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Design of CrackScope (VCrack) [Reprint]

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Patent Disclaimer: The University of Texas at Austin filed patent **"Real-Time, High-Speed Pavement Cracking Distress Inspection System"** on May 23, 2006. It is pending.

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Research Supervisor: Dr. Bugao Xu

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Products

This report contains depictions of the Crackscope (page 1), StokerYale Magnum laser (page 2), and Proximity sensors (page 3).

Technical Report —Design of CrackScope (VCrack) and Computer Algorithms for Classifying Concrete Pavement Distress

This report describes two major tasks accomplished for project 0-5807 in FY07.

Design of CrackScope

The CAD drawing of the CrackScope components in a custom design enclosure is displayed in Figure 1. The CrackScope uses one StockerYale Magnum II line projector (referred to as Laser), which has an 810nm 7w laser diode with a 4w output power to illuminate the pavement for image acquisition. The fan angle of the projector is nearly 80^{o}. It is mounted side by side with a GigE linescan camera in a custom design enclosure. The front plate of the enclosure has an 8" long and 0.5" wide open slot aligned with the central line of the optics of the Laser and the camera. The enclosure is installed vertically downward at height of 7 feet above the ground, and the laser line approximately covers 12 foot wide pavement surfaces (see Figure 2).

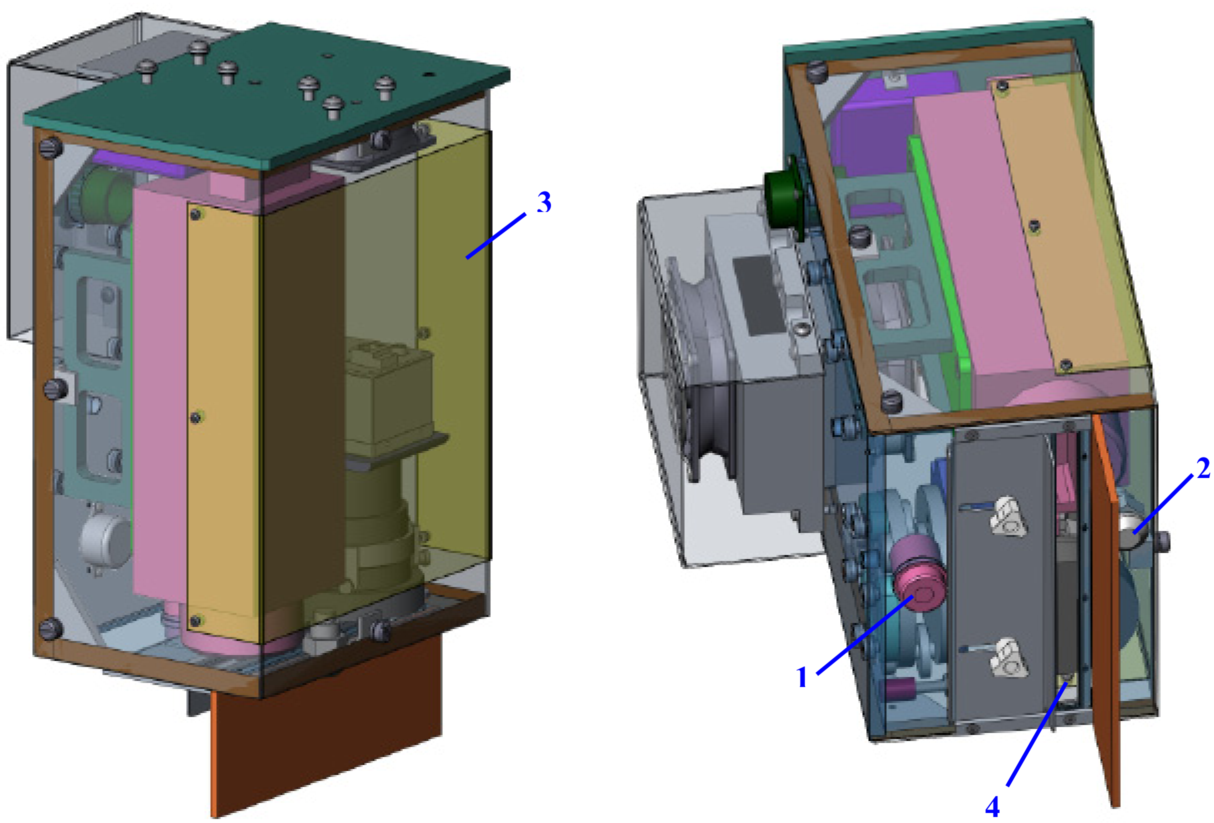


Figure 1: Components in CrackScope

1. Proximity sensor
2. LED Power Indicator
3. Laser warning Sign
4. Open window

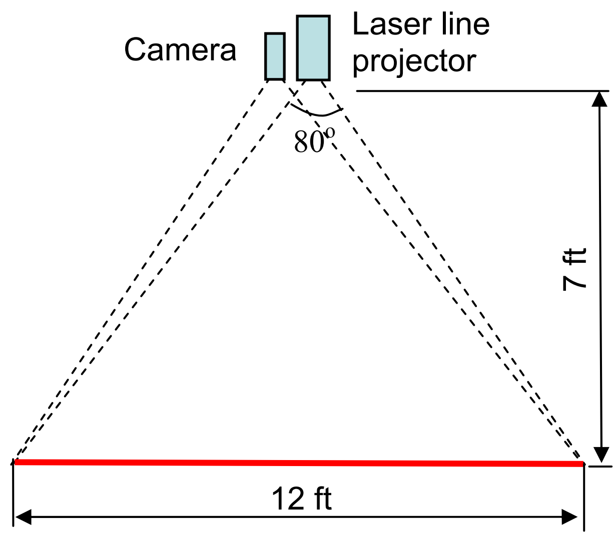


Figure 2: Mounting geometry

Magnum II laser

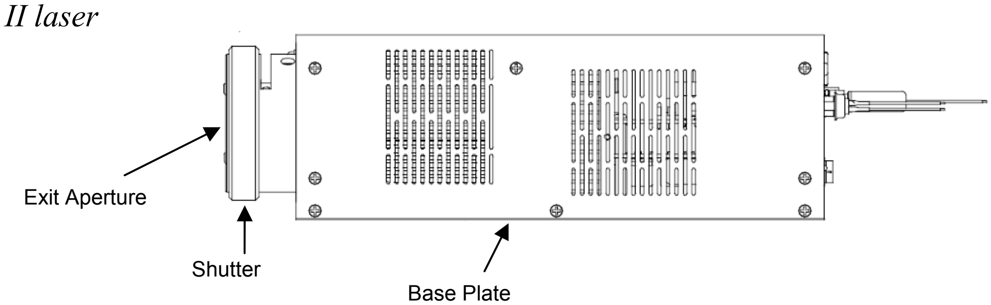


Figure 3: StokerYale Magnum II laser projector

The Lasers are tested by the manufacturer (StokerYale) prior to shipping to determine which class they belong to, and to provide United States Center for Device & Radiological Health (CDHR) and International Electrotechnical Commission (IEC) certification. The safety label is affixed on top of the Laser. Magnum II Lasers are classified according to the output power and the wavelength of a laser beam in a particular setup, according to CDRH Document 21 CFR 1040.10. The IEC has a similar document, 60825-1, version 1.2 2001-08. It is important to follow laser safety rules and wear appropriate protective eyewear when working around the Laser.

Proximity sensors

The proximity sensor on the enclosure provides obstacle detection. It detects in three distinct 'Zones," which correspond with the distance from the enclosure to an approaching subject (Figure 5). "Zone 1" is the range of 6-4 feet, the sensor sends signals to the speaker to alert the subject with slow beeps, "Zone 2" the range of 4-2 feet with rapid beeps, and "Zone 3" the range of 2 feet and inward with solid tones and also turn off the interlock switch of the Laser.

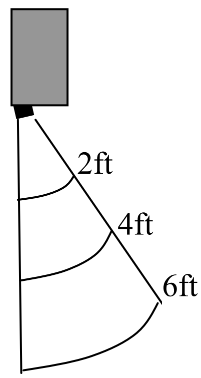
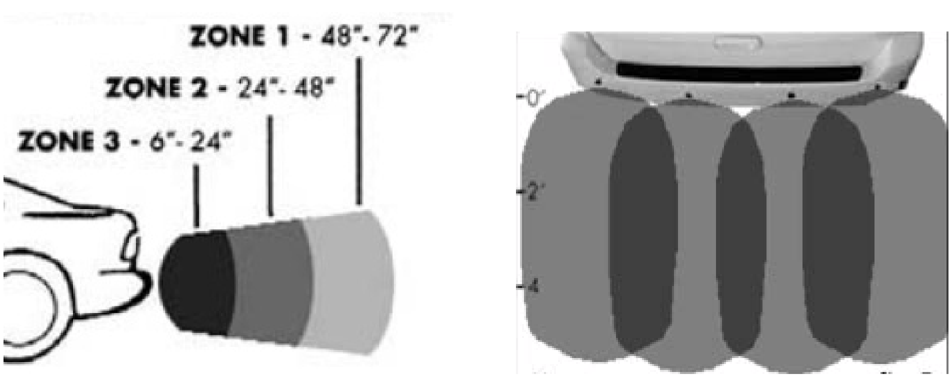


Figure 4: Sensor zone divisions from the enclosure

The user is also required to install the proximity sensors on the rear bumper that provide a safety zone in the horizontal direction (Figure 5). Reference attachment 2 for more details about technical and installation of the proximity sensor.



(side view) (top view)

Figure 5: Sensor zone divisions from the rear bumper

Vehicle speed control

The computer will receive the speed information from DMI or GPS at least three times/second. When the vehicle runs at a speed below 5mph, the computer will send a signal through a digital I/O to the modulation connector of the Laser to shut off the beam.

LED power indicator

When the power of the Laser is on, a red LED lamp on the bottom plate of the enclosure will remain on.

Controller (Operator's control box)

Inside the vehicle, a controller (control box) is placed near the operator to control the power supply and the interlock switch of the unit (Figure 7). The keylock switch is to turn on/off the 12 VDC to the unit. When it is at the OFF position, the entire unit is powered off. The rocker switch is to manually turn on/off the interlock switch of the Laser. When it is at the OFF position, no laser beam will be emitted from the unit, but the circuit is still powered on to maintain a constant diode temperature. When the vehicle stops, the operator should switch off the rocker switch to shut off the laser beam, regardless of the protective actions induced from the proximity sensor or from the vehicle speed signal.

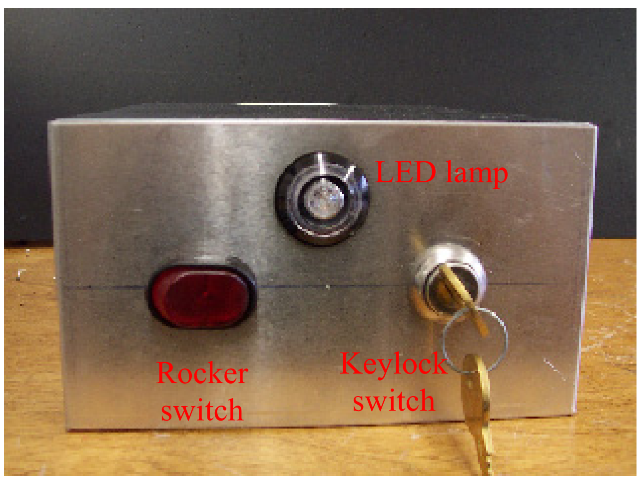


Figure 7: Controller

1. The GPS/DMI unit, which is not part of the CrackScope system but normally available on a pavement inspection vehicle, sends the actual speed of the vehicle to the computer at a rate of at least three times per second. Whenever the speed is below 5 mph, the computer sends a signal to the digital I/O unit, which is housed in the controller. The I/O unit can shut off the laser beam instantaneously. When the system is in maintenance or service, a pseudo speed can be set through the software to disable the digital I/O unit so that the beam can maintained.

2. The dashed box is the controller, in which there are five switches. Switch 1 is the keylock switch to turn on/off the power. The other four switches are connected to the interlock switch of the Laser. Switch 2 is the rocker switch on the front panel of the controller. Switch 3 is a relay controlled by the proximity sensor on the CrackScope enclosure.

Switch 4 is another relay controlled by the proximity sensor on the rear bumper. Switch 5 is the remote interlock switch.

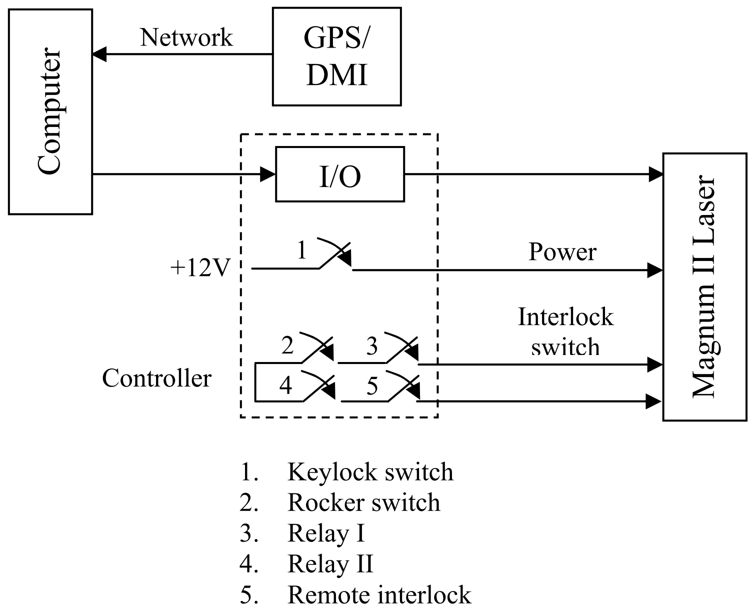


Figure 8: Safety Control

Concrete Pavement Distress Inspection by VCrack

The rater's manual defines various distress types for continuously reinforced concrete pavement (CRCP) and jointed concrete pavement (JCP). From the image processing perspective, these distress types can be grouped in two major categories, line-based (linear) and area-based (block) distress, each having a different array of measurable parameters defined as follows:

Parameters of Line-Based Distress: Definition and Computation

Definition:

- Length: the length of a traced crack segment, abbreviated as L (inch).
- Orientation: the angle of the best-fitting line of a traced crack segment relative to the horizontal direction. The orientation helps differentiate transverse or longitudinal cracks. This parameter is denoted as O and has a range of (0^o, 90^o).
- Straightness: the linearity of a traced crack segment. Straightness is expressed as S_t. It is calculated using the coefficient of correlation of a traced crack segment, and has a range of (0, 1).

Computation:

The calculations of O and S_t are based on the best-fitting line of a traced crack segment (Figure 9).

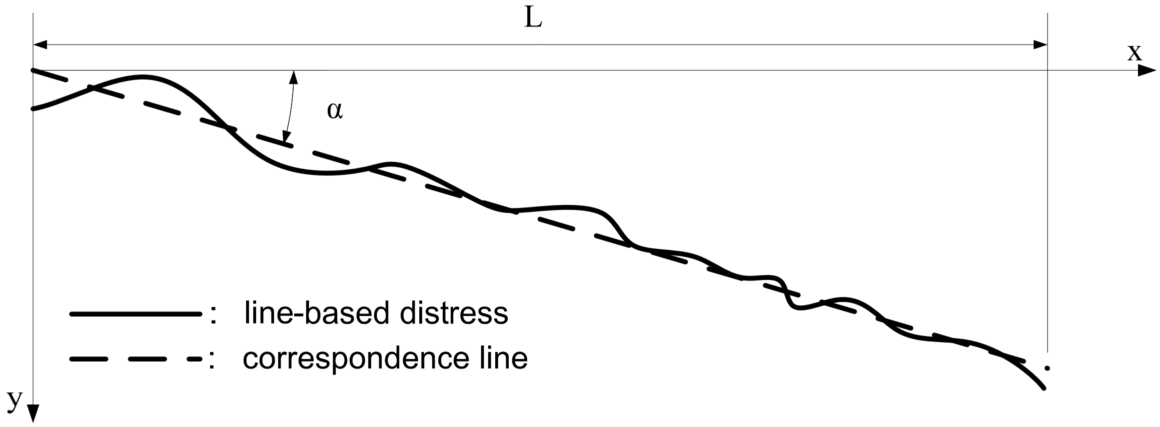


Figure 9: Line-based distress and its best-fitting line

Let the all pixel points of a line-based distress be $(x_i, y_i),\ i = 1, 2, \cdots, n$, and the fitting line be expressed as follows:

$$y = a + bx \tag{1}$$

a and b can be determined by the least squared root of error, i.e.,

$$\begin{cases} b = \dfrac{l_{xy}}{l_{xx}} \\ a = \overline{y} - b\overline{x} \end{cases} \tag{2}$$

where

$$\begin{aligned} &\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad \overline{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \\ &l_{xx} = \sum_{i=1}^{n}(x_i - \overline{x})^2, \quad l_{xy} = \sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y}) \end{aligned} \tag{3}$$

Also, the orientation angle O between the correspondence line and the horizontal axis is decided by

$$O = tg^{-1}(b) \tag{4}$$

The project (x_{ip}, y_{ip}) of the line-based distress to the best-fitting line is given by

$$\begin{cases} x_{ip} = \dfrac{by_i + x_i - ab}{b^2 + 1} \\ y_{ip} = a + \dfrac{b^2 y_i + bx_i - ab^2}{b^2 + 1} \end{cases} \tag{5}$$

The straightness S_t can be represented by the following:

$$S_t = \frac{l_{xy}}{\sqrt{l_{xx} l_{yy}}} \tag{6}$$

where $l_{xx} = \sum_{i=1}^{n} (y_i - \overline{y})^2$.

Parameters of Area-Based Distress: Definition and Computation

Definition:

- Height and Width (*H* and *W*): the bounding rectangle of a detected region.
- Grey Mean (*G*): the mean of grey level value in a distress region.
- Area (*A*): the total number of connected pixels in a detected region.
- Fitness to rectangle (*F*): the fitness of a distress shape to its bounding rectangle. Its range is (0,1).
- Uniformity (*U*): the grayscale uniformity of a distress region.

Computation:

Three parameters (*A*, *G* and *U*) can be obtained directly from the detected region, and the other three (*H, W* and *F*) are calculated based on the bounding rectangle of the detected region (Figure 10).

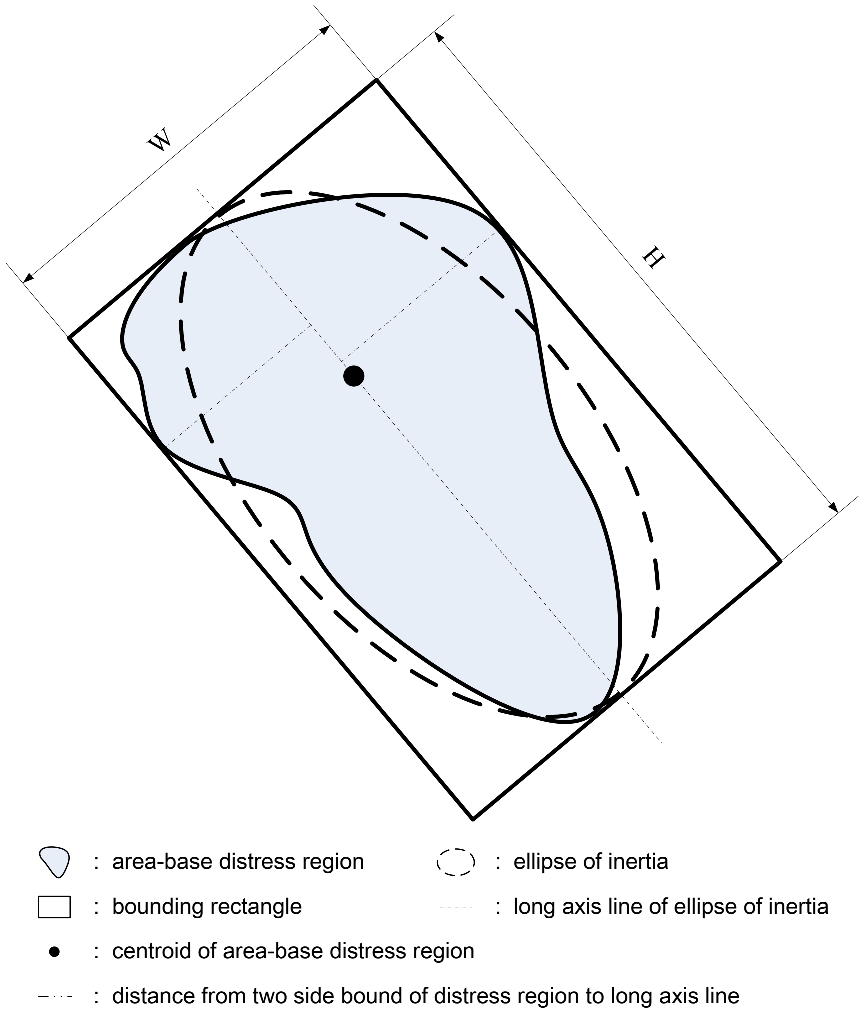


Figure 10: Area-based distress parameter computation

To obtain the height and width of an area-based distress region, the ellipse of inertia method is employed. Given an area-based distress region, its ellipse of inertia can be found by calculating the slope and length of long axis and short axis using the following equations:

$$k = \frac{1}{2D}\left[(A+B) - \sqrt{(A-B)^2 + 4D^2}\right] \tag{7}$$

$$l = \frac{1}{2D}\left[(A+B) + \sqrt{(A-B)^2 + 4D^2}\right] \tag{8}$$

$$p = 2\sqrt{2/\left[(A+B) + \sqrt{(A-B)^2 + 4D^2}\right]} \tag{9}$$

$$q = 2\sqrt{2/\left[(A+B) - \sqrt{(A-B)^2 + 4D^2}\right]} \tag{10}$$

where k, l, p, q is the slope and length of the of long axis and short axis of ellipse of inertia respectively, and,

$$A = \sum_{i=1}^{n} f(x_i, y_i) y_i^2 \tag{11}$$

$$B = \sum_{i=1}^{n} f(x_i, y_i) x_i^2 \tag{12}$$

$$D = \sum_{i=1}^{n} f(x_i, y_i) x_i y_i \tag{13}$$

In the above equations 11-13, n is the number of the pixels in the area-based distress region, and the $f(x_i, y_i)$ is the grayscale at point (x_i, y_i).

The length of the long axis p can be used approximately as the length of the long edge of bounding rectangle, that is,

$$H = p\,. \tag{14}$$

The width of the bounding rectangle takes more steps to calculate. The position of the centroid is given by

$$x_c = \frac{\sum_{i=1}^{n} f_i(x_i, y_i) x_i}{\sum_{i=1}^{n} f_i(x_i, y_i)}, \qquad y_c = \frac{\sum_{i=1}^{n} f_i(x_i, y_i) y_i}{\sum_{i=1}^{n} f_i(x_i, y_i)} \tag{15}$$

If the long axis passes the centroid, the equation of the long axis is:

$$y - y_c = k(x - x_c) \tag{16}$$

Use d_{rj}, d_{lk} to denote the distances from two sides of the distress region bound to the long axis respectively. Subscripts r and l indicate the right side and left side. Then, the parameter W is given by

$$W = \max_{j=1,2,\cdots,n_r}(d_{rj}) + \max_{k=1,2,\cdots,n_l}(d_{lk}) \tag{17}$$

According to the results, we can calculate the fitness to rectangle, parameter F is simply given as:

$$F = \frac{A}{H \times W} \tag{18}$$

Gray mean G is calculated as follows:

$$G = \frac{1}{n}\sum_{i=1}^{n} f(x_i, y_i) \tag{19}$$

U represents the degree of uniformity in the detected distress region, and is calculated using coefficient of variance of the distress region:

$$U = \frac{1}{n}\sum_{i=1}^{n} (f(x_i, y_i) - G)^2 / G \tag{20}$$

Threshold or Criteria: Definition and Explain

L_t: the threshold used to judge whether a crack is a full lane transverse or not. L_t can be set to half of the lane width, i.e., 6 feet.

O_t: the orientation threshold to judge whether a crack is transverse or longitudinal. O_t can be set to 45°.

S_{tt}: the threshold to judge whether a line-based distress is a crack or a concrete joint according to the degree of its linearity. It is reasonable to set S_{t1} above 0.8. If S_t:> S_{tt}, the line distress can be considered as a joint.

G_t: one of the thresholds used to differentiate the asphalt patches and concrete patches. An asphalt patch often has a lower grayscale mean than a concrete patch. G_t needs to be determined with measurements of these two regions in the real pavement images.

According to the rater's manual[1], *H* and *W* have a various of threshold to judge various area-based distress. For convenience, we directly use concrete figure to judge.

A_{t1} and A_{t2}: two area thresholds mainly used to differentiate small regions (noise), spalled cracks and punchouts. In general, a spall has a smaller area than a punchout. A_{t1} is used to eliminate small regions that may not be counted as spall. If $A<A_{t1}$, the detected region will not be counted as spall or punchout. If $A_{t1}< A<A_{t2}$, the distress is classified as a spall. Otherwise, it will be a punchout.

F_t: the shape threshold to separate asphalt patches from concrete patches. Normally, a concrete patch has a perfect rectangle shape. If $F>F_t$(say, 0.9), the detected region fits in a rectangle closely, and therefore can be labeled as a concrete patch. The final decision has to be made based on the conditions of other parameters such as *U*, *G* and *A*.

U_t: threshold used to identify asphalt and concrete patches from unpatched punchouts. If $U< U_t$, the region has an even grayscale distribution and meets the characters of a full depth asphalt patches and concrete patch.

Criteria of Identifying Distress

Based on the Pavement Management Information System Rater's Manual[1] and the measurements of training images, the thresholds for each parameter can be determined to classify the detected distress. The following tables list the criteria for distress identifications.

Table 1: Criteria for Distress Types in Continuously Reinforced Concrete Pavement (CRCP)

	Line-based Parameters			**Area-based Parameters**				
	L	*O*	S_t	*G*	*H, W*	*A*	*F*	*U*
Spalled Crack	$> L_t$ (half lane)	$<O_t$ (45°)	$<S_{tt}$ (0.8)	any	$H>1$ ft $W>3$ in	$A_{t1} <A< A_{t2}$	any	$> U_t$

Punchout				any	*H* and *W*>1ft if *H* or *W*>10ft number+=1	$A > A_{t2}$	$< F_t$	$> U_t$
Asphalt Patch				$< G_t$	*H* and *W*>1ft if *H* or *W*>10ft number+=1	A > A_{t2}	$> F_t$	$< U_t$
Concrete Patch				$> G_t$	*H* and *W*>1ft if *H* or *W*>10ft number+=1	A > A_{t2}	$> F_t$	$< U_t$

Table 2: Distress Types for Jointed Concrete Pavement (JCP) and Identify Criterion

Distress		**Linear distress**			**Area-based distress**				
		L	*O*	S_t	*G*	*H, W*	*A*	*F*	*U*
failed joints and cracks		$> 2L_t$ (full lane)	$< O_t$ (45^o)	$> S_{ft}$	any	*H* and *W*>1ft if *H* or *W*>10ft number+=1	$A_{t1} < A < A_{t2}$	any	$> U_t$
failures									
1	corner breaks				any		$A > A_{t2}$	any	any
2	punch outs				any	*H* and *W*>1ft if *H* or *W*>10ft number+=1	$A > A_{t2}$	any	$> U_t$
3	asphalt patches								

	a	full-depth patch				$< G_t$	H>10in If L>3ft Failure number+=1	$A>A_{t2}$	$> F_t$	$< U_t$
	b	shallow-depth patch of a corner break or punch out				$< G_t$	any	$A>A_{t2}$	any	$< U_t$
	c					$< G_t$	H>10in & W>12in	any	any	$< U_t$
4	failed concrete patches					any	any	$A>A_{t2}$	$> F_t$	$> U_t$
5	D-cracking					any	any	$A>A_{t2}$	$> F_t$	$> U_t$
6	spalls					any	H>10in & W>12in	$A_{t1}<A < A_{t2}$	any	any
7	popout					any	any	> AT2	any	any
Shattered Slabs			Enter total number of failures observed, if five or more failures are found, or if one or more failure cover more than half of a slab's area, rate the slab as a shallered slab.							
Slabs with longitudinal cracks				$> O_t$		any	any	any		any
Concrete Patches							H>10in If H>10ft Number+=1	$> A_{t2}$	$> F_t$	$< U_t$
Apparent Joint Spacing			$> 2L_t$	$< O_t$	$> S_{ft}$					

Examples

Robust classifications of pavement distress rely on the proper selections of the thresholds, which can be only determined by trial tests on an adequate number of characteristic images. The following examples tend to present some of the logics used to identify pavement distress.

Spalled Cracks

A spalled crack is a crack that shows signs of chipping on either side, along some or all of its width[1]. Figures 11-14 show a typical spalled crack in tinning concrete pavement and its processing.

Figure 11 is the original image, Figure 12 is the processed image after tinning removal, Figure 13 is the binary image of Figure 11, and the darker regions indicate the chipping on either side of a crack. Figure 14 is the processing result of the original image, in which the red line indicates the traced crack. Whether this crack is a spalled transverse crack depends on multiple conditions: $L > L_t$, $O < 45^o$, $A_{t1} < A < A_{t2}$, $W > 3$in and $H > 1$ft.

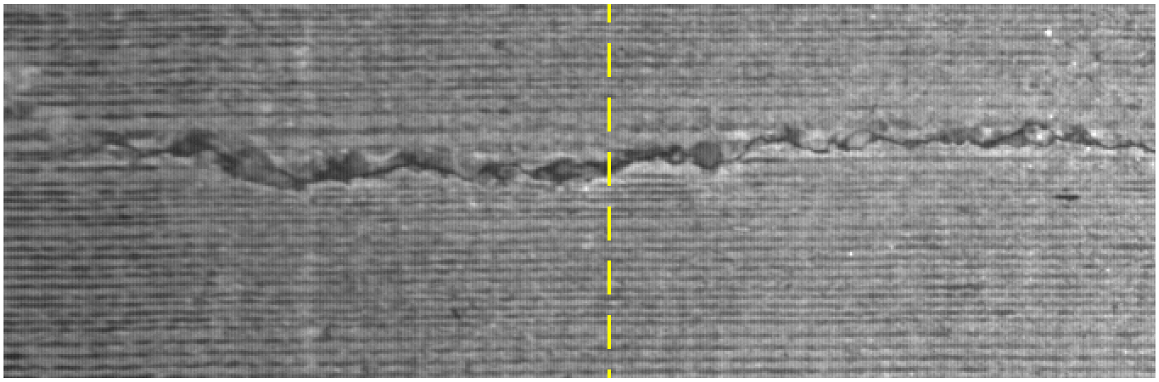


Figure 11: ***Original image of a typical spalled crack in tinning concrete pavement***

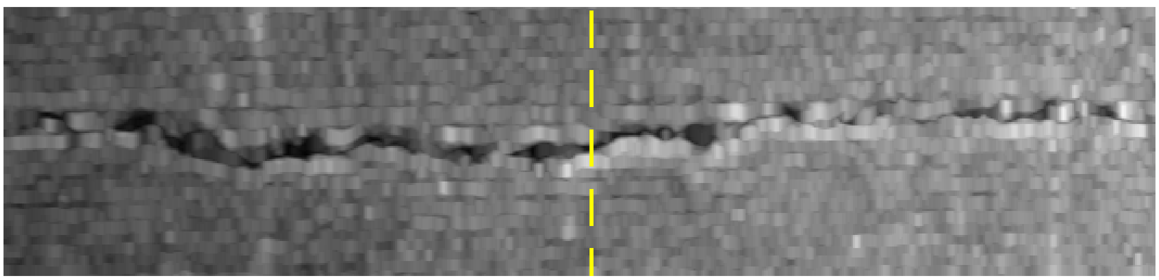


Figure 12: ***Image of after tinning removal****Figure*

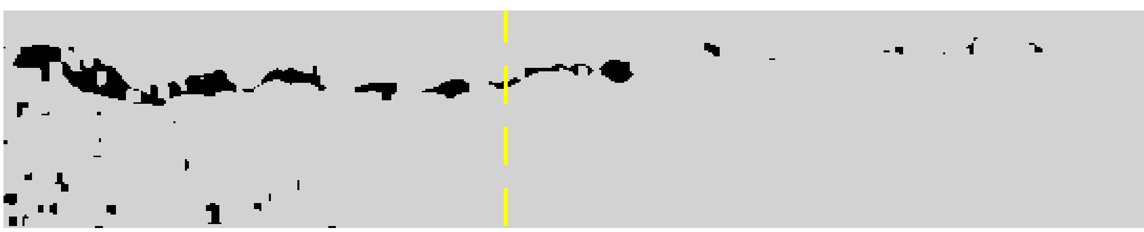


Figure 13: ***Binary image of Figure 11***

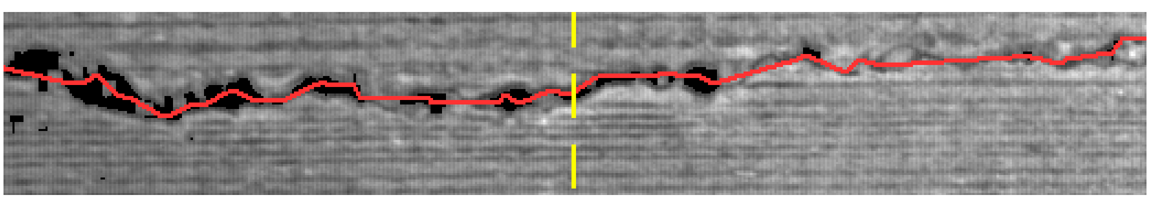


Figure 14: ***Inspection result display in original image***

For detecting joints, one more condition needs to be checked. If $S_t > S_{tt}$, the traced line segment is straight enough to be considered as a joint. Figure 15 gives an example for detecting a joint. The same condition can be applied to detecting edges of asphalt or concrete.

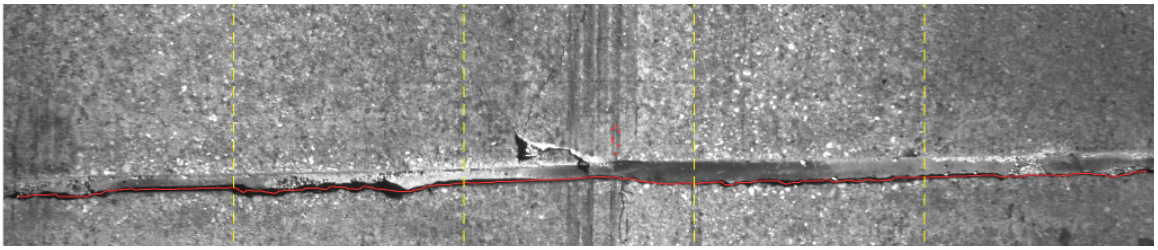


Figure 15: A joint inspection

Figures 16-18 show the detection of a spalled crack with asphalt fillings. The identifying of the asphalt area will be illustrated in following section.

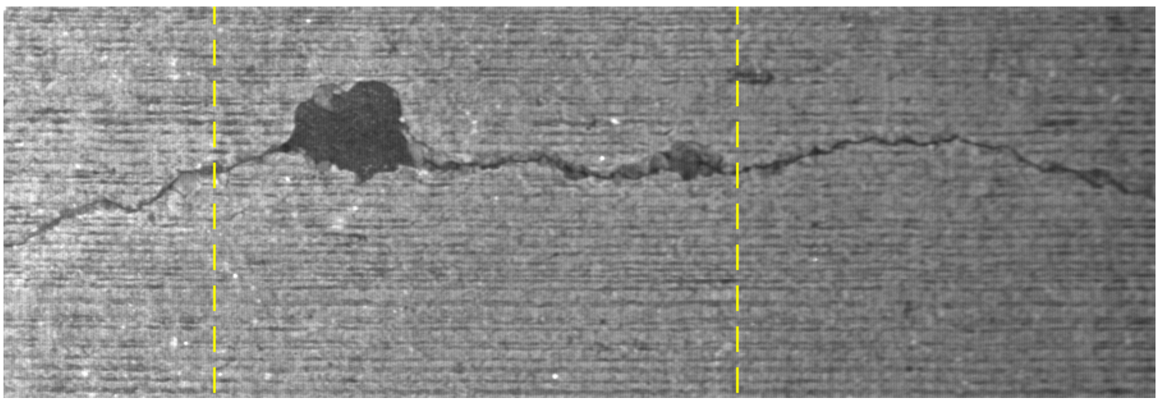


Figure 16: ***Original image of a spalled crack, in which a spalled area is filled with asphalt***

Figure 17: ***Binary image of Figure***

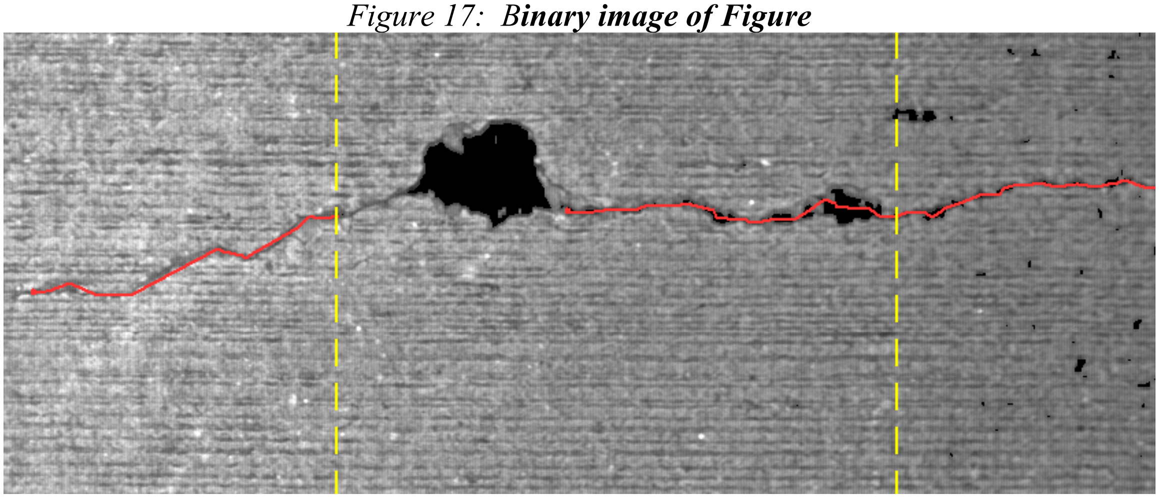


Figure 18: Traced crack

Punchouts and Block Distress

A typical punchout is a full depth block of pavement formed when one longitudinal crack crosses two transverse cracks. Although usually rectangular in shape, some punchouts may appear in other shapes[1].

Figures 19-21 show a punchout distress in concrete pavement. Figure 19 is the original image, and Figure 20 is an image showing detected blocks. Figure 21 is the binary image of Figure 19, in which bright pixels indicate the background, and black pixels represent the block distress. As required in [1], H and W should be larger than 1ft but smaller than 10ft, $A > A_{t2}$ (large enough to be a punchout, not a spall), $F < F_t$ (not a rectangular shape), and $U > U_t$ (not uniform intensity).

This example also suggests that the method can be used to inspect other large block distress, such as failed concrete patches and D-cracking. The difference between them is that they have various shapes which may be identifiable using more shape factors.

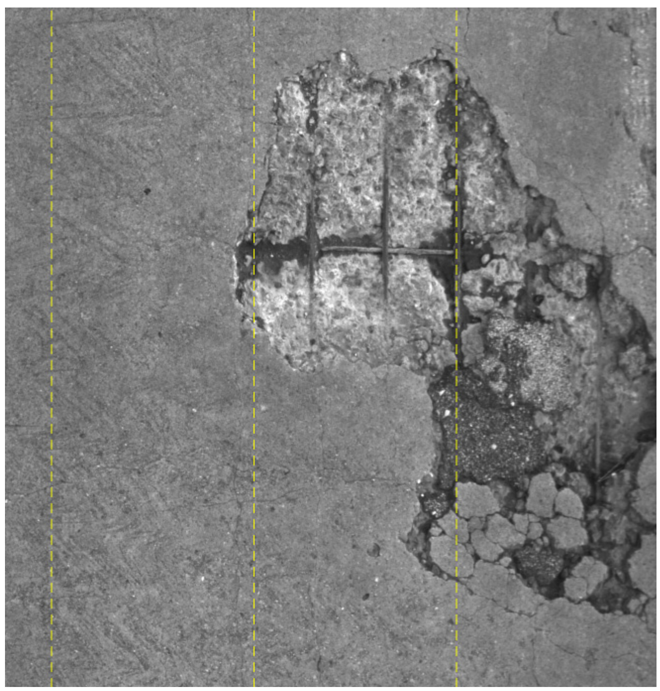


Figure 19: ***A block type crack in concrete pavement***

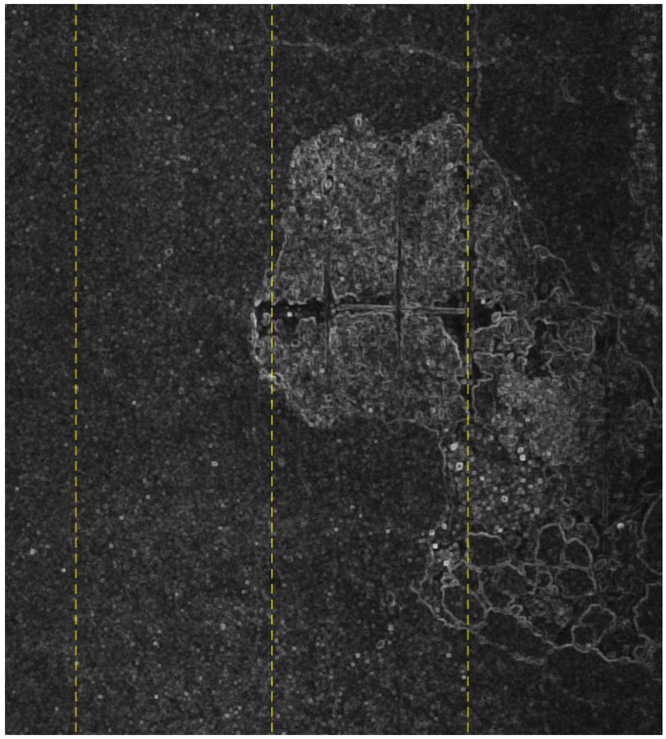


*Figure 20: Processed image of **Figure 1***

*Figure 21: **Binary image of Figure 19***

Asphalt Patch Inspection

Asphalt patch is an important feature in many concrete pavement distress.

Figures 22-23 show several asphalt patches in tinning concrete pavements. Figure is the original image, Figure is the processed and segmented image and Figure shows the result of detection.

In a detected region, if the parameter $G<G_t$, $U<U_t$ and $A>A_{t1}$, we can identify the region as an asphalt patch.

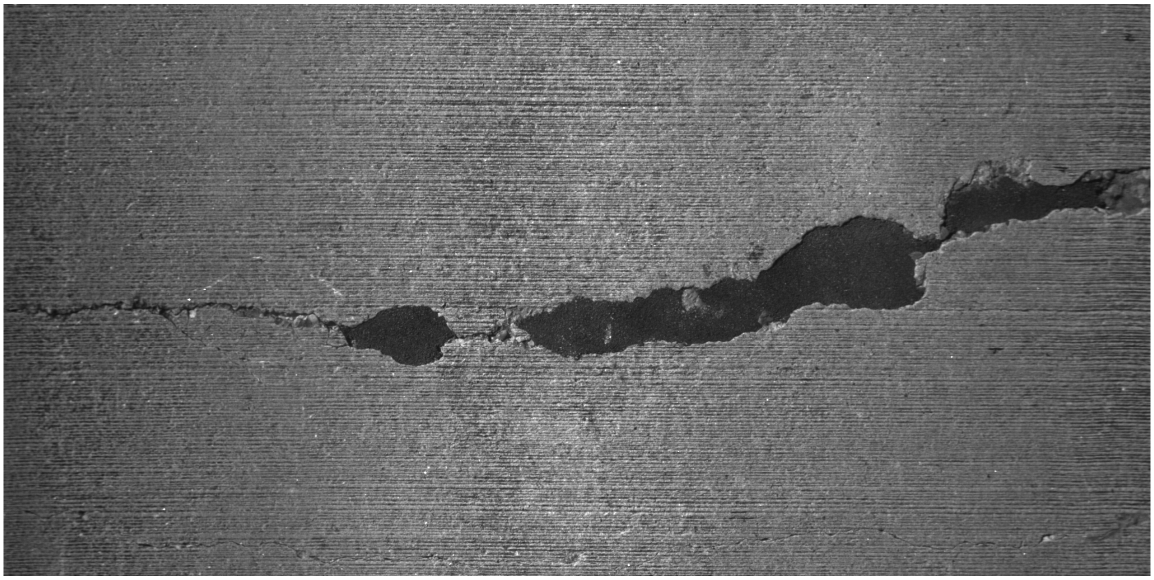


Figure 22: ***An example of asphalt patch in tinning concrete pavement***

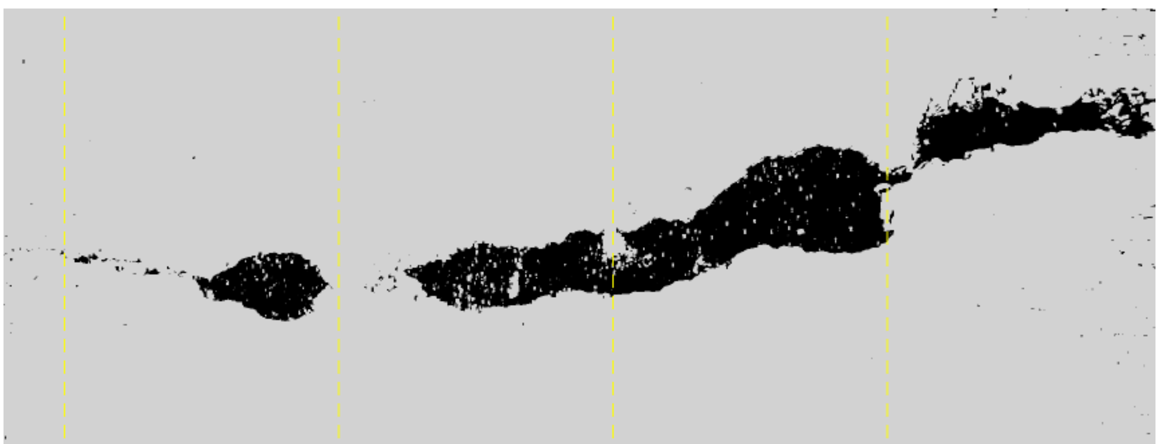


Figure 23: ***Processed and binary segmented image of Figure***

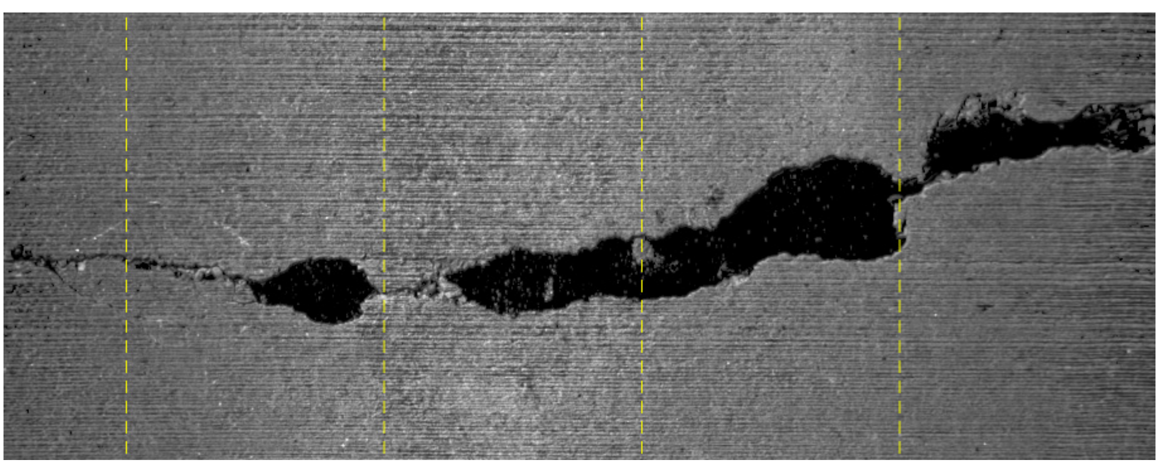


Figure 24: ***Inspection result display in original image***

Figures 25-27 show another asphalt patch and an unpatched chipping. These two regions may have similar areas *A*, but their gray means *G* and uniformities *U* can be very different.

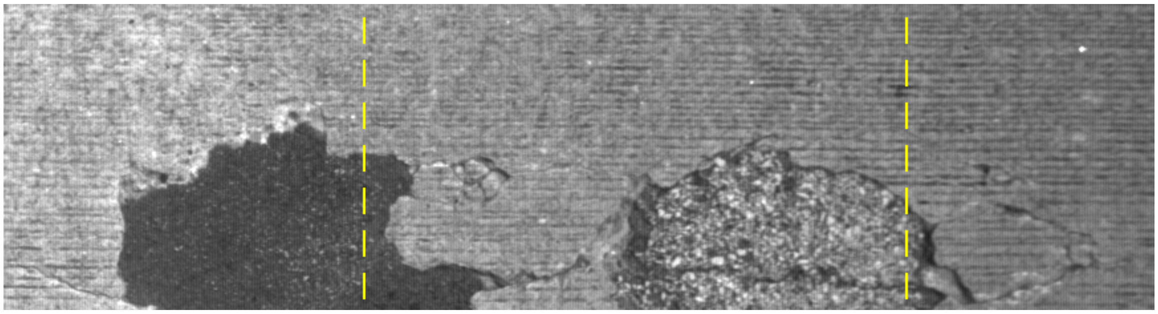


Figure 25: An example of an asphalt patch and a punchout located in one image

Figure 26: ***Processed and binary segmented image of Figure***

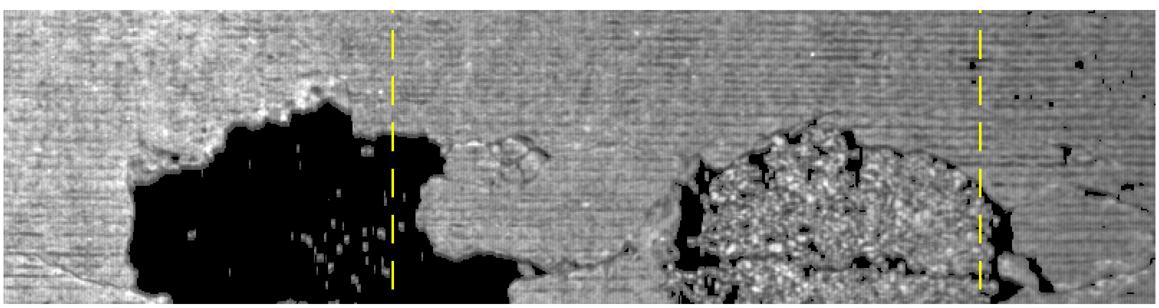


Figure 27: ***Inspection result display in original image***