Analysis of Pavement Cracking and Rutting Using Close-Range Photography

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ABSTRACT: A combination of a close-range photogrammetric data collection system and computerized analysis has been developed for evaluation of pavement condition. Previous approaches to pavement analysis have ranged from visual estimation to expensive ($100,000+) data collection systems. The discussed approach involved non-metric cameras mounted on a van, followed by analysis using a stereoplotter and software developed specifically for analysis. From a photogrammetric standpoint, the approach discussed here was unique for two reasons:

(1) Control was not required on the pavement, because an initial photo of a control panel defines camera orientation and proper scaling in the object space. This was a must for efficiency and accuracy in photograph analysis.

(2) The camera axes were not perpendicular to the pavement surface. Instead, the camera axes in tests were found to be optimally positioned at approximately 30 degrees below horizontal. Data collection could still be performed in any user-defined coordinate system due to the lack of mechanical restrictions in an analytical stereoplotter.

Results of this study demonstrated the utility of the approach, and provide an example of how greater information can be derived from "photologging" evaluations of pavement.

INTRODUCTION

QUANTITATIVE INSPECTION of roadway pavement is necessary for monitoring pavement performance. Different types of surfaces under differing conditions (number of vehicles per day, types of vehicles, weather conditions, etc.) will all perform in a unique fashion (Florida Department of Transportation (FDOT), 1986). Two of the most important factors which define pavement performance are cracking and rutting. Cracking classes and patterns have been explicitly defined (FDOT, 1986). Rutting is simply the vertical depressions (left and right) caused by vehicle wheels traveling the same basic path on a road surface. Recognition and classification of these types of damage are necessary if a proper evaluation is to be made.

The simplest form of quantitative analysis is visual inspection. Trained personnel can estimate the amount of each type (usually based on width and pattern) of crack, along with some depth measurement of left and right wheel ruts. This method is simplistic, but it is also subjective due to visual estimation as opposed to quantitative measurement. Direct measurement of rut depths is also potentially dangerous due to traffic. Another problem is that re-evaluation of conditions requires the site to be visited again. Hence, the capability to make an office or laboratory evaluation of a data source which requires minimal field time is highly desirable.

Photogrammetric analysis of any road situation (pavement, traffic sign and road paint conditions, accident reconstruction, etc.) from a camera in a moving vehicle is generally called "photologging" (Birge, 1985). Wolf (Gillen, 1986) described the photologging procedures implemented by the Wisconsin Department of Transportation for non-quantitative maintenance purposes and how he has used these photos in analysis of accidents. Both Birge (1985) and Gillen (1986) acknowledged that further applications in photologging have been limited by difficulty in obtaining sufficient control in photos taken from a camera in a road vehicle, and the metric problems associated with image motion, taking photos through the windshield, or other conditions.

BACKGROUND

A sophisticated system for pavement analysis, called PASCO, has been developed in Japan (PASCO Corp., 1984). A similar device was developed by the "Ministere de l' Equipement" (1975) of France in the early 1970s. The commercially available PASCO system uses a series of recording and measuring equipment mounted in a specially designed vehicle. Crack information is recorded at a scale of 1:200 by a 35-mm format strip pulse camera. The camera is mounted on the front of the vehicle, with the camera axis perpendicular to the road surface. The film is available for subsequent viewing in the office, or for crack quantification using a tablet digitizer.

Rutting is quantified by a "hair line projector" system mounted on the vehicle's bumper at a known angle with respect to the road surface. Because the projection is not perpendicular to the road surface, the line photographed in a rutted area will appear crooked instead of straight. The projected line was recorded on film using a camera mounted vertically above the projected line, and rut depth was quantified by measuring the projected line using a tablet digitizer.

In the late 1970s the California Department of Transportation's Office of Transportation Laboratory experimented with stereophotography in production of dimensionally accurate profiles of pavement texture (Apostolos and Mann, 1976), and the photogrammetric documentation of pavement wear due to studded tires (Cechetini, 1979). The system described in this paper expands on ideas presented in these studies.

Visual methods of pavement analysis have a distinct advantage over other methods, simplicity. Unfortunately, a drawback is their reliance on human judgement, and that there is no permanent record of the examined area.

The PASCO system, and its French counterpart, have distinct similarities. Both systems offer fast data acquisition and a permanent record of the examined area. The permanent record can be evaluated in quantitative ways. Traffic interference is minimized due to normal vehicle speed and night-time operation

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during data collection. The presented system simplifies the field collection hardware of these products, in addition to providing sophistication to the measurement and analysis of the data.

METHODS

A variety of equipment utilized in data collection included:

- two Hasselblad 500 ELX 70-mm format cameras,
- two Zeiss Distagon CF lenses (40-mm focal length),
- two Hasselblad "70" camera magazines,
- a Hasselblad Intervalometer III,
- a Hasselblad command unit (triggers the cameras' shutters simultaneously),
- a Hasselblad SB 40/120 Universal stereobar,
- two rechargeable 6-volt nickel-cadmium batteries (drives film advance and shutter),
- Kodak TRX-Pan black-and-white film (available in pre-loaded cassettes of 70 exposures), and
- a passenger van with an attachment for the camera system.

The selection of the components was based on the need for automatic film advance, simultaneous exposure of two cameras, and storage of a large number of exposures. The 70-mm format camera with a fairly short focal length was selected. This system provided stereo coverage of a 4-metre (12-ft) road lane without having the cameras extend significantly above the roof or on either side of the van. Non-metric cameras were used as the accuracy requirements of this study made the extra cost of metric cameras inappropriate. A minimum interval of 0.85 seconds between exposures was employed to fascilitate overlap between successive exposures. Overlap between successive stereopairs was needed to place data into a common coordinate datum using "pass points."

A camera mounting system was constructed such that a stereobar was not required. However, for purposes of this study the stereobar was used to provide a fast and simple camera locking system. The van attachment secured the stereobar to the rest of the vehicle.

Several additions were made to this system (Figure 1). Because the camera holders on the stereobar were intended for stationary use, a durable plastic strap system for the camera body further secured its rigidity. To protect a camera from failure of its holder, a plastic coated metallic cage was constructed which surrounds the camera body, lens, and magazine (Figure 2). A soft cushion was placed between the camera and the cage, which was open in the lens end for unobstructed field of view. An additional safety mechanism was provided by securing the lens to the camera and cage with monofilament line. The rear of the cage had an opening which enables easy changing of film magazines.

A sturdy iron cylinder was welded to the van chassis, and was topped by a bracket which fully supports the stereobar. The apparatus was constructed so that the cameras were positioned approximately 2.6 metres above the road surface. This height enabled proper stereo coverage of a traffic lane. Cloth pads protected the stereobar from excessive friction with the support system. Rubber straps connect the stereobar brackets with the sides of the van as a further support mechanism in preventing relative camera movement. The entire system does not block the field of view of the driver, or pose any other safety hazard.

A Kern DSR-1 analytical stereoplotter was used for all data measurements (both stereoscopic and monoscopic) on the photographs. This system is part of the Photogrammetric Laboratory of the Department of Civil Engineering at the University of Florida. Some additional monoscopic collection software was developed, but the stereoplotter's computer was not used for data analysis.

All analysis software was developed in FORTRAN 77 using the University of Florida's cluster of Vax computers. Files were uploaded to the mainframes for analysis. No map output of any type was deemed necessary for the analysis.

The system was designed so that the relative camera positions would remain fixed. This allowed all stereopairs to use the same relative and absolute orientation parameters. Only interior orientation of each subsequent stereopair of photos is required to define the location of the photocoordinate axes on the measuring plates of the plotter. A stereopair of some control configuration is required to define relative and absolute orientation.

Initial testing of the desired camera depression angle (camera axis relative to the road surface) was also required. Because it was desired to travel as fast as possible and maximize the area of the measurable road surface for a given stereopair, vertical photography proved undesirable. The camera depression angle had to be large enough to identify cracks. Image motion also had to be minimized. Extensive experimental testing resulted in the conclusion that a camera depression angle of approximately 30 degrees would be most suitable. The depression angle, coupled with a maximum vehicle speed of 35 mph, provided the best results with the camera system.

Initial stereoplotter orientation required the manufacture of a control panel consisting of three approximately orthogonal targetted bars. The panel can be constructed or dismantled easily in 5 minutes, and fits easily in the van. Because orthogonality

FIG. 1. The photographic collection system for pavement analysis.

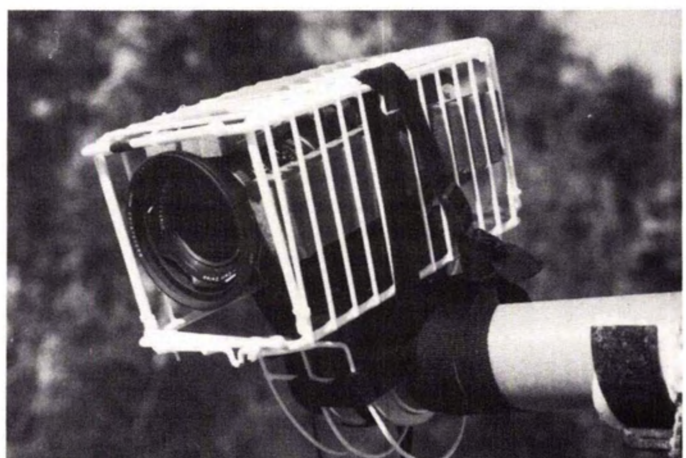

FIG. 2. The camera and its protection "cage."

of the bars cannot be assumed, a Wild T-2 theodolite was used to measure horizontal and vertical directions to the targets from both ends of a 10 metre baseline. A subsequent least-squares adjustment of these observations produced precise three-dimensional coordinate values for all control point targets.

Because 30 targets exist on this control panel, the absolute orientation solution resulting from a steropair was redundant. Maximum residuals from absolute orientation solutions using this panel rarely exceeded 15 mm (0.05 ft), which indicated that the reconstruction of the control panel was stable, and that the geometric fidelity of the nonmetric cameras was high.

The object coordinate system which provided easy movement of the floating dot, and was thus adopted, was *X*-perpendicular to traffic, *Y*-vehicle direction, and *Z*-vertical.

A simple test for relative camera movement, due to individual camera movement or axis flexibility, was finding *y*-parallax in a pavement stereopair when using orientation parameters from the calibration stereopair. This was not a problem in any road tests of the system.

Stability of the absolute orientation resulting from use of the control panel involved a stereopair of three level (Philadelphia) rods. Two rods were laid on the road surface perpendicular to one another, with the third rod held approximately vertical. The rods were photographed both before and after a road photography session. Note that the rods were not used in absolute orientation, as the control panel stereopair's relative and absolute orientation solution were used for that purpose.

Based on a series of more than 100 measurements on the three rods before and after the road photography session, more than 45 percent of the distances (44 percent before road photography, 46 percent afterwards) compared to within 3 mm of their labeled lengths on the rods. The maximum discrepancy was 8.5 mm, which indicated the stability of the relative orientation and the maintenance of scale in all dimensions in absolute orientation.

MONOSCOPIC AND STEREOSCOPIC DATA COLLECTION

The major drawback to monoscopic data collection is that rutting cannot be determined. This is because in monoscopic measurements only one pair of comparator coordinates is measured for each image position (opposed to two pairs in stereo mode), and thus only two object space coordinates can be determined for each of the image positions. Because the system design was towards elimination of as much vehicular hardware as possible, and an approach such as the "hairline projector" would add to this hardware, rutting was treated as strictly a stereo measurement procedure.

Other than rutting, the same analysis results can be determined by mono- or stereoscopic digitization. The monoscopic approach has the advantage of a slightly quicker collection rate, but theoretically less accuracy because the road is assumed to be a flat surface. In reality, most road lanes are slightly curved in a direction perpendicular to the direction of traffic. Steroscopic viewing also seems to aid the identification of crack widths.

Dental wire was implanted in the camera's image format to serve as fiducial marks. The ends of the wires proved to be effective fiducial marks once their photocoordinate positions were calibrated by repeated measurement on the analytical stereoplotter.

The same format for digitizing was used in both monoscopic and steroscopic modes, with the addition of rut digitization in the stereo operation. In the stereo mode this means going through the traditional steps of interior, relative, and absolute orientation (using the control panel). The first procedure was digitization of the control panel. The same relative and absolute orientation parameters were used for all subsequent stereomodels of the pavement; thus, only interior orientation was required for these. In the monoscopic mode, only the two bottom (horizontal) panels of targets are digitized along with the fiducial marks. This allowed for the determination of the two-dimensional projective transformation parameters (Wolf, 1983) which related photographic *x,y* coordinates to a corresponding two-dimensional coordinate position on the road surface. While the stereo mode involved use of Kern's orientation software, in the monoscopic mode a utility program was written, using Kern's user library, which determines the elements of the projective transformation and stores them in a file for later reference.

The next photo(s) (the first ones if the process is just starting) were placed in the plotter. Interior orientation was performed in the stereo operation, relative and absolute orientation files are allowed to update for the change in the photos' positions on the measuring plates, and map collection software is engaged for road digitization. In the monoscopic mode, a program allowed for digitization of fiducial marks prior to road digitization, with all information being collected in a file for later analysis.

The digitization steps prior to crack measurement were optional, but their inclusion allowed various options to be executed on the set of data. The inclusion/skipping of these options was executed by sending simple control identifications to the software.

The first option was digitization of a set of points on the road centerline, preferably covering the extent of the photograph. This option allowed the coordinate system defined by the control panel to be rotated and translated to a system in which the *Y* coordinate axis was parallel to the road centerline. While not required for measurement of cracks and ruts, it was valuable to look at coordinates which are defined by this option. If this was the beginning photo for the examined area, the user was also able to digitize a point which represented a *Y* coordinate of zero.

The last option prior to crack digitization enabled the user to combine all data into a common coordinate system using "pass" or "continuation" points. This option required one or more points to be identifiable on the next photo. These points, when digitized in the next photo or stereopair, allowed software to perform an appropriate coordinate transformation of the second photo's coordinates. The location of photo-identifiable points that appeared on a subsequent photo or stereopair was not always possible. It was found that an experienced operator could use centerline stripe corners, as they can be correlated to what exists near it in a direction perpendicular to the flow of traffic. This perpendicular correlation remained consistent in the next photo or stereopair. Update of coordinates does not result in any form of scaling; thus, distances resulting from the digitized coordinates will be preserved in the translated system.

The continuation point's coordinate translation was used to identify cracks which have been digitized twice, on successive photos or stereopairs. This duplication must be removed in obtaining proper estimates of the percent of the road surface which was affected by cracking, and the number of cracks for a given road distance. Subsequent analysis software identified this situation, and eliminated duplicates in the first data set because they were further from the camera, and thus more difficult to measure. If continuation points were not measured, this same procedure was accomplished using estimates of the vehicle's speed during photographic sessions.

Crack digitization allowed users to define their own measuring order, though a regular pattern was strongly advised for consistency purposes. Crack digitization allows determination of crack length and an average crack width, based on a series of distances generated from digitizing pairs of points on each side of a crack. Input of a control character tells the software that a crack was completed, and the next digitization defines a new crack. The operator can become competent at estimating when cracks appear on the next photo or stereopair. It was advantageous to leave these cracks until the next photo as their location was closer to the camera(s), enabling easier identification and better accuracy in length and average width delineation.

Reduction software was tailored to meet the analysis criteria established by the Florida Department of Transportation (1986). These criteria define "affected area" as 0.30 m (one foot) extended on all sides of the crack. In a heavily cracked surface affected areas overlap one another. The user was thus provided the option to digitize outlines of an "affected area," along with a series of crack width estimates in the affected area. This was extremely beneficial as the individual digitizing of all of the cracks in a large affected area would take an inordinate amount of time.

Finally, in stereo operation the user was provided with three choices for measurement of rutting depths - best-fit plane, best-fit line, and a double line approach. It was found that different pavement types, level of deterioration, and lighting conditions created unique situations which made one approach more appropriate than others.

In the best-fit plane method a series of points were digitized across the road surface in a fashion that geometrically allowed the least-squares fitting of a plane through the points. A series of points was then digitized in the left and right wheel ruts, and subsequent software calculated the average depth of rut below the best-fit plane for these measurements.

The best-fit line approach involved digitizing points on the left and right edges of the road lane, two points near the middle of the lane, and a point in each wheel rut. A least-squares "best-fit" line was determined through the edge and middle points, then depths below this line to points in the rut area were computed. This approach, in addition to the best-fit plane, assumed a non-curved road surface.

In the double line approach each rut was treated separately by digitizing two points on the exterior of each rut, and a point in the deepest portion of each rut. Depth was the perpendicular distance from the line connecting the two points on either side of the rut to the point in the bottom.

DATA ANALYSIS

In data collection, digitized data were not immediately reduced to crack and rut spatial measurement information. This was because it was not possible to alter the stereoplotter software which was used in stereo data capture. Because many of the analysis procedures are common to both stereo and monoscopic aspects, the stated criteria made it sensible to make analysis in monoscopic operations a post-collection operation, too.

The first utilized program combined all digitized coordinate files into one file with a common coordinate datum, utilizing continuation points and center-line points as discussed previously. Duplicate data were removed in this step.

If the analysis was monoscopic, the first file (control) was used to determine the projective transformation parameters. All subsequent digitized road information was first transferred into a photocoordinate system using the digitized fiducial "wires." Those coordinates were then transferred to the coordinate system defined by the control photo's projective transformation solution, and finally they were transferred into a continuous road coordinate system using the discussed continuation ideas. The stereo data was only processed through the continuation transformation as it was digitized in three-dimensional object space coordinates using the stereoplotter software.

The completion of the data analysis was the transfer of the coordinate file into a coherent set of information which can be analyzed for decision making processes. All crack information has a length, average width, and affected area computed for it. A crack was classified according to Florida Department of Transportation (1986) standards:

(1) Class IB-Hairline to 1/8 inch average width cracks
(2) Class II-1/8 to 1/4 inch average width cracks
(3) Class II-1/4 inch or greater average width cracks

The continuation procedure allowed transformation into a common coordinate datum, enabling calculation of the entire length of studied pavement area. If identification of continuation points was a problem, causing an error in the calculated length, the length of the examined pavement could be input by the operator. The number of cracks and the total amount of affected area in each category were then summarized as a useful summary for the engineer.

If the data were collected in a stereo mode, the rutting information was determined at this stage. The left and right rut depths determined from each stereopair were output, along with the average values of each rut depth for the entire examined area.

The system was tested on three one-mile sections of road surface, with one of the sections being evaluated twice. Two of the pavements were of standard composition, while the third was a course aggregate. Both stereoscopic and monoscopic analysis was performed at all test sections.

The tests illustrated that the acquisition hardware was extremely durable under operating conditions, and that the digitizing system and software analysis have provided meaningful results. The results have indicated that a production-oriented digitization system would need to utilize software specific to pavement analysis.

The results have not indicated whether mono-or stereoscopic digitization is preferable in crack analysis, but instead indicate that the chosen analysis method depends upon the user's needs. The tests have indicated that the monsocopic results tend to result in 5 to 10 percent less crack-affected pavement area than the stereo derived quantities. This was due to the fact that some cracks are more identifiable in stereo.

As an example, the first test site provided an example of mild cracking. Stereoscopic analysis provided sums of crack lengths in types IB, II, and III to be 24.0 m, 498.9 m, and 780.8 m, respectively. Monoscopic analysis produced values for the same parameters to be 28.9 m, 173.3 m, and 848.0 m, respectively. A visual estimate of percent affected area was 20 percent, as opposed to the photogrammetric estimate of 8 percent.

This discrepancy was partially due to the non-quantitative nature of the visual approach. Tests also have shown that the photogrammetric approach produces higher cracking percentages in the larger crack width categories. This again is partially due to a person's estimate of crack width category using strictly a visual approach. A second photogrammetric determination (different photographic session) of the same site produced sums of crack lengths within 5 percent of the first photogrammetric determination.

Results from different operators, digitizing the same road section in a "crack to crack" fashion, have been shown to be within 5 percent of one another in percent affected area for the various crack categories. If the affected area is digitized in areas of heavy cracking, instead of individual cracks, interpretation of the affected area could differ greatly among operators. Operator training is the only solution to this inevitable problem.

In most situations the more precise rut depths resulted when each rut was treated separately, as opposed to a best-fit plane for the road surface or best-fit line perpendicular to the direction of traffic. The best-fit methods assume a flat road surface exists, which significant amounts of rut determinations has been shown to be false for many types of pavements. Photogrammetric rut depths tended to be smaller than their visual field estimates by

30 to 35 percent in all cases tested. However, the difference between left and right rut depth seems to compare very well between methods (less than 1 mm in 75 percent of the tested cases). This indicates a difference in what is actually defined as a rut depth, similar in nature to the difference that can exist in a measurement of a crack width by the two methods.

The approach described in this paper does not intend to be a total answer to the drawbacks of other pavement analysis systems. Instead, the developed system is an alternative which could be more favorable to the needs of a possible user. The new approach consists of a collection system which is far less complex than those described. It is also a collection system which users can change to optimize their needs.

The other distinct difference in the presented system addresses the major drawback to the other systems. This fact is that the information obtained by incredibly sophisticated (and thus expensive) vehicle mounted collection systems is analyzed in a very primitive fashion - visually, scale, or a tablet digitizer. Assuming that an operator of a tablet digitizer has a pointing precision of 0.25 mm (0.01 inches), this corresponds to 50 mm (2 inches) on the road surface at the photographic scale of 1:200 which the PASCO system utilizes. It is evident that the higher accuracy which could be obtained using an analytical stereoplotter for the analysis (generally 0.001 mm photographic measurement resolution) would be crucial in determination of accurate estimates of crack widths and lengths, in addition to rut depths.

Another advantage of the presented system is that both cracking and rutting are analyzed using the same photographs. This completes the philosophy behind the system's design - simplification of the collection system followed by more sophisticated analysis techniques.

CONCLUSIONS

The use of a non-metric camera collection system, combined with digitization using an analytical stereoplotter and analysis software, has been shown to be a useful approach in analysis of pavement cracking and rutting. The uniqueness in the photogrammetric approach was twofold. There was no need for control in the pavement photographs, and the photographs were taken with a camera axis that was tilted with respect to the measured surface.

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