and the mean value changes. Based on this concept, CDA can always separate the input data into at least two homogeneous segments unless the measurements in the input data are all identical to each other (Misra & Das, 2003). Since in the closely-spaced pavement condition data (e.g. rut depth measurements at 5 mm intervals) adjacent values are essentially always different, CDA is not suited to deal with this jagged data, and it will produce

some segments with very close average measurement, as well as too short segments (Thomas, 2005; Gaoqiang Zhang, 2013). Accordingly, Divinsky et al. (1997) preprocessed the input data by applying a moving average before performing CDA. However, the moving average smooths out minor changes and blurs significant, big changes. Instead of smoothing out the input data, Ping et al. (1999) proposed a variation of CDA by adding exogenous restrictions, e.g., the minimal length of a homogeneous segment and the minimal difference between means of adjacent homogeneous segments; however, the choice of the values of these parameters obviously affects the outcome of the road sectioning process by introducing an element of subjectivity whose effects are not always easily evaluated in advance (D'Apuzzo, 2012). In addition, it can only be used for single-parameter analysis (Hongduo Zhao, 2011). Tejada et al. (2008) proposed a data segmentation procedure and employed the accumulated sum (CUSUM) method, a generalized version of CDA, for segmenting the skid resistance data.

The French Laboratory of Roads and Bridges developed the LCPC method (Thomas, 2004). It uses a dichotomist technique to recursively identify partition points where the mean changes. The LCPC Method has the advantage of being implemented in an automatic computational procedure in which the only arbitrary parameter is the probability of false rejection. On the other hand, it requires collected data be equally spaced with no systematic variations (trends), or mutual correlations. A method with a similar concept is the absolute differences in sliding mean values method (ADS) (Thomas, 2004). The only difference is that ADS locates partition points sequentially from the start to the end of the input data. Instead of setting a constraint on the change of mean values, El Gendy et al. (2008) applied the absolute difference approach (ADA) and C-chart method to resolve the segmentation problem. Both approaches limit the variation of data within a homogeneous segment. The methods either set a maximum range of response or upper and lower control limits based on the estimated standard deviation (El Gendy et al., 2008).

Misra and Das (2003) proposed the classification and regression tree (CART) plus an exhaustive search method. This method first builds a classification and regression tree by recursively dividing the parent segment into two child segments and minimizing the sum of the squared differences within each segment until reaching a predefined limit, e.g., the minimum length of a homogeneous segment. Then it searches the tree exhaustively and selects the best sub-tree with the specified number of segments and the minimum sum of the squared differences.

Thomas (2003) proposed an AMOC algorithm (the at-most-one-change assumption), which is based on the Bayesian concept. Because the AMOC algorithm is based on the statistical model, the data series should be close with the assumptions made in the statistical model; Box-Cox transformations of the measurement series are discussed prior to their formal analysis (Thomas, 2005) and because the AMOC algorithm only locates one partition point at a time, Thomas (2005) proposed a heuristic scheme that uses the AMOC algorithm as a building block and identifies multiple partition points recursively. However, the need of using data transformations that must be chosen depending on the type of measured data, and also on the road characteristics, requires a preliminary analysis of data that makes, therefore, impossible the implementation in an automatic computer code; the large number of homogeneous sections found in several case studies makes the results of the analysis not directly usable in the PMS (i.e. the sections must then be aggregated through a subjective analysis) (D'Apuzzo, 2012).

Cuhadar et al. (2002) presented a wavelet-based algorithm for automated segmentation of pavement condition data. The algorithm first detects the singularities of the smoothed waveform. Those singularities that are not isolated are used as border points to segment the pavement condition data.

To optimally identify uniform spatial regions for performance modeling, Mishalani and Koutsopoulos (2002) developed a methodology based on nonparametric cluster analysis and dynamic programming. Under the given stopping criterion (e.g., the incremental contribution of an additional partition point to the reduction in the total variance), the methodology can provide the optimal solution. However, it does not incorporate crucial engineers' knowledge, such as the minimal segment length and the minimal mean difference.

Gaoqing Zhang (2012) compared seven algorithms using the deflection measurements obtained from two sections in the United Kingdom and found that there were very large differences in the segmentation results. Data pretreatment can help use the algorithms properly that wavelet has obvious effect on decline of the number of segments, normally over 50%, by de-noising for the algorithms based on mean value analysis, such as CDA, CUMSUM, ADA and ADSMV. The other means, smoothing with "moving" or "loess" regression serves the objective very well for all of the promising algorithms except for the LCPC method.

The methods discussed above can only be used for single parameter analysis. Pavement segmentation could also be determined based on more than one parameter. Therefore, some researchers consider the segmentation problem as a multidimensional clustering problem. The most popular methods are clustering analysis, including fuzzy clustering, grey clustering, dynamic clustering, hierarchical clustering, sequential clustering, etc. Tsai et al. (2009) used fuzzy c-mean clustering to cluster pavement sections based on condition uniformity for let project determination and Kim et al. (2010) used the multidimensional clustering method for performance-based contracting. However, the limitation of clustering method except sequential clustering is that sections that are not contiguous with each other might be clustered together, which makes it difficult to be used for pavement maintenance decisions.

2. Fisher Clustering Algorithms

Based on literature review, some algorithms are not suitable for clustering spatially sequential pavements; some other algorithms are too complicated and computational expensive and, thus, are not suitable for practical application. Through careful comparison, we propose to adopt the Fisher clustering algorithms that were originally proposed by Fisher in 1958. These algorithms are optimal regarding the minimization of within-class variation for a partitioning of n elements into a predefined set of k groups. The big difference and advantages of Fisher clustering algorithms are that they are suitable for clustering ordered data and the clustering results will not change the order of each element, as shown in Figure 5.1.



Figure 5.1: Segmentation using Fisher Clustering Algorithm

The detailed formulations of Fisher clustering algorithms are introduced in the following subsections.

2.1 Statistical Description

Give a set of n elements which is ordered by location or year, etc. and a numerical measure x_1, x_2, \dots, x_n (x_n is p dimensional vectors), the example X will be:

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1p} \\ x_{21} & x_{22} & \dots & x_{2p} \\ \dots & \dots & \dots & \dots \\ x_{n1} & x_{n2} & \dots & x_{np} \end{bmatrix} \quad (5-1)$$

Give a positive integer k that is less than n ; Define $G_{ij} = \{x_i, x_{i+1}, \dots, x_j\}$ ($i < j$) as one segment, to find a systematic and practical procedure for grouping the n elements into G mutually exclusive and exhaustive subsets such that the diameter of G_{ij} , that is the Sum of Squares of Deviations (SSD):

$$D(ij) = \sum_{k=i}^j (x_k - \bar{x}_{ij})^T (x_k - \bar{x}_{ij}) \quad (5-2)$$

where $\bar{x} = \frac{1}{j-i+1} \sum_{k=i}^j x_k$, that is the mean of those x 's that are assigned to the subset to which element k is assigned.

2.2 Loss Function

Grouped n elements into k subsets, the clustering results will be $\{x_1, x_2, \dots, x_{i_2-1}\}$,

$\{x_{i_2}, x_{i_2+1}, \dots, x_{i_3-1}\}$, $\{x_{i_k}, \dots, x_n\}$, where $1 < x_{i_2} < \dots < x_{i_k} \leq n$, the loss function $L(P(n, k))$ will be:

$$L(P(n, k)) = \sum_{l=1}^k D(i_l, i_{l+1} - 1) \quad (5-3)$$

The smaller $L(P(n, k))$ is, the smaller the sum of SSD of all segments will be, which means more similarity of each element in one segment and more difference of each element in different segments. Therefore, in order to find the best clustering results, seek a contiguous partition of these n elements so ordered that minimized the loss function.

$$\begin{cases} L(P(n, 2)) = \min_{2 \leq j \leq n} \{D(1, j-1) + D(j, n)\} \\ L(P(n, k)) = \min_{k \leq j \leq n} \{L(P(j-1, k-1)) + D(j, n)\} \end{cases} \quad (5-4)$$

2.3 Optimal Solution

Find i_k which will make $L(P(i_k - 1, k - 1)) + D(i_k, n)$ to be smallest, that is $L(P(i_k - 1, k - 1)) + D(i_k, n) = \min_{k \leq j_k \leq n} \{L(P(j_k - 1, k - 1)) + D(j_k, n)\}$. Then, find i_{k-1} which will make

$L(P(i_{k-1} - 1, k - 2)) + D(i_{k-1}, n) = \min_{k-1 \leq j_{k-1} \leq i_k} \{L(P(j_{k-1} - 1, k - 1)) + D(j_{k-1}, n)\}$. Then, find

$i_{k-2}, i_{k-3}, \dots, i_2 (i_1 = 1)$, and the break points will be $\{i_2, i_3, \dots, i_k\}$.

2.4 Number of Segments K

There are three methods to define the number of segments:

- 1) Define K by the experienced engineer;
- 2) Give a threshold $W > 0$, the value which can make $|E_0(P(n, k - 1)) - E_0(P(n, k))| < W$ Will be the min K .
- 3) Plotting the trend chart of $L(P(n, k))$ with k , then we can determine the inflection point as the number of segments K .

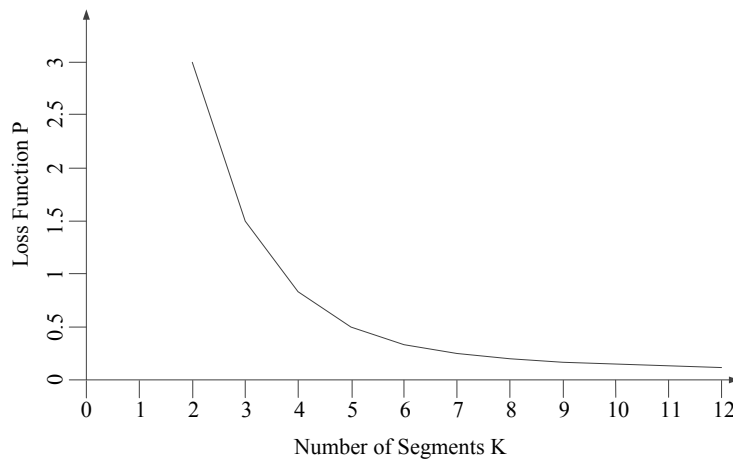


Figure 5.2: Loss Function vs. Number of Segments K

3. Case study

In this section, a case study, using 5.5 miles of 3D pavement data collected on State Route 26/ U.S. 80 near Savannah, Georgia, is presented to evaluate the feasibility of the Fisher clustering algorithms for project segmentation using the proposed crack characteristics. There are a total of 1,771 3D pavement images; each image covers a 5-m pavement section.

3.1 Crack Characteristics

As analyzed in Chapter 4, crack type, crack length/crack density, and crack width are three main crack characteristics that could be directly related to CS/CF effectiveness. Thus, they can be used to represent pavement crack conditions for segmenting CS/CF projects. In this case study, the total transverse crack length, total wheel-path longitudinal crack length, total non-wheel-path

longitudinal crack length, and the 85 percentile of crack width in each 5-m section are used as factors for pavement segmentation.

3.2 Analysis Results

Table 5.1 lists the automatic segmentation results. To assess the impact of each individual crack characteristics, a segmentation was also performed based on each factor. It can be seen that 3 segments are generated. The first segment is about 1.7 miles; it is a little shorter, 1.3 miles if only transverse cracking is considered. The second segment is about 1.5 ~ 2.1 miles. The third segment is the shortest one, about 0.6 ~ 1.3 miles. Though the segmentation results are not very significantly different, the variation based on different factors indicates the distribution of each factor varies. Since the four factors are considered to be related to CS/CF effectiveness based on the study presented in Chapter 4, it is suggested to use the four-factor-based segmentation results.

Table 5.1: Automatic Segmentation Results

Crack Characteristics	Segment 1	Segment 2	Segment 3
Non-wheel-path cracking length	1-2.7 mile	2.7-4.18 mile	4.18-5.5 mile
Whee-lpath cracking length	1-2.82 mile	2.82-4.88 mile	4.88-5.5 mile
Transverse cracking length	1-2.29 mile	2.29-4.90 mile	4.90-5.5 mile
85% percentile crack width	1-2.89 mile	2.89-4.87 mile	4.87-5.5 mile
Combination of above four factors	1-2.7 mile	2.7-4.88 mile	4.88-5.5 mile

Figure 5.3 shows the distribution of each single crack factor and the combination of them. Each data point represents a 5-m pavement section. It can be seen that the distribution of each factor varies. It is difficult to visually identify a definite separation point between two segments. Nevertheless, some trend can be observed. For example, if non-wheel-path cracking and 85% percentile of crack width is considered, the difference between segment 2 and 3 is not significant. However, from the distributions of wheel-path cracking and transverse cracking, the separation point between segment 2 and 3 is clear. Segment 3 has much less wheel-path cracking and transverse cracking than segment 2. This can be verified by looking into the typical pavement images in each segment (Figure 5.4).

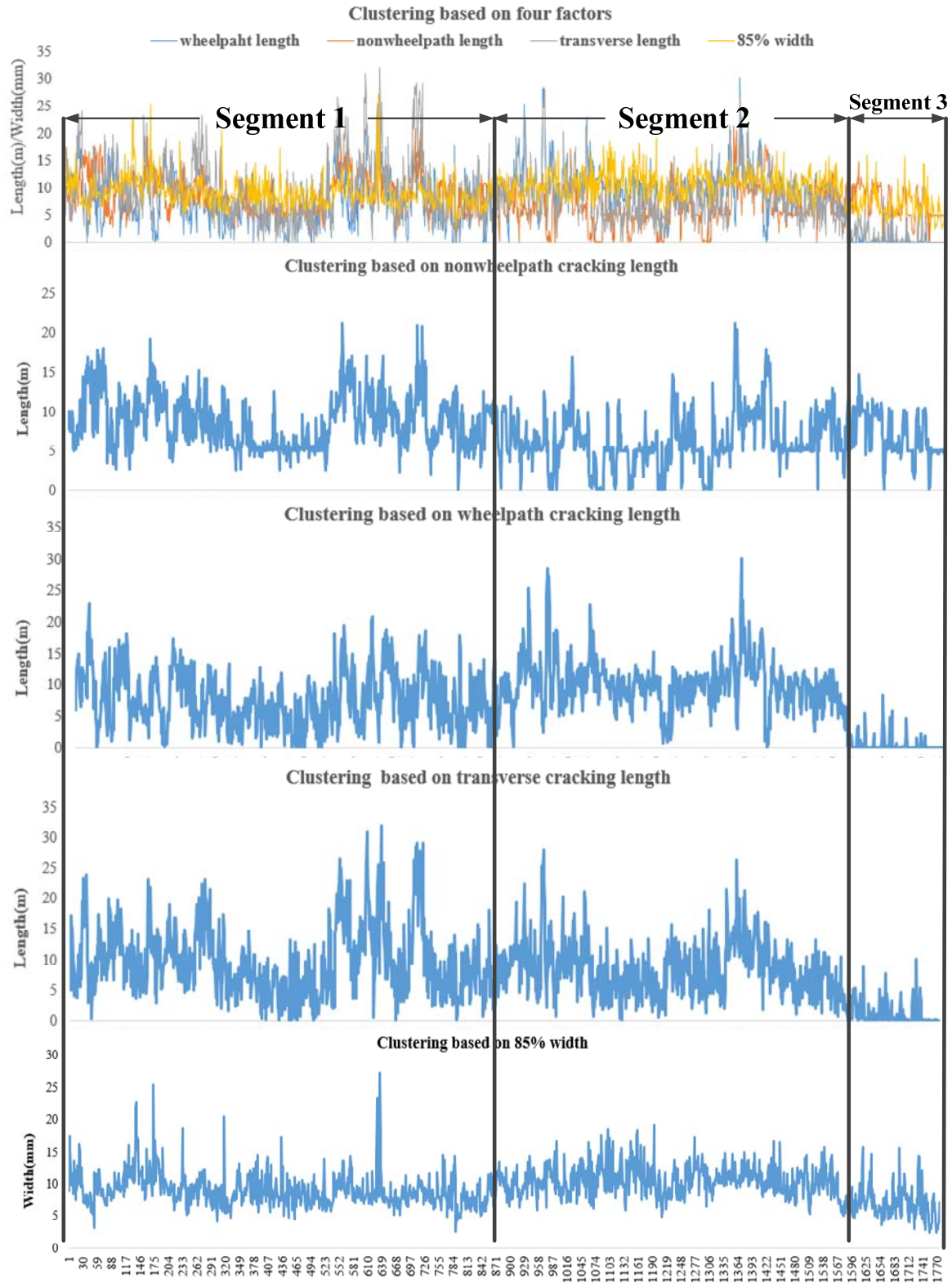
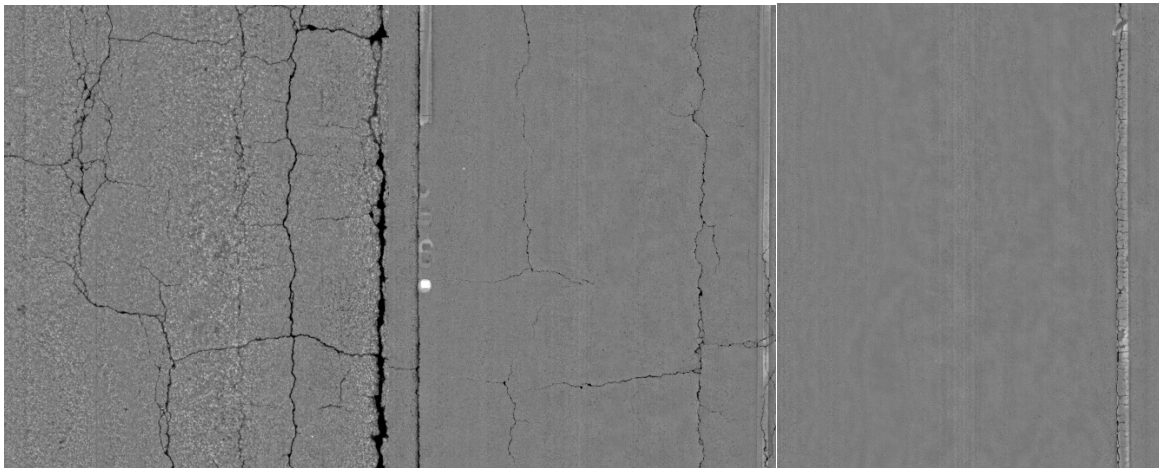


Figure 5.3: Automatic Segmentation Results

Figure 5.4 shows the typical pavement images in each segment. Apparently, segment 1 has the worst pavement condition with significant load cracking and block cracking. Segment 2 shows severity-level-1 load cracking and a little transverse cracking. Segment 3 shows little load cracking and block cracking. However, in this case study, we also count the cracking in the construction joint as non-wheel-path longitudinal cracking.



a) Segment 1

b) Segment 2

c) Segment 3

Figure 5.4: Typical 3D Pavement Images

4. Summary

For CS/CF project planning at the network level, pavement segmentation is very important, which divides the entire pavement network into individual pavement sections, i.e. projects. The pavement conditions in each CS/CF project should be statistically identical in terms of CS/CF effectiveness. Thus, the selected CS/CF projects at the network level could be more cost-effective. In this research project, the Fisher clustering algorithms were recommended to perform a spatially sequential segmentation of pavement network. The CS/CF-effectiveness-related crack characteristics, i.e. the total transverse crack length, total wheel-path longitudinal crack length, total non-wheel-path longitudinal crack length, and the 85 percentile of crack width in each 5-m 3D pavement image, were used as clustering factors. The case study, conducted on a 5.5-mile pavement section on State Route 26 near Savannah, Georgia, showed that the automatic segmentation results comply with visual identification.

A large-scale test is recommended to plan CS/CF projects by segmenting the entire pavement network based on detailed crack characteristics that are directly related to CS/CF effectiveness. Other than the proposed Fisher clustering algorithms, other spatially sequential clustering methods should also be evaluated. The automatic segmentation results should be assessed by experienced pavement engineers. Then, further refinement of the clustering algorithms can be made.

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Chapter 6 Conclusions and Recommendations

As one of the most popular preventive maintenance methods, CS/CF has been widely used in state highway agencies. In the past, it was normally considered as a routine maintenance and performed by agencies' internal force. Nowadays, due to the stringent highway budget and the lack of work force in state highway agencies, CS/CF is considered as one of the most efficient preventive maintenance methods in the pavement preservation toolbox. To maximize the return on investment, it is urged to incorporate CS/CF, as well as other types of pavement preservation methods, in a PMS. For this purpose, the cost and effectiveness of CS/CF need to be determined. This research project aimed at proposing a systematic framework to facilitate the cost-effectiveness study of CS/CF by using the emerging 3D laser technology and computer-vision-based automatic crack detection and classification algorithms. It is hoped to advance the state-of-good-repair practices for asphalt pavement crack sealing into next generation to better prolong the life of pavements. The following summarize the research outcomes and major findings:

- 1) For each CS/CF project, a reliable cost estimation is needed for two purposes. First, it is needed in a PMS when competing projects are to be selected within a given budget constraint. Second, it is crucial when outsourcing is required, which has become a hurdle in state highway agencies, e.g. GDOT, since the traditional manual method is very time-consuming, subjective, and inaccurate when crack lengths and crack widths need to be manually measured in the field. To address the above challenge, an automatic approach was proposed, which uses 3D laser technology and automatic algorithms for crack detection and crack width measurement. Based on the crack maps and the associated crack characteristics (i.e. crack widths), all the cracks can be classified in terms of their CS/CF treatment specification. Finally, accurate cost can be computed according to the crack length in each category of cracks using different CS/CF methods. Besides cost estimation, the detected crack maps and the crack classification information can also be used as a means for construction contractors and agencies to conduct construction quality checking. The case study, performed on a runway shoulder at Atlanta's airport, shows that the proposed method is very promising for providing an automatic approach that cost-effectively and reliably generates categorized crack maps and accurately estimates crack sealing costs. Due to the

use of sensing vehicle for field data collection and automatic computer programs for data processing, it is practical to conduct large-scale, e.g. network level, analysis in considering time and effort needed. The tested case can be easily extended to other highway agencies' practice.

- 2) Quantitative effectiveness of CS/CF is the key to incorporate it into a PMS. When the effectiveness and cost of CS/CF projects are known, their planning at network level could be done using an optimization model or a simple prioritization framework to come up with the optimal project selection within a given budget. However, the past study of CS/CF effectiveness is still very limited. Traditionally, a composite pavement condition measure is used to quantify the effectiveness of CS/CF, which contains both relative and irrelative pavement condition measures and is normally subjectively defined. Thus, there is a need to objectively quantify the effectiveness of CS/CF. For this purpose, an objective method was proposed in this research project to accurately evaluate the effectiveness of CS/CF. To eliminate the subjectivity of the definition of a crack index that is often used in a protocol of pavement distress identification, the measures of fundamental crack characteristics, such as total crack length, CS/CF patched density, and crack width of the initial cracks were recommended. In addition, because different types of cracks at different locations might have different benefits from a CS/CF, the effectiveness relative to different types of cracks at different locations were also analyzed. To obtain the detailed, fundamental crack characteristics, the emerging 3D laser technology, automatic crack detection, and the CFE model were employed in the proposed methodology, which has been very hard and even infeasible for a visual inspection method in the past. A case study, using the real-world 3D pavement data collected on State Route 26 near Savannah, Georgia, at different times, validated the feasibility of using 3D pavement data and the proposed methodology to objectively evaluate the effectiveness of CS/CF.
- 3) For CS/CF project planning at the network level, pavement segmentation is indispensable, which divides the entire pavement network into individual pavement sections, i.e. projects. The pavement conditions in each CS/CF project should be statistically identical in terms of CS/CF effectiveness. Thus, the selected CS/CF projects at the network level could be more cost-effective. In this research project, the Fisher clustering algorithms were recommended

to perform a spatially sequential segmentation of pavement network. The CS/CF-effectiveness-related crack characteristics, i.e. the total transverse crack length, total wheel-path longitudinal crack length, total non-wheel-path longitudinal crack length, and the 85 percentile of crack width in each 5-m 3D pavement image, were used as clustering factors. The case study, conducted on a 5.5-mile pavement section on State Route 26 near Savannah, Georgia, showed that the automatic segmentation results comply with visual identification.

In summary, this research project proposed a systematic framework to study the cost-effectiveness of CS/CF and incorporate CS/CF planning in a PMS. Three key research goals have been pursued: 1) to propose an accurate workload estimation method using 3D laser data and automatic crack detection and crack width measurement method, 2) to propose a quantitative methodology to objectively evaluate CS/CF effectiveness, and 3) to propose a Fisher-clustering-algorithms-based pavement segmentation method to partition pavement network into individual CS/CF projects. The proposed methodology has been evaluated using different case studies and demonstrated the promising results. The following recommendations are for future research and implementation:

- 1) A large-scale test is recommended to calibrate and validate the automatic workload estimation for CS/CF projects. The testing projects are divided into two sets. The first sets of projects are used for calibration purposes. Before CS/CF, crack maps are generated using automatic crack detection and crack width measurement methods. Then, the tonnage of consumed CS/CF materials will be recorded. Based on the total crack length and total consumed CS/CF materials, the material volume used for each linear foot crack can be computed. The second set of projects will be used for validation purpose. First, the total needed CS/CF materials will be computed using detected crack maps and the calibrated unit material volume. Then, the estimated results will be compared with the actual material consumption. The accuracy of the workload estimation can then be evaluated.
- 2) An experimental test is recommended to study the effectiveness of CS/CF based on the proposed crack characteristics. Different pavement test sections need to be selected in terms of location, traffic, pavement age, pavement structure, initial pavement conditions, and initial crack characteristics. At each test site, at least one control section should be selected without

any treatment. Continuous monitoring will be performed by collecting 3D pavement laser data at a certain time interval, e.g. 6 months. Other pavement condition data, such as IRI and FWD, are also suggested to be collected.

- 3) A large-scale test is recommended to plan CS/CF projects by segmenting the entire pavement network based on detailed crack characteristics that are directly related to CS/CF effectiveness. Other than the proposed Fisher clustering algorithms, other spatially sequential clustering methods should also be evaluated. The automatic segmentation results should be assessed by experienced pavement engineers. Then, further refinement of the clustering algorithms can be made.