Feasibility of Automating Pavement Distress Assessment Using Mathematical Morphology

DIMITRI A. GRIVAS, CHAKRAVARTHY BHAGVATI, MICHAEL M. SKOLNICK, AND B. CAMERON SCHULTZ

Surface distress assessment is an essential pavement management task. Developing and refining morphology-based image analysis techniques and evaluating the feasibility of their application to the automation of pavement distress surveys are discussed. Cracking and other distresses on asphalt and concrete pavement surfaces are analyzed. Significant advantages of the morphology-based approach include substantial reductions in data requirements and computational costs. Sample photographic images of pavements are analyzed, and the ability of the developed image-processing technique to identify distress types, severities, and extents is demonstrated. It is concluded that the developed morphology-based approach is capable of detecting noncracking distresses and assessing cracking on various types of pavement without manual intervention. It promises to become suitable for automating pavement distress surveys and thus to increase the effectiveness and efficiency of pavement condition assessment.

Surface distress assessment is an essential pavement management task. Available methods vary in cost as well as data quality and range from sketch mapping to visual surveys with automated data logging. However, the various manual methods are subject to nonrepeatability, subjectivity, and high personnel costs (*1*). Computerized image processing and analysis promise to reduce or eliminate the limitations associated with manual survey methods. Several computerized image-processing systems have been developed to analyze photographic or video images of the pavement surface (*1–4*). However, although they demonstrate the potential for distress survey automation, the simple edge detection and segmentation analysis schemes employed by these systems perform poorly on noncracking distresses and in the presence of pavement texture (*5,6*). Distress assessment on various types of pavement surfaces, especially those that exhibit extensive texture, has also proved problematic for existing systems. In the existing systems, analysis is typically based on interpreting differences between the intensity (gray scale) of distresses and the surrounding area. However, many situations occur in which the intensity ranges in an image do not provide sufficient discrimination between distresses and surrounding texture.

SCOPE OF WORK

The objectives of this study are to develop and refine mathematical morphology (MM)-based image analysis techniques and to evaluate the feasibility of applying this approach to improve the automation of pavement distress surveys. Preliminary tests are conducted to evaluate the ability of the developed image-processing technique to (*a*) identify cracking and other types of distresses on both asphalt and concrete surfaces and (*b*) assess cracking distresses to derive a rating in accordance with the linguistic scale currently used for manual distress surveying (*7*).

The tests were performed using digitized photographs of distresses on concrete pavements and asphalt shoulders of the New York State Thruway. Morphological measures were computed from the images, which were analyzed to obtain information about crack type, dimensions, and area, and the computed measures were then related to established distress rating scales. The algorithms designed as part of the current study were tested using 25 photographs representing various severities of slab cracking, slab surface defects, and shoulder defects, as defined by Thruway distress survey procedures. The distress types and scales used in the testing are summarized in Table 1.

The photographed pavement surfaces also were assessed manually by trained raters using the scales in Table 1 and the distress survey procedures defined previously (*7*). The rating obtained by morphology-based image processing is compared with the rating determined by the raters to test the performance of the current approach.

MATHEMATICAL MORPHOLOGY

The MM-based approach does not rely on intensity ranges to assess cracking and other distresses. Rather, it uses pavement texture as the basis for analysis and examines the distributions of sizes and shapes of "particles" in the image to evaluate distress types and severities. Thus, texture is analyzed to associate inhomogeneities in the texture with various types of distresses. MM operations and tools are not discussed rigorously in this paper. They are treated mainly from the functional perspective of their use in distress assessment. A rigorous treatment of this topic has been given in a previous publication (*8*).

MM analyzes textures on the basis of geometric features of textural particles such as size, orientation, shape, overlap, and so on. The power of the MM technique is based on a structural sorting of texture. Texture is analyzed through the use of geometric probes known as structuring elements. When various shapes and sizes of these elements are used, different features of interest are highlighted. For example, a circular structuring element of a specific diameter d sorts the texture under study so that structures

D. A. Grivas and B. C. Schultz, Department of Civil and Environmental Engineering; C. Bhagvati and M. M. Skolnick, Computer Science Department, Rensselaer Polytechnic Institute, Troy, N.Y. 12180.

possessing a similar geometry (i.e., circles of diameter d) are emphasized.

The morphological ''opening'' operation forms the basis for the current approach to assessment of pavement distresses. The approach is somewhat analogous to sieving a soil sample. Probing (or opening) an image with a structuring element has the effect of removing from the image all objects smaller than the structuring element. Performing a series of openings with increasingly larger structuring elements of the same shape is similar to shaking a soil sample through a series of sieves with increasing mesh openings, where the shape of the mesh corresponds to the shape of the structuring element. The generated morphological opening distribution based on the series of openings is analogous to the amounts of soil retained on screens of various sizes. Thus, an opening distribution provides important information about the size distribution of particles in an image.

IMAGE-PROCESSING METHODOLOGY

Morphology-based image processing for distress assessment is a four-step process. First, the pavement photographs are digitized and reduced to binary images by employing a threshold. Second, opening size distributions of pavement texture particles are computed from the images. Third, a ''normalization'' scheme is applied to increase the sensitivity of the distributions for capturing the essential distress features. Fourth, measures of the distributions are computed and related to features such as area, dimension, and type of distress, which are used to determine the linguistic ratings.

Thresholding

The simple relationship between morphological distributions and the particle size distributions discussed earlier is valid only in the case of binary images (black and white only; no shades of gray). Although opening distributions can also be used for computing size distributions in gray scale images, the methods are not as direct. For the purposes of the current feasibility study, the gray scale images produced from black-and-white photographs are digitized and then reduced to binary images by employing a ''threshold.''

Digitization translates the photographs into pixels of varying shades of gray. Because darker pixels generally occur in distressed areas (cracks appear darker than the surrounding texture), they are more useful in isolating pavement texture indicative of distress. In the current study, the threshold is automatically set such that 40 percent of the darkest pixels from the digitized photograph are converted to white in the binary image, and the remainder of the pixels are converted to black. The 40 percent value is determined empirically from the data set of 40 Thruway pavement images so that a sufficient amount of pavement texture is retained for subjecting each image to morphological analysis. Figure 1 shows an example of a digitized photograph and its corresponding binary image.

Opening Distributions

The morphological approach for crack assessment is illustrated in Figure 2. A thresholded image of alligator cracking on an asphalt shoulder is shown along with its opening distribution. There is a

TABLE 1 Manual Distress Assessment Scales

DISTRESS	SEVERITY	DESCRIPTION	EXTENT	RATING
Concrete slab cracking	None	No cracks	All slabs	N
	Small	Tight cracks spall free	1 or 2 slabs	SL
			$\geq$ 3 slabs	SG
	Medium	Full depth asphalt repairs	1 or 2 slabs	ML
			$\geq$ 3 slabs	MG
	Large	Open cracks spall free	1 or 2 slabs	LL
			$\geq$ 3 slabs	LG
	Total	Wide spalled cracks	1 or 2 slabs	TL
			$\geq$ 3 slabs	TG
Concrete slab surface defects	None	No defects	All slabs	N
	Small	Pitting	1 or 2 slabs	SL
			$\geq$ 3 slabs	SG
	Medium	Spalls $<$ 6 inches	1 or 2 slabs	ML
			$\geq$ 3 slabs	MG
	Large	Spalls $>$ 6 inches	1 or 2 slabs	LL
			$\geq$ 3 slabs	LG
Asphalt shoulder defects	None	No cracks	Entire Section	N
	Small	Longitudinal cracks or Transverse cracks	Occasional	SL
			Frequent	SG
	Medium	Alligator cracks	Occasional	ML
			Frequent	MG
	Large	Material loss or potholes or patches	Occasional	LL
			Frequent	LG

fine-grained texture in the original image caused by particles having dimensions of approximately 8 pixels or less. Two major cracks running vertically in the image have much greater widths (approximately 26 to 32 pixels).

The opening distribution is obtained by using a series of horizontally oriented line-shaped structuring elements with lengths varying from 2 to 46 pixels. As the image is opened with structuring elements of successively increasing lengths, the fine-grained texture is continuously removed until an element's length reaches 8 pixels. Thus, the opening distribution exhibits a large slope at scales less than 8 pixels. Since a line-shaped structuring element fits inside cracks (which are also long features), the structuring element preserves cracking until its length becomes longer than that of the crack. Structuring elements of lengths in the range of 26 to 32 pixels begin to remove the cracking from the image, which results in the sharper slopes at these scales in the distribution. Therefore, cracking is revealed by slopes in the opening distribution at "large" scales, where large, in most pavement images, implies exceeding 16 to 20 pixels.

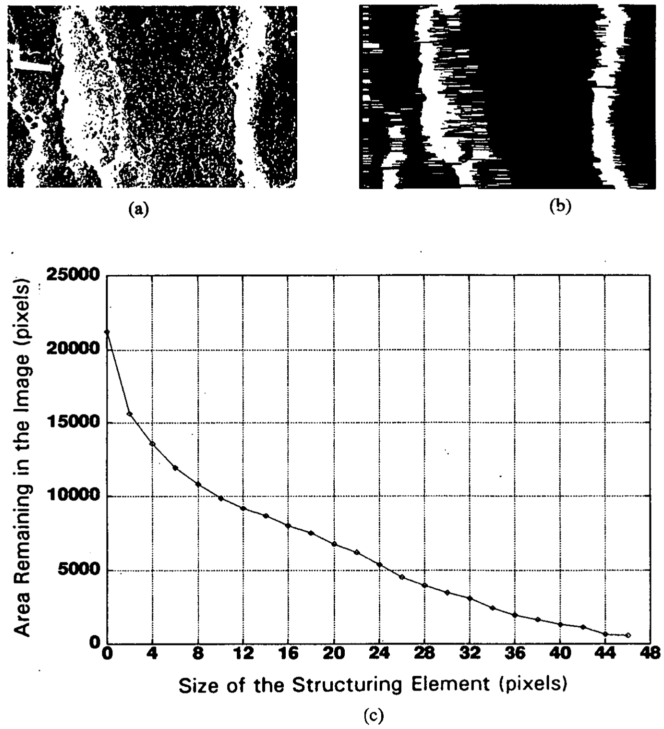

FIGURE 2 Process of developing an opening distribution: (*a*) binary image; (*b*) result of opening with a horizontal line-structuring element with a length of 8 pixels; and (*c*) opening distribution.

Normalization

A normalizing scheme has been developed to remove the effects of the normal pavement texture from the opening distributions. Normalizing emphasizes deviations from normal surface texture, such as polishing, raveling, and pitting and also increases the sensitivity of crack detection.

"Raw" opening distributions are transformed into normalized distributions by removing information about normal texture. As a result, the normalized distribution for a pavement image with no distress (only normal texture is present) is a straight line parallel to the x-axis at $y = 1$. Deviations from the normal straight line indicate the presence of abnormal texture or distress. In an opening distribution generated from line-shaped structuring elements, cracks, which are large-scale features, are revealed as overshoots in the normalized distribution at scales corresponding to crack dimensions. Abnormal texture related to other types of distress is revealed as either an undershoot or an overshoot at scales corresponding to the scale of distress.

Figure 3 presents normalized distributions for four images of shoulder defects that were determined to have a severity of none, small, medium, and large in accordance with the Thruway's manual distress survey procedure (*7*). Note that the normalized distribution of the image rated none is almost a straight line parallel to the x-axis at $y = 1$, which indicates it has a normal pavement surface. The rest of the distributions show deviations from the flat line of varying magnitudes at varying scales. The images of small and medium severity distress exhibit cracking, and their normalized distributions reveal this as overshoots at large scales (26 to 32 pixels). The distribution from the image of large severity shows a large overshoot at scales between 4 and 12 pixels. It does not show any deviations at larger scales, indicating that it has little or no cracking. The distribution is thus consistent with the photograph, which shows that the distress is mostly material loss (a pothole).

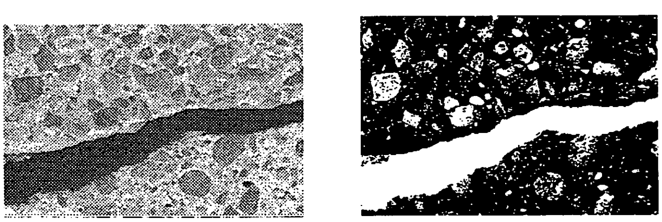

FIGURE 1 Gray scale and corresponding binary images.

Distress Rating

Normalized distributions form the basis of the current morphology-based approach by capturing pavement texture information. The deviations from normal texture are analyzed to obtain numerical measures useful for determining distress ratings. The manual distress survey requires identification of distress type, severity, and extent. The automated procedure parallels this approach through development and application of rules for interpreting image analysis results. A summary of the distress rating algorithm is provided in Figure 4.

Type

Cracks are typically long, slender, large-scale features. Their presence is revealed by large-scale overshoots in normalized opening distributions. Determination of crack type is relatively straightforward, based mainly on the dominant direction of cracking. Crack direction is determined by comparing the differences be-

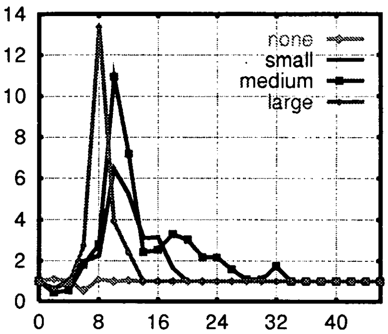

FIGURE 3 Normalized distributions of shoulder defects (*x*-axis, size of structuring element; *y*-axis, normalized area).

tween opening distributions made with structuring elements of various geometries. A vertical line structuring element preserves cracking in the vertical direction, and a horizontal line structuring element preserves cracking in the horizontal direction. If there is cracking in the horizontal direction, the normalized distribution in the horizontal direction shows overshoots at large scales. Similarly, normalized distributions in the vertical direction exhibit overshoots at large scales for vertical cracking. Based on the orientation of the photographs, vertical cracks are interpreted as longitudinal, and horizontal cracks are considered transverse. If both horizontal and vertical distributions show overshoots at large scales, there may be cracking in both directions, which is interpreted as alligator cracking. A simple quantitative rule embodies this logic: if $T^h_{cr} \geq 2\ T^v_{cr}$, then crack type is transverse; otherwise, if $T^v_{cr} \geq 2\ T^h_{cr}$, then crack type is longitudinal; otherwise, crack type is alligator, where T^h_{cr} is the largest scale at which an overshoot occurs in the horizontal direction, and T^v_{cr} is the largest scale at which an overshoot occurs in the vertical direction.

Determination of noncracking distress types (potholes, pitting, spalling, raveling, and so on) is similarly determined from consideration of properties of opening distributions. Such texture-related distresses are revealed on normalized distributions as undershoots and overshoots at small scales. Analysis at small scales, however, is less straightforward than that for cracking, and efforts are ongoing to improve discrimination between such cases.

Severity and Extent

In the manual survey procedure, severity and extent are defined by various measures, as appropriate for each distress type (see Table 1). The morphology-based procedure uses rules that duplicate the logic embedded in the manual distress scales (Table 1) to determine distress severities and extents from analysis of normalized opening distributions. For example, one rule for deducing the severity of concrete slab cracking is if the distress type is cracking, and cracking is tight and free of spalls, then the severity is small (*7*). Supplementary rules are added to aid quantification. For example, in the manual survey, tight cracks are defined as less than 1/4 in. wide. On an image, tight cracks are assumed to be

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For each pavement image
1.  Threshold the input image into a binary image
2.  Compute Opening Distributions using horizontal line-shaped
    structuring elements (SE)
3.  Compute Opening Distributions using vertical line-shaped
    structuring elements (SE)
4.  Normalize the distributions extracted in (2) and (3)
5.  If the normalized distribution is 'close to' the ideal line Y = 1, then
        there are NO DEFECTS in the image
    If there are significant deviations from the ideal line at 'large'
    scales, then
        there is CRACKING present in the image
    If there are either undershoots or overshoots at 'small' scales, then
        there may be NON-CRACKING distresses in the image
6.  If there is CRACKING present in the image (see step 5) AND
    If the normalized distribution using horizontal line SEs exhibits
    overshoots at large scales,
        there is LONGITUDINAL CRACKING in the image
    else
        there is TRANSVERSE CRACKING in the image
    If there are deviations in both distributions at large scales, then
        there is ALLIGATOR CRACKING in the image
7.  Compute the area of distress from the magnitude of the deviations in
    the normalized distributions
8.  From the information obtained in steps (6) and (7), obtain severity
    and extent ratings
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FIGURE 4 Summary of distress rating algorithm.

TABLE 2 Comparison of Morphology-Based and Manual Ratings of Shoulder Cracking Distresses

Image	Crack Measures			Crack Area	% Area	Automated Rating		Manual Rating	
	Type	T^h_{cr}	T^v_{cr}			Severity	Extent	Severity	Extent
1	–	8	8	78	0.04	N		N	
2	T	36	18	2544	12.72	S	L	S	L
3	T	>60	42	2579	12.84	S	L	S	L
4	A	42	50	4664	23.32	M	L	M	L
5	T	56	26	4119	20.59	S	L	M	L
6	A	>60	>60	7582	37.91	M	G	M	G

less than 30 pixels wide. (Crack width can be estimated from the scale at which overshoots occur.) For the purposes of the current feasibility study, no attempt is made to rigorously calibrate pixel size with true physical dimensions. However, the assumptions defining tight or open cracks appear reasonable on the basis of the data set used.

Determination of distress extent in a manner consistent with the manual procedure is somewhat problematic with the available test set of photographs. The individual photographs are from isolated locations, and each covers an area <1 ft^2. However, the manual survey defines distress extents by the amount of distress that occurs throughout a 0.10-mi sample section. On concrete pavement, extent is based on the number of slabs affected, while on asphalt pavement, it is the percentage of surface area affected. A simple rule was developed to test the potential of the technique to assess cracking extent on asphalt pavement: if less than one-third of the area in the photograph exhibits cracking, then extent is local; otherwise, extent is general (*7*).

TEST RESULTS

A total of 25 photographs representing various severities of concrete slab cracking, concrete slab surface defects (pitting and spalling), and asphalt shoulder defects (cracking and potholes) were analyzed to test the ability of the morphology-based approach to duplicate the ratings determined by the manual procedure. In the photographs, 16 contained cracking, and 9 contained noncracking types of distresses.

Cracking

Tables 2 and 3 present the test results for asphalt shoulder cracking and concrete slab cracking, respectively. Morphological measures, automated ratings from the morphology-based approach, and manual ratings from human raters are presented. In Table 2, no extents are reported for Image 1 because it has a severity of none. Extents are not shown in Table 3, because determination requires a count of slabs in a 0.10-sample section, and this information is not available for the test data set.

Of the 16 test images 14 were categorized correctly by morphological measures. The manual and automated severity ratings differed for two images. Severity in Image 5 was computed as small by the automated method but was classified as medium by the human raters. Image 15 was rated total by the automated analysis, but the human raters considered it large. Possible reasons for these discrepancies are as follows: (*a*) the rules for determining crack width on the basis of the number of pixels need adjustment; (*b*) the set of test photographs (which were taken for another purpose) are not exactly a constant height above the pavement surface and therefore, the correspondence between widths and number of pixels varies between photographs; and (*c*) there is a variety of uncertainties associated with subjective, human assessments using the manual scales.

Noncracking Distresses

Nine images representing various types of surface wear on asphalt and concrete pavements were analyzed. The results presented in

TABLE 3 Comparison of Morphology-Based and Manual Ratings of Slab Cracking Distresses

Image	Crack Measures			Crack Area	% Area	Severity (Auto.)	Severity (Manual)
	Type	T^h_{cr}	T^v_{cr}				
10	T	52	24	1378	6.86	S	S
11	T	48	10	440	2.20	S	S
12	T	50	28	2331	11.52	S	S
13	T	58	36	3523	17.62	L	L
14	T	56	32	3102	15.50	L	L
15	A	60	52	6887	34.44	T	L
16	A	60	60	6132	30.62	T	T
17	A	56	60	5912	29.56	T	T
18	A	>60	60	5992	29.96	T	T
19	A	56	44	3468	17.34	T	T

TABLE 4 Morphological Measures Indicating Noncracking Distress

Image	Distress	Manual Severity Rating	Surface	*Scales of Deviations*	*Distress Area*	*% Area*
7	Pothole	Large	Asphalt	34 - 48	3770	18.85
8	Material loss	Large	Asphalt	34 - 50	3352	16.76
9	Material loss	Large	Asphalt	28 - 40	2461	18.19
20	Pitting	Small	Concrete	32 - 40	2733	18.46
21	Pitting	Small	Concrete	34 - 44	4048	27.21
22	Spalling	Medium	Concrete	48 - 60	6371	54.18
23	Spalling	Medium	Concrete	36 - 46	2117	19.17
24	Spalling	Large	Concrete	46 - 60	6684	40.24
25	Spalling	Large	Concrete	48 - 60	11010	60.84

Table 4 indicate that the morphology-based method is capable of detecting such distresses. Work is currently in progress to develop morphological measures and rules for assessment of severities and extents of noncracking distresses. Two measures computed at the current stage of development are (*a*) the scale at which undershoots and overshoots occur and (*b*) the area exhibiting distress.

DISCUSSION OF RESULTS

The morphology-based approach provides a unified basis for automating distress surveys. This approach represents a significant departure from existing systems that use different image-processing algorithms for detecting different types of distress. Significant advantages of the morphology-based approach are (*a*) a substantial reduction in computational cost resulting from use of a single algorithm, (*b*) a substantial reduction in data requirements, and (*c*) reduction of manual intervention.

The morphological approach incorporates a thresholding procedure that reduces the effect of variations in gray scale intensities on various types of pavement surfaces. This decrease in variation effects will eliminate the need for manual intervention to indicate pavement type. Further reduction in manual intervention is made possible by the ability to assess different distress types.

Data needs are reduced because image data can be discarded once the distributions are computed. This ability to work from the distributions only is in contrast to existing systems, which detect distresses on the basis of selecting thresholds on original images. Therefore, with existing systems, performing various types of analysis may not be feasible if the image data are discarded. With the morphology-based approach, many different normalizing functions can be applied to the stored distributions to perform complex analyses and extract precise information about distresses. The distributions capture all essential distress information and are the basis for all further processing. Computational expense is thus significantly reduced because of the small size of the distributions. A typical image is 250,000 bytes in size, compared with its computed distribution, which may be about 200 bytes. Such a data reduction is extremely desirable.

Work is currently under way to establish whether morphological distributions capture all the information necessary to automate the distress survey procedures for all distress types, severities, and extents. If the distributions contain the needed information, and if they can be computed in real time, the choice of storing images versus storing only distributions will arise. The engineering use of the images has yet to be evaluated, but even if a visual data base of photographs is desired, a significant data reduction could be achieved by storing only those images whose distributions indicate the presence of "interesting" features such as large-scale distresses.

SUMMARY AND CONCLUSIONS

This study addressed the development of a new image-processing technique and evaluated the feasibility of applying this approach to improve the automation of pavement distress surveys. Significant advantages of the morphology-based approach are (*a*) reduction in computational cost resulting from use of a single algorithm, (*b*) reduction in data requirements, and (*c*) reduction of manual intervention.

Preliminary tests were conducted to evaluate the ability of the procedure to (*a*) identify and assess cracking and other types of distresses on both asphalt and concrete surfaces, and (*b*) derive ratings in accordance with a linguistic scale currently used for manual distress surveying. Results demonstrated that the approach is capable of

- Assessing distresses on various types of pavement surfaces without manual intervention;
- Detecting various distress types, such as cracking, material loss, surface wear, and spalling; and
- Evaluating crack types, severities, and extents.

These results demonstrate the potential of the approach in extracting measures for evaluating pavement surface condition. Further testing and refinement of the algorithm are currently under study to increase the utility and reliability of the computed measures. It is concluded that the developed approach is a feasible and promising technique for automating pavement distress surveys.

ACKNOWLEDGMENT

The research presented in this paper was sponsored by the New York State Thruway Authority. It is part of a broader effort to develop and implement a pavement management system for the Authority's pavements. The assistance provided by Thruway maintenance personnel is gratefully acknowledged.

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Views and opinions expressed herein do not necessarily reflect those of the New York State Thruway Authority.

Publication of this paper sponsored by Committee on Pavement Monitoring, Evaluation, and Data Storage.