Automation of Pavement Surface Distress Survey through Parallel Processing

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ABSTRACT

As a part of the Digital Highway Data Vehicle (DHDV), the automated survey system developed at the University of Arkansas is the implementation of a real-time system for pavement surface cracking survey. The researchers faced tremendous tasks in optimizing imaging algorithms to speed up the processing at the same time without sacrificing accuracy in identifying and classifying cracks. This report introduces the automated real-time system and summarizes the experiences in developing parallel algorithms in imaging processing used in the real-time system. The hardware system for processing images is based on the ubiquitous multi-CPU x86 platform that has the capability of parallel processing at multi-CPU level (Symmetrical Processing, SMP) and within CPU level (Single Instruction Multiple Data, SIMD). The paper also presents results of a network level survey with the Digital Highway Data Vehicle (DHDV) and the Distress Analyzer on a network of about 161 kilometers (100 miles) of pavements. In addition, a manual survey was conducted on the same network of pavements. World Bank's Universal Cracking

Indicator (CI) is used in the study. Because the Distress Analyzer is fully automated and results of the analysis are provided in synch with image collection, the potential cost savings when compared with manual survey methods and other semi-automated survey technologies are tremendous.

Subject Headings: Pavement condition, Pavement management, Parallel processing, Automatic identification systems

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INTRODUCTION

Analysis of pavement surface cracks is a major part of pavement condition survey. The predominant method in conducting such survey and analysis is still based on human vision, which is slow, expensive, prone to error, and poses safety problems. In recent years, there have been several applications of using automated methods, which acquire pavement surface images, identify and classify cracks with human assistance (Wang 2000). The image processing of such systems is usually based on post-processing and requires certain degree of human assistance. The Digital Highway Data Vehicle (DHDV) developed at the University of Arkansas (Wang et al 2002) integrates digital image acquisition and image processing into a real-time system that is able to acquire high-resolution images, identify, and classify surface cracks at real-time. Real-time processing of pavement surface cracks occurs about at the same time that pavement images are being obtained while the data vehicle is traveling at highway speed.

Figure 1 illustrates the framework of the data acquisition and processing in a parallel environment. Figure 2 shows a screen shot of the distress analyzer working with two CPUs. With a computer containing two Pentium 4 processors at 2.0-GHz per CPU, the processing speed for the distress analyzer is well over 97 KPH (60 MPH) on consistent basis (Wang, et al, 2002).

The DHDV's pavement imaging system has the resolution of 1300-pixel by 1024-pixel at the maximum frame rate of 15 per second. The next-generation system has the resolution of 4,096 pixels across a pavement lane. The relationship between image resolution and corresponding crack width is important in selecting proper imaging

technology in pavement condition survey. Table 1 shows that relationship. It should be noted that pavement surface crack does not present as a uniform line at fixed width. A crack varies greatly in width and is rarely a straight line. Experiences show that cracks with finer width than that shown in Table 1 can be visible for a corresponding camera resolution.

It is also important to understand that pavement images in 8-bit have 256 levels of shades, indicating that representation of a crack in an image may include many levels of shades. It is therefore subjective to determine crack width from images. In addition, experience also shows that visual inspection of pavement surface in the field may not yield commonly agreeable crack width either. The images used in this analysis were of the resolution of 1,300 pixels across a pavement lane, translating into theoretical detectable crack width of 3.0-mm.

At 97 KPH (60 MPH), the Distress Analyzer processes about 10 images per second, considering overlapping if images due to stitching. At that speed, the image data rate is about 13 MB per second and the number of image pixels to be processed in one second is about 13 million. As imaging algorithms mostly work on individual pixels, the computation needs are extraordinary and may require supercomputer level devices if real-time processing is needed. In developing algorithms for DHDV, it was found out that new desktop Central Processing Units (CPUs) based on the x86 structure have certain parallel processing capabilities that can speed up image processing.

The first parallel feature of the real-time system is based on industry standard Symmetrical Processing (SMP). The dual-processor SMP system used for DHDV is programmed with multi-thread techniques, so that each CPU has its own resources and

instructions to carry out the image analysis tasks. The second parallel feature is based on the within-CPU parallel capability called Single Instruction Multiple Data (SIMD). This paper addresses both capabilities and implementations of SMP and SIMD for the real-time survey system, and discusses on the use of finer parallelism within the CPU (SIMD) and the implementation of algorithms tailored to take advantage of SIMD features.

The basic capabilities of the Distress Analyzer as incorporated into the DHDV include real-time analysis of pavement images for cracks, creation of crack maps with geometric crack information, and storage of cracking information in database tables. Report Writer software can then be applied to the database tables to summarize the data into distress indices. Wang (2000) published a summary of distress survey system designs and performance over the last two decades. Wang (2002) presents an initial study on the use of the Distress Analyzer and Report Writer for sample sections. The same publication also has a detailed description of the general capabilities of the DHDV and the Distress Analyzer, which are not addressed in this paper. Particularly, that paper presents a study on using the DHDV and the Distress Analyzer for a section of 4.5 kilometers (2.8 miles) and applies three different distress protocols to summarize the cracking conditions of that pavement section.

To study the applicability of the DHDV and the Distress Analyzer, the Arkansas State Highway and Transportation Department (AHTD) in 2002 contracted the University of Arkansas to conduct a distress survey of a large portion of its non-interstate Nation Highway System (NHS). This paper presents data findings on about 161 kilometers (100 miles) of US 412 pavement across four adjacent counties in northern Arkansas (Figure 3).

SYMMETRICAL PROCESSING (SMP) AND ITS APPLICATION IN DHDV

Image processing can require substantial amount of processing power. In this application, there are tens of megabytes of raw image data per second that need to be read and analyzed for cracks. A few years back, only supercomputer class equipment can deal with this level of data rate on continuing basis. Recent implementations of parallel circuits in new class of Pentium CPU have provided an opportunity to explore the parallelism of these circuits to increase processing speed without resorting to expensive platforms. More interestingly, when images can be rapidly processed, the results from the processing can be obtained at real-time. This would benefit the application of the technology, as post-processing may not be necessary, resulting in saving of labor and time.

When a SMP system is to be used, the following factors should all be considered (IBM 1996). The analysis of the image processing application for detecting cracks made all the factors true:

- The workload is processor-limited and has saturated its uniprocessor system.
- The workload contains multiple processor-intensive elements, such as complex calculations, that can be performed simultaneously and independently.
- The existing uniprocessor cannot be upgraded or replaced with another uniprocessor of adequate power.
- Other considerations preclude dividing the workload among multiple uniprocessor systems.

Although unchanged single-thread applications normally function correctly in a multiprocessor environment, migration to a multiprocessor seldom improves the response time of individual, single-thread commands.

In designing our SMP system, additional factors were also considered:

Data Serialization: to avoid disaster, programs that share data must arrange to access that data *serially*, rather than in parallel. Before a program touches a shared data item, it must ensure that no other program (including another copy of itself running on another thread) will change the item. The primary mechanism to keep programs from interfering with one another is the *lock*, an abstraction representing permission to access one or more data items. If the lock is already held by another program (or another thread running the same program), the requesting program must defer its access until the lock becomes available. The Locking mechanism introduces overhead penalty in performance.

Memory and Bus Contention: In a uniprocessor, contention for some internal resources, such as banks of memory and I/O or memory buses, is usually a minor component processing time. In a multiprocessor these effects can become more significant, particularly if cache-coherency algorithms add to the number of accesses to RAM.

Even though these two factors are directly considered in the operating system, Windows 2000 and Windows XP Professional, the software algorithms for the DHDV were carefully written to avoid locking overhead and reduce memory and bus contention.

In designing the distress analyzer in Figure 2, there are three general steps to complete the analysis. The first step is to receive the real-time images and positioning data from the acquisition computer, cut and stitch the images together to form contiguous surface. The

second step is image analysis, including division of images, noise removal, determining characteristics of vector elements, and others. The third step is to display analysis results and save data into the real-time database tables. The three-step work flow was determined to fit into SMP processing very well, and techniques such as threading is used to achieve coarse-level parallelism.

Threading is the execution path of a software process. It has its own independent memory stack and CPU registers. However, all threads share all other resources, including system memory, input/output devices and files. All thread in one software process share the same 32-bit address space. Threads can be assigned priority levels for execution preference. The execution of threads is controlled by a master dispatcher in DHDV, which manages the incoming real-time images and data, and maintains two parallel processes.

Figure 4 shows the design and work flow of the distress analyzer. When the master dispatcher receives images and data from the acquisition computer, it creates and maintains two processes in parallel. Each of the three steps is a thread. The result is that the performance of the distress analyzer is nearly doubled versus a single process implementation.

BASICS OF MMX AND SSE

For the second generation of Pentium processors, Intel Corporation started using MultiMedia eXtensions (MMX) was used to extend the instruction set for Intel Architecture (IA). MMX uses the principles of Single Instruction Multi Data (SIMD) that have been traditionally used in large commercial computers for parallel processing. Generally, hardware capable of SIMD allows the application of a single instruction, such

as addition, to more than one set of data at the same time, therefore accelerating the processing speed by a large margin.

SIMD execution is the concept of performing multiple computations with a single instruction in parallel. For example, several times faster computation is possible with proper written code for SIMD hardware than with conventional code written in sequential execution. The new capabilities along with MMX are called SSE, and also SSE2, standing for Streaming SIMD Extensions. These computations are performed concurrently 128-bits at a time. It is expected that in the future, new parallel extensions will be introduced to further enhance desktop level parallel processing.

For example, in Figure 5, X_i and Y_i are data sets, each contained within a register (Register1 and Register 2 respectively). The "Result Register" contains the values from the operation performed on the two data sets. The computations of the four operations are carried out simultaneously, achieving parallelism and therefore acceleration. It was apparent to the authors that such parallel capability at the desktop level would vastly increase the speed of processing images to detect cracks. The actual implementation of imaging algorithms in the parallel environment proved that it is indeed fruitful.

SIMD ALGORITHMS FOR PAVEMENT SURFACE IMAGING

Overview of the General Imaging Techniques for the DHDV

The image analysis used in DHDV includes the following steps:

- Image combination: images collected at real-time are streamed into the distress analyzer computer along with locations data, such as distance information from the Distance Measurement Device. In order to stitch the images into a

contiguous surface images of pavements, the streamed images need to be cut and combined to form the needed surface. This task primarily uses JPEG decoding and encoding algorithms for cutting and combining.

- Image enhancement: in order to produce binary image with cracking information, images are all enhanced to eliminate noises. DHDV uses histogram equalization and adaptive thresholding to generate binary images for further processing (Russ 1999). Particularly, image segmentation is used to divide images into smaller areas and different thresholding values are used for image enhancement.
- Feature analysis: in order to determine geometric characteristics of cracks, such as length, width, orientation (angle), algorithms such as closing, thinning, and Hough transformations are conducted to the preprocessed images.
- Classification and analysis of cracks: based on results from previous steps, methods such as projection are used to determine the main types of cracks, such as longitudinal and transverse cracks, and fatigue and block cracks.

The above algorithms all use 8-bit gray-scale images. These computations involve large amounts of data, such as applying a filter on adjacent pixels at the rate of over 10 million pixels per second. The data types introduced by SSE allow the use of one variable to represent four or eight pixel values, therefore achieving much better computation efficiency.

Through the use of SMP dual-processing, proper separation and communication in software of the two processes for two CPUs, speed of image analysis can be nearly

doubled. However, the huge amount of data to be processed still posed substantial challenge in getting the distress analyzer in DHDV to run at highway speed. The implementation of techniques based on SIMD in SSE helped further increase the output of the distress analyzer.

Except for the classification of cracks, which relies on the general characteristics of cracks in the entire image, all other analyses described previous can be conducted by breaking images into several areas. As the operation with these algorithms on the areas is identical, the techniques in SIMD in SSE can be conveniently applied to the imaging algorithms. Results obtained from operating on these areas in parallel are then combined to produce analysis on the entire image.

Data Definition and Imaging Examples for SIMD Parallelization

Data variables must be declared and used properly before SIMD parallelization in SSE can be executed. That is, instructions in SSE can only operate on specially defined data variables. After parallel execution, data in the specially defined variables are then transformed back into normal data types for regular processing, which takes additional CPU resources. Therefore, in order to render the use of SIMD in SSE efficiently, frequent transformations between the specially defined data types and regular data types should be avoided. One data type used for SIMD of SSE is call Iu8vec8. Iu8vec8 is a 64-bit integer data type. Each of the eight 8-bit segments in the 64-bit data can be individually used, therefore achieving parallelism when the eight 8-bit segments are used as individual variables and a common instruction is applied.

Figure 6 illustrates the use of Iu8vec8 data type to prepare an image for parallel processing. The image is broken down into eight even pieces. Eight 8-bit values of each

corresponding pixel in the eight image pieces are contained in a 64-bit variable of the Iu8vec8 data type. After this preparation, a number of imaging algorithms can be then applied to all eight image pieces at the same time. The following examples discusses how SIMD techniques in SSE are used in several important imaging methods in the DHDV's distress analyzer.

MEDIAN FILTER

Median filter is a type of low-pass filter that is normally used to reserve edges of image and at the same time remove certain noises. In a 8-bit image, a median filter works on each pixel in the image and its adjacent eight pixels. The value of that pixel is replaced by the median value out of the nine values of the adjacent eight pixels and the pixel itself. This operation fits the SIMD operation well, as an image can be divided into eight areas of the same size; values of all eight corresponding pixels in the eight areas are then contained in one Iu8vec8 data variable. After the application of medium filter to all pixels, an additional processing is needed to adjust values for pixels at the borders of the areas and combine the areas together.

THINNING

Thinning in a binary image is to eliminate simple edge pixels of image characters that are not ending points, and at the same time without changing the shape nor the length of the characters. The purpose is to prepare for vectorization of the image character and using Hough method to identify the direction of the character. Figure 7 is a nine-pixel image area. The task is to determine if the pixel *p*, which is black, should be thinned for elimination. Pixel *p* has four immediate adjacent pixels, *n*, *s*, *w*, and *e*. The values for the

five pixels are either 1 for black or 0 for white. In reference to pixel *n*, the following set equation shall be satisfied to eliminate pixel *p*:

$$w\bar{s}e + \bar{w}(nw) + (ne)\bar{e} + \bar{e}(se)\bar{s} + \bar{s}(sw)\bar{w} = 0 \quad \text{.....(1)}$$

Where:

n, *s*, *w*, and *e*: pixel values (0 or 1) for the four immediate adjacent pixels of pixel *p*.

Iu8vec8 data types are directly employed here to parallelize the processing for thinning. Figure 8 (a, b) shows the original image and the result from thinning using SIMD technique. The image is divided into eight rows shown in Figure 8(b). Values of corresponding pixels in the eight rows are contained in Iu8vec8 data variables for simultaneous processing.

CLOSING

Closing is a Morphing technique to connect and smooth objects, such as cracks in images. The technique includes Dilution and then Erosion, represented by the following equation:

$$\text{CLOSE(X)=E(D(X))} \quad \text{.....(2)}$$

Where:

X: original image in pixel formation shown upper-left in Figure 9

D(X): dilution action on the image X shown bottom-left in Figure 9

E(D(X)): erosion action on the diluted image shown bottom right in Figure 9

B in Figure 9 is the dilution filter. Similarly, the use of SIMD technique is based on the operation on eight evenly divided areas of an image. Application of SMP and SSE techniques for the Distress Analyzer improves processing speed by a factor of three to four versus conventional uni-processor based and one process based coding. However, because communication between threads and processes, commonly called thread messaging, can slow down the parallel system, it is important to design and code the programs so that the this type of communication can be minimized.

SURVEY PROTOCOLS

Universal Cracking Indicator

The Universal Cracking indicator (CI) (Patterson 1994) is the simple product of the three primary physical dimensions observed for cracks:

$$CI = extent \times intensity \times crack\ width \quad \text{..... (3)}$$

Where extent is the area of cracked pavement defined within a sample area, which may be the perimeter bounding a set of cracks, expressed as a percentage of total pavement area. The intensity is the total length of cracks within the area defining the extent (expressed in m/m^2). The crack width is the mean width of crack opening at the surface of a set of cracks (expressed in mm). Figure 10 illustrates the basic graphical concept for Universal Crack Indicator (CI).) (Patterson 1994) provides detailed algorithm discussion on calculating CI with varying types of cracks.

Protocol Implementations

For the 161-kilometer (100-mile) network level survey, both the manual rating and Distress Analyzer systems used exactly the same set of digital images to conduct pavement distress analyses. The Distress Analyzer rated 100% of the project road surface images

and determined cracking criteria values by actual measurement of discontinuities. Data was stored in Microsoft Access database files that were then examined by Report Writer software. Protocol results are calculated with the Report Writer by section and produced into Microsoft Excel spreadsheet format. Manual survey results were based upon visual examination of images of the first 260 feet of each mile (5% of pavements) viewed on a computer monitor at resolution of 1600 x 1200. The decision to conduct survey on only 5% of pavements is due to limitation of availability of raters and time. Estimated rating values were recorded manually onto hardcopy worksheets and later transferred to Microsoft Excel spreadsheets where custom functions were developed for data and statistical analysis. Results from manual surveys are assumed to be representative of the entire mile. The Distress Analyzer is sensitive to image quality. In order to have time to tune image quality, the first mile of each county was omitted for both the Distress Analyzer and manual survey from the study.

For the application of Universal Cracking Indicator (CI), to determine *extent* values, the manual survey added the estimated areas of all cracks in the 79-meter (260-foot) sample area for each mile. Length of longitudinal and transverse cracks are directly used in Equations 4 to 7 letting the width value remaining as 1, due to the fact that manually determining crack width for extent values would take too much time for the rater and would lack necessary precision. In addition, because the unit of measurement is in foot, the result for extent values is actually the summation of lengths of cracks over total area. All fatigue cracks were given widths of 2.49 feet (0.76 meters), the width of a wheelpath. Block cracks were assumed to be equidimensional, and their longitudinal length was squared to calculate area. The summed total of all crack areas were then divided by the

total area of the 79-meter (260-foot) sample zone. The Distress Analyzer performed more accurate quantification of crack areas by using precise measurement capabilities within the software.

Both manual survey and Distress Analyzer *intensity* values were calculated by summing cracking data for all wheelpath positions in all severity levels as outlined in the AASHTO protocol. *Crack width* was calculated for the manual survey by multiplying the crack length of each type of crack by its average crack width in each 6.1-meter (20-foot) division then dividing that product by the total crack length for each division. Table 2 shows correlations between marked severity levels and their corresponding average crack width. The Distress Analyzer used actual measurements to average crack widths for each section.

DATA ANALYSIS AND RESULTS

Data Collection

TEST SECTION

Prior to the data collection of the network of pavements, seven consecutive sections of severely distressed pavement within the Fayetteville, Arkansas, city limits were chosen as a test section. Two manual raters and the Distress Analyzer inspected the entire seven-tenths of a mile in order to make direct comparisons over the section. This exercise was necessary to get the raters to be familiar with the distress protocols and the application of the Distress Analyzer.

NHS NETWORK

To compare manual and Distress Analyzer systems on a network level, a total of 161 kilometers (100 miles) of US 412 across four adjacent northern Arkansas counties (Figure 3) were surveyed by both rating techniques.

Data Analysis

Data compilations output by the Report Writer and results manually entered by the rater were compared in Excel via standard deviation analyses. CI values for the first section of each mile and the first mile as a whole were used in the analyses. Figures 11 to 16 and Tables 3 and 4 illustrate the results from the use of CI as the index for cracking survey of the network. Particularly, Tables 3 and 4 present data for the 161 kilometers (100 miles) of pavements in the four counties: Madison, Carroll, Boone, and Marion. Table 3 includes results based on 5% manual survey and 100% automated survey (the entire pavements). Table 4 shows results based on 5% manual survey and 10% automated survey. The 10% pavements used in the automated survey includes 5% pavement sections used in manual survey. The reason for using 10% automated survey is because the current Report Writer did not have the capability to produce data at the 5% interval, which has been subsequently enhanced to include any internals. However, this change was too late for being used for this paper.

After compilation of all automated and manual survey data, results from the two methods were compared using a standard deviation statistical analysis. Where standard deviation between manual survey and Distress Analyzer data was high, both rating methods were reviewed in an attempt to isolate and correct the cause of the discrepancy.

Based on the standard deviation values from the two tables, both analysis approaches generate similar results, even though the overall value for standard deviation shown in Table 4 is smaller than that in Table 3. This is expected and reasonable, since the 5% survey is more representative of the 10% pavements than the entire mile.

Figures 11 to 14 graphically present data from surveys conducted in Madison and Carroll Counties from Tables 2 and 3. Each pair of images uses data from the two approaches. It can be seen from the graphs that when cracking presence on pavement sections is limited or does not exist, results from both manual survey and the Distress Analyzer are very close. For a large number of sections where cracking presence is substantial, differences between results from manual survey and results from the Distress Analyzer do exist. But, in most cases the results from the two surveys are similar, particularly when cracking presence is small to moderate.

MADISON COUNTY

In Figure 12, pavements on miles 9, 16, and 21 have results from the Distress Analyzer well above these from the manual survey. This is due to the capture of cracks to the left of the near lane marker of the center double line. Figure 15 illustrates this problem. An adjustment to the lane size algorithm in the Distress Analyzer will create a better measure of the amount of cracking within the lane. This work is underway and will be completed shortly. Figure 11 shows comparison of data from the Distress Analyzer over each entire mile versus results from the 5% manual survey. In Figure 11, for pavements on miles 13, 15, 23, and 24, cracking indices from the Distress Analyzer are much higher than the results from the manual survey. In miles 13, 15, and 24, it was found out by examining all relevant images that there exists large number of dense areas of

cracking after the first 10% of each mile. This is particularly true for miles 13 and 15. In mile 23 of Figure 11, there exist a large number of cracks over the second 5% of the mile, therefore the manual survey could not catch the cracks, while the Distress Analyzer did.

Overall, the Distress Analyzer produces higher cracking index values than the manual survey for most of the pavement sections on Madison 412. There are two reasons for this. The first is that the automated procedure may have found more cracks because it grades 100% of each mile. The second reason is the Distress Analyzer picked up some noises for cracks, such as stains, tire tracks, train rails. The Distress Analyzer ignores most noises. When the image quality is not of the highest, it may occasionally make errors, such as including certain noises as cracks.

CARROLL COUNTY

In Figure 14, pavements on miles 5, 9, 10, 14, and 17, have higher cracking indices from the Distress Analyzer than those from the manual survey. One reason for this discrepancy is the capturing and recording of cracking outside the lane markers, similar to the problem in Figure 15. Particularly for mile 9, the vehicle strayed off during this section of pavement from the center of the lane, causing the Distress Analyzer to recognize substantial amount of cracks outside of lane markings. Miles 5, 10, 14, and 17 all have substantial cracking beyond the first 5% of pavement, but within the 2nd 5%, thus the higher cracking index. In Figure 13, data from the Distress Analyzer on entire miles are more representative of the results from manual survey than data from Figure 14. However, some discrepancies are present. Miles 4 and 7 have some image quality problems. Miles 18 and 19 have moderate cracking indices for the entire mile but do not have recorded

values from the rater. Again, this is due to cracking occurring in the rest of mile, but not for the first 10% of each mile.

Experiences with the Distress Analyzer

The Distress Analyzer does offer several advantages over manual distress surveys. The Distress Analyzer is fully automated, resulting saving in terms of time and resources. Although results from the Distress Analyzer and manual surveys in this paper do not agree perfectly, tabulated data comparisons show favorable correlations between results from automated and manual surveys. Even for the manual surveys conducted for the demonstration section, CI values produced from inspection of two different raters may show significant variations. Distress Analyzer results are consistent. As demonstrated by Wang (2002), Distress Analyzer results for multiple passes over the same sample are consistent to within about 15%.

In addition, the Distress Analyzer eliminates human error. There are several opportunities for human error in the manual rating process. These include errors estimating crack dimensions from viewed images, recording data on the survey chart, and transferring data from the chart to the Excel spreadsheet. Distress Analyzer software can perform and complete analysis of collected digital images at normal highway speeds while images and positioning data are being acquired. This means that when a data collection run is finished, that data will have already been analyzed for distress. Distress Analyzer software can also be run in an unsupervised lab environment at equivalent highway speeds if simultaneous collection and inspection are not required. Manual rating of digitally-collected images is labor-intensive and time-consuming. For this survey of 161 kilometers

(100 miles), manual rating time was 24 hours with an additional 4 hours for data entry. Manual surveys in the field require even much more man-hours to perform.

CONCLUSION

In the past, rapid processing for distress survey required supercomputer level devices. The rapid advances of x86 structure and its new parallel features provided us an opportunity to explore a low-cost approach to this difficult and potentially expensive problem. However, real-time processing is just one part of the whole story. Consistency of results is also important. Preliminary analysis results presented in the paper compare results from the automated distress analyzer and manual surveys, particularly in view that baseline cracking survey with manual method is also a difficult and subjective process. A new image acquisition system with transverse resolution of 4,096 pixels has replaced the current system at the time of final submission of the paper. This new acquisition technique establishes a system capable of capturing cracks at 1 mm size. The application of parallel processing and faster CPUs is even more important in this new system, as raw image data rate can exceed 100 megabytes per second with the new system.

There are several necessary improvements to be made to the DHDV, the Distress Analyzer, and the Report Writer. For example, the Report Writer will be more flexible in sectioning pavement analysis length. The future goals include further improving the operating performance and efficiency of the automated system and incorporating new image capturing sub-system. It is anticipated that in the next few years that widespread use of fully automated crack survey systems will be a reality.

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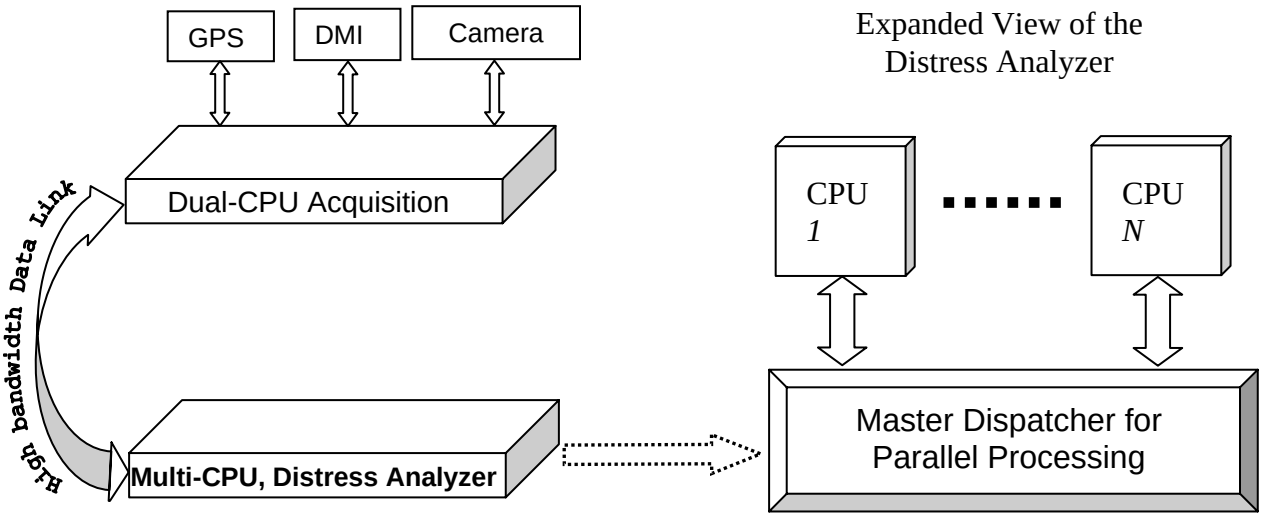


Fig. 1 The Framework of the Data Acquisition and Processing

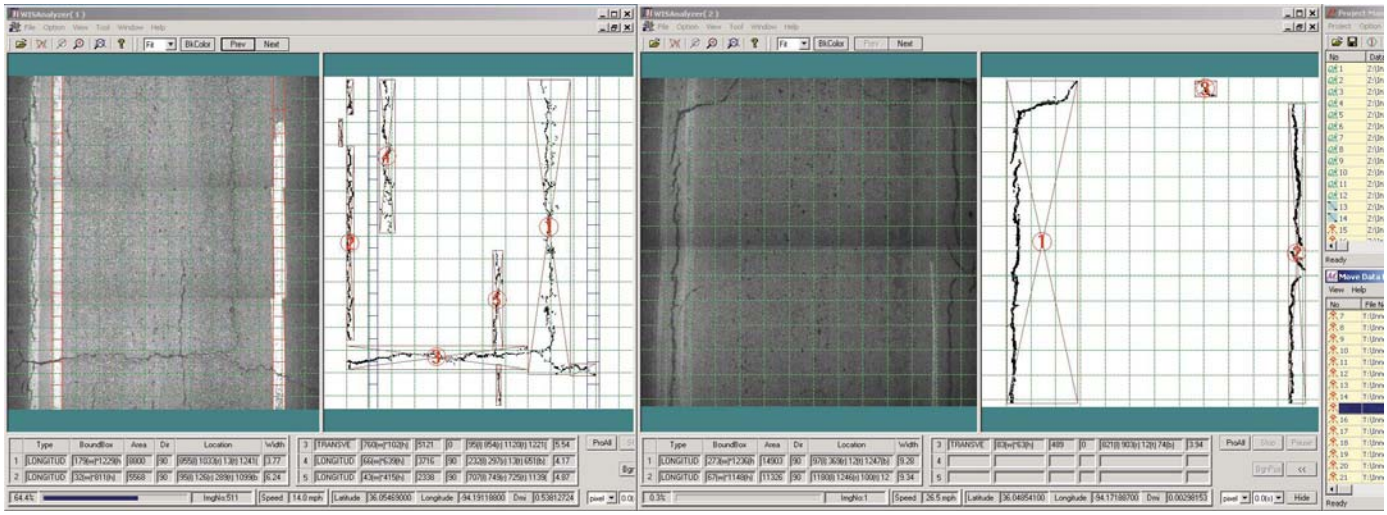


Fig. 2 Dual-Processing for Cracks in a Parallel Environment with the Distress Analyzer

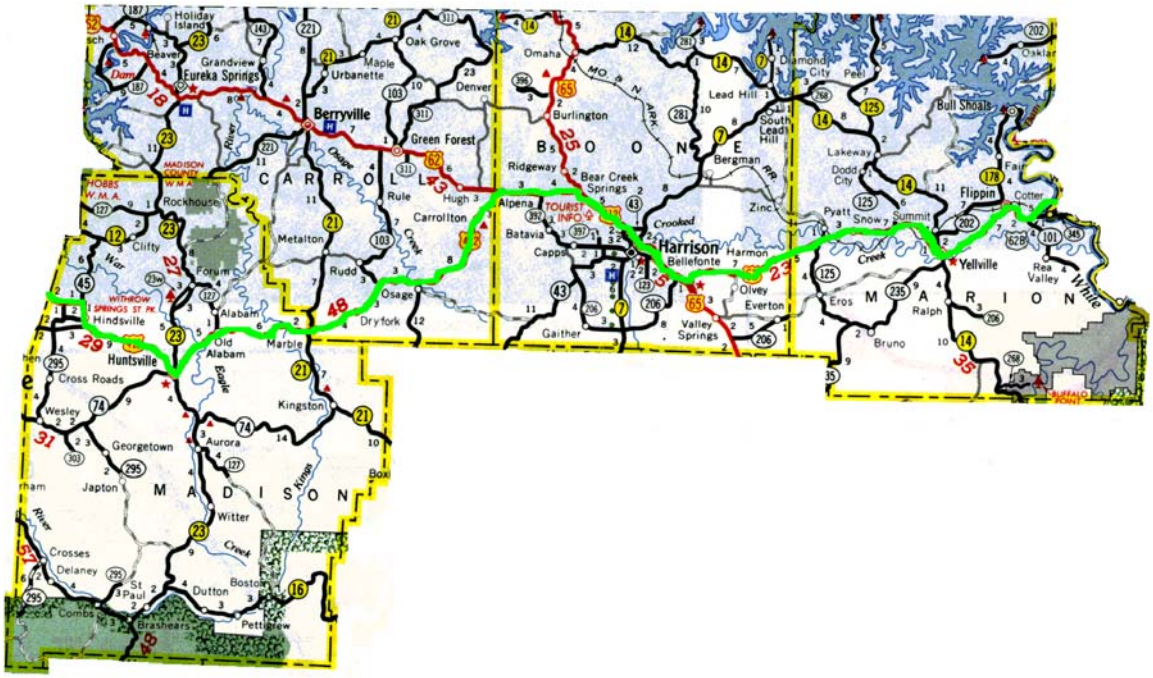


Fig. 3 US 412 (heavier line from left to right in the middle of the map) across distress survey counties totaling about 161 kilometers (100 miles).

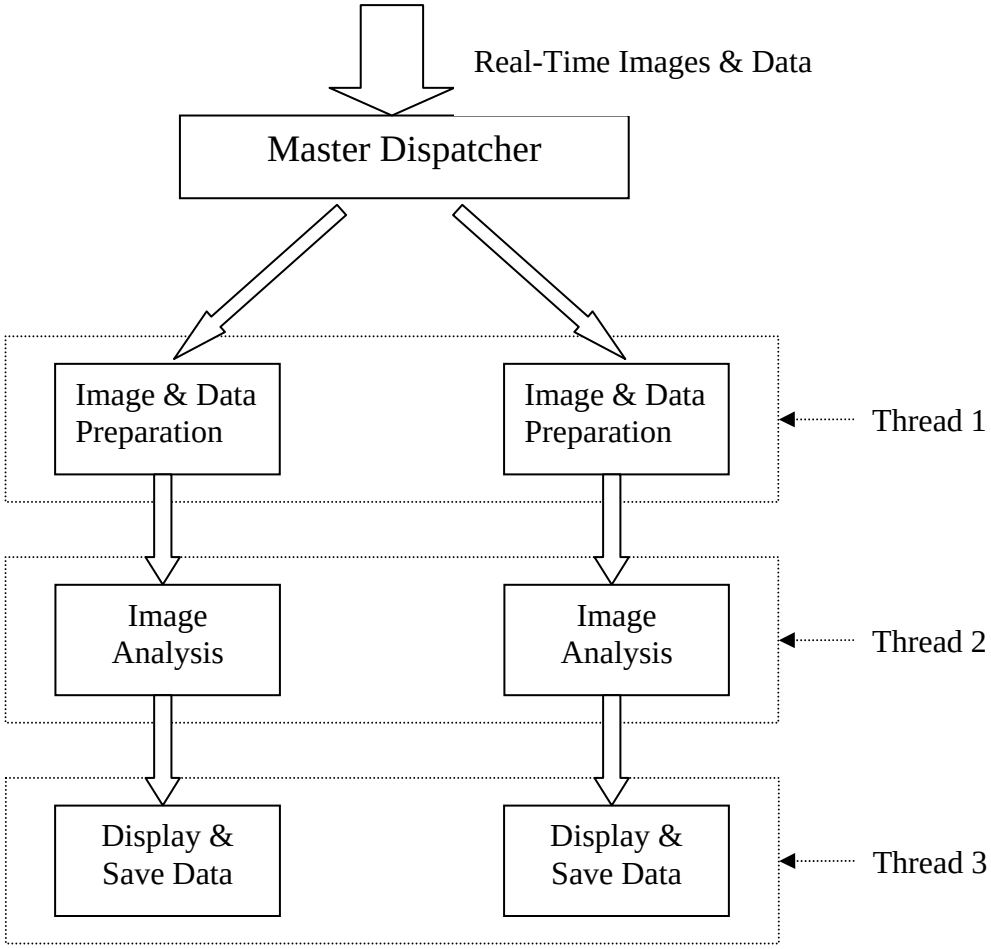


Fig. 4 SMP parallel processing for the distress analyzer

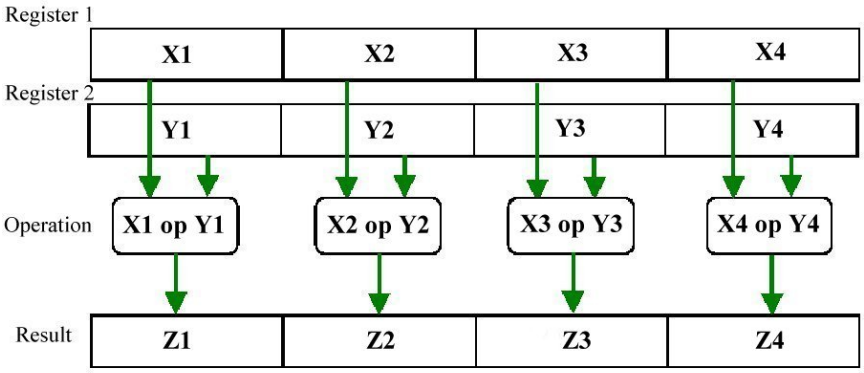


Fig. 5 Illustration of using SIMD for x86 processors

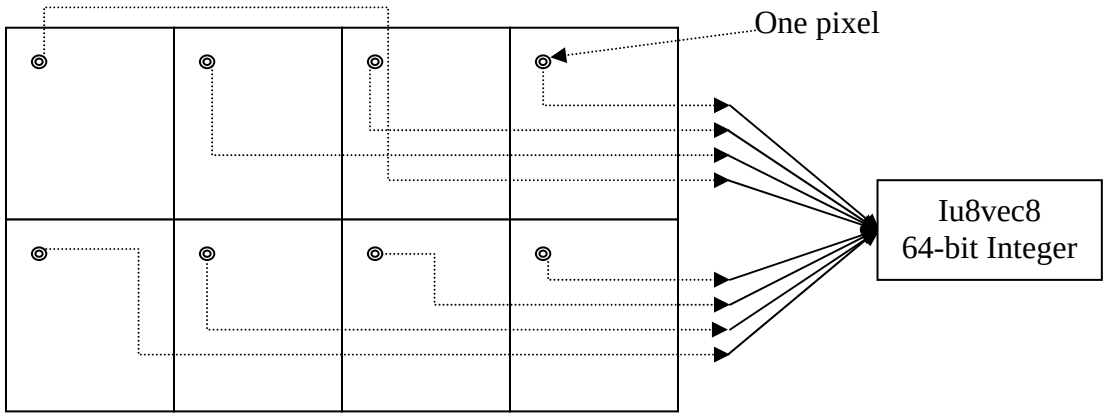
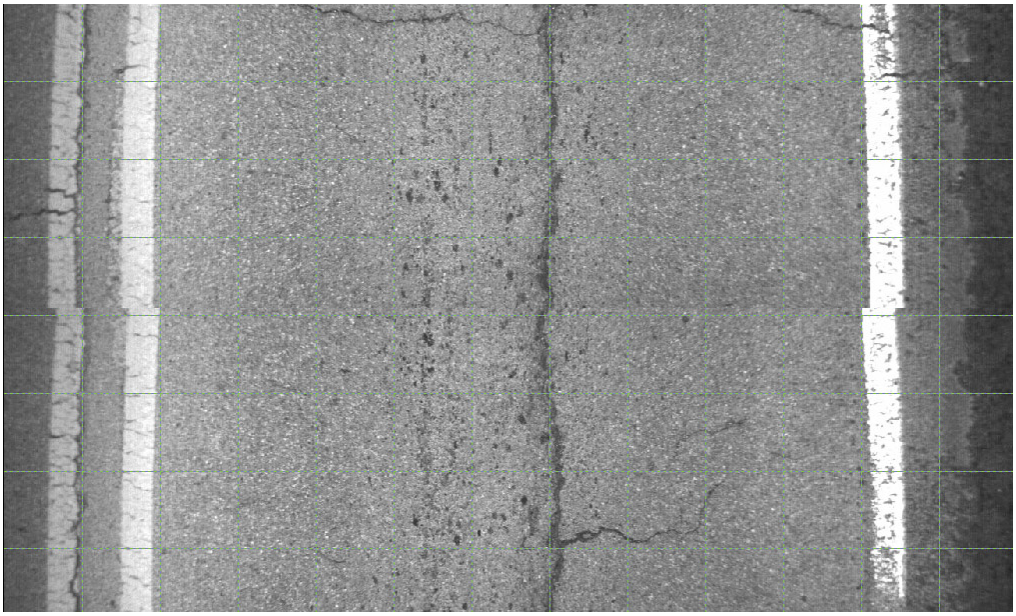


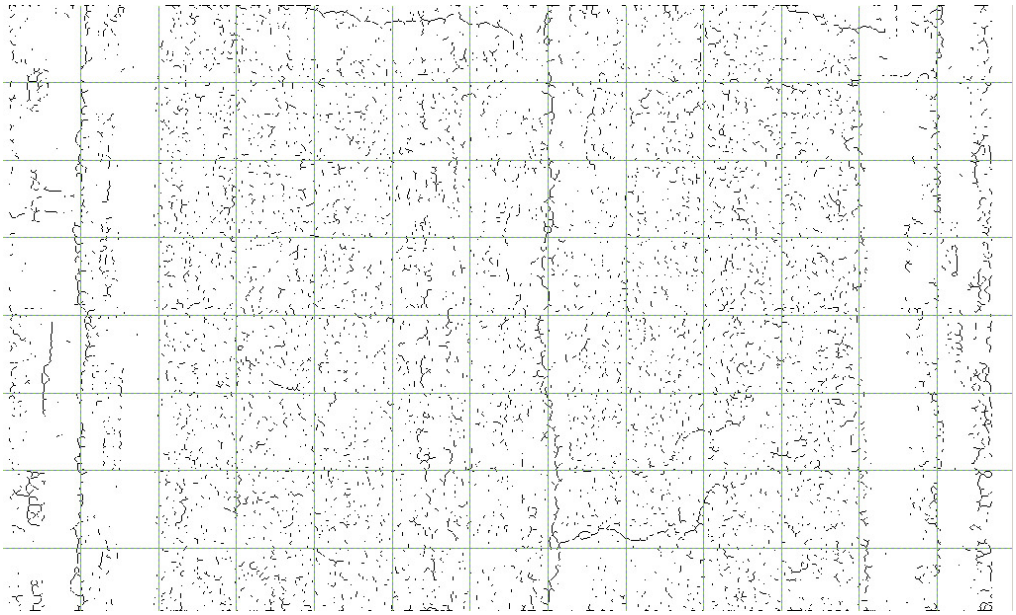
Fig. 6 Using SSE data type to hold values of 8 pixels for simultaneous processing

nw	**n**	ne
w	**p**	**e**
sw	**s**	se

Fig. 7 Thinning principle for the northern pixel n



(a) Before thinning



(b) After thinning with SSE

Fig. 8 Thinning using 13 loops with each column being processed with SSE SIMD techniques

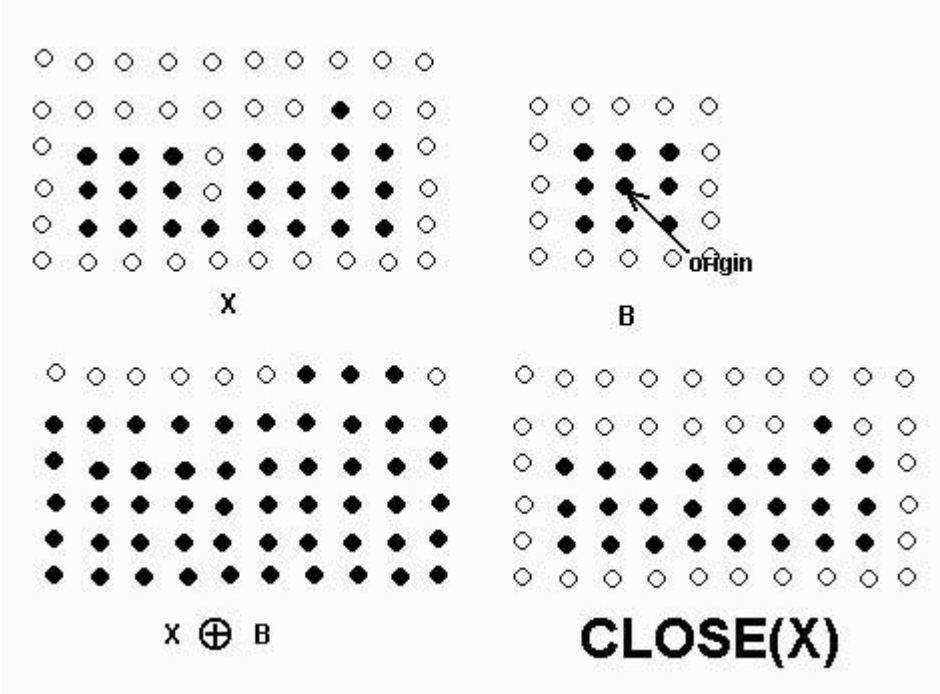


Fig. 9 Dilution and erosion for the Closing technique

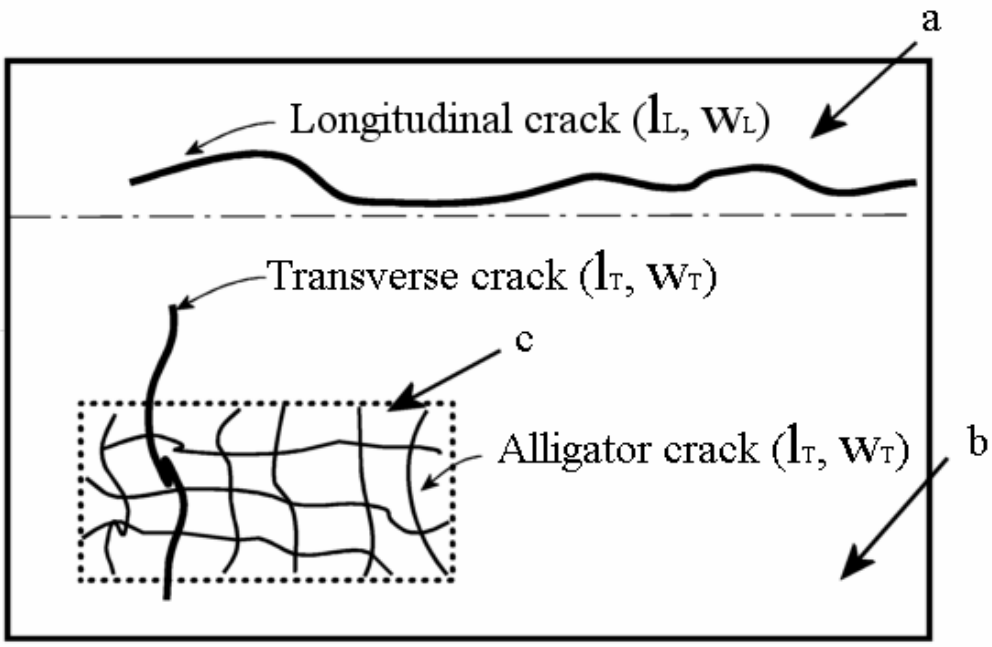


Fig. 10 The Basic Graphical Concept for the Universal Crack Indicator.

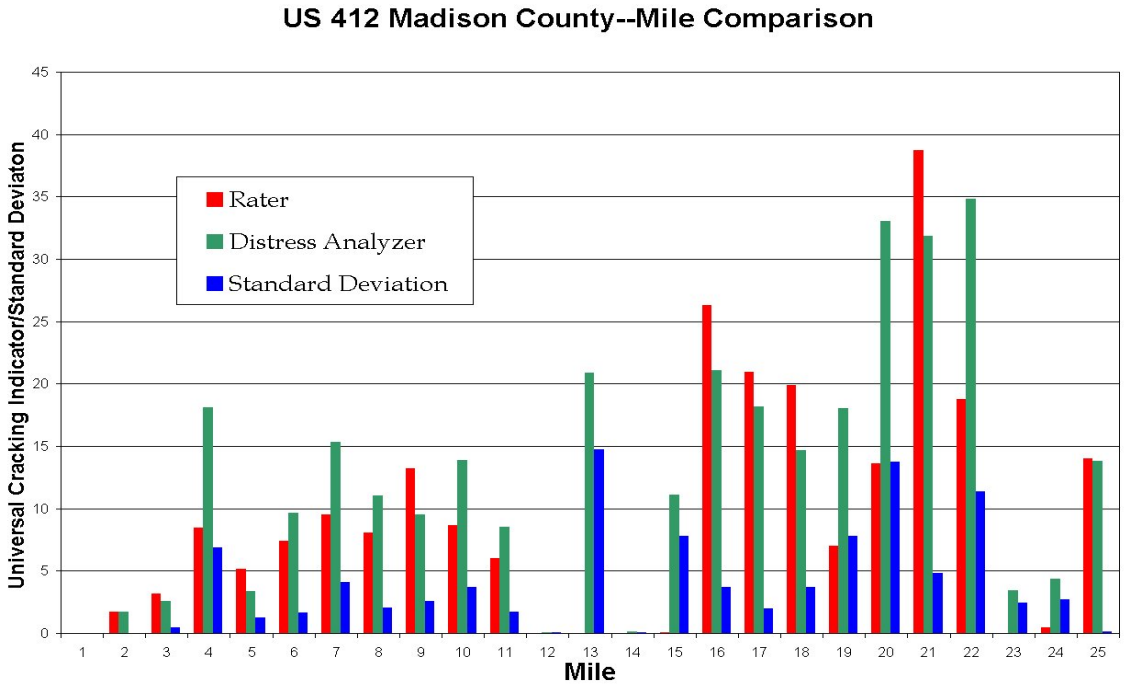


Fig. 11 Cracking (CI) Results for US 412, Madison County, 5% Manual Survey Versus 100% Automated Survey

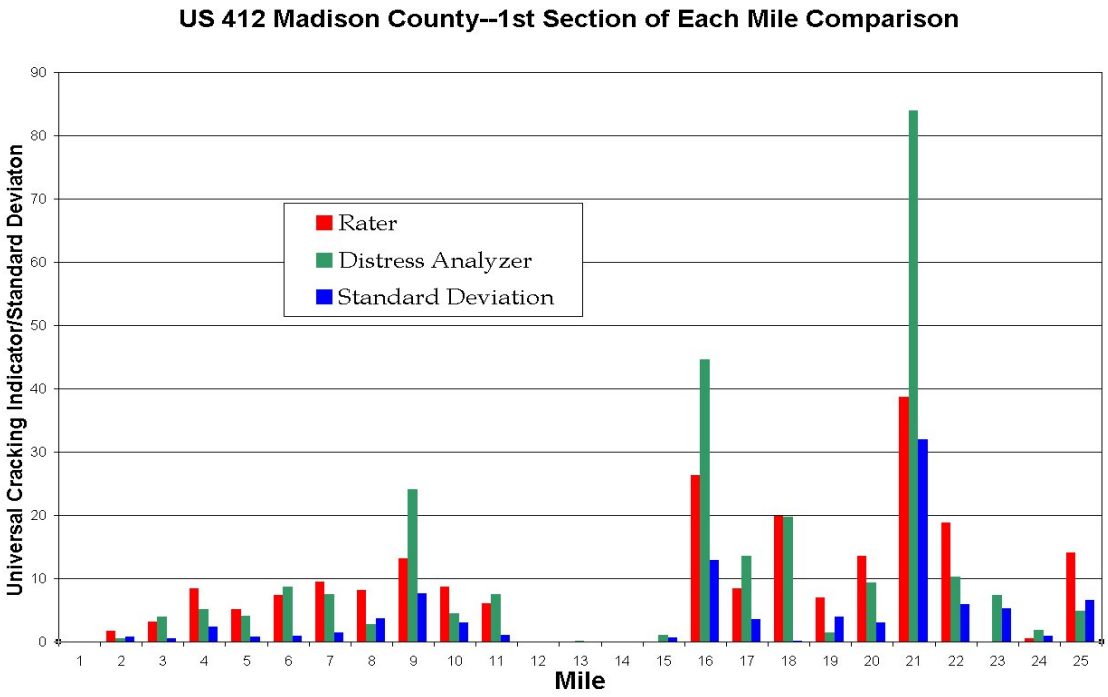


Fig. 12 Cracking (CI) Results for US 412, Madison County, 5% Manual Survey Versus 10% Automated Survey

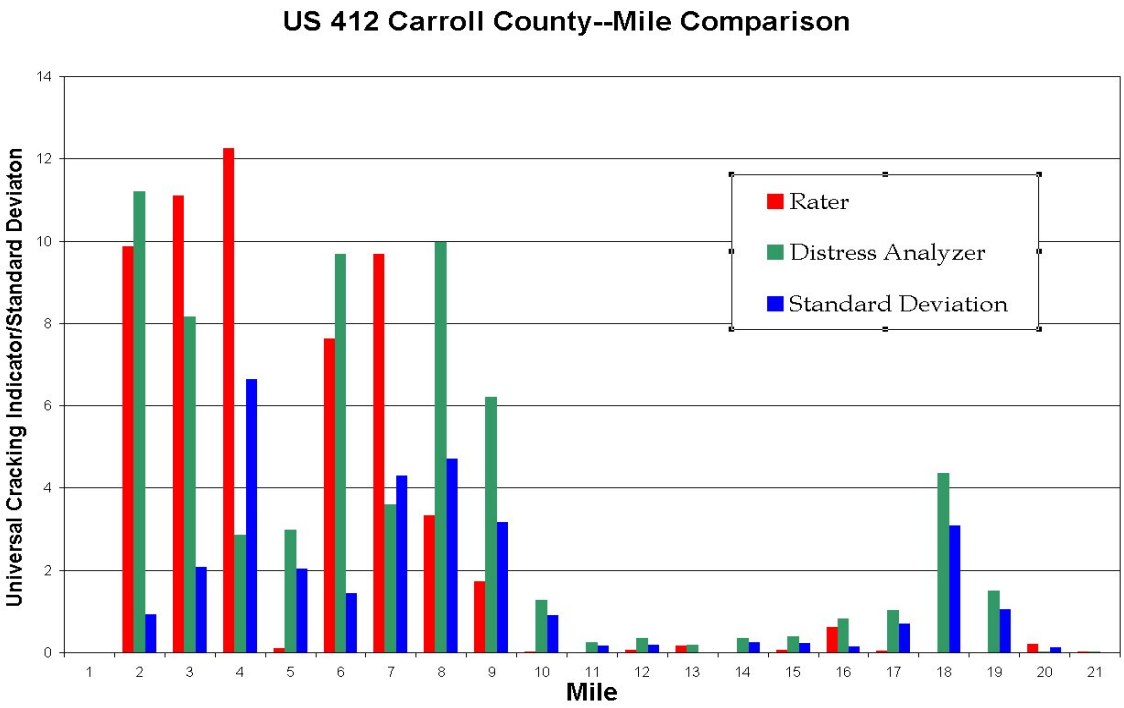


Fig. 13 Cracking (CI) Results for US 412, Carroll County, 5% Manual Survey Versus 100% Automated Survey

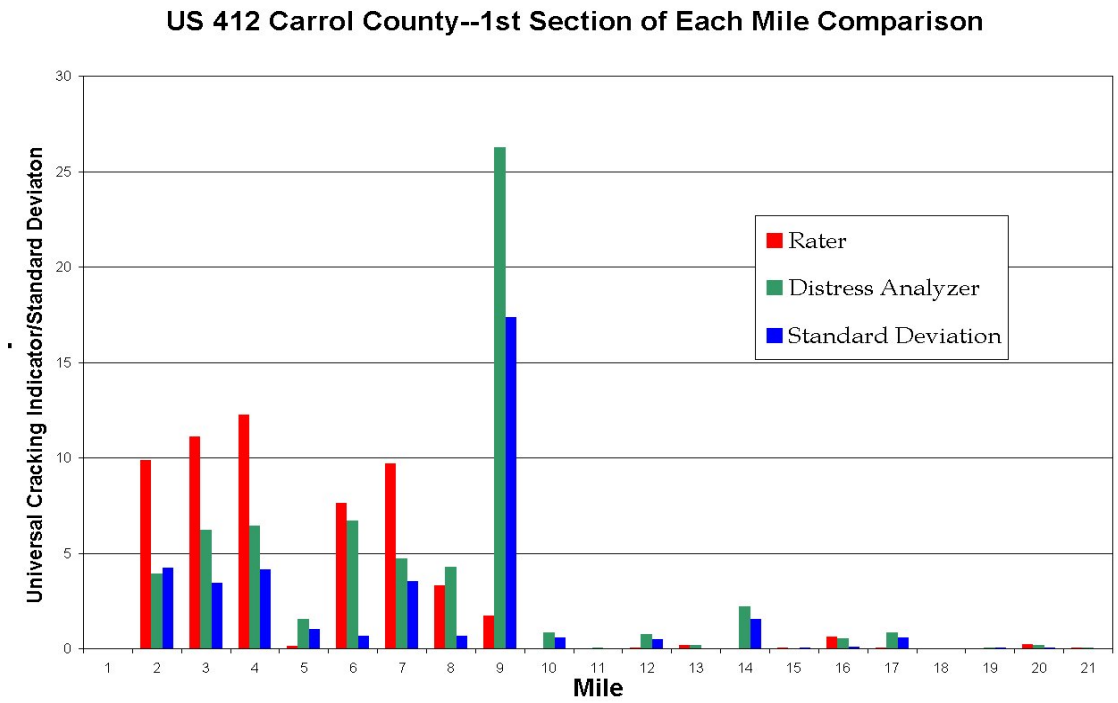


Fig. 14 Cracking (CI) Results for US 412, Carroll County, 5% Manual Survey Versus 10% Automated Survey

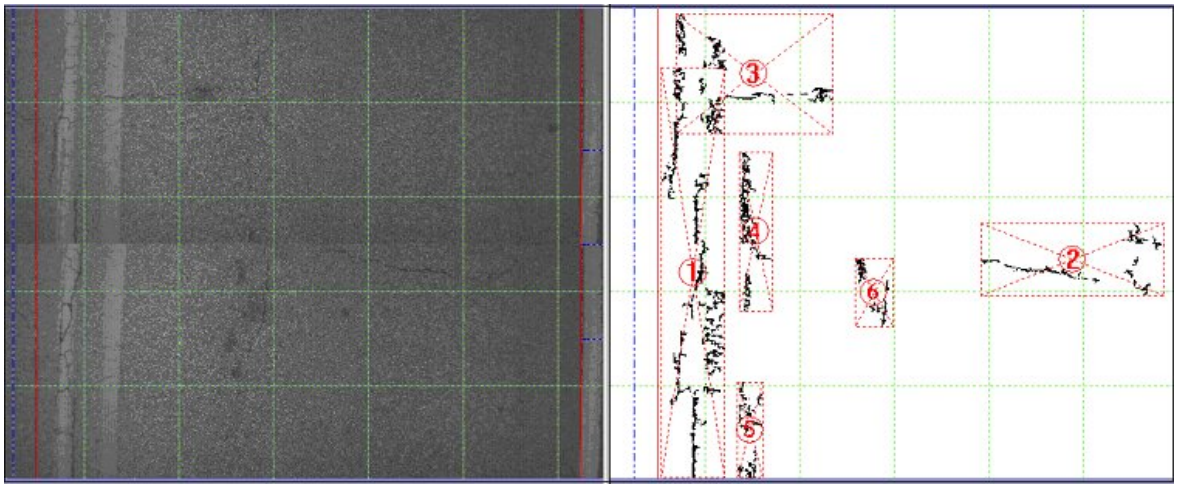


Fig. 15 Cracking within and outside of double-line picked up by analyzer, Mile 21, Hwy 412, Madison County

Table 1 Image Resolution and Theoretical Visible Crack Width (4-Meter Wide Lane)

Transverse Resolution	1300-Pixel	2048-Pixel	4096-Pixel
Visible Crack Width	3-mm	2-mm	1-mm

Table 2 Manual survey average crack width values assigned to recorded severity levels

Recorded Severity Level(s)	Average Crack Width Value (mm)
1	2
1 & 2	3.25
1 & 3	4.5
1, 2, & 3	4.5
2	4.5
2 & 3	5.75
3	7

Table 3 Universal Cracking Indicator (CI) Values, Manual Rating with 0.08-Kilometer (0.05-Mile), Distress Analyzer with Complete Coverage

County	Madison			Carroll			Boone			Benton		
Mile	Rater	ADS	Stan. Dev.	Rater	ADS	Stan. Dev.	Rater	ADS	Stan. Dev.	Rater	ADS	Stan. Dev.
1												
2	1.721852	1.721000	0.000602	9.876061	11.195000	0.932631	0.957427	0.016000	0.665689	7.875452	7.422000	0.320639
3	3.182426	2.557000	0.442243	11.099004	8.170000	2.071119	0.055882	0.002000	0.038100	22.886501	2.313000	14.547662
4	8.459525	18.137000	6.843008	12.261201	2.865000	6.644118	0.017712	0.001000	0.011817	0.538214	1.872000	0.943129
5	5.168806	3.348000	1.287504	0.111042	2.985000	2.032195	0.000000	0.008000	0.005657	2.763169	1.766000	0.705105
6	7.383446	9.678000	1.622495	7.630226	9.678000	1.447995	0.082749	8.140000	5.697336	1.657045	0.762000	0.632892
7	9.524259	15.355000	4.122956	9.679027	3.601000	4.297814	25.501242	4.668000	14.731327	4.683871	0.398000	3.030568
8	8.094540	11.010000	2.061541	3.320530	9.974000	4.704713	0.008748	0.001000	0.005479	18.034350	5.648000	8.758472
9	13.184992	9.525000	2.588005	1.725552	6.207000	3.168863	0.000000	0.005000	0.003536	14.322608	12.437000	1.333327
10	8.643582	13.899000	3.716142	0.012465	1.280000	0.896283	0.047908	0.989000	0.665453	11.962513	8.168000	2.683126
11	6.037629	8.495000	1.737624	0.010042	0.244000	0.165433	23.294359	1.131000	15.671861	27.600741	6.412000	14.982703
12	0.000000	0.082000	0.057983	0.065371	0.341000	0.194899	0.032649	0.927000	0.632402	22.532178	26.367000	2.711629
13	0.000000	20.864000	14.753076	0.165899	0.178000	0.008557	1.395877	3.387000	1.407937	16.037039	4.170000	8.391264
14	0.000000	0.132000	0.093338	0.000000	0.359000	0.253851	1.475159	1.200000	0.194567			
15	0.052168	11.092000	7.806340	0.058977	0.381000	0.227704	26.094138	0.677000	17.972631			
16	26.323999	21.105000	3.690389	0.620697	0.817000	0.138807	9.828784	0.352000	6.701098			
17	20.974192	18.148000	1.998419	0.049860	1.037000	0.698014	0.000000	0.640000	0.452548			
18	19.922474	14.648000	3.729617	0.000000	4.350000	3.075914	0.540681	0.231000	0.218977			
19	7.032918	18.046000	7.787425	0.006565	1.502000	1.057433	5.311309	1.111000	2.970067			
20	13.599226	33.058000	13.759431	0.201187	0.028000	0.122462	6.599127	16.463000	6.974811			
21	38.690930	31.872000	4.821712	0.024724	0.015000	0.006876	6.807715	7.089000	0.198899			
22	18.754641	34.805000	11.349318				12.169977	4.220000	5.621483			
23	0.000000	3.451000	2.440226				10.821123	7.721000	2.192118			
24	0.492133	4.356000	2.732167				13.158743	2.111000	7.811934			
25	14.041229	13.822000	0.155018				2.300284	1.440000	0.608312			
26							6.428668	5.007000	1.005271			
27							27.042171	9.225000	12.598643			
28							6.294325	3.951000	1.656981			
29							0.002918	1.210000	0.853536			
County Averages:			**4.14985748**			**1.60728401**			**3.76100962**			**2.56697888**
Route Average:			**3.0212825**									

Table 4 Universal Cracking Indicator (CI) Values, Manual Rating with 0.08-Kilometer (0.05-Mile), Distress Analyzer with 0.16-Kilometer (0.1-Mile) Coverage

County	Madison			Carroll			Boone			Benton		
Mile	Rater	ADS	Stan. Dev.	Rater	ADS	Stan. Dev.	Rater	ADS	Stan. Dev.	Rater	ADS	Stan. Dev.
1												
2	1.721852	0.540000	0.835695	9.876061	3.920000	4.211571	0.957427	0.130000	0.585079	7.875452	0.850000	4.967745
3	3.182426	3.890000	0.500330	11.099004	6.210000	3.457048	0.055882	0.000000	0.039515	22.886501	10.840000	8.518163
4	8.459525	5.130000	2.354329	12.261201	6.420000	4.130353	0.017712	0.000000	0.012524	0.538214	6.220000	4.017629
5	5.168806	4.040000	0.798186	0.111042	1.520000	0.996284	0.000000	0.000000	0.000000	2.763169	0.390000	1.678084
6	7.383446	8.690000	0.923873	7.630226	6.680000	0.671911	0.082749	0.000000	0.058513	1.657045	0.010000	1.164636
7	9.524259	7.560000	1.388941	9.679027	4.720000	3.506562	25.501242	28.150000	1.872954	4.683871	1.700000	2.109915
8	8.094540	2.810000	3.736734	3.320530	4.260000	0.664305	0.008748	0.000000	0.006186	18.034350	17.860000	0.123284
9	13.184992	24.040000	7.675650	1.725552	26.270000	17.355546	0.000000	0.000000	0.000000	14.322608	0.420000	9.830629
10	8.643582	4.430000	2.979452	0.012465	0.820000	0.571014	0.047908	0.030000	0.012663	11.962513	2.480000	6.705149
11	6.037629	7.550000	1.069408	0.010042	0.030000	0.014112	23.294359	2.350000	14.809898	27.600741	14.830000	9.030278
12	0.000000	0.020000	0.014142	0.065371	0.740000	0.477035	0.032649	0.390000	0.252685	22.532178	11.020000	8.140339
13	0.000000	0.080000	0.056569	0.165899	0.170000	0.002900	1.395877	4.070000	1.890891	16.037039	6.030000	7.076045
14	0.000000	0.030000	0.021213	0.000000	2.210000	1.562706	1.475159	0.020000	1.028953			
15	0.052168	1.010000	0.677290	0.058977	0.020000	0.027561	26.094138	0.540000	18.069505			
16	26.323999	44.590000	12.916013	0.620697	0.520000	0.071203	9.828784	0.160000	6.836863			
17	8.459525	13.540000	3.592439	0.049860	0.850000	0.565785	0.000000	0.430000	0.304056			
18	19.922474	19.770000	0.107816	0.000000	0.010000	0.007071	0.540681	0.040000	0.354035			
19	7.032918	1.390000	3.990146	0.006565	0.060000	0.037785	5.311309	1.180000	2.921277			
20	13.599226	9.300000	3.040012	0.201187	0.170000	0.022052	6.599127	0.420000	4.369303			
21	38.690930	83.910000	31.974711	0.024724	0.030000	0.003730	6.807715	8.710000	1.345119			
22	18.754641	10.290000	5.985405				12.169977	9.320000	2.015238			
23	0.000000	7.370000	5.211377				10.821123	4.560000	4.427282			
24	0.492133	1.810000	0.931873				13.158743	0.980000	8.611672			
25	14.041229	4.820000	6.520394				2.300284	0.260000	1.442698			
26							6.428668	1.700000	3.343673			
27							27.042171	27.790000	0.528795			
28							6.294325	2.060000	2.994120			
29							0.002918	1.140000	0.804039			
County Averages:			**4.0542499**			**1.9178267**			**2.73850085**			**2.75486501**
Route Average:			**2.86636062**									

Figure Captions:

Fig. 1 The Framework of the Data Acquisition and Processing

Fig. 2 Dual-Processing for Cracks in a Parallel Environment with the Distress Analyzer

Fig. 3 US 412 across distress survey counties totaling about 161 kilometers (100 miles)

Fig. 4 SMP parallel processing for the distress analyzer

Fig. 5 Illustration of using SIMD for x86 processors

Fig. 6 Using SSE data type to hold values of 8 pixels for simultaneous processing

Fig. 7 Thinning principle for the northern pixel n

Fig. 8 Thinning using 13 loops with each column being processed with SSE SIMD techniques

Fig. 9 Dilution and erosion for the Closing technique

Fig. 10 The Basic Graphical Concept for the Universal Crack Indicator.

Fig. 11 Cracking (CI) Results for US 412, Madison County, 5% Manual Survey Versus 100% Automated Survey

Fig. 12 Cracking (CI) Results for US 412, Madison County, 5% Manual Survey Versus 10% Automated Survey

Fig. 13 Cracking (CI) Results for US 412, Carroll County, 5% Manual Survey Versus 100% Automated Survey

Fig. 14 Cracking (CI) Results for US 412, Carroll County, 5% Manual Survey Versus 10% Automated Survey

Fig. 15 Cracking within and outside of double-line picked up by analyzer, Mile 21, Hwy 412, Madison County