Lighting Design for Automated Pavement Surface Distress Evaluation

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Automated pavement surface distress evaluation would be a useful component of computerized pavement management systems. Methods are described for applying computer simulations of pavement distress appearance to the design of those evaluation systems. By generalizing the results of crack visibility calculations under varying conditions of lighting, a number of conclusions about automated evaluation systems can be drawn, including the fact that there will always be some distress that escapes detection but that the detection probability is calculable. Lighting is important in determining which types of distress and what fraction of distress will evade detection. Differences between controlled and natural lighting, between ambient or omnidirectional lighting and directed lighting, and between single versus multiple light sources are discussed. Finally, there is consideration of how detailed examination of modeling results can be used to optimize the design of lighting, data acquisition hardware, and image-processing software. Because the conclusions depend strongly on the assumptions made in the work, a detailed listing of the assumptions is presented along with suggestions for further testing.

The pavement management system (PMS) is increasingly being used as a tool for providing assessments of road and pavement conditions and for allocating pavement maintenance and restoration funds efficiently (*1–6*). Its role in maintaining and preserving the integrity and serviceability of roads and highways through timely maintenance and rehabilitation of pavements is expected to increase. An important data component used in PMS evaluations is pavement condition data, especially pavement surface evaluation reports (*1*). Typically, the pavement is rated using one of the pavement distress indices developed by federal and state transportation agencies. Although the rating process is often computerized, the raw data (counts and locations of cracks and other forms of visible surface distress) are usually collected manually—a laborious, expensive, dangerous, and highly subjective task. Several projects have been recently funded by FHWA to develop automated pavement surface distress evaluation systems which use computers and cameras to perform the inspections (e.g., SHRP IDEA Project ID004 and NCHRP Project 1-27). These systems are similar to the machine vision systems used to inspect industrial products. Although engineering tools exist for designing industrial machine vision systems (*7,8*), the visual differences between defects in manufactured products and pavements require modification in design methods. The engineering tools required for designing automated pavement surface distress evaluation systems and some preliminary conclusions of research into the lighting design of such systems are described.

Pavement surface distress evaluation systems collect and analyze video images of pavements. In moving from manual to automated evaluation, it is important to realize that automated systems can differ significantly from systems designed to aid human evaluation. For example, data acquisition for automatic evaluation is performed by an instrumented survey vehicle, shown schematically in Figure 1. A camera observes the pavement and its video signal is recorded on a VCR or, after image processing is used to produce a digital image, the image is stored on a computer tape or disk. The purpose of the evaluation system is to identify, classify, and characterize the severity and extent of pavement surface distress, so it is important that the images possess the maximum amount of useful information. The data collection system is designed to minimize the geometric distortions in the image and to equalize the resolution across the lane width, which is achieved by arranging the cameras to look straight down at the pavement and by using optical designs that minimize the field of view (using lenses of long focal length mounted as far from the pavement as possible). These requirements differ from those for pavement logging vehicles, whose cameras have wide fields of view and observe forward along the vehicle so that the images approximate the driver's view of the pavement. Comparable design differences can be expected in all components of the evaluation system. The images that are optimal for automated pavement evaluation would not be expected to be the same as those that are optimal for human pavement evaluation. In this work, computer simulations of data acquisition have been used generally to aid in the system design process and specifically to optimize the lighting.

Data acquisition system design requires carefully matching the technical specifications of the equipment with the signal and noise characteristics of the signal (*8–10*). For pavement evaluation, the camera's video signal (or its digital counterpart) is proportional to the pavement luminance. Pavements are visible because they reflect light: the luminance of each visible region, including pavement surface and crack sides and bottom, is proportional to its reflectivity times the illuminance it receives. El-Korchi and Wittels (*11,12*) have indicated methods for measuring the reflectivities of paving materials and methods for determining the relative crack luminance, both through laboratory measurements on test paving samples and through computer modeling. Therefore, only a brief summary will be presented here.

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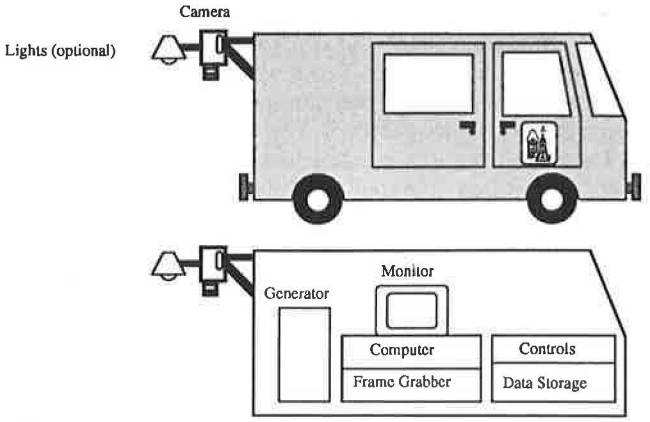

FIGURE 1 Schematic drawing of a pavement data collection system.

PCC mortar has a reflectivity of 0.30 to 0.35 for freshly prepared, cut, or fractured surfaces, meaning that between 30 and 35 percent of all of the incident light is reflected back from its surface. Aggregate materials have reflectivities as low as 0.05 and as high as 0.65 or above, an enormous range. Worn PCC pavement surfaces are visually similar to freshly prepared samples except that the reflectivities of all materials, mortar and aggregate alike, are reduced by a factor of about two. This condition allows using the results of laboratory measurements to predict the appearance of old pavements. In summary, from laboratory measurements of reflectivities of paving material samples, it is possible to predict how they will appear as part of an in-service pavement that is being evaluated.

Cracks are visible because they are darker or lighter than the surrounding pavement surface, depending on the reflectivities of all of the visible surfaces and on the lighting. When cracks are dark it is because the lighting produces less illuminance at the bottom of the crack than on the pavement surface, for example when sunlight from the side casts a dark shadow at the bottom of the crack. Under some lighting conditions described by El-Korchi and Wittels (*11*), the crack bottom receives the same amount of direct sunlight as the pavement surface, plus an additional component of light reflected from the crack sidewall, so the crack is lighter. The greater the contrast (relative difference in lightness) between crack and surface, the greater the probability that the crack will be detected. This condition is true whether the rater is a person or a computer. Therefore, it is important to understand contrast in pavement images and to match it to the detection abilities of the rater. When humans are doing the rating, this means using lighting that causes the thin, dark lines that particularly attract attention (*13*). This research investigated whether the same guidelines would apply when using automated pavement evaluation systems, given that video cameras have more compressed linear responses and different saturation characteristics than the human eye (*10,14*). The computer simulation methods and results of that investigation are described in the next sections.

TECHNICAL APPROACH

The mathematical details of the simulation methods have been provided by El-Korchi and Wittels (*12,15*), so they will only be summarized here. In order to optimize lighting for automated pavement surface distress evaluation, it is necessary to determine distress visibility over a wide range of imaging conditions: paving material reflectivities, crack geometry and orientation, lighting quality, and positioning. Although laboratory measurements of crack contrast can be used in this determination, the large number of possible combinations (tens of thousands) preclude this as an effective method.

As an alternative, analytical models have been developed to simulate the crack contrast and laboratory measurements (*11*) have been used to validate the models. Model validation is a two-step process. Mortar and aggregate luminances were measured on the surface of pavement samples illuminated by simulated sunlight. The measurements were within about 5 percent of the values predicted from the material reflectivities, which established that separate reflectivity measurements on the paving materials can be used to predict the appearance of the pavement surface, if the illumination of that surface is known. Next, comparisons were used to demonstrate that computer simulations of interreflection between the crack surfaces can accurately predict the illumination of the interior crack surfaces. Thus, computer simulations can be used to predict the contrast of a given crack. By running the simulation repetitively, with different imaging conditions each time, it is possible to generalize which sets of conditions contribute to good crack visibility and detectability.

Before presenting the results of the calculations, a review of the current state of image-processing software is useful. Inside the computer, a scene is represented by a digital image, an array of numbers. The rows and columns of the array correspond to horizontal and vertical lines in the corresponding scene and an array value represents the luminance at the corresponding point in the scene. Because the actual scene luminance is sampled to produce a digital image, only a finite number of scene points, called pixels, are represented and only a finite number of luminance values, called gray levels, are allowed. Digital images produced from a VCR tape recording of a pavement usually contain 512 rows and columns of pixels and 256 possible gray levels for each pixel: although these images have resolution below that required for most pavement maintenance needs (*13*), they are typical of those produced by most present pavement evaluation equipment.

Image-processing software uses mathematical calculations on the array of numbers to determine the presence, severity, and extent of surface distress in the corresponding pavement area. In its present stage of development, design and selection of image-processing algorithms are more art than science (*16*), so heuristic approaches are often used. In industrial machine vision applications, cracks are usually located by using threshold or derivative-based edge operators (*7*). Pavement images are visually more complex than most industrial images. The contrast between distressed and sound pavement surfaces is often less than that between aggregates or between aggregate and mortar, which negates the effectiveness of these simple edge-finding algorithms. Although algorithms have been found that work successfully with a limited set of pavement images, the enormous range of possible material reflectivities and distress contrast (*11*) makes it unlikely that standard industrial machine vision image-processing algorithms will work universally. Model-based image-processing algorithms might improve on existing methods (*17*) but no results on that approach have yet been published. NCHRP Project 1-27 is developing a universal image-processing software package that will allow analysis of pavement images collected by commercially available data acquisition systems. In summary, there does not appear to be available any image-processing software that reliably measures the location of pavement surface distress under the full range of anticipated conditions. However, current research efforts can be expected ultimately to provide such software.

Without knowing the exact image-processing algorithms that will be used, it is not possible to accurately predict whether a given crack, whose contrast is calculated using the computer simulation described earlier, will be detected. Therefore, a primitive method for predicting distress detectability has been selected. Whenever the crack contrast is greater than some threshold value, the crack is considered to be detectable. This criterion represents a conservative, pessimistic bound on the performance of the improved image-processing algorithms that can be expected to be developed, but it provides a useful measure for comparing lighting designs.

Pavement evaluation systems use natural lighting (combinations of skylight and sunlight) or artificial illumination (arrays of spot lights), so six lighting cases have been investigated: direct illumination (sunlight or spotlight), ambient or diffuse illumination coming equally from all directions (skylight or spotlights arranged inside an enclosing canopy), and three mixtures of skylight and sunlight in the ratios 1:1, 1:2, 1:4, and 1:8. The ambient lighting was assumed to cover the complete hemisphere of sky (no shadowing by roadside objects). It was assumed that all pavement surfaces reflect diffusely and have reflectivity 0.3. This assumption corresponds to the case of cracks in PCC pavements prepared with medium-reflectivity aggregates. Rectangular-slot cracks with five depth to width ratios, 3:1, 1.5:1, 1:1, 1:1.5, and 1:3, were considered. In order to further simplify the calculations, the sun was constrained to vertical angles in increments of 15° from directly overhead down to the horizon and to horizontal angles of 0° (perpendicular to the crack's longitudinal axis), 30°, 45°, 60°, and 90°. These assumptions reduced the number of combinations to about 1,000 cases.

An example of one case is shown in Figure 2. This simulated rectangular crack has a depth to width ratio of 1:3. The illumination is provided by skylight and sunlight with intensities such that the sunlight produced twice the surface luminance as the skylight. The sunlight is directed from a vertical angle of 30° and a horizontal angle of 60° from the normal to the crack sidewall. The average bottom luminance is 87 percent of the surface luminance; this crack appears to be darker than the pavement surface. This crack would only be detected by a system whose detection threshold is at least 13 percent. That value is marginal for detection by a human.

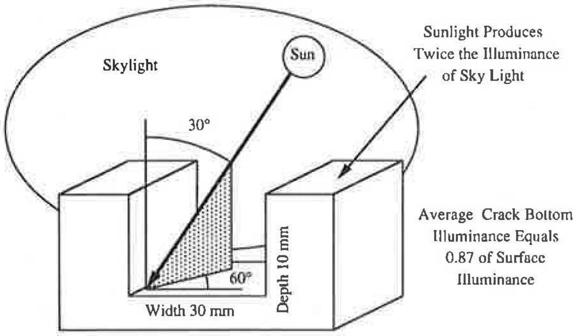

FIGURE 2 Typical crack contrast calculation geometry.

The crack contrast was calculated as found for each of the cases summarized. The contrasts were thresholded at 5 percent increments between 5 percent, corresponding to a low-noise image acquisition system with excellent image-processing software, and 25 percent, corresponding to noisy images and typical industrial machine vision image-processing software. Note that this implies that detection threshold is a key parameter to which the system hardware and software should be designed, not an engineering detail left to the last stages of the design project. The fraction of the cases in which the cracks were visible (contrast greater than the threshold) was calculated for five threshold values. The results are shown in Figure 3 in which the fraction of visible cases is plotted versus lighting quality. These results are discussed in the next section.

DISCUSSION AND CONCLUSIONS

A number of conclusions can be drawn from the calculation results that are summarized in Figure 3.

Some of the conclusions were expected:

- Low-threshold systems miss fewer cases than high-threshold systems. In other words, high-quality equipment and algorithms perform better than low-quality systems. This suggests a way to calculate the quality-cost tradeoff in designing image acquisition systems.
- The human vision system, which has a detection threshold of between 10 and 20 percent, can be expected to miss many cracks. This could explain part of the subjectivity; different ratings by different humans or by the same human on days with different lighting conditions.
- Sunlight and skylight produce different detection probabilities. With natural lighting, the same results would not be expected on bright sunny days as on overcast days.

However, other conclusions were not expected or were counterintuitive:

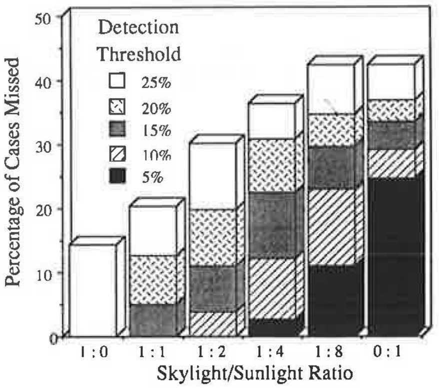

FIGURE 3 Undetectable cracks under various lighting conditions.

- Figure 3 shows that there will always be some details that a vision system will not be able to detect because the contrast is too small compared with the system noise level. That is a consequence of the nature of the signal. Any visual detection system will miss some cracks—even humans. However, during the design stage it is possible to predict which cases will be missed and what the fraction of missed cases will be. Prudence requires that those fractions be used during system design.
- Ambient or skylight produces fewer missed cases than direct or sunlight at all threshold levels. This fact is counterintuitive because the standard way that humans inspect for cracks is to illuminate the surface at an oblique angle and look for the shadow that the crack edge casts on the opposite crack sidewall. Ambient lighting is considered to be the worst possible lighting for industrial inspectors who are looking for cracks, but it appears to be the best possible lighting for automated pavement inspection.
- In systems with high thresholds (lower-quality hardware and software), the disparity between sunlight and skylight becomes even greater. The worse the equipment, the more important lighting design becomes.

These conclusions have implications for inspection system designers. First, the fact that some distress is inherently undetectable (the crack contrast is too low) means that the users of the data, the PMS designers, need to incorporate that assumption into their models. Second, because the fraction of distress that remains undetected is calculable, PMS designers need to place distress types in order so that the data acquisition system can be optimized for those distress types that are most important. That is, design of automated pavement surface distress evaluation systems and PMSs are better done in concert than in isolation. Third, controlled lighting appears to be useful in minimizing the number of missed cracks; omnidirectional lighting appears to be preferable to a single directed light source. Although cases with multiple-spot lights (more than two) have not been calculated, with enough lights those systems should produce the same results as ambient lighting. Fourth, more system improvement seems to be achievable by optimal lighting than by optimal selections of image acquisition hardware and image-processing software. These are strong generalizations so a careful reading of the cautions following is suggested before implementing system designs on the basis of these conclusions.

One conclusion presented earlier is that directed light is suboptimal for locating cracks, despite the nearly universal use of this lighting for human inspection of industrial parts. Because direct lighting casts shadows that tend to make transverse cracks highly visible while making longitudinal cracks barely visible or invisible, the case of using two direct lighting sources 90° apart was investigated. These could be two strobe lights taking sequential images of the same pavement surface or different color lights (which would cast different-color shadows) observed with a color video camera. The idea is that cracks that would be hard to detect with one light source would be easily visible with the other; no image would be acquired with the directed lighting more than 45° from the crack sidewall. The crack contrasts were calculated as described earlier, and a crack was considered to be visible if the contrast was above the threshold in either or both of the lighting cases. The results are shown in Figure 4. Although there is general improvement over the single direct-light case, Figure 3, this calculation indicates that ambient lighting is still somewhat better. With even more light sources, the directed lighting case should approach the ambient lighting condition. With several lights (two may be enough, but no detailed lighting designs have confirmed this speculation), directed lighting systems may perform as well as ambient lighting, especially when the system detection threshold is less than about 20 percent. However, it may be necessary to use the lights independently, doubling the number of images that have to be analyzed, to achieve the system improvement.

Although the emphasis has been on how to use crack contrast calculations to design lighting systems, they are also useful for designing other system components. For example, the system designer can trade off the cost of lighting equipment with the cost of data acquisition hardware by allowing the crack detection threshold to vary. This procedure can be used to write a detectability specification for the algorithm designer. Although this specification does not tell how to design an image-processing algorithm, it does allow testing any algorithm to determine whether it is capable of meeting the overall system performance specifications when used with known lighting and data acquisition hardware. Thresholding was used for segmenting distress in pavement images in this research. Although no optimal threshold is provided nor is it suggested that thresholding is the best edge detector methodology for pavements, algorithms development may be combined with lighting design to ensure optimal system performance.

The need to match the design of automated pavement surface distress evaluation systems to the special characteristics of pavement images has been described. As an example of the process, it was shown that, under some assumptions, computer modeling can be used to optimize lighting for evaluations systems. Typically, a system designer would use the simulation methods to identify the worst distress detection cases, would design a system to detect an acceptable fraction of those cases, and would verify the design over the full range of cases. Before using the results of that analysis in system design, discussion of the assumptions and conclusions is necessary.

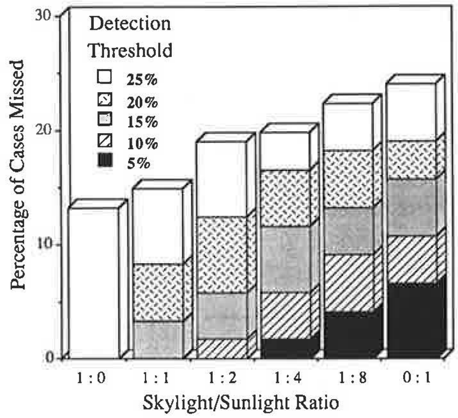

FIGURE 4 Undetectable cracks with two lights 90° apart.

Some of the assumptions in this work are overly simplistic. First, only a few cases of lighting, crack geometry, and reflectivities have been studied. A much larger study should be done; a minimum of 20,000 cases would be required to adequately test lighting conditions for PCC pavements; a comparable number would be required for asphaltic pavements. Second, all cases of lighting and crack geometry were counted equally. In fact, the mechanics of pavement distress cause some crack geometries to be more probable than others. Also, when natural lighting is used, some combinations of sunlight and skylight are more probable than others. Weighting the case counts by the probability of each would improve the quality of the conclusions. Third, evaluation systems rarely use simple detection thresholds to decide whether a feature is real or noise. The reduction of the calculated contrast data to produce Figures 3 and 4 should be redone when better crack detection algorithms are available. Fourth, the modeling programs calculated crack luminances at many points along the crack bottom and sidewalls. In computing the distress image contrast, the assumption was made that the luminance of a crack is just the average of its bottom pixel values. This assumption, which is reasonable for narrow cracks (usually the hardest to detect), is not correct for wide cracks nor is it correct for longitudinal cracks that lie near the edge of the camera's field of view, for which the image will include portions of the sidewall. The effects of this assumption should be more thoroughly investigated. Finally, the assumption that cracks are the only interesting form of pavement surface distress is unrealistic. Wittels et al. (*17*) suggested ways to extend these modeling methods to other forms of surface distress. This process should be done before final system design strategies are selected.

In summary, this work has indicated that simulations of pavement distress can be a useful tool in designing automated pavement surface distress evaluation systems. Calculations have been used to draw conclusions about design of lighting, image acquisition hardware, and image-processing software. Many assumptions were used in this work on which the results depend critically. Suggestions for further testing of some of the assumptions and for follow-on work that will enhance the usefulness of the engineering approach are as follows:

- Calculations of missed case probabilities should be weighted by observed distress types;
- Detection threshold methods could be elaborated to include more sophisticated distress algorithms;
- The consequences of averaging the luminances along the crack bottom should be investigated; and
- The methods need to be extended to handle a wider range of distress types.

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