A REPORT/PROPOSAL TO:

THE ADVANCED HIGHWAY MAINTENANCE TECHNOLOGY RESEARCH GROUP

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On the Automatic Sealing of Cracks in Pavement

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Introduction

Caltrans is responsible for the maintenance of approximately 38,000 miles of flexible pavement (Asphalt Concrete - AC) and 17,000 miles of rigid pavement (Portland Cement Concrete - PCC). On an annual basis, Caltrans allocates over $100 million to maintain highway pavement. A portion of these maintenance activities involves the sealing of cracks (approximately $10 million per year) which when performed properly can help retain the structural integrity of roadways and extend considerably the mean time between major rehabilitation. As part of the Caltrans Advanced Highway Maintenance Technology (AHMT) Program, a group of individuals at UC-Davis and Caltrans has been investigating methods to automate crack sealing operations in pavement. Initial efforts have been directed towards developing an understanding of current methods and applicable technologies. The ultimate goal of this project is to design an automated machine that will sense, prepare and seal cracks on pavement. Initially, the group will consider the sealing of cracks in AC pavement since the majority of sealing operations take place on this type of pavement. It is expected that the results of this work will later be extended to cover PCC as well.

Currently, the crack sealing process is a tedious, labor-intensive operation involving approximately eight individuals. A typical crack sealing operation seals between one and two lane miles per day. It costs about $1800 per mile to seal cracks with 66% attributed to labor, 22% to equipment, and 12% to materials. Furthermore, the procedure is not standardized and there is a large distribution in the quality of the resultant seal. By developing an automated crack sealing machine, we hope to:

- Minimize the exposure of workers to the dangers associated with working on a major highway.
- Considerably increase the speed of the operation.
- Improve the quality of the resultant seal.

Increasing the speed of the operation will in turn reduce the accompanying traffic congestion since lane closing times will decrease. The combination of the increased speed and the higher quality seal will prove to be extremely cost effective by reducing the frequency of major highway rehabilitations.

The purpose of this report is twofold; 1) to present a summary of the efforts and conclusions to date, and 2) to propose the path for future efforts. The content of this report is as follows. We will first summarize the desired seal characteristics based on an extensive literature review and discussions with experts. We will then outline the the critical aspects of the design of a machine for automatic crack sealing. In subsequent sections, we will detail tasks accomplished, summarize conclusions, and justify additional work for each of the subtasks. Finally, through a PERT chart, we will summarize the project schedule through completion in June 1992. The milestones of the PERT chart are shown at the end of the report. The fully detailed PERT chart which shows all project tasks is avialable upon request .

Criteria for the Sealing of Cracks in AC Pavement

Cracking in AC pavement primarily occurs due to thermal stresses and loss of binder in the asphalt. The first significant cracks which occur usually span the entire road perpendicular to the road direction and also occur in the middle of the road with the road direction. This occurs due to the inability of the road to accommodate tensile stresses during its cyclical heating and cooling. When cracking is significant (1/4" or more), water intrusion into the subbase is inevitable. When moving traffic depresses the pavement near a crack, the water is "pumped out" along with subbase material. The loss of the subbase then allows for greater pavement deflection near the original crack which causes further cracking parallel to the original thermal cracking. This process continues until significant damage occurs creating pot holes requiring major repair and possible rehabilitation. In order to curb this process the cracks must be "sealed" to prevent water intrusion. Simply "filling" the cracks gives no benefit as a preventative maintenance procedure. However, filling is useful for maintaining the road surface on significantly damaged roads. It is the intention of this work to prevent the type of damage that would require crack filling by identifying minor cracks and sealing them at the earliest possible time.

Currently, Caltrans specifies two types of crack sealant for use on AC pavement; rubberized asphalt (crumb rubber and asphalt), and emulsified asphalt (asphalt in water). Rubberized asphalt is a low cost, hot applied sealant which is usually applied as an overband on cracks which are 1/4" to 1/2" in width. In order for the sealant to be applied, the crack must be free of debris and moisture. The longevity of this type of seal is usually one to two years. Rubberized asphalt is used by most states, including California.

Emulsified asphalt is a low cost cold applied sealant which is usually poured into a crack 1/8" to 1/2" in width, and then the seal is covered with sand to fill the crack and blot up excess oil. No crack preparation is required for this sealant. The longevity of this type of seal is not well known as it is used primarily as a crack seal prior to an overlay. Emulsified asphalt is used by some states, including California. Caltrans has developed specifications for the use of both rubberized asphalt and the emulsion, and we have included these as Appendix 1.

A recent value engineering study, based on the experiences of the Departments of Transportation from 23 different states, recommended a crack sealant and sealing method for maximum economic return. This recommendation is employed as the crack sealing goals for this project. The sealant material recommended is a hot applied polymer modified (low modulus) asphalt. Currently, different polymer modified asphalts are developed for hot and cool climates. The property that is compromised with a cold climate sealant is the softening point which tends to be lower by about 10 to 20 degrees making it vulnerable to tracking at high temperatures. It is hoped that by the time of the completed development of this machine that this difference will no longer exist. The specifications for this sealant are given in Table 1. Usually, a sealant which shows a softening point of 200°F will lose some of its resilience and ductility which degrades its performance in working (moving) cracks. In the noted specification, the resilience, ductility, and softening point are at acceptable levels.

The preparation method recommended employs a source of hot compressed air to clean and heat the area on either side of the crack. A visual criteria is recommended to determine if an adequate amount of heat is supplied to the pavement; i.e., when there is a slight darkening of the pavement, it is said to be adequately heated. This criteria is too vague for our purposes, so some brief experimentation has been performed. By heating sample pavement with an Acetylene torch and employing an infrared gun to measure temperature, we have concluded that pavement darkening occurs at approximately 280°F. In order to approximate the hot air requirements to bring the pavement to this "optimum" temperature, we have developed a heat transfer model for AC pavement. Detailed results emanating from the use of this model to simulate a hot air source moving across the pavement at 4 miles per hour are included as Appendix 2.

Following crack preparation, the study recommends that the sealant be applied at approximately 380°F for maximum adhesion. Either following the sealant or integral to the wand (dispenser) is a "U" shaped squeegee which helps distribute a greater amount of sealant directly over the crack and develops the desired "optimal" seal profile shown in Figure 1.

The performance of this "optimal" seal is estimated to be 3 to 6 years and it is applicable to cracks with widths between 1/8" and 1". It should be noted that the seal longevity is based on current application methods which are not optimal. As recommended, sealant should be applied to a preheated road. However, due to the delay time between heating the road and applying sealant in current operations, the road surface cools to well below the optimum application temperature. Thus, the development of an automated machine can dramatically improve seal quality. The interested reader is referred to the full value engineering report in Appendix 3, and in particular the section of the report entitled Recommendations-Crack Sealing which begins on page 35.

Cold to Hot Climate Sealant

Ductility 39.2°F (ASTM D 113-76 Modified)- The primary modifications to the ASTM test are a reduction in temperature to 39.2°F and elongation rate to 1 cm/min, versus 77°F and 5 cm/min respectively in ASTM D 113. The test gives numerical values of elongation to material failure. Sealants with elongations over *20 cm* are considered to have passed this test.
Force Ductility - The Ductility at 39.2°F and the Force-Ductility tests are run simultaneously. The Force-Ductility is accomplished by inserting a proving ring and a strain gauge into the ductility apparatus. This permits the measurement of the forces developed as the sealant is elongated during the Ductility test. Force and elongation readings for the respective tests are taken concurrently. Sealants developing less than *4 lb.* of force during elongation are considered to have passed the Force-Ductility test.
Tensile Strength Adhesion - Material shall comply with ASTM D-3406, Section 4.7 Tensile Adhesion; except that sealant specimens shall be cured 4 hours (not 7 days).
Flow - Material shall comply to ASTM D-3405, Section (4.3) Flow.
Cold Bend - The Cold Bend test is performed by bending a 1/8" x 1" x 6" sample through a 90 degree arc over a 1-1/8" mandrel in two seconds with both mandrel and sample cooled to 0F. The *appearance of a crack* indicates failure.
Brookfield Viscosity, 380°F (ASTM D3236)-40-60 poise. Material must be self-leveling.

Softening Point	(ASTM D-36)	200°F
Cone Penetration@77°F 150 g, 5 sec	(ASTM D-1191)	30dmm min
Resilience @ 77°F	(ASTM D-3407)	50% min

Any sealant material should not be sensitive to UV radiation and should perform acceptably for 3-6 years.

Table 1 - Sealant Criteria (Rossman, 1988 and Ron Reese, Caltrans Office of Transportation, Materials, and Research-Pavement Branch)

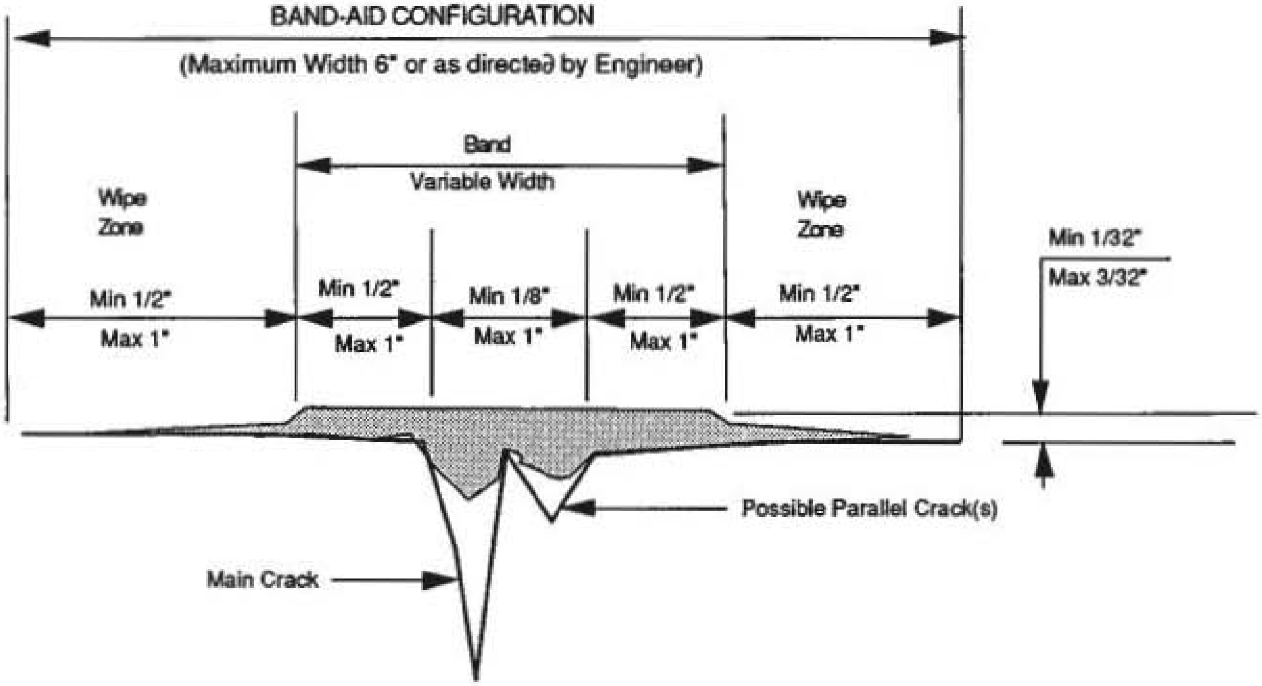

Fig. 1 - Schematic of the Optimal Band-Aid Seal

Component Elements of an Automated Crack Sealing Machine

The primary objective of this project is to design a machine to automatically sense, prepare and seal cracks of widths between 1/8" and 1" in AC pavement. In the previous section, we have discussed the preferred methods for sealing cracks; i.e. seal configuration, surface preparation, etc. In this section, we will discuss more details of our overall design objectives and the necessary machine components.

The objectives of the future machine are to automatically:

- Sense the occurrence and location of cracks that are between 1/8" and 1" wide in AC pavement.
- Prepare the crack and surrounding road surface for sealing by removing entrapped moisture and debris, and by preheating the road to ensure maximum sealant adhesion.
- Dispense the sealant.
- Form the seal into the optimum "band-aid" configuration.
- Perform these functions with as many "off-the-shelf" components as possible.

The goal of this project is that all of the above operations ultimately take place at approximately two miles per hour, about ten times the current rate.

The crack sealing machine will require four primary systems as depicted in Figure 2. The Crack Sensing System will be primarily responsible for locating and describing roadway cracks. The Applicator Assembly and Peripherals includes all the hardware necessary to heat, dispense, and shape sealant, and to prepare the road. This system may be comprised of any number of dispensers, valves, etc. The Positioning System will include the hardware necessary to move the applicator assembly along the required path. The Integration and Control System will coordinate the Crack Sensing, Applicator, and Positioning Systems. It will transform the information from the Sensing System into a desired path for the applicator assembly. The Integration and Control System will then control the motion of the applicator through the Positioning System as well as controlling the individual functions of the Applicator System. Additionally, the Integration and Control System will monitor all of the peripherals to ensure proper sealant supply, sealant temperature, heat supply, etc. The following sections provide more details of each of these systems, which are all in the early design concept stage. A schedule for future efforts is provided as a PERT chart in the Conclusions and Schedule Section and this will be referred to throughout the document.

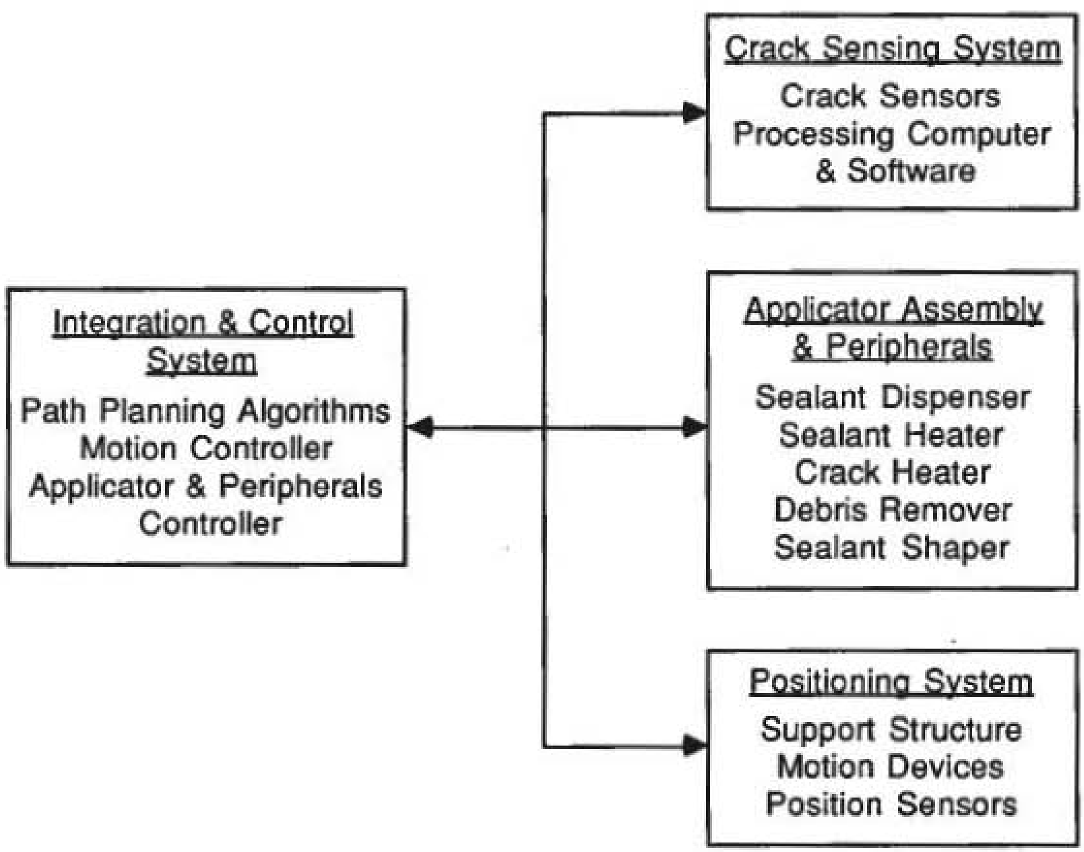

Fig. 2 - Component Systems of the Automated Crack Sealing Machine

Sensing of Cracks

The purpose of crack sensing is to determine the location and widths of cracks on the road in sufficient detail so that crack preparation, sealant application, and shaping of the seal can be performed automatically. No type of machine vision which satisfies these goals is currently known to exist; therefore, the solution to this problem, when established, will be unique. The distinguishing features of the crack sensing problem will be discussed to follow.

Through a literature search which began in October 1989, a specific direction has been chosen towards crack sensing. Specifically, the use of video cameras accompanied by a range sensor (most likely a near infrared laser). This section is intended to summarize the results of the sensing portion of this study and the interested reader is referred to Appendix 4 for additional details. Prior to the literature search, sensor criteria were established. These criteria are summarized in Table 2.

The sensing technologies investigated thus far are summarized pictorially in Figure 3. The most favorable prospects show a striped background. Other potentially promising areas are shown with a dotted background.

Of those technologies investigated, array detectors that operate in the visible range show considerable promise due to past and present research activities concerning their use in roadway crack detection (Bomar, 1988; Mahler, 1990; Hendrickson, 1989). The state-of-the-art array detector systems use CCD (Charge Coupled Device) sensors incorporated in cameras. These sensors are lightweight, require little power, and are very rugged. With a camera, cracks can be identified by converting the image into grey levels (black to white level of intensity). The cracked portion of the pavement has been found utilizing the relative darkness of the crack with respect to the pavement. The crack can then be extracted based on the "darker" grey levels of the image. Currently data about cracks is acquired using cameras and image processing by several contractors (PCES in Sparks, Nevada, ARIA in South Bend, Indiana) for the purpose of determining the general condition of pavement. Algorithms have also been developed to reduce noise in images of cracks and to determine type and severity of cracking (Bomar, 1988; Mahler, 1985). This has historically been done as a statistical process and requires no detailed correspondence between the images and the actual cracks on the road. While the current approaches do determine the general type and severity of cracking, they do not determine the connectiveness of the cracks (it is not necessary for their purposes).

Resolution:
The sensor should be able to resolve a roadway crack 1/8 inch in width.

Cycle Time:
The sensor system should be able to provide crack information continuously from a vehicle moving at a minimum speed of 2 mph.

Type of interference and possible failure:
The sensor system should be resistant to the following:

- condensating moisture,
- acoustic noise,
- mechanical vibration and shock-3 g's peak vibration from 15 Hz to 100 Hz and 15g's non-operating for transport,
- heat (-20-160F),
- dust and roadway debris (must be sufficiently strong to survive impacts from 3/8" aggregate and roadway debris not exceeding 8 ounces,
- moisture on pavement,
- debris in cracks,
- road surface height variations,
- temperature variations,
- interference between adjacent detectors or between source and detectors,
- variations in lighting conditions, and
- electromagnetic interference from nearby machinery, such as a generator.

Reliability:
The sensor system and its expected maintenence should provide for a service life of 10 years.

Maintainability:
The system should be easily accessible for component replacement or adjustment.

Components should make use of off-the-shelf technology.

Table 2 - Sensor Criteria

Our current proposed strategy is to utilize some of the noise reduction methods previously developed with some unique ideas for further noise reduction and connectivity and algorithm development is on-going. An example of a preliminary algorithm is included as Appendix 5. Since the image processing associated with crack detection is an active area of commercial application, future development and system support can be expected in this area. Development in this area would also contribute and draw from vehicle lateral guidance research at the Caltrans Transportation Laboratory (Ung, 1990).

An additional sensor may be needed to distinguish true cracks from apparent cracks which are actually shadows, wet areas, oil spots, or previously sealed cracks. To reduce this type of noise, a range sensor in the near infrared region can be utilized. Laser range sensors detect distances by the geometry of the reflecting beam. Typical units can sense in the range extending from approximately four inches from the sensor and terminating at a distance of about eight inches from the sensor. They are usually designed to provide a linear output signal as a function of an object's distance within their range. The ruggedness of this type of sensor is apparent from its use in automobile racing applications as well as by foreign automobile manufacturers for vehicle suspension studies. We envision a single sensor being mounted to the applicator head to verify crack existence prior to sealing.

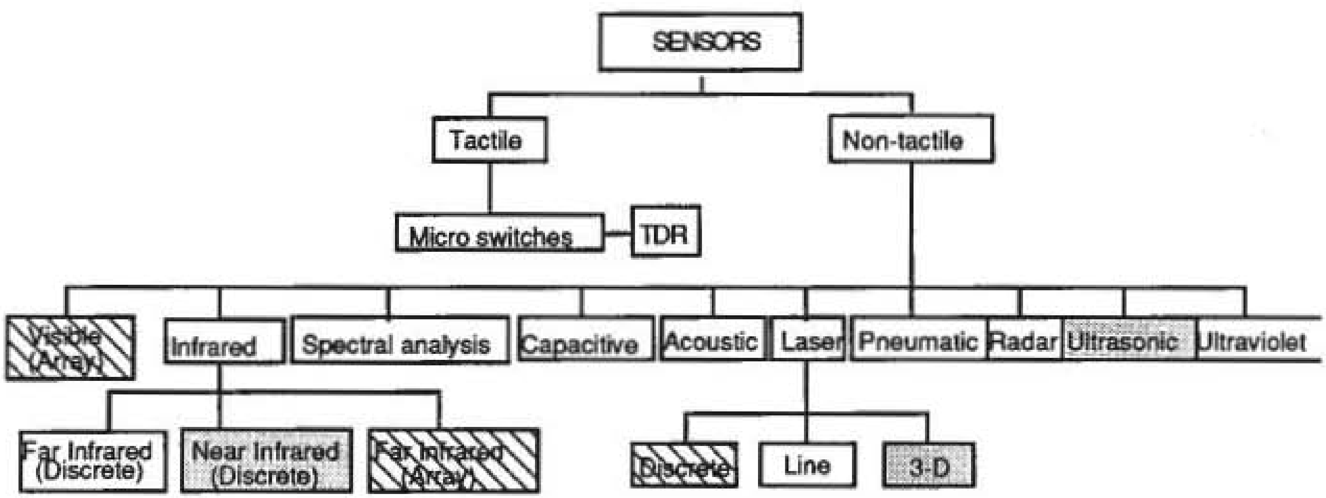

Fig. 3 - Schematic of Sensor Technologies Investigated

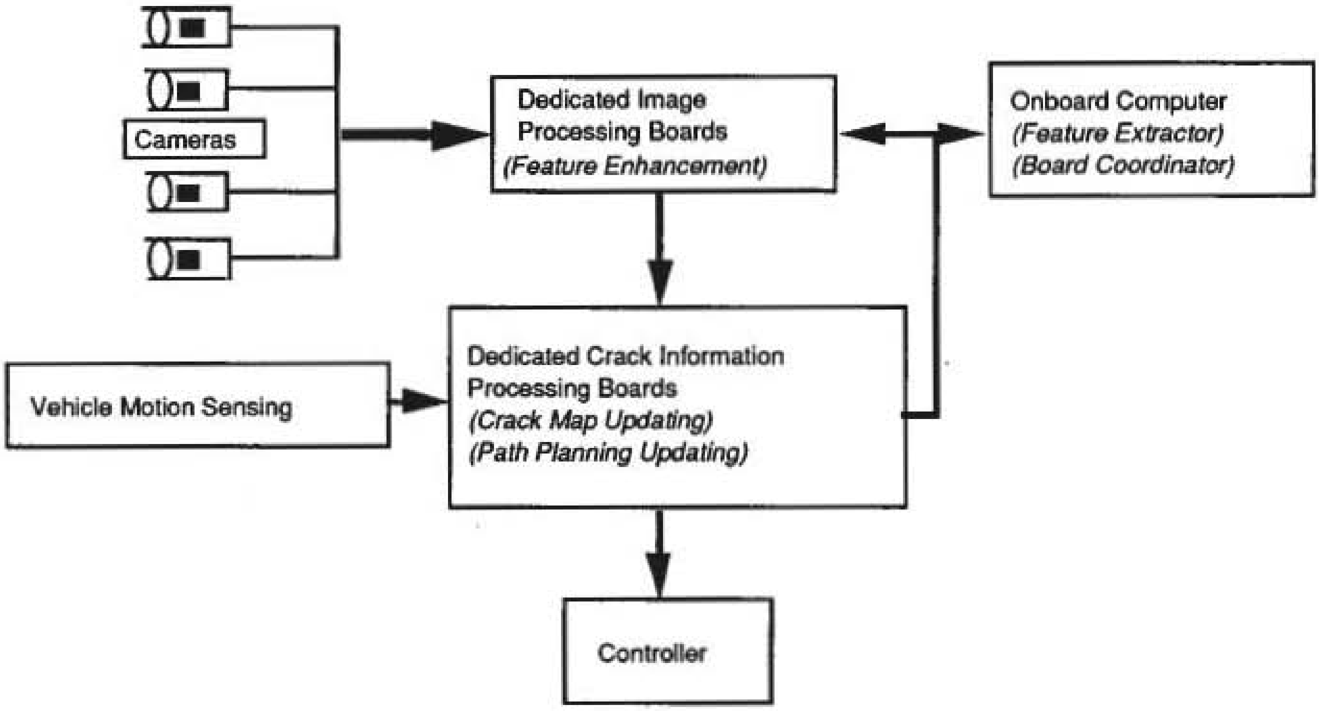

Fig. 4 - Sensing System Configuration

Figure 4 depicts a design concept for the camera system configuration. The dedicated crack information processing boards are responsible for taking the processed image and maintaining an accumulation of crack patterns (x,y points and orientation) and a path planning scheme (sets precedence for x,y points) relative to the coordinate frame of the applicator (see Figure 5). Use of fundamental robotics concepts allows for a straight forward implementation for tracking x,y, points relative to the applicator based on images taken from a camera. This would allow the flexibility of placing the applicator on a trailer or on the rear portion of the crack sealing machine. Additionally, a concept for full road coverage by multiple cameras is shown in Figure 6.

The part of the PERT chart relating to this section begins at the milestone, "Crack sensing system development". In order to develop this part of the crack sealing machine, four principle areas will have to be developed: crack sensors, coordinate transformations from sensors to road, test sites for system testing, and the determination of the processing and software requirements. The crack sensors will include most probably one or more cameras in order to gather general scene information for crack detection and a range sensor which will be mounted on the applicator head to verify the presence of cracks once they are established by the image processing system. The coordinate transformations from the sensors to the road are established for motion control purposes of the applicator head by first deciding on a mounting position for the sensors and second developing a mathematical model which identifies where the crack identified is relative to the applicator head. The test sites will be actual road locations which be a representative sample of road conditions anticipated for the crack sealing machine. These test sites will then be hurdles for system component development. Determining the actual hardware and software requirements will consist of first acquiring a development system in order to determine which crack detection algorithms will be used and then finding commercially available products which satisfy the requirements imposed by the algorithms and speed of operation requirements. Once these four principle areas are developed, a major milestone will be the test for compatibility with the applicator assembly and positioning system components. As part of assuring this compatibility, a path planning algorithm will be developed as a team effort. A team effort in this area is especially important to assure that the instructions given by the Integration and Control System are compatible with capabilities of the positioning system. Following the path planning effort, the actual hardware requirements for the image processing system will be specified as an integral part of the crack sealing machine.

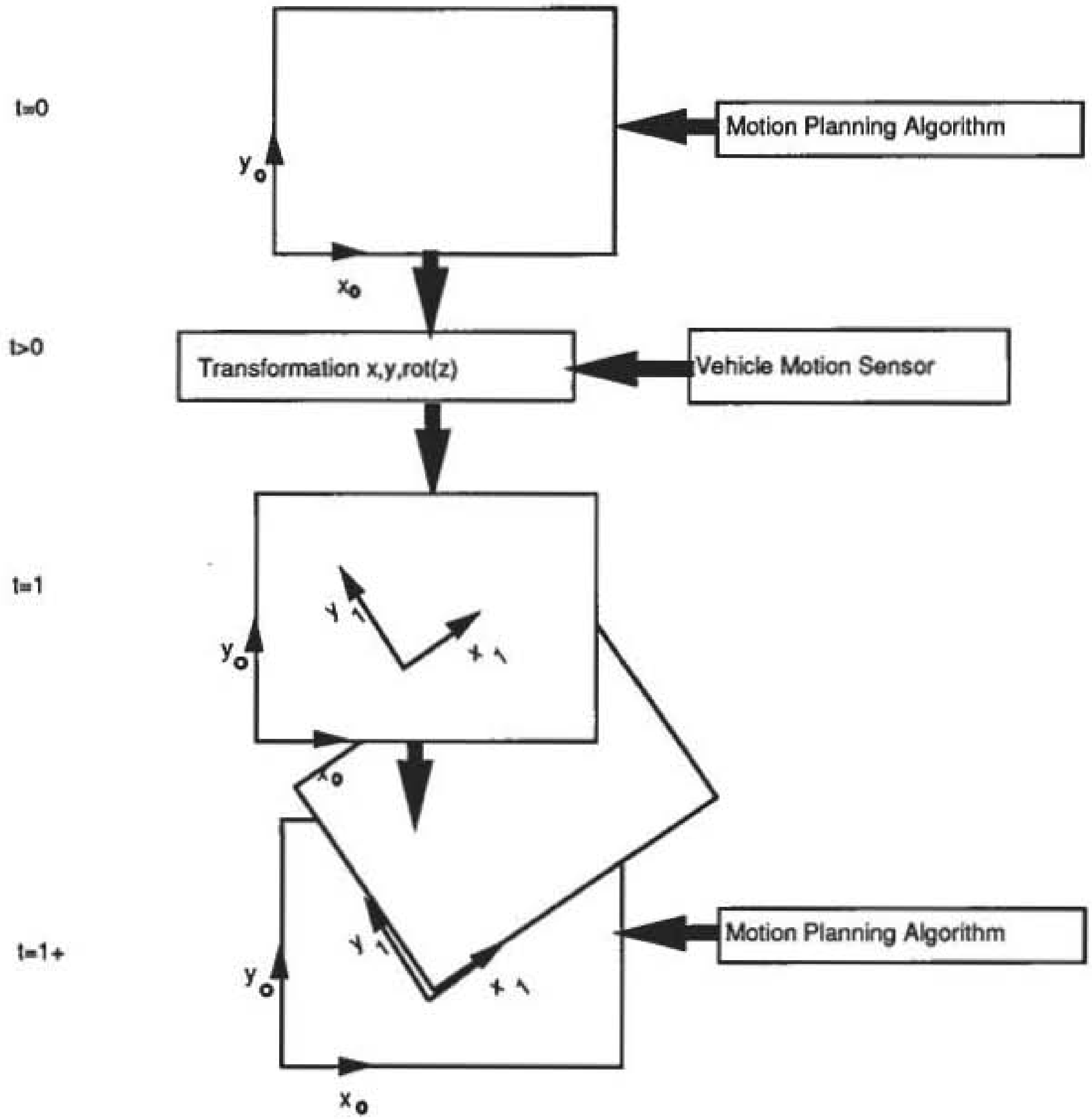

Fig 5 - Schematic of Crack Information Processing

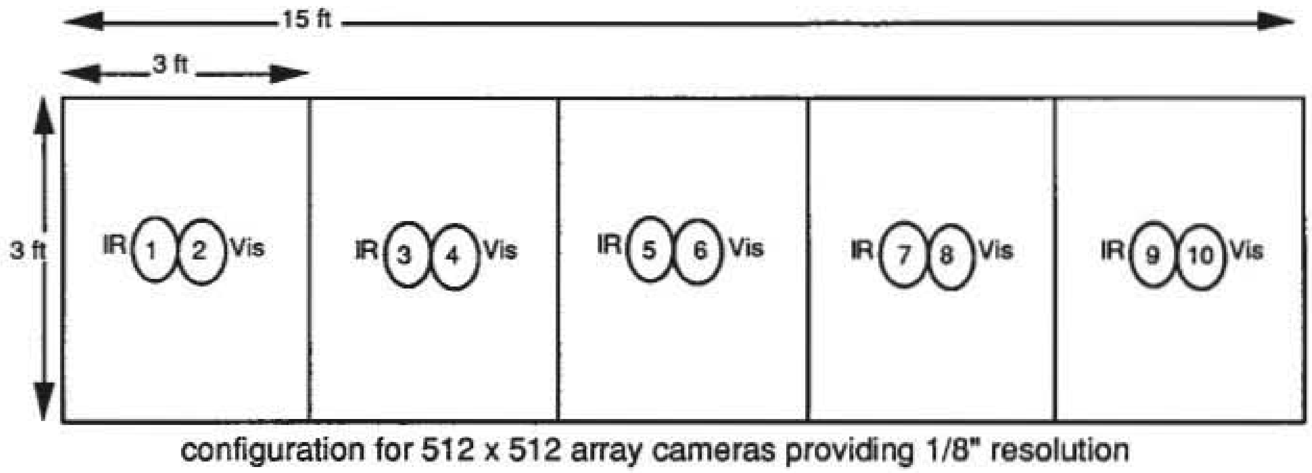

Fig. 6 - Concept for Road Coverage by Multiple Cameras

Applicator Assembly and Peripherals

Although there exists many irregularities in crack profile, there is one facet which unifies all crack profiles, entrapped aggregate and moisture contamination. The key to sealed crack longevity is directly attributable to the absence of entrapped aggregate and moisture as well as uniform surface heating prior to application.

Tests supporting the value engineering study have shown that the ideal method for crack preparation should include the use of a two phase hot air system. The primary phase of this system should include a source of high temperature and high velocity compressed air to remove entrained aggregate and moisture. The second phase of the heating system should be used to warm, to approximately 280°F, the surrounding horizontal crack margins to ensure a highly adherent bond between the surface and the sealant material. Once the crack is cleaned, dried and heated, a suitable sealant can be applied.

The optimal band-aid patch configuration, as earlier described, requires moderate penetration of sealant material into the vertical crack surfaces. In addition, the horizontal surface on either side of the crack itself must have sufficient sealant material applied so as to minimize degradation of the entire repair. Sealant penetration can be sharply increased as the temperature differential between the surface and the sealant material is minimized. Furthermore if the sealant melting point is below the prepared surface temperature of the roadway, the sealant mobility will be increased in the narrower portions of the crack.

Once the application of sealant is accomplished, the band-aid profile can be achieved through the use of a squeegee type mechanism. The purpose of the squeegee is to minimize the fluctuation of surface sealant height as well as to promote additional accumulation of sealant material over the crack itself. The squeegee mechanism can be as simple as a small rubber block attached to the sealant applicator head, or as complex as a vibratory screen similar to that which can be found on asphalt paving machines.

Summary of Results to Date:

Early investigation has shown that selection of the appropriate equipment from existing manufacturers can substantially reduce the overall cost of the delivered vehicle. The minimum required equipment must include an sealant heating pot, heated hoses, dispenser nozzles, air compressor, and a device to heat the surface to 280°F.

The preliminary requirements for the sealant heating pot have been established. It is felt that the minimum capacity and delivery rate shall be no less than 350 gallons/hour. The selected sealant must be delivered to the point of hose attachment at a temperature that shall be no less than 380°F and not more than 450°F. The sealant pot shall be configured in such a manner that minimum modifications to the vehicle will be required. Although a trailer mounted sealant pot has not been excluded, it is felt that such a vehicle will experience serious convenience and maneuverability problems. In addition, the final configuration for the sealant heating source has not been finalized. It is our desire to minimize supplementary fuel storage requirements, while maintaining high operational efficiency. Although resistance heat would allow the use of existing vehicle mounted generators for power, the inefficiency of this type of heating system has decreased the attractiveness of this system. On the other hand, propane fired sealant tanks have been widely used in industry for years, and they are a markedly more efficient heating source making this option more attractive.

The essential part of sealant transport is the heated hose. There exists essentially two methods of transporting asphalt based sealants. The wire mesh wrapped electrical resistant heat type hose affords the increased convenience of a lightweight fairly flexible sealant transport system. The significant drawbacks to such a hose are its high sensitivity to external abrasion and its lower mean time between failure (MTBF) as compared to oil jacketed hoses. In addition, electrically heated hoses are characteristically less efficient than oil jacketed hoses. Oil jacketed hoses are less flexible and heavier per linear foot as compared to electrically heated hoses. These facts are significantly outweighed by the inherent durability, convenience and efficiency of this type of hose.

Sealant application nozzles represent the most operationally sensitive link in the system. This is attributed primarily to high probability of clogging due to the extreme temperature differential between the sealant and the ambient temperature. For this reason, the literature search has focused on locating a suitable externally heated nozzle which will deliver speed dependant flow rate. In addition, the flow rate and spray pattern should be matched such that peripheral coverage is adequate for the band-aid configuration.

The selection of an appropriate air compressor will be ultimately based on the power and flow requirements for the surface heating system. The preliminary size estimation for the compressor will require a minimum of 125 cfm. at a minimum deliver pressure of 100 psi.

Based on the value engineering study, surface heating is a necessary precursor to the application of sealant. Heating the surface and thereby minimizing the temperature differential between the surface and the sealant helps promote and increase sealant flow and adhesion, both of which are directly linked to crack repair longevity. Recently three separate and distinct surface heating devices were tested and evaluated. Additional details can be found in Appendix 6. The test results have shown that these particular devices cannot, or should not, be adapted to either the initial or final vehicle. It is important to note that although the three heating devices tested did not represent the entirety of the research for off the shelf surface heating equipment, they did represent a large portion of the compact surface heating devices currently available.

In summary, the initial investigation of the problems surrounding road surface crack repair have shown that there exists many "off the shelf" components which can meet or exceed specific requirements of the overall design. At this time it is obvious that the primary limiting factor to the successful application of sealant is largely a function of the ability to prepare the crack adequately. Recent testing at UC-Davis has shown the limitations of existing technology in this area; it is therefore our opinion that additional time will need to be invested in the area of designing and constructing a suitable surface heating device. The design and construction of such a device would allow for maximum flexibility and optimal compatibility with the integrated system.

Positioning System

The various components of the crack sealing machine are physically connected through the positioning system. Our initial efforts concerning this portion of the work have been directed at developing design goals which are summarized to follow.

- The Positioning System shall provide the capability to seal one lane width (approximately 13 feet) of road surface at a speed of 2 miles per hour.
- The Positioning System shall allow for a seal with a "band-aid" type configuration.
- The machine shall be rugged and stable. It shall also be capable of properly maintaining the position of the crack sensors, applicator assemblies and peripherals while being subjected to physical disturbances (i.e. road bumps and curves, vibration, speed fluctuations, etc.).
- The machine shall have the capability of converting from the "road travel" configuration to the "crack sealing" configuration in a minimum amount of time.
- The machine shall be comprised of as many commercially available elements as possible.

This Positioning System will consist of three primary components; the machine support structure, the applicator assembly motion devices, and the position sensors. The machine support structure is the framework that physically supports the crack sensing system, applicator assemblies and peripherals, applicator assembly motion devices, and position sensors. The support structure (frame) will be mounted on a wheel assembly which will support the frame during the crack sealing operation as well as during high speed road travel.

The applicator assembly motion devices consist of stepper motors, drives, translation and rotation positioning components, cables, and other equipment which are used for the purpose of positioning and actuating the applicator assemblies.

The position sensors will be a combination of linear and rotary encoders. The purpose of the encoders is to determine the exact position of the support structure and applicator assemblies with respect to the road surface. The data from these encoders will be used to accurately position the applicator assemblies while adjusting for fluctuations in the forward speed of the machine, curves in the road surface, and other disturbances.

Based on the design goals and the necessary system components, three initial design concepts for this system have been developed. A brief explanation of the design concepts currently under consideration follows.

ARRAY SYSTEM

A large number (approximately 80) applicator assemblies would be located at equal intervals across the lane width of the machine. The assemblies would be fixed to the frame of the machine. They would not translate or rotate. The operation of the assemblies would be controlled simply by a series of on/off switches. The components of the assembly would be turned on as the assembly passes over a crack in the road surface and then turned off after that portion of the crack has been sealed.

CARTESIAN COORDINATE BASED SYSTEM

The applicator assembly (including crack heater, debris remover, sealant dispenser and sealant shaper) would be mounted as an end effector on a robot positioner that utilizes an X-Y-THETA coordinate system. The applicator assembly would move transversely across the highway lane (X direction) as well as parallel to the lane direction of travel (Y direction). In addition to the X-Y motion, the applicator assembly would have the capability to rotate 360 degrees in the X-Y plane so as to orientate the assembly with its current direction of travel. These design features would allow the applicator assembly to sufficiently track any crack in the road surface.

The system described above could initially be developed and tested using only one applicator assembly. Once the design concept is proven and the system perfected, the machine could be fitted with additional applicator assemblies so that the overall crack sealing speed could be increased.

ROBOTIC ARM MANIPULATION SYSTEM

The applicator assembly would be mounted as an end effector on a robotic arm manipulator. The end effector would have the capability to translate and rotate in the X, Y, and Z directions. The design features would be sufficient for the applicator assembly to properly track and orientate itself with any crack in the road surface.

As with the cartesian coordinate system, this system could initially be developed and tested using only one applicator assembly. Once the design concept is proven and the system perfected, the machine could be fitted with additional applicator assemblies so that the overall crack sealing speed could be increased.

In light of the project design goals, commercially available hardware that will be compatible with or adaptable to the concept designs is being identified. A large amount of literature has been obtained for such products including:

- translation/rotation positioning components and systems,
- drives and controls,
- sensors,
- vision systems,
- road maintenance equipment,
- robots, and
- sealant products.

Currently, additional design concepts are being developed in addition to comparing the relative advantages and disadvantages of the existing concepts. Promising ideas will be further developed prior to final concept design configuration selection. The advantages and disadvantages of array systems, cartesian coordinate systems, and robotic arm systems are summarized to follow.

Since the array system is the least mechanically complicated of the three, it would be the preferable system for crack sealing if certain developments occur. For example, one of the limitations of an array system is that heat treatment of the crack zone would be inefficient or impractical. Preheating of the entire road surface is not efficient because fuel is wasted. Preheating of a localized area of the crack zone would be difficult since it would require individual heaters for each applicator assembly (or small group of assemblies). Those heaters would have to be turned on and off continuously. However, if advances in sealant technology produced a sealant which could be applied without preheating, then this problem would be solved. Another current problem with the array system involves the difficulty in producing the ideal "band-aid" type patch configuration. This problem would be reduced if it is determined that a near-ideal band-aid patch is not necessary. Finally, due to the design of the array system, it will be necessary to remove debris from cracks (with a high pressure air jet) while the applicator assembly is traveling transversely with respect to the crack. There is some doubt whether this can be done effectively. However, if it is determined (after preliminary testing) that the operation can be accomplished effectively, then the array system would be a more attractive alternative.

The robot arm system also presents substantial design difficulties. Inherent to the design of the structure, the entire arm must be supported at one localized area of the machine support structure. This would create large bending stresses at each of the assembly attachment points. There is also some doubt that the machine structure and robot arm would be rigid enough to maintain proper positioning of the applicator assembly. Also, the addition of several applicator assemblies would be more difficult than for a cartesian system. Much more effort would be needed to assure that the applicator assemblies would not physically interfere with each other.

For the reasons given above, it seems likely at this time that the best choice would be a cartesian based system. However, this is only a preliminary observation and not a final conclusion. A final decision will be made at a later date. A detailed list of the advantages and disadvantages of each system is included as Appendix 7.

Summary of Future Efforts

The gathering of literature for commercially available hardware is a continuing process as it is essential to maintain a current file and avoid overseeing new technological breakthroughs. Additionally, as noted above, alternative unique design concepts are being considered. While preliminary observations indicate the superiority of the cartesian based system, some experimental work is necessary in order to further clarify design goals and to determine the physical limitations of certain system components. As such, a summary of proposed future tasks follows.

1) Perform preliminary testing to:
   - determine if a close approximation to the ideal band-aid patch configuration can be obtained without the use of a squeegee; i.e., by varying the flow rate out of a nozzle or varying the speed at which a nozzle moves relative to the ground.
   - determine if debris can be reliably removed from a crack when an air nozzle is traveling perfectly normal to the crack and when it is not focused directly into the crack.

2) Select the best concept design configuration.

3) Complete final design and development of the motion system.
   - complete development of the chosen concept design configuration
   - determine specific machine components and vendors
   - develop final design drawings and specifications

4) Manufacture the positioning system.
   - purchase equipment, components, and materials
   - manufacture machine
   - assemble machine

5) Perform testing, troubleshooting, and evaluation of the positioning system.

The coordination of these tasks with the remaining project tasks is depicted in the PERT chart of the Conclusions Section.

System Integration and Control

The Integration and Control System oversees the entire operation and coordinates the activities of the other subsystems. The information forwarded from the Crack Sensing System will be translated into a planned path for the Applicator. Thus, the Integration and Control System will include the necessary algorithms (to be developed as part of this project) to plan a crack sealing path. This path will either be the relative positioning of the Applicator System or the appropriate actuation time for parts in an array type system. If multiple applicators are employed, the Integration and Control System will need to first allocate cracks to the individual applicators and will do so in a manner to maximize speed and avoid interference. This system will keep account of the actual position of the total machine and its components by interacting with sensors on the Positioning System. It will additionally monitor the Applicator Assembly and Peripherals to ensure adequate volume and temperature of sealant, air, etc. Following the planning of the appropriate path(s), the Integration and Control System will control the motion of the applicator(s) and the individual applicator functions. Initially an open-loop control law (off-line path planning) will be employed. However, it is expected that the loop will be closed in the future by employing appropriate sensors on the applicator head(s). Quite obviously, the nature of the System Integration and Control System is highly dependent on the system configuration chosen. While it is difficult to predict details related to the development of this system, a general summary of future tasks to be performed include:

1) Select sensors to monitor applicator peripherals (e.g., temperatures of sealant and hot air supplies, etc.) and develop appropriate control algorithms to supervise the operation of these components.

2) Develop appropriate control algorithms for the positioning system.

3) Develop appropriate control algorithms for the applicator assembly.

4) Integrate the positioning system with the control system and test.

5) Integrate the applicator assembly with the positioning system and their respective controllers and test.

6) Integrate the peripherals with the applicator/positioning/control system and seal cracks in a manual mode; i.e., cracks will be identified manually and the controller will be provided with a path manually.

7) Incorporate the vision system with the existing system to determine if cracks can be identified and followed.

8) Perform final testing, troubleshooting, and evaluation of the entire crack sealing machine.

As with the other systems, the manner in which this work coordinates with other project activities is depicted in the PERT chart of the next section.

Conclusions and Schedule

This report has presented a summary of the efforts and conclusions thus far on the AHMT crack sealing project. This project is in its infancy and most of the efforts have been directed towards developing design goals and identifying the required future tasks. The overall project objectives are to design a machine to automatically:

- Sense the occurrence and location of cracks that are between 1/8" and 1" wide in AC pavement.
- Prepare the crack and surrounding road surface for sealing by removing entrapped moisture and debris, and by preheating the road to ensure maximum sealant adhesion.
- Dispense the sealant.
- Form the seal into the optimum "band-aid" configuration.
- Perform these functions with as many "off-the-shelf" components as possible.

The ultimate goal is for all of the above operations to take place at approximately 2 miles per hour.

A detailed project schedule has been developed in the form of a PERT chart clarifying the necessary subtasks and their coordination. The total chart is quite lengthy so an abbreviated version which depicts only the milestones of this project is included as Fig. 7. It is quite evident that the successful completion of this project will require a great deal of effort and coordination among the individuals involved. However, the benefits that will result are extremely high; saving the state of California tremendous revenue, minimizing the risks of Caltrans workers, and minimizing traffic delays.

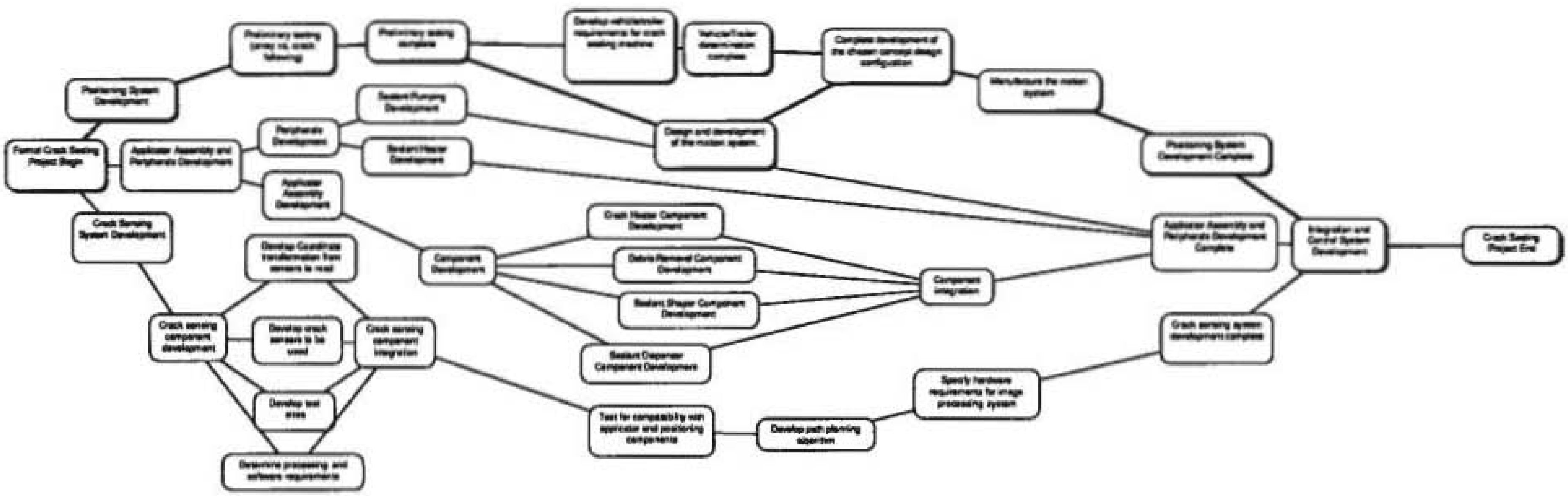

Fig. 7 - Abbreviated PERT Chart of the Crack Sealing Project

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Appendices

1. Caltrans Crack Sealant Specifications
2. AC Pavement Heat Transfer Model
3. Value Engineering Report
4. Machine Vision Recommendation for Crack Sealing
5. Preliminary Crack Finding Algorithm
6. Report on the Testing of Road Surface Heat Lances
7. Advantages/Disadvantages of the Preliminary Concept Machine Configurations

Appendix 1

Caltrans Crack Sealant Specifications

August 1984

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF ADMINISTRATIVE SERVICES
OFFICE OF BUSINESS MANAGEMENT

SPECIFICATIONS FOR CRACK FILLER

The material shall be an emulsified crack filler which is readily handled at ambient temperatures. It must be capable of being stored for periods of up to six months and be formulated to withstand freeze-thaw cycles. The base materials shall remain ductile with aging and provide resiliency under extreme climatic conditions.

The crack filler shall contain no volatile organic compounds which may contribute to air pollution. Specifications are as follows:

PROPERTY	TEST METHOD	REQUIREMENTS
Viscosity @ 77°F (25°C), SFS	ASTM D-244	25-150
Pumping stability	GB method (1)	pass
5-day settlement test, %	ASTM D-244	5.0 max.
Cement mixing test, %	ASTM D-244	2.0 max.
Sieve test, %	ASTM D-244 (MOD) (2)	0.1 max.
Particle charge test	ASTM D-244 (MOD)	positive
Residue, %	ASTM D-244 (MOD) (3)	64 min.
Test of Residue from ASTM D-244		
Viscosity @ 140°F (60°C), cSt	ASTM D-2170	4'500-9,500

NOTES:

1) Pumping stability is determined by charging 450 ml. of emulsion into a one-liter beaker and circulating emulsion through a gear pump (Roper 29 B22621) having 1/4-inch inlet and outlet. The emulsion passes if there is not significant oil separation after circulating ten minutes.

2) Test procedure identical with ASTM D-244 except that distilled water shall be used in place of two percent sodium oleate solution.

3) ASTM D-244 Evaporation Test for percent of residue is modified by heating a 50 gram sample to 300°F (149°C) until foaming ceases, then cooling immediately and calculating results.

SPECIFICATIONS FOR RUBBER-ASPHALT JOINT SEALANT

The joint sealant shall be a mixture of paving asphalt and ground rubber and shall conform to the following requirements:

TEST	TEST METHOD	SPECIFICATION
Softening Point	ASTM D-36	160°F - 200°F
Cone Penetration @77°F	ASTM D-1191	15 dmm - 35 dmm
Resilience @77°F	ASTM D-3407	40% minimum

Ground rubber shall be vulcanized or a combination of vulcanized and devulcanized materials. The gradation of the rubber shall be such that 100% will pass a No. 8 Sieve.

The asphalt and rubber shall be blended in proportions, by weight, of 75% ± 3% paving asphalt and 25% ± 3% ground rubber. Modifiers may be used to facilitate blending.

The rubber-asphalt material shall be furnished premixed in containers with an inside liner of polyethylene. Packaged material shall not exceed 75 lbs in weight. Storage and heating instructions and cautions shall be supplied by the vendor with each shipment.

The material shall be capable of being melted and applied to cracks and joints at temperatures below 400°F. When heated, it shall readily penetrate cracks 1/4 inch wide or larger.

The vendor shall furnish certification that the joint sealant material complies with the above requirement.

A certificate of compliance conforming with Section 6-1.07 (Certificates of Compliance) of the Department of Transportation Standard Specifications dated July 1984 shall be supplied with each shipment.

Appendix 2

AC Pavement Heat Transfer Model

HEAT TRANSFER MODEL FOR AC PAVEMENT (Spread Sheet Explanation)

Heat transfer through a semi-infinite solid with a convective boundary condition.

1. Calculation of Convective heat transfer coefficient, h

(A-6) Temperature of air blowing over surface (F)
(A-7) Conversion to C = (A6-32) *5/9
(A-8) u dynamic viscosity at air 1bf-s/ft.^2
table interpolation

Calculation of Density
(A-12) Atmospheric pressure
(A-13) (A12 + 14.6) *144
(A-14) R = 1716 ft-lbf/(slug - R)
(A-15) T(F) = (A-6)
(A-16) A15 + 460
(A-17) A13/(A14.x A16) = P/RT
(A-18) A17 *32.2 (unit conversion)

Reynolds #CALC (Air) Re = pVL/(mu)

(A-22) Six inches of pavement covered by air in longitudinal direction
(A-23) A22/12
(A-24) Input expected velocity
(A-25) *No Effect on Calculated Values*
(A-26) Re = pVL/u

Praudtl calculation (Air)

(A-30) Cp = .2761086
(A-31) K = .0584
(A-32) Praudtl# = A8 *A30/(A31 *3600 *32.174)
(A-33) Table value

(A-37) Nusselt #(Reynolds analogy for turbulent flow over a flat plate)

$= .036(Pr)^{1/3}Re\ 0.8$
= .036 * A32^(1/3) *B26^ (0.8)

(A38) $h = \frac{Nuk}{L}$
=A31*A37/A23

2. Transient Conduction through a semi-infinite solid

Properties of AC

(D6) Thermal Conductivity[1] = 0.7

[1] 1972 asphalt paving technology
The Association of Asphalt Paving Technologies Vol 41, page 52

(D7) Thermal conductivity = D6 *1.731 W/m -K
(D8) Thermal Diffusivity
D6/(D9*D10)= K/pc

(D9) 140 lbm/ft^3
(D10) 22 Btu /lbm -R1
(D14) Check to make sure internal resistance is not negligible.

Biot # = A38*A23/D6

(D19) mph (vehicle speed)
(D20) Approx time period for .5 ft.= A23*1/(D19*5280/3600)
(D21) =D20/3600
(D22) Fourier #; If Fo # < 1 then body is Semi-infinite

$$Fo = \frac{Alpha*t}{L\char`^2} = \frac{D8*D20}{(A23\char`^2)}$$

Solution of semi-infinite solid problem, see photocopy, next page (Kreith and Black)

p144 Basic Heat Transfer
(Kreith and Black 1980)

(D26) Air temperature of hot air being applied to pavement
(D27) Hot air velocity from lance at pavement surface

(D27) T_o
(D29) x
(D30) D29/12
(D31) eda
(D32) sqrt (D31)
(D33) zeta
(D34) D33 + D32
(D35) Bi + eda = (B38 * E30/E6) + E31
(D36) erf (zeta + sqrt(eda))
(D37) erf (zeta)
(D38) RHS
(D39) F(x,t)
(D40) Heat transfer = h(T(inf) - T (surface))*(*characteristic length from Reynolds number)

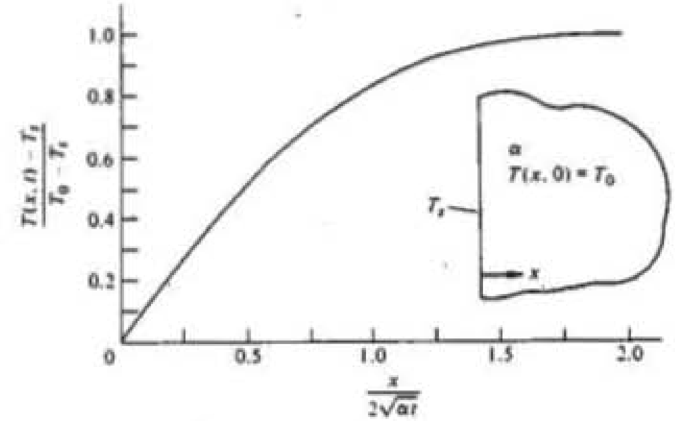

Figure 3-4 Temperature distribution in a semi-infinite solid subject to sudden change in surface temperature.

or

$$Q''(t) = 2k(T_s - T_0)\sqrt{\frac{t}{\pi\alpha}} \tag{3-17}$$

Case II: Convection Boundary Condition

Instead of changing the surface temperature of the infinite solid, we could subject the surface to a fluid with an ambient temperature of T_∞ and an average convective-heat-transfer coefficient of $\bar{h}_c$. The heat transferred into the solid must then be convected through the fluid and then conducted into the solid. The appropriate boundary condition for this type of problem is then

$$\bar{h}_c[T_\infty - T(0,t)] = -k\left(\frac{\partial T}{\partial x}\right)\Big|_{x=0} \tag{3-18}$$

The solution to Eq. 3-11 subject to the initial condition (3-12) and the two boundary conditions (3-13) and (3-18) is given in Schneider (Ref. 5) as

$$\frac{T(x,t) - T_0}{T_\infty - T_0} = 1 - \text{erf}\,\xi - \{\exp[(\text{Bi}) + \eta][1 - \text{erf}(\xi + \sqrt{\eta})]\} \tag{3-19}$$

where

$$\xi = \sqrt{\frac{x^2}{4\alpha t}} = \frac{\text{Fo}^{-1/2}}{2}$$

$$\text{Fo} = \frac{\alpha t}{x^2}$$

$$\text{Bi} = \frac{\bar{h}_c x}{k}$$

$$\eta = \frac{\bar{h}_c^2 \alpha t}{k^2} = (\text{Bi})^2(\text{Fo})$$

	A	B	C
1			
2	*Convective heat transfer coefficient for air*		
3			
4	**Calculation of µ (air)**		
5			
6	Temperature F	800.00	
7	Temperature C	426.67	
8	µ lbf-s/ft^2	7.41E-07	
9			
10	**Calculation of density (air)**		
11			
12	Pressure (gage,psi)	0	
13	Pressure (abs,psf)	2102.4	
14	Gas Constant	1716	
15	Temperature F	0	
16	Temperature R	460	
17	Density (slug/ft^3)	0.0026634235	
18	"Density" (lb/ft^3)	0.0857622378	
19			
20	**Reynolds # Calculation (air)**		
21			
22	Characteristic length (in)	6	
23	Characteristic length (ft)	0.5	
24	Velocity(fps)	900	
25	Angle	90	
26	Reynolds #	1617463.68	
27			
28	**Prandtl # Calculation(Air)**		
29			
30	Specific Heat (Btu/lbmF)	0.2536899928	
31	Thermal Conductivity (Btu/FtFhr)	0.0294665896	
32	Prandtl#	0.7389230725	
33	should be	0.71	
34			
35	**Nusselt # Calculation (Air)**		
36			
37	Nusselt #	3016.9622358	
38	h (Btu/F-hr-ft^2)	177.80	
39			
40			
41			

	D	E	F
1			
2	*Transient conduction through a semi-infinite solid*		
3			
4	**Properties of AC**		
5			
6	Thermal conductivity Btu/hr-ft-R	0.7	
7	Thermal conductivity W/m-K	1.2117	
8	Thermal Diffusivity ft^2/hr	0.02272727	
9	Density lbm/ft^3	140	
10	Heat capacity Btu/lbm-R	0.22	
11	Heat capacity J/kg-K	921.14	
12			
13	**Biot #**	126.999412	
14	if Bi<<1 then IR is negligible		
15			
16	**Fourier # calculation**		
17	if Fo<1 then body is semi-infinite		
18			
19	miles per hour	2	
20	approximate time period; sec	0.17	
21	time period; hr	4.7348E-05	
22	Fourier #	0.01549587	
23			
24	**Solution p144 Kreith and Black**		
25			
26	Input hot air temperature; F	800	
27	Input hot air velocity; ft/sec	900	
28	Input initial pavement temperature; F	100	
29	Input distance from surface; in	0	
30	distance from surface; ft	0	
31	eda (n)	0.06942515	
32	eda (√n)	0.26348652	
33	zeta	0	
34	zeta+√n	0.26348652	
35	Bi+n	0.06942515	
36	Gauss error function f(zeta+√n)	0.29057334	
37	Gauss error function f(zeta)	0	
38	RHS	0.23957136	
39	Temperature of pavement at depth of interest; F	267.699955	
40	Heat transfer(Btu/hr)	746756.541	
41			

Appendix 3

Value Engineering Report

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Value Engineering Study - Repair of Transverse Cracking in Asphalt Concrete		5. Report Date
		6. Performing Organization Code
7. Author(s) Robert H. Rossman, Harold G. Tufty, Larry Nicholas, & Michael Belangie		8. Performing Organization Report No.
9. Performing Organization Name and Address Kempter-Rossman International 1199 National Press Building Washington, D.C. 20045		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Implementation (HRT-10) 6300 Georgetown Pike McLean, VA 22101		13. Type of Report and Period Covered
		14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted by team members from the States of California, North Dakota, Iowa, Minnesota, Pennsylvania and North Carolina.

16. Abstract

This report summarizes the results of a cooperative Value Engineering Study on the repair of transverse cracks in asphalt concrete pavements. The objective of the study was to optimize the expenditure of maintenance funding through an in-depth study of the present methods, materials and equipments being used, and the development of better methods, materials and equipments, and work crews, for the optimum and safe repair of such cracks.

This report contains recommendations and guidelines on crack preparation, materials, equipment, and timing to effect cost-effective repairs to transverse cracks in asphalt pavements. All team members agree that timely, effective crack sealing will extend pavement life and reduce future maintenance costs.

17. Key Words	18. Distribution Statement
Value Engineering, crack repair, crack sealing, asphalt pavements, extend pavement life	This document is available to the public from the National Technical Information Center, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLAS	UNCLAS		

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PREFACE

This report is the seventeenth in a series of Federal Highway Administration (FHWA) studies to apply Value Engineering techniques to improve various maintenance practices.

This report benefitted from the extensive information gathering phase of four Value Engineering teams with members from six states, each of which received information from their own states and other selected states. The coverage of the material was national in the context of the 48-contiguous states.

One report (1), a "Value Engineering Study of Crack and Joint Sealing," FHWA No. FHWA-TS-84-221, of December 1984, was used as a guide; and it indicated areas that could benefit from being updated.

All the team members were effective contributors, and are listed in Appendix I.

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

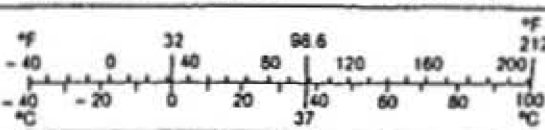
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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LIST OF ILLUSTRATIONS

STUDY BACKGROUND

Pavement surface maintenance represents a significant portion of highway maintenance activities. Pavement cracking is one of the most troublesome aspects of surface pavement condition.

The vast majority of the nation's highway are asphalt surfaced, estimated to be as high as 94 percent.

Pavement cracking of asphalt surfaces is the predominant indicator of approaching pavement failure. In the view of many maintenance managers and highway engineers, cracking contributes to accelerated failure, effectively shortening the pavement's useful life.

The apparent need to repair cracks is beset with a number of troublesome problems.

A wide discrepancy exists in the measurement of costs of crack sealing and filling operations among the states. Some measure cost by gallons of sealant used, others by lane miles, linear foot, or road mile. There is no correlation factor for these disparate methods of measuring cost.

In addition, agreement is lacking among highway maintenance managers, engineers and researchers on approach, effectiveness or need to repair cracks. Some of the questions are:

Does crack sealing prolong pavement life?
Is crack sealing cost effective?
Are there optimum methods and materials for performing the crack sealing operations

Oddly, little research has been conducted in crack sealing and filling, and conclusions are not easily drawn from the sketchy results to date.

This study recognizes the problems and the need for improvement. To that end a methodology was developed which examines current practices used by different states. Methods, materials, equipment and work crews presently being used were examined.

A Value Engineering (VE) approach was used to perform the study. The typical approach to VE follows a formal job plan. The Investigation Phase collects all relevant information and functionally analyzes the problem. It further selects those areas or aspects that appear most applicable for cost improvement. The Specualtion or Creative Phase develops numerous alternatives to the present methods for the selected areas. The Evaluation Phase analyzes the alternates developed in the previous phase and selects the optimum solutions. The Development Phase prepares the optimum solutions as changes to the current approach. These solutions are then normally offered to management during the Presentation Phase.

In this study, information was gathered over a two-month period. To set the stage for the study, creative thinking was applied earlier than normal; and then reapplied when all information had been collected and analyzed. A random sample of 18 states, in addition to the 6 states participating in the study, was solicited for pertinent information.

The Presentation Phase could not be offered to the 50 state maintenance and engineering managers. This Final Report is intended to provide recommendations and guidelines to all concerned.

INTRODUCTION TO THE REPORT

This Value Engineering (VE) study was performed in three sessions of about four days each, in three cities, over a four month period.

This innovation (the normal VE Study is usually accomplished in four (4) to eight (8) continuous working days) greatly enhanced the nation-wide scope of the information gathering functions of the 24 team members from six state highway departments.

The scene-setting, project explanation, and Information Phase were stressed at the meeting in San Francisco, California, from February 29th through March 3rd, 1988.

The Creative Phase was concentrated at the Des Moines, Iowa session, from April 5th to 8th, along with the Evaluation Phase and part of the Development Phase. Also, in Iowa, the teams reported the answers to additional questions about maintenance practices in states other than the six states in attendance. These questions had been assigned at the end of the California meeting.

The Presentation Phase and Draft Final Report presented in Washington, DC, during the June 6th through June 9th -- 1988 meeting carried the VE Job Plan to its customary conclusion, with some extra emphasis on implementation.

Not only does this Final Report include the VE teams' findings, conclusions, recommendations, and an estimate of the benefits of the recommendations, it also spells out, in implementable detail, some guidelines to reap the benefits of the recommendations.

The states which sent representatives to all three meetings were North Carolina, Pennsylvania, Iowa, Minnesota, North Dakota and California. The teams queried another eighteen states to determine their repair practices for tranverse cracks in asphalt concrete pavements.

The VE Team agreed that crack sealing and crack filling prolong pavement life by precluding the intrusion of water and other non-compressibles which lead to rapid deterioration of the pavement and eventual pavement failure. The Team members reached this conclusion with no dissent.

SUMMARY RESULTS

The Value Engineering (VE) Team recommends elimination of routing/sawing of cracks in AC pavements prior to sealing, except in areas where underbody plows or graders will be used for snow removal. This will eliminate one person per sealing team, which amounts to one-half person year per team. The savings from this recommendation should conservatively amount to $33.5 million per year plus the cost of the router or saw, and its maintenance.

The Team also recommended that the vehicle which tows the melter-applicator be configured to carry the air compressor for each sealing team. This eliminates one truck and driver per sealing team, which amounts to one-half person year per team. The savings from this recommendation should conservatively amount to $33.5 million per year, plus the cost of one truck and its operating and maintenance cost.

The savings available from the above two recommendations amount to at least $67.5 million per year for the 48 contiguous states. A safety improvement also accrues since one less truck per team will be on the road, one less semi-hazardous piece of equipment per team will be used (router/saw), and 2 less people on each sealing team will be subject to traffic hazards during operations.

The third recommendation for which cost savings could be derived, based on the sketchy cost information available, nationwide, concerns the use of low modulus materials as the sealant of choice in all climatic conditions. This action should double or triple the life of the seal (3-6 years). A very conservative estimate of savings for this recommendation is $25 million per year in the 48 contiguous states. In addition, further savings will accrue from reduction in pothole patching and extended time between overlays or seal coats attendant with the longer life of the sealed cracks. Safety improvements are apparent when the sealing teams are exposed to traffic only 1/2 to 1/3 of their present exposure time.

Additional areas for value improvement are as follows:

* Develop a piece of equipment that can distribute the materials and spread the materials in a one-pass operation. This will eliminate one person from each sealing team. ($33.5 million per year)

* Consider research into sawing /routing new asphalt pavements and overlays, and filling with suitable

materials, before opening to traffic, to relieve built-in stresses and prevent or defer "normal" cracking. ($25+ million per year)

* Consider establishing a National testing program for determining optimum materials and optimum preparation for repairing cracks in asphalt concrete pavements.

THE REPORT

The team members' Investigation Phase revealed the following aspects to be considered in their studies.

Pavement types. All paved roadways generally fall into three categories: (1) rigid pavement - Portland Cement Concrete (PCC), (2) flexible pavement - Asphalt Concrete (AC), or (3) composite pavement, PCC with asphalt overlays. Approximately 94 percent of all lane miles of pavement in the nation are asphalt surfaced.

The following comments may apply to PCC, but are written specifically for AC repairs.

Types of Cracks. Team members agreed that the types of cracks in AC pavements which lend themselves to repair by sealing or filling, fall into the following categories:

- Thermal cracks
- Reflective (transmitted from below)
- Block cracking
- Map cracking

Figure 1 illustrates a typical transverse crack prior to sealing or filling.

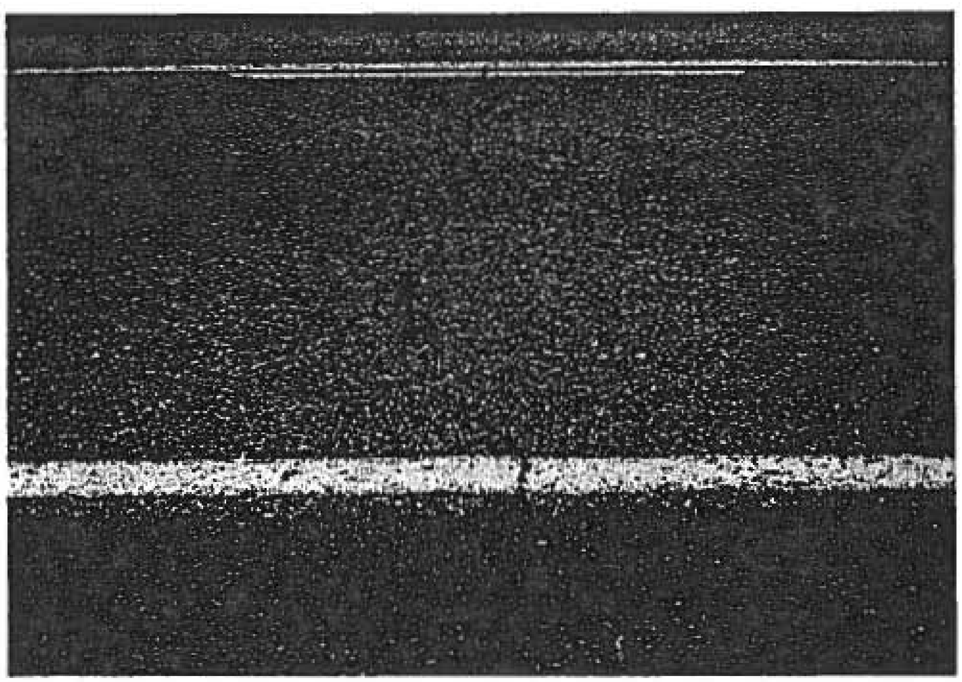

FIG. 1: TYPICAL TRANSVERSE CRACK

Cracks are either well defined, with no spalls and no parallel cracking; or not well defined. Cracks can be said to be either "working" (horizontal and/or vertical movement); or "non-working".

<u>Methods of Repair</u>. Cracks in asphalt pavements can be repaired by filling or sealing. In general the objectives are similar: To preclude foreign material and prolong pavement life. Figure 2 illustrates severe damage in the lower portion of the pavement where a crack had not been repaired.

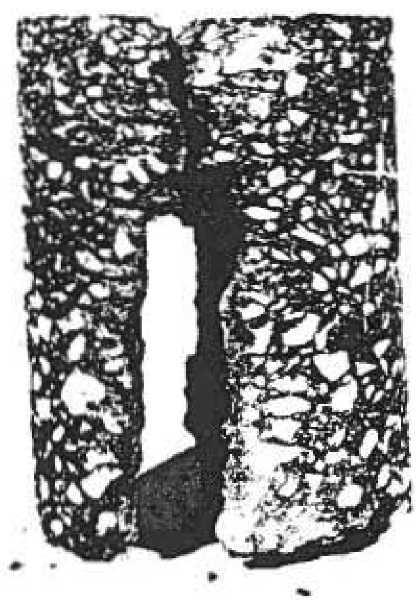

FIG. 2: PAVEMENT DETERIORATION BENEATH THE SURFACE CRACK

This study was restricted to consideration of cracks less than one-and-one half-inches (1 1/2") in width. Cracks of greater width require special treatments, not covered in this study.

Figures 3 and 4 indicate delamination between the pavement layers in core samples taken adjacent to a crack in a pavement with no maintenance provided.

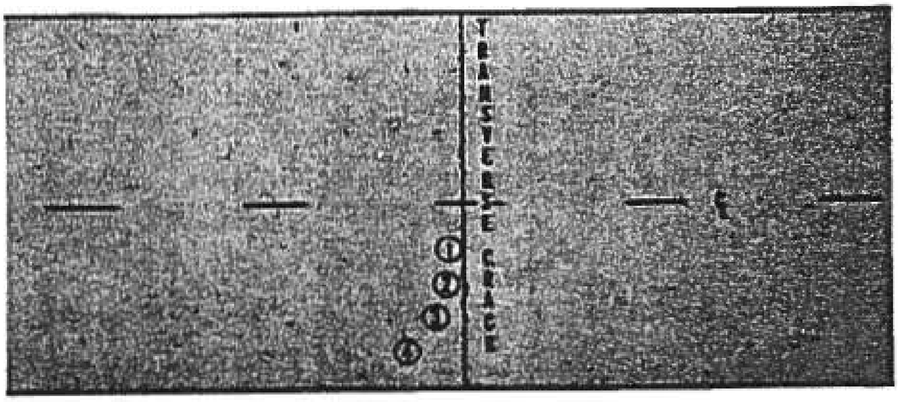

FIG. 3: CORE SAMPLE LOCATIONS ADJACENT TO TRANSVERSE CRACK

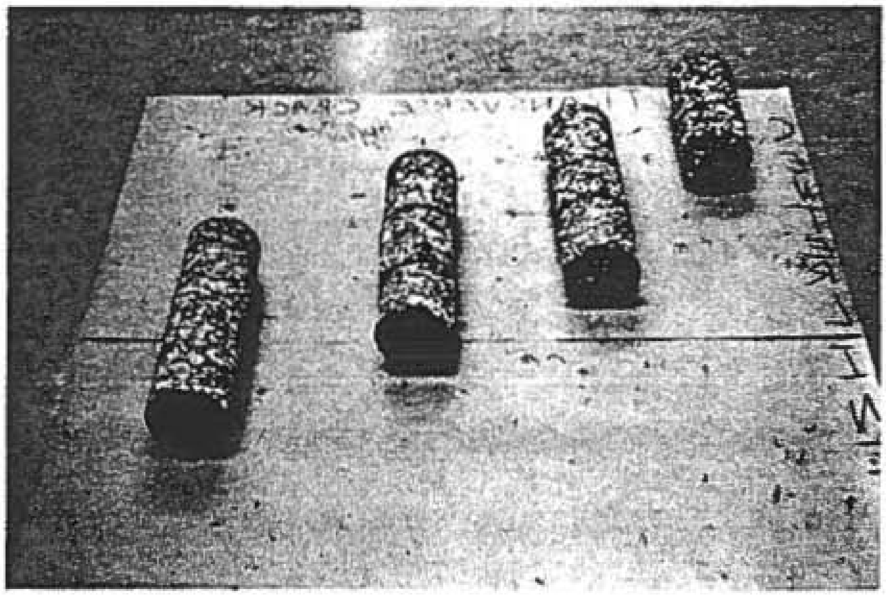

FIG. 4: LWR. PORTION OF PVT. COULD NOT BE RET. IN CORE

Crack Sealing.

Crack sealing is a method of repair for well defined cracks without secondary cracking deterioration. It is distinct from crack filling and was defined by the teams as a pavement preservation measure intended to prolong pavement life. Crack sealants are designed to preclude the intrusion of water into cracks for an extended period of time.

Normal crack sealing operations are conducted on cracks less than one-and-one-half inches in width.

Sealing preparation. Cracks in asphalt concrete pavements will require some preparation prior to placing the sealant. Three conditions which interfere with adhesion must be dealt with: cold temperatures, dirt and moisture.

Crack preparation may also include, as a first step, sawing or routing the crack to form a uniform vessel to receive and hold the sealant. Figure 5 shows routers being used to form a reservoir for crack sealing.

FIG. 5: ROUTING OF TRANSVERSE CRACKS

Whether or not sawing or routing is used, the crack needs to be cleaned. A number of alternatives exist for this purpose: Cleaning and drying with a hot air lance, compressed air only, sand cleaning, wire brushes and brooms. All can be used singly or in some combination.

Sealing Materials - The sealant material selected, and its application, is subject to a variety of factors for success:

Temperature Range - The maximum and minimum temperatures which can be expected throughout the year in the particular geographic region.

Performance - The material's ability to perform based on the vessel (crack) size, shape ratio, and extent of the joint movement.

Adhesion - Condition of the adhesion surfaces and the environmental conditions present to preclude breaking of the seal upon movement of the crack.

Recent research has shown that the best performing sealants are the low-modulus, polymer modified, asphaltic materials. (2,3). The properties of these materials are such that, in cold temperatures, the sealant will demonstrate resistance to stretching with crack movement, and resist tracking in hot temperatures.

The tests used to determine good cold temperature properties are the "cold bend," the "ductility," and "force-ductility" tests. The resistance to tracking is reflected by the "Flow" test and "Softening Point". (See Appendix II)

The State of Utah has been using several low-modulus materials for the last few years. The current Utah specifications are presented in Appendix II. These specifications may need modification for cold temperature compliance or hot temperature tracking resistance in climates that are significantly different than ambient low and high temperatures of 0 degrees F. and 100 degrees F.

Material Placement - The 24 states studied are now using a variety of material placement techniques. States are currently conducting crack sealing at all times of the year: fall, winter, spring and summer. Arguments are made to support each choice of the time of year selected. Factors considered are:

maximum opening of the crack (winter)
minimum opening of the crack (summer)
average opening (late spring or early fall)
absence of ice and snow
absence of rain, and
workforce availability

Presently it seems that overbanding, flush squeegeeing, flush filling and underfilling are done throughout the year except during inclement weather. Figure 6 shows a typical squeegee used for joint and crack repair. Figure 7 indicates a tight squeegee immediately following a crack repair. The squeegee should follow within about one foot of the wand placing the material. Figure 8 shows a completed repair where a squeegee was not used.

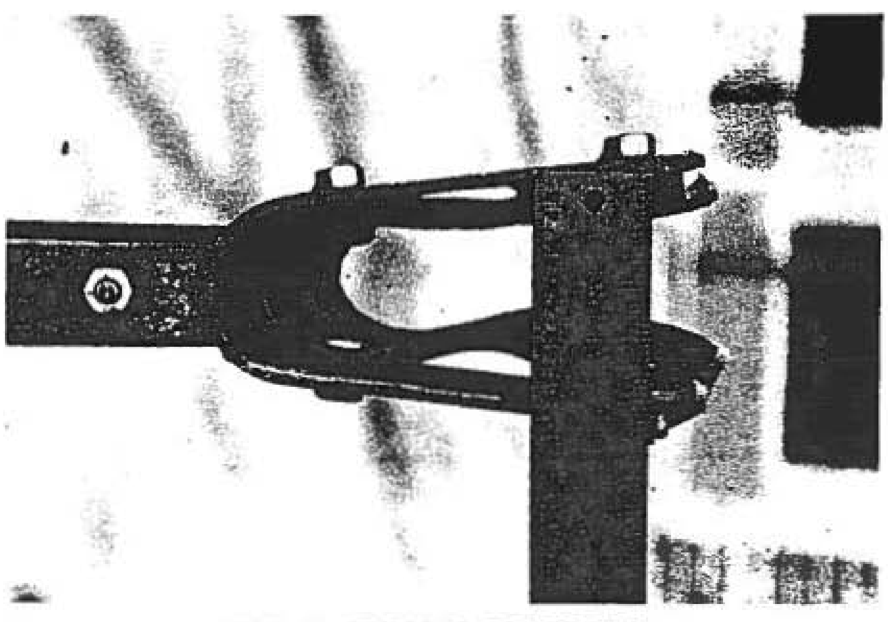

FIG. 6: TYPICAL SQUEEGEE

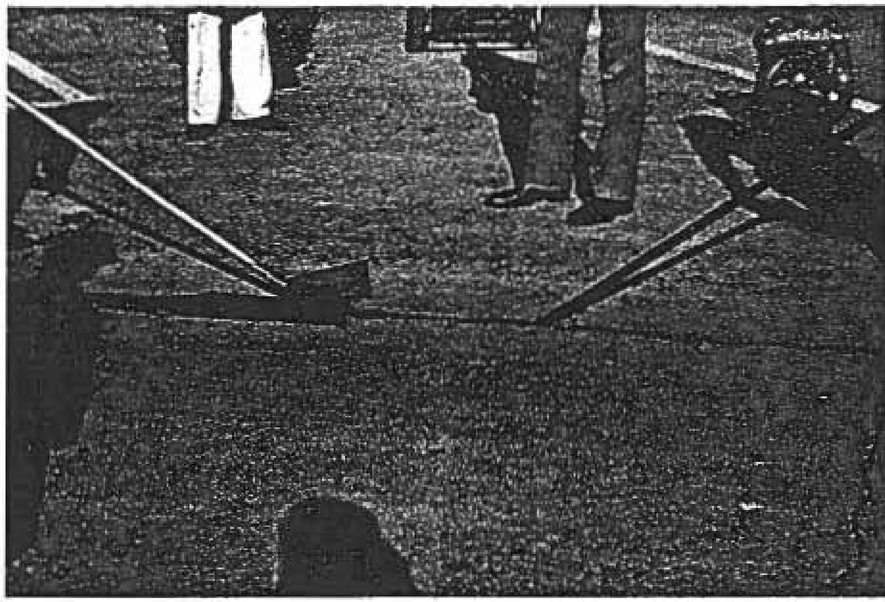

FIG. 7: SQUEEGEE IN USE IN CRACK REPAIR

FIG.8: CRACK AND JOINT REPAIR ACCOMPLISHED WITHOUT SQUEEGEE

Currently, the states which the teams studied begin their crack sealing operations at different times in the pavement's useful life. Some states seal cracks when they first appear, usually within the first three years after construction. Other states conduct crack sealing as a primary strategy to extend the pavement's useful life.

Failed pavements and areas of alligator or block cracking are generally not sealed by conventional crack sealing methods.

Some states utilize pavement maintenance management systems to track pavement condition and predict when crack sealing would be most beneficial.

Equipment - There is a variety of melting kettles used for hot-applied sealing compounds at the present time.

Study team members were concerned with features affecting productivity and safety issues, such as:

Melting time
Material loading features
Hose handling, storage, and clogging
Burners and the effect of wind
Temperature control and monitoring

Study team members were also concerned with equipment to be used for sawing and/or routing. The issues were:

Size and maneuverability of equipment
Secondary cracking
Spalling and tearing of joints
Vessel size and shape
Need to saw/rout and/or benefit

Crack Filling.

Crack filling is a procedure to fill the pavement voids and/or reinforce the adjacent pavement. It is accomplished to prevent intrusion of water into the sub-base of the roadway and to strengthen the pavement section.

The filling of a crack implies different expectations of performance, as discussed above, as compared to sealing. The material used may, in fact, perform a short term seal. However, the sealing properties of the material are not critical.

Normal filling operations can be conducted on all cracks which, as defined in this study, are those of one-and-one-half inches or less in width. Figures 9 and 10 show a crack filling operation with CRS-2 and a sand blotter to prevent tracking.

FIG. 9: LONGITUDINAL AND TRANSVERSE CRACK FILLING

FIG. 10: TRANSVERSE CRACK FILLING WITH CRS-2 AND SAND BLOTTER

Preparation - Filling preparation may require the use of compressed air or a heat lance to clean the crack prior to filling, depending upon the material used. However, some states do not clean cracks prior to filling.

Material - Both hot and cold applied bituminous materials can be used for filling cracks. Cold applied materials are either cutback asphalts, i.e., RC250 & MC800, or emulsified asphalts, i.e., CRS-2. A number of additives can be used with the appropriate asphalt binders, such as rejuvenating agents, rubber, aggregates, fibers and polymers. Hot applied materials include asphalt cements such as paving grade asphalt and air refined asphalt. Figure 11 shows the use of two wands from one distributor, with squeegees being used. If squeegees are tightly applied, the roadway can be opened to traffic very quickly.

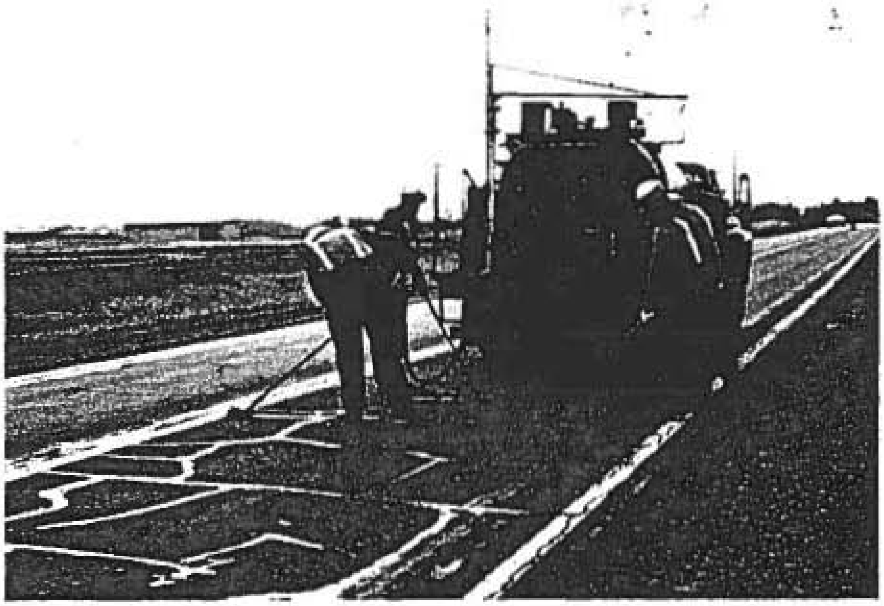

FIG. 11: TWO WANDS BEING USED WITH ONE DISTRIBUTOR

Timing - With the exception that filling should not be conducted during periods of precipitation or extreme cold, conditions associated with weather and temperature are not critical for application.

Equipment - Specialized equipment is not necessarily required to apply the fill material. Ordinary asphalt distributors or direct heat kettles will meet the application requirements of some materials. Other materials will require the use of indirect heat equipment, if additives are used. Figure 12 shows the results of a filling operation. The pavement layers are held together and, thus, the pavement is more stable than one on which no maintenance has been done. (See also figure 4).

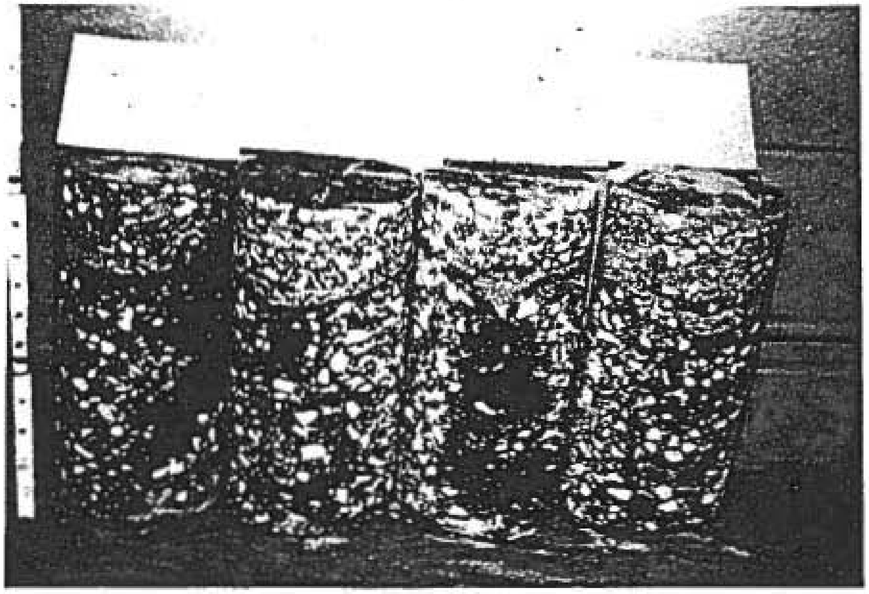

FIG. 12: CORE SAMPLES AFTER JOINT AND CRACK FILLING

Figure 13 indicates tracking of filler material on a roadway where hot weather has forced filler material out of cracks.

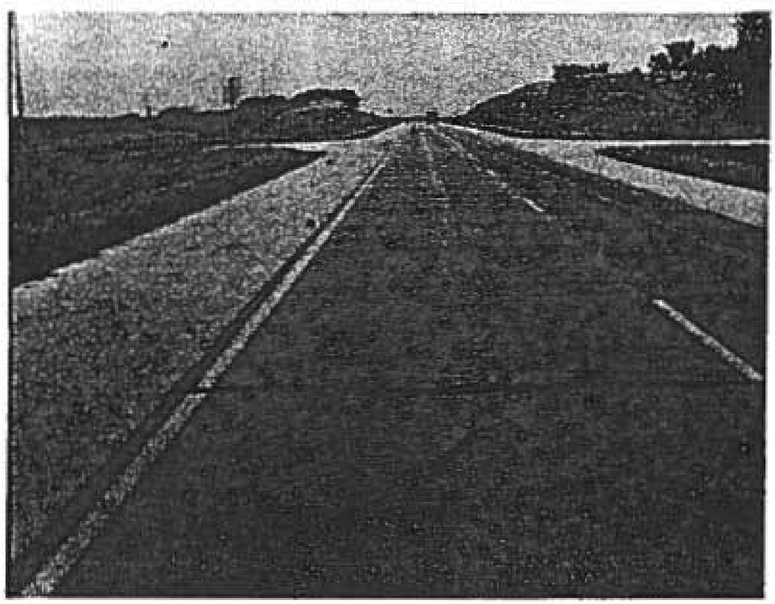

FIG. 13: TRACKING CAUSED BY THERMAL EXPANSION

SUMMARY COMMENTS

The majority of the states contacted indicate that they have a uniform statewide policy for crack sealing. Most state that they have a performance standard. This is indicative of the general importance associated with crack sealing operations.

A majority of the states also reported a general satisfaction with their programs, but felt an opportunity for improvement existed and that work needed to be done on materials and equipment, especially to reduce manpower requirements and improve safety.

Methods vary, but the majority of the states are using ASTM D 3405 and asphalt rubber as a sealant material. A number of states reported the practice of sawing or routing cracks prior to placing the sealant. The effectiveness of this practice is doubtful, however, because many states questioned its value or have discontinued sawing/routing except where underbody plows or graders will be used for snow removal.

The principal equipment used for cleaning cracks are the heat lance or compressed air.

Little or no information was made available on the cost of crack sealing by states other than the participating states. A wide discrepancy exists in the measure of unit costs. It appears that maintenance management systems are not being keyed to track costs of crack filling and sealing.

SIX STATES' PROFILES

Each of the six states which sent representatives was asked for a more detailed report of crack repairs in their jurisdictions. The highlights of these reports follows:

<u>California</u> uses three different methods of repairing transverse cracks in AC pavement:

* Applying an emulsion and rejuvenating agent into the crack, followed by covering the area sealed with a damp sand to fill the crack and blot up the surface and excess oil.
* Applying a hot-pour petroleum based material or a blended compound into the crack.
* Utilization of radiant heat asphalt repair equipment

to heat the asphalt adjacent to the transverse crack, loosen the surface asphalt with a rake or similar tool, add sufficient reheated asphalt to fill the crack and repair any other deficiencies, level, apply a liquid rejuvenator to the surface, and roll.

Pennsylvania's methods and procedures manual states:

For rigid base roads -

A - Well defined transverse crack.

* If routing, rout well defined transverse reflective cracks to a depth of 1/2" to 3/4" and to a width of 1/2". Transverse cracks wider than 3/8" generally do not require routing. Routing is not required if using the overbanding process with applicator head.
* Clean all cracks with compressed air to remove fines and dust. Cracks must be as clean as possible to insure good bonding.
* A hot (heat) lance may be used to dry damp cracks.
* Seal cracks with any of the following bituminous materials:
  - AC and rubber
  - AC and fibers
  - Prepackaged AC & rubber
  - Prepackaged AC & fiber
* A squeegee should be used to level the sealant when using AC and rubber.

B - Multiple cracking condition - a reflective crack which has developed multiple secondary cracks that radiate approximately 6"-12" in each direction from, and parallel with it.

* Clean area to be sealed using compressed air. In addition to using any of the materials used in the single cracking condition, RC-250 can be used to seal multiple cracks in the winter. This material should be covered with sand or aggregate before exposing to traffic.

For flexible base roads -

A - Well defined cracks - a single crack.

* Clean crack using compressed air.
* A hot lance may be used to dry damp cracks.
* Seal cracks with any of the following bituminous materials: (Preferred) AC and rubber; AC and fibers, prepackaged AC and rubber or fibers. (Acceptable) RC-250 winter only.

Iowa's DOT has three maintenance activities to repair transverse cracks in asphalt cement concrete surfaces:

* joint and crack filling

* joint and crack routing and sealing, and
* slurry leveling.

Pavements which have recently been paved or resurfaced with an asphaltic cement concrete mix, and where crack repair is completed, are good candidates for routing and sealing.

All transverse cracks are filled, if sealing is not appropriate. If depressions have occurred in a crack area, slurry leveling is performed.

North Dakota for more than 40 years has coated (painted) the sides of visible cracks. This is usually done in the cold weather using a towed, single well distributor, and hand carts with built-on squeegees.

For the past 15 years, double-walled, melter applicators have been employed using modified asphalt (crumb-rubber, etc.) material. The Department has a very limited number of these and only a minority of cracks are sealed using this method.

North Dakota has let contracts for the last four or five years to rout and seal cracks with polymer materials. In general, these have been demonstration projects to gain knowledge, and will be discontinued if it is found that contracting is inappropriate for this work.

The state intends to expand sealing with melter applicators and modified asphalt materials, depending on avaialable funds.

Minnesota's current crack repair program consists mainly of using an air refined asphalt cement (AC-3). There is also some use of emulsions and cutbacks.

The majority of the work is done in the winter and the spring when the work force is available.

During the past several years some test sections have been established to look at new methods and materials for crack sealing. This included examining various new routing and sawcutting configurations, heat lances, double jacketed kettles and various types of materials.

The experimental work also included some airport runways which had very severe transverse cracking.

The Operations Division of Minn DOT has established a peer review group to examine crack sealing. They are charged with reviewing current practices and recommending changes.

North Carolina has 121,950 miles of state, county and some city streets maintained by the state forces. About 95 percent of these roads are bituminous surfaced pavements.

Routinely, the transverse cracks are sealed by cleaning with compressed air (15 percent of the time), and pouring them with RC-250 or CRS-2, using pour pots. The cracks are then blotted with sawdust or sand. The typical crew consists of twelve workers, not including traffic control.

Generally, the cracks are sealed during the winter months when the cracks are more open. The results of this sealing method are unsatisfactory; usually the cracks reappear in one year or less. The state would like the sealant to last at least three to five years.

In 1984, the state began using asphalt rubber to seal transverse cracks, and better results were obtained. Currently there are several sealing projects which are using the asphalt rubber material.

CURRENT PRACTICE

A total of 24 states were questioned about current practices of crack sealing and filling. Table I provides a detailed summary of current practices of the six states which sent team members to this VE study. Table II summarizes general practices of the other 18 states contacted by the VE team members.

TABLE I - SUMMARY FOR PARTICIPANT STATES

ASPHALT CONCRETE PAVEMENT - CRACK SEALING AND FILLING SUMMARY

Total Lane miles bit. surf. DOT inventory	Calif. 38,200	Iowa 13,085	Minn. 23,000	N. Car. 121,950*	N. Dak. 11,000	Penn. 61,031
Pav't mgmt. sys.	y	y	y	no	y	no
Uniform state-wide policy	y	y	no	no	no	y
Contract	y	y	no	y	y	y
State forces	y	y	y	y	y	y
Performances Std.	no	y	y	y	y	y
METHODS						
Rout and seal individual cracks	y	y	no	y	y	y
Seal only individual cracks	y	y	y	y	y	y
Full width seal chip/slurry	y	y	y	secondary roads	no	y
Full width, fog seal	no	no	shldrs only	secondary roads	y	no
Full width, bit. overlay	y	y	y	y	y	y
Partial width chip/slurry seal	y	y	depressions low vol rds	y	no	y
Partial width fog seal	no	no	no	y	y	no
Mill & patch	y	y	y	some	y	y
Other	heat plane fabric	slurry leveling	no	no	no	RC 250, winter patch
Do nothing	no	no	no	no	no	no
CLEANING						
Compressed air	y	y	y	15%	y	y
Heat lance	y	no	no	y	no	optional
Wire brush/blower	no	no	no	no	no	y
Saw/rout	no	w/compressed backer rope	no	no	y	y
Sand blast	no	no	no	no	y	no
High pressure water	no	y	no	no	no	no
EQUIPMENT						
Indirect heat Melter applicator	y	y	y	y	y	y
original	y	y	y	y	y	no
modified	y	no	no	no	no	y
Distrib./asphalt kettle	y	y	y	y	no	y
Wand original	y	y	no	no	y	no
Wand modified	no	y	y	y	y	special head
Squeegee	y	y	y	y	y	y

TABLE I continued

States	Calif.	Iowa	Minn.	N. Car.	N. Dak.	Penn.
MATERIAL						
Asphalt rubber	y	no	y(exp.)	no	D3405	AC+rubber
ASTM D 3405	y	y	no	y	D3405-78	AC+fibers
ASTM D 1190	y	no	no	y		D3405
Emulsified asph.	CRS-2+ reclamite CRS-2+latex	CRS-2 CRS-2P(pol.) CRS-2M(mod.)	CRS-2	CRS-2	no	no
Cut back asph.	no	no	MC800 RC250 MC250	RC250	MC250	RC250 winter only
Blotting material	y	y	y	y	y	y
TIMING, RESEARCH, COSTS						
When performed	fall pref. 40F min.	40F min.	winter+spring	winter dry	suitable dry wthr	spring fall
Results satisfactory	y	gen'ly	gen'ly	no	gen'ly	gen'ly
Research program	no	y	y	y, new	y	y
Innovative/experimental equipment/material	y	no	y	no	no	y
Annual maint. budget in $1,000s	102,000 (flex)	75,000	123,000	298,208	35,000	637,000
Annual cost sealing program, in $1,000s	9,546	3,642	na	1144	1,500	6,658
Unit costs	1,783 /ln. mi.	**(see below)	na	RC 250 $400/ln. mi.	$1,700 to $2,000/rd. mi.	$6.57 /gal.
				rubber asph. $800/ln. mi.	$0.32/lf	

* Includes state, some city and all county roads

** Iowa unit costs:

crack fill by DOT - $7.48/gal., includes prep.
crack fill by contract - $1.65 - 2.54/gal. at $700 - 1,000/mile for prep.

crack sealing by DOT - $13.12/gal.
crack sealing by contract - $0.35 - 0.48/lf

slurry leveling by contract - $1.64 - 2.11/gal. at $687 - 1,038/mile prep.

Key:

y = yes
na = not applicable

TABLE II

ASPHALT CRACK SEALING, CONDENSED SUMMARY, OTHER STATES REPORTING

	Uniform state-wide Policy	Performance standard	Do nothing	Rout and seal	Seal only	Asphalt and rubber	Cutback asphalt	Emulsified asphalt	Satisfied with results	Innovative/experimental Equipment, materials	Total lane miles	Percent bituminous surface
Arizona	y	y	no	no	y	y	no	no	no	y	17,063	98
Arkansas	y	y	no	no	y	y	no	y	no	y	35,087	89
Florida	no	no	y	no	no	no	no	no	y	no	34,000	96
Georgia	na	na	no	no	y	y	y	no	y	y	na	na
Illinois	y	y	no	y	no	y	no	no	y	no	25,000	na
Louisiana	no	no	y	no	no	no	y	no	y	no	na	na
Missouri	y	y	no	no	y	no	y	no	no	no	29,660	92
Nebraska	no	no	no	y	no	y	no	no	y	no	13,085	53
New Hampshire	no	no	no	na	na	y	no	no	y	na	8,444	94
New Jersey	y	y	no	no	y	y	no	no	y	na	6,842	73
New York	y	y	no	no	y	y	no	no	no	no	32,007	76
Ohio	y	y	no	y	no	y	y	no	y	na	35,887	95
Oklahoma	na	na	no	na	na	y	y	y	y	na	na	na
Texas	na	no	no	na	na	y	no	no	y	no	172,000	na
South Dakota	y	y	no	y	y	y	y	no	y	na	na	na
Utah	y	y	no	y	y	y	no	no	y	y	na	na
Wisconsin	y	y	no	y	y	y	y	y	no	y	na	na
Washington	y	y	no	y	y	y	no	no	y	y	17,000	80

CONCLUSIONS - GENERAL

Sealing and filling of transverse cracks in asphalt pavements extends the service life of the pavement by precluding introduction of water and non-compressibles into the crack, protecting the sub-base and, in the case of filling, strengthening the adjacent pavement.

A review of cost allocation in several states indicated that labor costs amounted to approximately 66% of total cost; equipment costs were about 22%, and material costs about 12% of total cost for crack sealing and filling operations. Any method for reducing recurring labor costs by use of better materials would be very cost-effective.

CONCLUSIONS-CRACK SEALING

Methods of Repair. Crack sealing is the appropriate method of repair for well defined cracks without secondary cracking.

Preparation. All cracks scheduled for sealing should be clean and dry prior to application. There is a benefit from heating the surrounding area prior to sealing.

Sawing and/or routing is a repair procedure used by some states for cracks. Four industry experts presented information to the teams on vessel size and configuration. Testimony conflicted on both equipment to use, and vessel configuration ratios. Arguments were made to support ratios of 1:1, 2:1, 1:2, and 1:4. No conclusive evidence was presented that sawing and/or routing produces any significant benefit. Moreover, some evidence was offered that showed that routing may produce secondary cracking. Therefore the VE teams concluded that sawing and/or routing should not be done on transverse or random cracks prior to placing the sealant. If later research should prove claims of longer life of repairs, and agreement can be reached on vessel size, the operation may provide enough benefit to justify the expense. It does not do so today.

In some instances consideration may be given to sawing and/or routing in areas where underbody plows or graders are used for snow removal.

Sawing and sealing new overlays on jointed concrete pavements, to control cracks, has been relatively successful in Pennsylvania and other states. The process involves referencing, sawing and sealing the overlay to relieve built in stresses. Pennsylvania specifications require a reservoir to be created and sealed with ASTM D 3405 material.

This process has resulted in controlling cracks and has provided adequate sealing for up to six years.

Cleaning. The presence of dirt or moisture will interfere with sealant adhesion. Appropriate cleaning of the crack is necessary.

The VE teams concluded that the heat lance is the most effective preparation tool for the majority of conditions encountered. However, compressed air, sand blasting, wire brushes, etc. may also be used.

Material. The use of low modulus materials for crack sealing in all climate zones of the country is indicated. Polymer modified asphalts (low modulus materials) have yielded successful field performance in working cracks, which is the most severe condition. Different climatic zones may require more flexibility and ductibility at low temperatures, and better anti-tracking properties at high temperatures.

Application. Most sealant materials are temperature sensitive. Following the manufacturer's recommendations will produce the required result both in melting the material for application, and a longer sealant life.

Adhesion is improved if the pavement surface and crack interfaces are warm. Application should closely follow cleaning with the heat lance.

Correct use of the heat lance regulates the production rate. Heat lance operation requires softening of the surface asphalt which is indicated by a color change. Burning, which is indicated by smoke, must not occur.

Winter plowing activities may have a significant impact on sealant performance. An exposed band-aid is not recommended where underbody plows, or graders are used. However, the inverted band obtained by sawing and filling (1:4 ratio) used by the Province of Ontario, Canada, has demonstrated adequate performance under these conditions.

Equipment. Application equipment should be capable of applying the sealant in accordance with the material manufacturers recommendations.

The VE team members expressed dissatisfaction with most melter applicators presently being used. Improvements need to be made in the following areas:

* Melting time is too long for most melter applicators.
* Material loading features are unsafe and most users need to retrofit equipment to protect workers.
* Hose handling, storage and clogging problems need to be addressed. Cabinets or other means to retain heat within operating ranges need to be provided. The ability to backflush hoses is also desirable. Some manufacturers have produced new equipment which purports to solve these problems.
* Burners on some models are easily affected by wind and cannot be used during adverse conditions, or while being towed to the job site.
* Temperature control and monitoring on some models is poor. Users generally need to retrofit equipment to provide adequate controls to prevent overheating and to safeguard personnel.
* The use of multiple fuels creates service problems.

Time of Year, Weather. The VE teams concluded that the extent of crack opening produced by thermal expansion or contraction is an important factor in crack sealing. Consequently, operations should be conducted during the appropriate time of year, when temperatures produce approximately average openings.

Actual operations should be conducted consistent with weather conditions. In particular, sealing may not be appropriate when the air temperature is below freezing, or when excessive moisture is present in the pavement. No sealing should be done during periods of precipitation.

The use of the heat lance effectively extends the conditions under which the crack sealing operations can take place.

CONCLUSIONS-CRACK FILLING

Pavements with cracks that exhibit depressions, parallel cracking or other failures, which would reduce the chance for sealant success, should be filled by the most cost effective method available. Figure 14 shows joint deterioration and settlement due to moisture. This failure lends itself to filling.

FIG. 14: JOINT DETERIORATION DUE TO MOISTURE

Cleaning and Preparation. The presence of dirt or moisture will interfere with material adhesion. All cracks scheduled for filling should be relatively clean and dry.

Materials. A wide variety of materials can be used for crack filling, such as: asphalt cements, asphalt cements mixed with crumb rubber, polyfibers, or certain polymer modifiers, emulsions and cut backs.

Application. Filling materials are applied over a wide range of temperatures. Most mixture temperatures are controlled by the additive. Asphalt cement, cut back and emulsion temperatures are controlled by material specifications.

Equipment. Because of the type of material used for filling, a wide variety of equipment is available. Materials with additives such as fibers or rubber must be applied with an indirect heating kettle with a pumping system capable of applying the material through a wand.

Figure 15 shows slurry material spread across the width of a crack, using a lute.

FIG. 15: USING LUTE TO SPREAD SLURRY

Figure 16 shows a completed repair after slurry material has cured. When cured sufficiently, the lane can be opened to traffic.

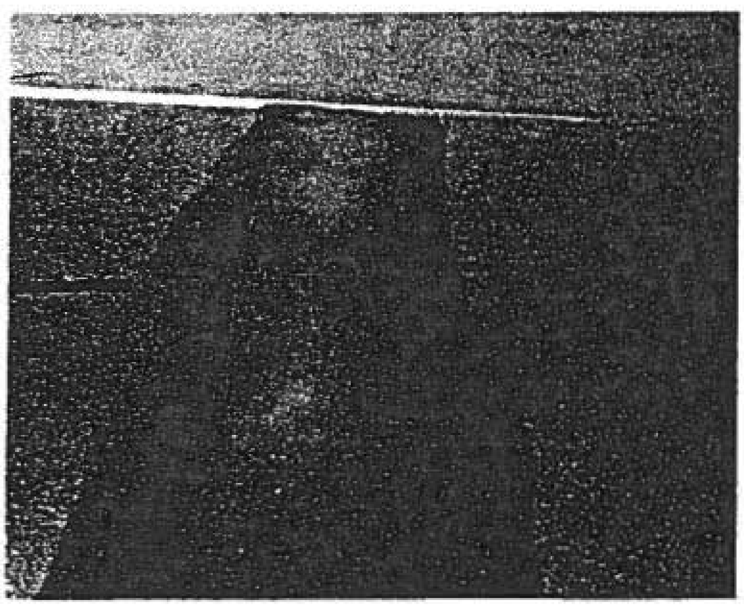

FIG. 16: REPAIR COMPLETED ON THE NOW-LEVELED JOINT

Crack filling is not totally dependent upon the opening of the crack. Filling generally can be done in all seasons of the year. The critical factor is moisture. Filling should not be done during precipitation or while excessive moisture is present.

RECOMMENDATIONS - GENERAL

All cracks in asphalt concrete pavements should be repaired as soon after initiation as possible.

All cracks should be sealed or filled to prevent pavement failure and to extend pavement life.

Material research should be done to provide longer-lived materials in order to reduce the high labor costs associated with asphalt pavement repair.

RECOMMENDATIONS-CRACK SEALING

Sawing and or routing of existing cracks is not recommended at this time except where underbody plows or graders are used for snow removal.

The heat lance is recommended as the preferred tool for cleaning cracks prior to sealant application. Heat lances capable of producing approximately 3,000 degree F. air with operating velocities of approximately 3,000 fps at the nozzle orifice have produced good results, and are recommended.

The use of low-modulus materials is recommended for crack sealants. Research should continue to be done on sealant materials to identify superior performance characteristics. In addition, specifications and test procedures should be developed specifically for bituminous pavement crack sealants. The high labor cost in crack sealing operations (66% of total costs) could be greatly reduced by using customized, longer lasting materials.

Indirect heat transfer equipment should be used to melt and apply hot-pour sealant materials. Material manufacturers recommendations should be strictly adhered to.

Application equipment which can meet both the material manufacturer's specifications and the expected range of ambient conditions during application should be used.

The sealant material should be applied as soon as possible after cleaning with the heat lance. To assure satisfactory adhesion, the pavement should be warm and dry.

Users should develop equipment specifications which eliminate the problems delineated in the conclusions section of the report.

Crack sealing should be performed from early spring to late fall.

Use a vehicle capable of carrying or towing the combinations of required equipment (piggy-backing).

Repairs should be performed as a single-pass, moving, operation to reduce the number of set-ups for traffic control, and their the attendant safety hazards.

Consideration should be given to the use of multiple crews to expedite the operation.

RECOMMENDATIONS-CRACK FILLING

Recommended procedures for crack filling operations, depending on conditions are:

Assure that cracks to be filled are relatively clean and dry.

Apply asphalt cements, emulsions, and cutbacks in the crack, followed by sand that acts as a filler and also a blotter to prevent pickup by traffic.

Overband the cracks with a mixture of asphalt and six percent fiber or 25 percent rubber. The fiber mixture is placed by means of a wand with an applicator head attached. The rubber mixture is placed with a wand and squeegee. Consideration should be given to applying all filling materials with an applicator head, or squeegee attached to the end of the wand.

Slurry patching should be done using a drag box, or screed, to feather the material.

In advanced stages of crack deterioration, the following activities may be appropriate:

Mill or otherwise cut and remove the area of failure and patch with hot bituminous mixture.

Repair by heating the area with infrared heaters, add material, smooth and compact. Infrared heaters are capable of heating the pavement from 1" to 3" in depth. The material is then redistributed and compacted.

GUIDELINES

Develop a uniform statewide crack repair policy.

Develop performance standards outlining the procedures to be followed, the equipment and materials to be used and the production anticipated.

Each agency should develop training materials and training programs on the proper methods to repair cracks.

Each agency should provide training to the crews within a reasonable time prior to start-up of sealing activities.

Agencies should develop pavement maintenance management programs which include a pavement condition survey feature to indicate when crack repair would best be accomplished. Condition survey data should be in sufficient detail to rank locations requiring crack repair on a priority basis.

The low modulus crack sealant should a be homogeneous blend of materials with the following properties: Flexibility, Ductility, Force Ductility and Flow.

Please see Appendix II, under Crack Sealing Compound, paragraphs 2,4,5,6 and 8, for recommended specifications for each of the above.

APPENDIX A - ATTENDEES

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* = Point of Contact

APPENDIX B

(State of Utah) <u>SPECIAL PROVISION</u>

Asphalt Pavement Crack Sealing

Description: This work shall consist of cleaning, and sealing the cracks in the existing pavement.

Construction Requirements: Visible thermal cracking six (6) feet or more between cracks or as directed by the Engineer shall be cleaned and sealed. Immediately prior to sealing the crack and surface area for at least six (6) inches on both sides of the crack(s) shall be cleaned of foreign matter and loosened particles with a HCA (hot compressed air) heat lance. Adequate cleaning is determined by a darkening of the surface at least two inches in width, centered on the crack. Where dirt is still being retained on the unmelted (undarkened) surface the darkened width may be expanded to match the sealant configuration or as directed by the Engineer. The heat lance shall meet the following requirements: temperature of heated air at exit orifice minimum of 2,800°F. Velocity of exiting heated air minimum of 2,800 fps. Direct flame dryers shall not be used. The crack shall be overfilled and immediately squeegeed to form a band-aid; the squeegee shall be either attached to the wand or be kept within five (5) feet of the sealant applicator at all times. The band shall have the following configuration (see drawing Band-Aid Configuration). It shall have a band extending a minimum of one-half (1/2) inch to a maximum of one (1) inch on either side of the crack(s). The maximum width of the band shall be 3 inches. The band shall have a minimum thickness of 1/32 inch and a maximum thickness of 3/32 inch; at least ninety percent (90%) of the band placed shall have a thickness of 1/16 inch ± 1/64 inch. A wipe zone, (anchor zone) flush with the pavement surface shall extend for a minimum of one-half (1/2) inch to a maximum of one (1) inch on either side of the band. The band shall be centered on the crack.

Where traffic or construction activities may cause tracking or pullout of the sealant material the contractor shall sand the sealant as it is placed or as directed by the Engineer.

Cracks in excess of 1" in width shall be filled with 1/2" minus plant mix or road mix or as directed by the Engineer.

Sealant material picked up or pulled out shall be replaced at contractor expense. Any damage to the traveling public resulting from sealant application or sealant pullout shall be paid for by the contractor.

Cleaning and sealing shall extend across the full width of the bituminous surfacing including the side slopes, or as directed by the Engineer.

Sealing shall be done only when the cracks are clean and dry and only upon inspection and approval by the Engineer.

Equipment: Sealant placement equipment shall use circulating hot oil heat transfer for heating the product (sealant machines). No direct heat transfer units (tar pots) shall be used. Maximum product tank capacity of sealant placement equipment shall not exceed 500 gallons. Alternate equipment shall be approved by the Engineer.

Temperature Control: Sealant manufacturer's instructions on application temperature shall be observed. The contractor's sealant unit shall have available at all times an operating ASTM 11-F thermometer with an intact mercury column or a certified, calibrated digital pyrometer, electronic thermometer, or equivalent direct reading temperature measurement device capable of reading within $\pm 5^{\circ}F$ from $200^{\circ}F$ to $600^{\circ}F$.

A log of product tank temperatures shall be recorded at one hour, ± 10 minute intervals, and kept available for inspection by the Engineer. Product tank temperatures shall be taken with one of the certified calibrated devices described. Temperature gauge readings are not acceptable.

Material that has been overheated in excess of $30^{\circ}F$ above the manufacturer's recommended maximum temperature for one (1) hour or $60^{\circ}F$ for 1/2 hour shall be wasted at the contractor's expense. Material shall not be placed if the temperature is below the manufacturer's recommended minimum application temperature.

The contractor's procedures for loading material into the product tank shall not depress the sealant temperature at the wand tip below the manufacturer's recommended application temperature.

Crack Sealing Compound: The crack sealant shall be a homogenous blend of materials combined in such a manner as to produce a material with the following properties:

1. Workability: The material shall pour readily over its specified application temperatures and penetrate a 1/4 inch crack for the entire ambient temperature range recommended by the manufacturer for application of this material.

2. Flexibility: A (1/8 " x 1" x 6") specimen of the product conditioned to $0^{\circ}F$. shall be capable of being bent to a 90° angle over a 1.125" mandrel conditioned to $0^{\circ}F$ in 2 seconds without cracking. (State of Utah Test).

3. Curing: The product shall cure sufficiently within 45 minutes of application, over the manufacturer's recommended ambient temperature range for application, to allow normal traffic without tracking.

4. Ductility: A standard specimen shall be capable of being pulled a minimum of 30 cm at 1 cm/min at $39.2^{\circ}F$. (State of Utah Test).

5. Force-Ductility: The standard specimen (See Ductility) shall not exceed a force of 4 lb. during the specified elongation: 30 cm at 1 cm/min at 39.2°F. (State of Utah Test).

6. Flow: Material shall comply to ASTM D-3405, Section (4.3) Flow.

7. Tensile Strength Adhesion: Material shall comply with ASTM D-3406, Section 4.7 Tensile Adhesion; except that sealant specimens shall be cured 4 hours (not 7 days).

8. Asphalt Compatibility: There shall be no failure in adhesion, or formation of an oily ooze at the interface between the sealant and the asphaltic concrete or softening or other harmful effects on the asphaltic concrete when tested at 140°F (60°C).

9. Packaging and Marking: Sealant material shall be supplied preblended, prereacted and prepackaged. If supplied in solid form the blocks of completed material shall be cast in a plastic or other disolvable liner having the capability of becoming part of the crack sealing liquid. The sealant shall be delivered in the manufacturer's original sealed container. Each container shall be legibly marked with the manufacturer's name, the trade name of the sealer, the manufacturer's batch or lot number, the application temperature range, the recommended application temperature and the safe heating temperature.

10. Sampling: All sealant to be used on the project will be stockpiled at the site at least ten (10) working days prior to use, or at least twenty (20) working days prior to use if stockpiled at the vendor's place of business. Subsequent deliveries shall be placed in separate stockpiles. Stockpiles shall be waterproofed. The Engineer shall be notified when each stockpile has been established and ready to be sampled. Not less then one random sample of each lot or batch number (minimum of 10 lbs/sample) will be taken. No material shall be placed until the Engineer has approved the material for placement.

11. Compliance: Failure to meet specification shall not be cause for claim or extension of contract.
The contractor shall be held liable for all costs incurred in procuring and testing of materials that are found to be out of specification.

12. Field Performance Tests: Sealant shall have performed satisfactorily for at least one (1) year at a U.D.O.T. approved test site before the manufacturer shall be permitted to bid.

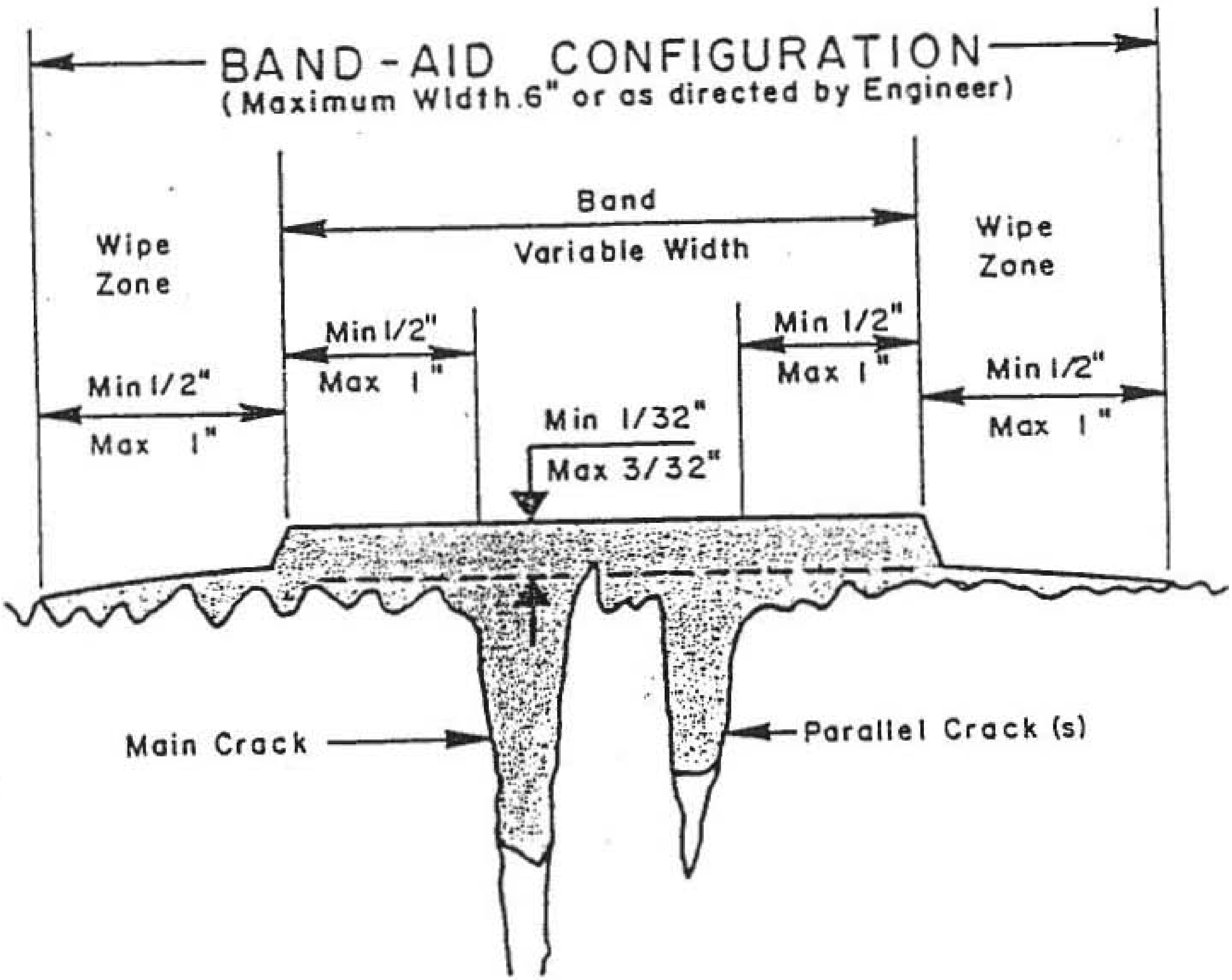
13. Dissimilar Materials: Mixing of different manufacturer's brands or different types of sealant shall be prohibited.

The type of materials used shall be at the discretion of the supplier to produce the desired finished product.

Applicable Vendor Certificates as required by the Utah Department of Transportation shall accompany all shipments supplied to the Department.

Method of Measurement: Crack sealing shall be measured by the ton of material used. The measured quantity shall include the blended mixture and dissolvable liner. The Engineer may require the weighing of equipment for determination of actual quantities of material used.

Basis of Payment: The completed and accepted quantities of this item shall be paid for at the contract unit bid price per ton of "Crack Sealing". The price per ton shall include all specialized equipment, specialized materials, labor, tools, and other incidentals necessary to complete the work, including brooming, and sanding.



Appendix 4

Machine Vision Recommendation for Crack Sealing

Machine Vision Recommendation for Crack Sealing Project

Ken Kirschke
December 13, 1989

Caltrans
Office of New Technology and Development

Introduction

The crack sealing project objectives are to design a machine which will sense, prepare, and seal in a band-aid configuration, cracks on AC pavement from 1/8" to 1" wide. Within the sensing aspects are crack recognition, coordinate transformation, and path planning. Through a literature search which began in October 1989, a specific direction has been chosen towards crack recognition. Specifically, the use of video and/or far infrared cameras accompanied by a range sensor (most likely a near infrared laser or ultrasonic sensor). This report is intended to document the rationale for this direction and tentative results of the literature search.

Criteria were established prior to the literature search and are:

Resolution:
The sensor should be able to resolve a roadway crack 1/8 inch in width.

Cycle Time:
The sensor system should be able to provide crack information continuously from a vehicle moving at a minimum speed of 2 mph.

Type of interference and possible failure:
The sensor system should be resistant to the following:

- condensating moisture,
- acoustic noise,
- mechanical vibration and shock-3 g's peak vibration from 15 Hz to 100 Hz and 15g's non-operating for transport,
- heat (-20-160F),
- dust and roadway debris (must be sufficiently strong to survive impacts from 3/8" aggregate and roadway debris not exceeding 8 ounces,
- moisture on pavement,
- debris in cracks,
- road surface height variations,
- temperature variations,

- interference between adjacent detectors or between source and detectors,
- variations in lighting conditions, and
- electromagnetic interference from nearby machinery, such as a generator.

Reliability:
The sensor system and its expected maintenence should provide for a service life of 10 years.

Maintainability:
The system should be easily accessible for component replacement or adjustment. Also, components should make use of off-the-shelf technology.

The sensing media investigated are shown in Figure 1. Some of this chart existed at the onset and some categories were added during the literature search. The most favorable prospects show a striped background. Other potentially promising areas are shown with a dotted background.

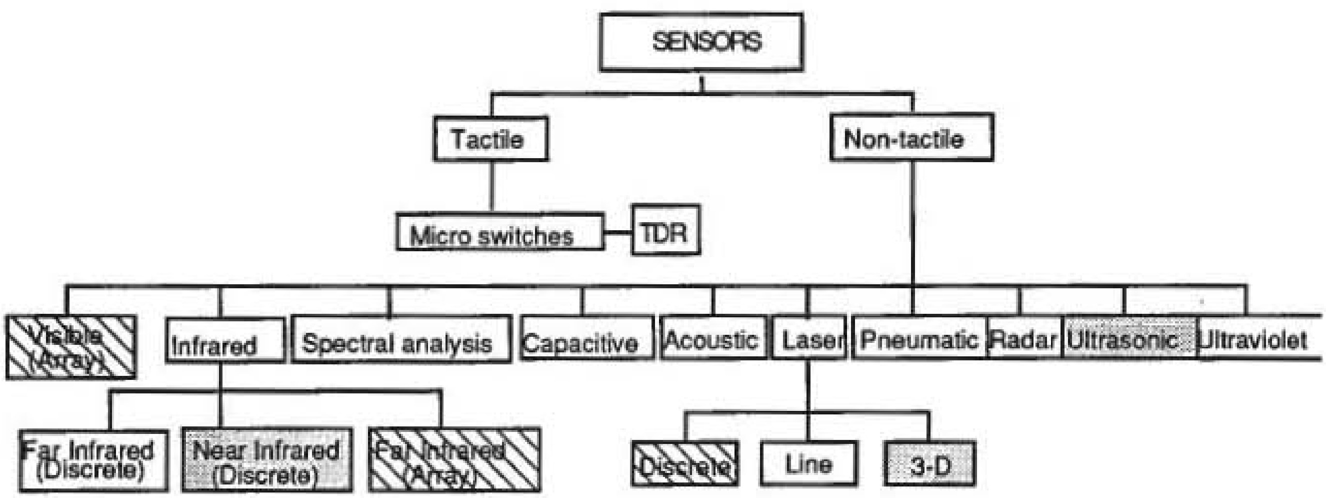


Figure 1

The most obvious divisions for categorizing media for achieving machine vision is tactile and non-tactile.

Tactile

A tactile sensor is one which recognizes a crack by being in direct contact with the pavement. A tactile sensor is thought to be the least desirable due to high amounts of wear associated with approximately 80 or so discrete sensing elements that would be required to cover 13 feet of lane width. Two types of sensors were considered.

Microswitches

Microswitches are commercially available in many forms (Siemens Industrial Control Products Catalog, 1987) The typical application usually involves the contacting of a smooth surface by a rolling element or a spring loaded by bending. The application to sensing cracks would involve the riding of the rolling element or the spring along the pavement. The smallest crack resolution is 1/8" which is small enough that a sensor of this type would have trouble distinguishing between valleys among pieces of aggregate and true cracks. A sensor of this type would also have difficulty in sensing longitudinal cracks (parallel to vehicle direction of travel).

TDR

TDR stands for Time Domain Reflectometry and is a method for sensing the dielectric constant of a material between electrodes. TDR is currently used by Caltrans to detect moisture under the pavement (Cramer, 1989). TDR might be used for sensing cracks by allowing electrodes to ride along the pavement separated by a longitudinal and/or lateral distance of one to two inches. When a crack appears between electrodes, the change of dielectric from asphalt to asphalt and air would generate a spike. This information could be manipulated to plot crack locations in x-y coordinates. Each electrode pair and TDR electrical hardware sells for around $7000. The that would be required could be multiplexed and processed for crack detection using several sets of electrical hardware. Whether TDR would work in a "sliding along the surface" mode is not known. However, positive results in this area would be worth following up on.

Non-Tactile

A non-tactile sensor is one in which there is no physical contact with the pavement to establish the presence of a crack. This mode is thought to be the most desirable because it is associated with low amounts of wear. Several sensors were considered in this area.

Spectral Analysis

Spectral Analysis is mentioned as a possibility due to the oxidizing which naturally occurs on the surface of AC pavement. Spectral analysis would involve looking for emission and absorption characteristics of the pavement surface. Oxidized pavement has less emissions that non oxidized pavement. Since cracks are newly open to sunlight, their oxidation rate would be thought to be greater than the older surface. What would be required for this type of sensor would be a gun type "spectrascope". Currently, no device exists of this type although some near term development is being attempted (Hartman, 1989) The sensor developed of this type would most likely be a discrete sensor. Since these are not in production, the 80 or so (one for every 2 inches of horizontal resolution) that may be required could be prohibitively expensive although it is not known how much it would cost to manufacture one of these units. There is also uncertainties to whether this sort of a strategy would work. Another method of spectral analysis would be to introduce a light source which accentuates significant absorbtion or emission bands of material surrounding a crack. For example, water is known to have several absorption bands in the near infrared region of the spectrum. Coulpled with this would be a CCD (charge coupled device) camera with good response in the range of wavelengths sought after.

Acoustic

Acoustic sensing is down here as a sensing method but sound waves are not anticipated to provide the resolution, or data acquisition rates required.

Capacitive

Capacitive sensors are widely used in precision sensing of metallic objects in manufacturing environments. The sensor is itself one half of a capacitor and requires an object to be sensed to be a grounded conductor. Capacitive sensors are not possible for this application due to the non-conducting properties of asphalt.

Inductive

Inductive sensors contain an oscillator which shows damping depending upon the material contained within the electromagnetic field of the sensor (Locon Inductive Proximity Sensors Catalog, 1989) They are not useable due to the shape of the field at the end of the sensor which does not provide enough resolution. The width of the field is usually about two times the sensing range. Therefore, in order to have 1/8" resolution, a sensor would have to be 1/16" from the pavement. Inductive sensors are primarily used for sensing the proximity of metal objects.

Infrared

Infrared sensors showed promise in the near and far infrared regions.

Far infrared, Discrete

Discrete far infrared sensors were looked at due to the anticipation that a crack would be evident by higher temperatures due to the radiation shape factor of the crack, or lower temperatures due to water intrusion. Initial experimentation with an infrared temperature gun showed that cracks were usually at a different temperature than surface pavement. Cracks in the direct sunlight showed hotter temperatures and shaded cracks or cracks with water intrusion showed cooler temperatures. The most positive results occurred when the pavement was preheated. This introduced a heat source to the cracks and the surface pavement. The surface pavement lost its heat rapidly leaving the crack at a temperature higher (1-5 degrees F) than adjacent pavement. The response time of the infrared temperature gun was slow and an attempt was made to use infrared sensing elements with amplifiers in order to get the desired response time that would be required for a discrete infrared sensor (300-600Hz). Two sensors were tried which utilized PvdF piezo film as a sensing element with no success. .The best response time was approximately 3 Hz.

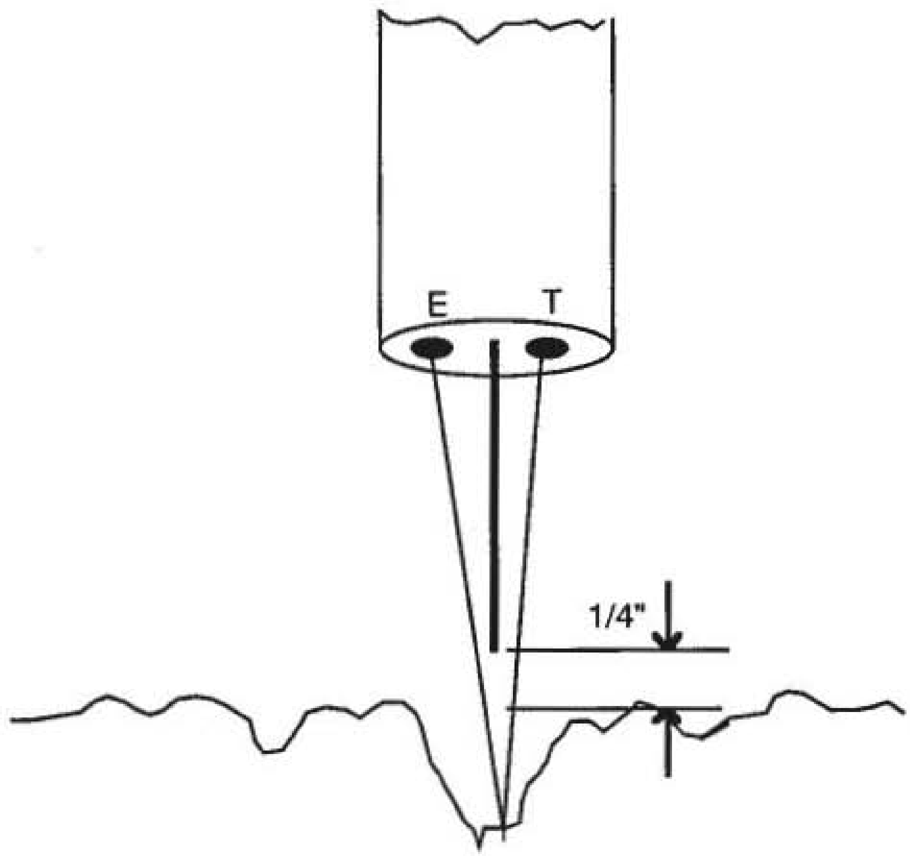
Far infrared, Array

Another area of far infrared sensors lies the area of array sensors. To employ these sensors, a camera is usually used. The resolution in the array approaches video resolution with the highest found to be 512x512. Of the different types of infra red cameras there are vidicon tube based cameras and solid state based cameras without tube sensing elements. The tube element is least preferred due to the 1000 hour mean time between failure rate. With the increased wear due to constant vibration on the road a solid state sensing element is preferable. A camera could be mounted above the roadway and grab a frame of approximately a three foot square. At two miles per hour the vehicle would travel this distance in 1 second which could be enough time for image processing hardware/software to process the image and generate a path for the sealant applicator to follow. Single operations over an image take approximately 1/30 of a second with PC based commercially available hardware. A far infrared camera would be expected to take advantage of the thermal properties of the pavement mentioned previously a discrete sensor would. Currently, a solid state, far infrared camera runs about $95,000 and five would be required for a full lane width.

Near infrared, Discrete

Near infrared sensors were looked at due to their prolific commercial use. These are the units that usually sense your entrance into an apartment store and count presence and flow of materials in mass production environments. These units are discrete and are of the retroreflective type which create and receive their own signal. The rationale for using this sensor is that under normal operation, the sender and receiver are in view of one another through the reflection from the pavement. When a crack occurs this geometry is disturbed and the view is lost thus indicating a crack. However, this type of method is also just as sensitive to rises in pavement due to aggregate. In order to eliminate this a divider was placed between the sender and the receiver with the sender and receiver normally unaware of each other (see Figure 2). In the presence of a crack, the increased distance provides the geometry necessary for receipt of the near infrared light source. If a rise in pavement occurs, the light source is still not visible just as it is in the presence of continuous pavement. This strategy could also be accomplished using fiber optic cable.

Also, commercially available sensors have been found which incorporate a divider and a polarizer. The polarizer is an attempt to reduce reflection from light colored objects in industrial applications such as labels on Aluminum soft drink cans. Reflection from light colored objects is also a problem on AC pavement. Light colored aggregate will give false readings with a divider due to the intensity of the light reflected from the white aggregate. The reflection is at such a high intensity that it seems to become a new source at this point and further reflects from other pieces of



aggregate thereby giving the receiver a false reading. A commercially available polarized unit used showed no improvement in sensitivity to light colored objects over the divider alone. This type of sensor would be a good check; however, on verifying the information provided by a sensor which is not sensitive to light colored objects such as a video camera which identifies cracks by finding dark colored objects.

Figure 2

Lasers

Three known methods are available for machine vision using lasers. Discrete range sensors are available, as well as line scanning lasers, and also 3-D laser imaging.

Laser, Discrete

Laser range sensors operate in the near infrared region. They detect distances by the geometry of the reflecting beam. Typical units can have sensing ranges extending four inches from the sensor and terminating at a distance of eight inches from the sensor. It is usually designed to provide a linear output signal as a function of an object's distance within it's range. The sensing head for these units costs approximately $1000 and the controller for the sensor costs approximately $1300. The only problem being that approximately 80 of these would be required which would amount to $138,000 (not accounting for the possiblity of multiplexing); and this would still leave longitudinal cracks at risk of being missed. The focused beam of the laser helps with reflection from light colored objects such as aggregate. This could also be an ideal candidate for verification of a crack in the pavement. The ruggedness of this sensor is such that it is used by the Penske racing team and foreign automobile manufacturers for vehicle suspension studies.

Laser, Line scanning

Line scanning lasers usually involve a laser source, a rotating mirror, and a receiver. Currently, a line scanning laser is used to measure the reflective properties of road markers. The laser was developed under an F.H.W.A. contract by Advanced Retro Technology Inc. Whether this laser would work for detecting cracks is uncertain as the intensity of the reflectance can change due to many varying surface conditions which are not cracks.

Laser, 3-D

Another sensor involves the use of a laser as a radar component to achieve 3-D images, this has been coined Lidar. Lidar systems obtain three-dimensional information by interrogating a scene with a beam of light, typically a laser pulsed or modulated in some way. The light reflects from the subject, returns to a receiver system, and is detected. Distance information is obtained by determining the time it took light to travel to the object and back or by measuring the phase angle of the returning system. Three developers are currently known: ERIM, Odetics, and Digital

Optronics. Since Lidar was just learned of in writing this report, no follow up has been initiated as yet.

Visible, Array

Array detectors in the visible range are used by cameras. The state of the art in cameras involves the use of CCD (Charge Coupled Device) sensors which come in line scan and area scan formats. These sensors are lightweight, require little power, and are very rugged. CCD sensors can also be sensitive to areas outside of the visible range such as the ultraviolet region and infrared region. Fairchild Weston manufactures both ultraviolet sensitive and infrared sensitive CCD array sensors. With a camera gathering images in the visible region, cracks can be identified by converting the image into grey levels (black to white level of intensity). The value of a grey level of a cracked portion of the pavement can be found by assuming that it is darker than the rest of the pavement. .The crack can then be extracted based on the "darker" portions of the image. Currently data about cracks is acquired using cameras and image processing by several contractors for determining the condition of pavement. Two contractors have been contacted; PCES and ARIA. Both use algorithms to reduce noise in their image and perform histogram based analyses in order to determine type and severity of cracking. This is a statistical process and requires no detailed correspondence between actual cracks on the road. PCES is however employing consultants to help reduce noise due to shadows. Much development is also occurring in industrial applications of image processing. The application usually involves checking orientation of parts moving down a conveyor belt or inspection of items for defects. This is also where line scan cameras are most often used. A line scan camera most often utilizes a single line (as apposed to an array) of CCD elements for higher data acquisition rates. Currently Carnegie Melon University is working on a federal contract where they are trying to identify and fill routed cracks. The machine vision initially chosen for development by Carnegie Melon involves the use of a camera (visible) and an ultrasonic range sensor to verify cracks (Hendrickson, 1989).

Pneumatic

A pneumatic sensor was investigated due to its simplicity of construction. An annular air flow surrounds a tube from which vacuum is measured. The tip of the cone created by the annular air flow is placed in range of the pavement. when the annular air flow is disturbed by the change in height of the pavement, the pressure in the tube changes indicating a crack or rise. The phenomena itself however is highly nonlinear and unstable. Several annuluses were constructed at the UC Davis student lab and consistent results were impossible to obtain. It was immediately obvious that the sensor was not stable enough to use in crack sensing. Some basic research and development on the geometry of the sensor may solve this problem, however. Commercial use of the sensors usually involves sensing the presence or absence of large objects such as rapidly moving sheet metal during hot rolling.

Radar

No information was found for the explicit detection of cracks in AC pavement using radar. Some work was discovered for large void detection, however.(Bomar, 1987)

Ultrasonic

An ultrasonic sensor is not recommended for sensing cracks 1/8" wide at 300 Hz sample rate. Manufacturers that were consulted mentioned that these sample rates were not obtainable and that noise problems would be encountered in trying to use these in a working environment. This has been verified by attempts of Carnegie Melon to use an ultrasonic sensor as a range sensor. One possible exception is a product called a "sonic laser" this sensor is said to achieve sample rates to 800Hz and can resolve cracks 1/8" wide as long as the sensor traverses the crack somewhat perpendicular. The difference between the sonic laser and other ultrasonic devices which are used mostly for level detection is the 140 kHz Operating frequency for the Ultrasonic laser as compared to 30-50kHz of standard operating frequency for most ultrasonic sensors. This sensor seems as though it could be applicable as a range sensor.

Ultraviolet

No alternatives have been investigated for sensing in the ultraviolet region at this point; however, as mentioned above there is the possibility of using CCD cameras should there develop some property in the ultraviolet which would help to identify cracks.

Conclusions

Of the media mentioned, the 3-D Laser looks like the best solution if it could be used. Some further exploration will be done in this area.

Of what has been investigated, array sensors in the infrared and visible region look promising. Since the image processing associated with crack detection is an active area of commercial application, future development and system support can be expected in this area. Development in this area would also contribute and draw from vehicle lateral guidance research at the Caltrans Transportation Laboratory.

An array sensor contains no moving parts and thus is durable. An array sensor also allows for static operation of a crack sealing machine. The rough requirements of a system of this type are contained in Appendix A. The strategy could involve cameras operating in the visible region, far infrared, or both.

A possible strategy for a vision system would be as shown in Figure 3.

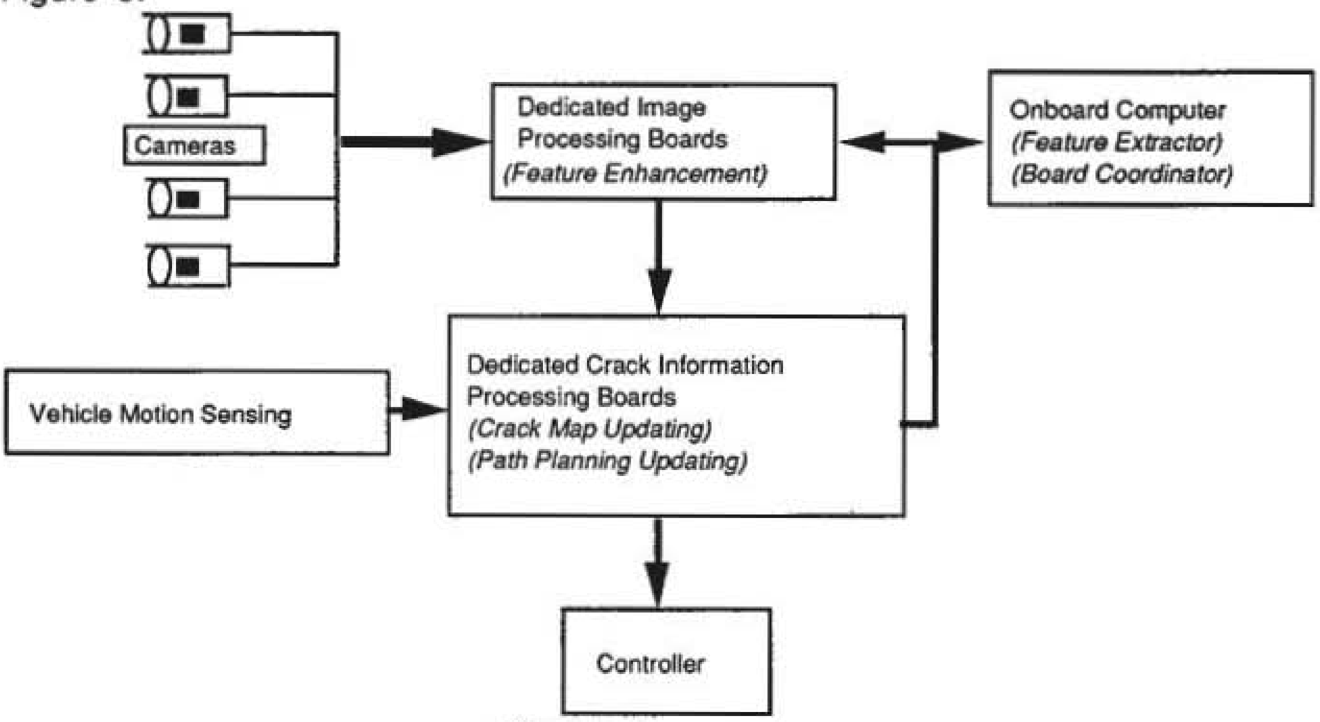


Figure 3

The dedicated crack information processing boards are responsible for taking the processed image and maintaining an accumulation of crack patterns (x,y points and orientation) and a path planning scheme (sets precedence for x,y points) relative to the coordinate frame of the applicator (see figure 4). Use of fundamental robotics concepts allows for a straight forward implementation for tracking x,y, points relative to the applicator based on images taken from a camera. This would allow the flexibility of placing the applicator on a trailer or on the rear portion of the crack sealing machine. This would also allow the operator a liberal control of the vehicle.

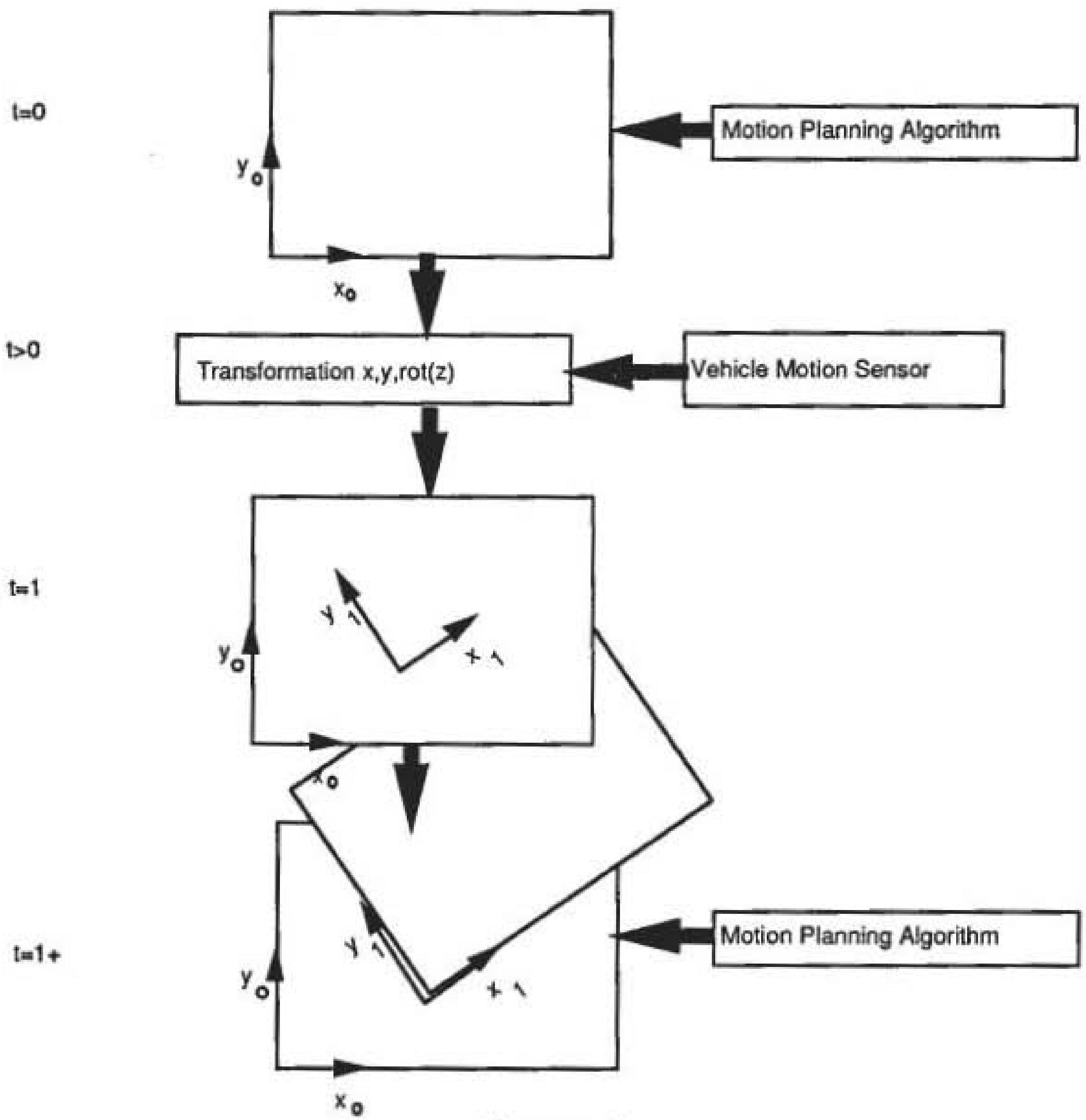
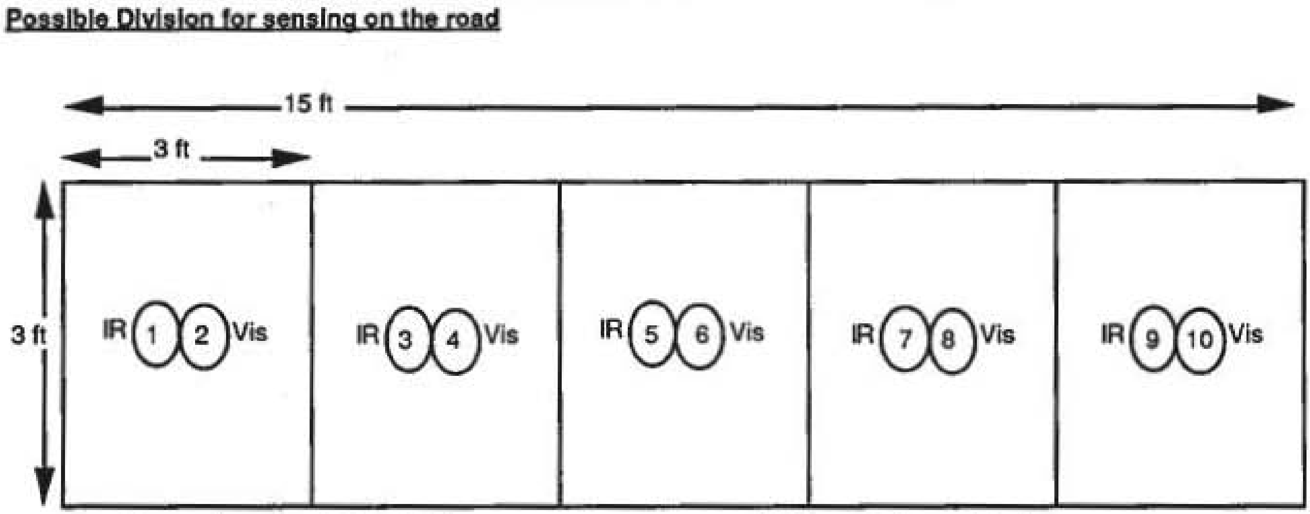


Figure 4

The road coverage by cameras would be as shown in figure 5.



configuration for 5 12x512 array cameras provideing 1/8" resolution

Figure 5

Discretė sensors are the least desirable because of the need for multiple sensors, and the limitation of having to be in motion to sense cracks. However, a discrete sensor may be needed to distinguish cracks that are already sealed from cracks which are true voids or to distinguish sharply defined shadows from cracks. This single sensor could be mounted to the applicator head to verify the existence of a crack just prior to sealing.

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Photonics Spectra, May 1988, page 91

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Appendix 5

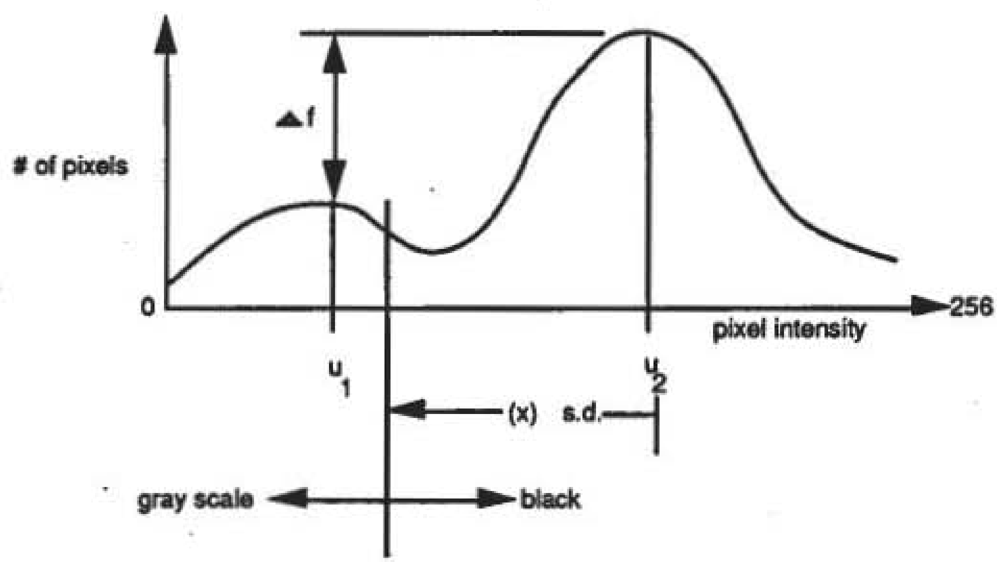
Preliminary Crack Finding Algorithm

This paper describes on a general level an algorithm for detection of cracks in AC pavement. The algorithm is intended to operate on a gray scale image of a top view of pavement 13ft wide by 12ft long. The specific steps include:

1. PARTIAL THRESHOLDING
2. GRID DEVELOPMENT
3. DIGITAL FILTERING
4. FINAL THRESHOLDING
5. CONNECTIVITY (RELAY RACE)

PARTIAL THRESHOLDING

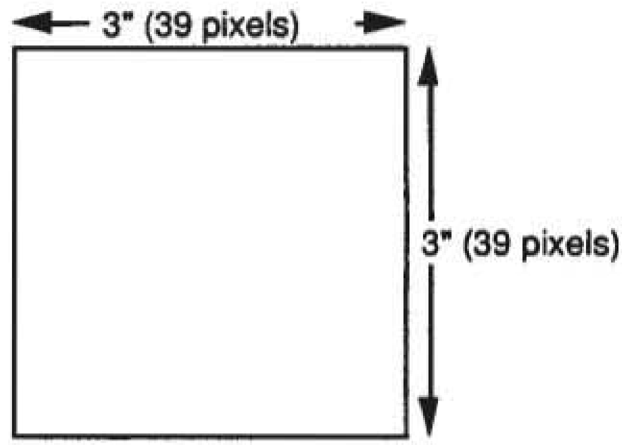
Pictures with cracks usually show bimodal frequency distributions with a peak number of pixels concentrated at an average background pixel intensity. A typical frequency distribution is shown below:



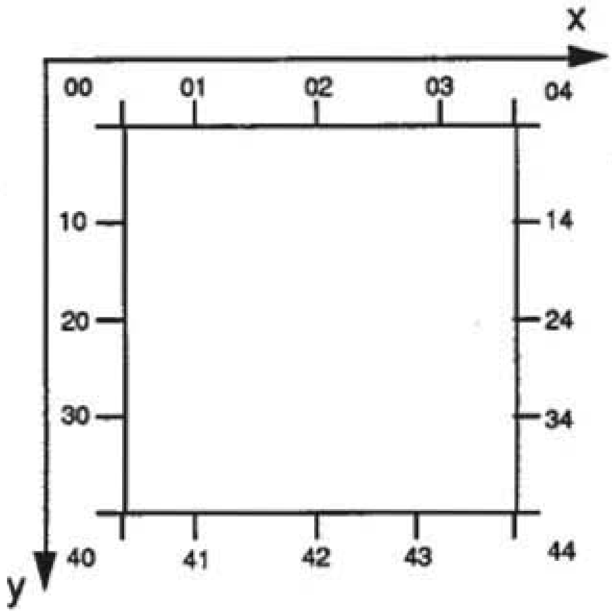
The larger peak usually represents background, and the smaller cracks. An initial measure of "delta f" should be made so as to catch a situation where delta f becomes too small indicating the presence of an oil spot, or alligator cracking; both of which should not be sealed. If delta f becomes too large than it is likely that there are no significant cracks to seal. In either of these situations, it may be desireable to have a manual override to assure efficiency of operation. From the histogram a number of standard deviations below the backgroung intensity are chosen for thresholding. All pixel intensities above this value are turned to black and all pixel values below the threshold are left as thier original gray scale values. Finally, the gray scale image that is left is inverted relative to the mean of the remaining gray scale image to emphasize the darkest pixels which are usually cracks. The stage is now set for grid development.

GRID DEVELOPMENT

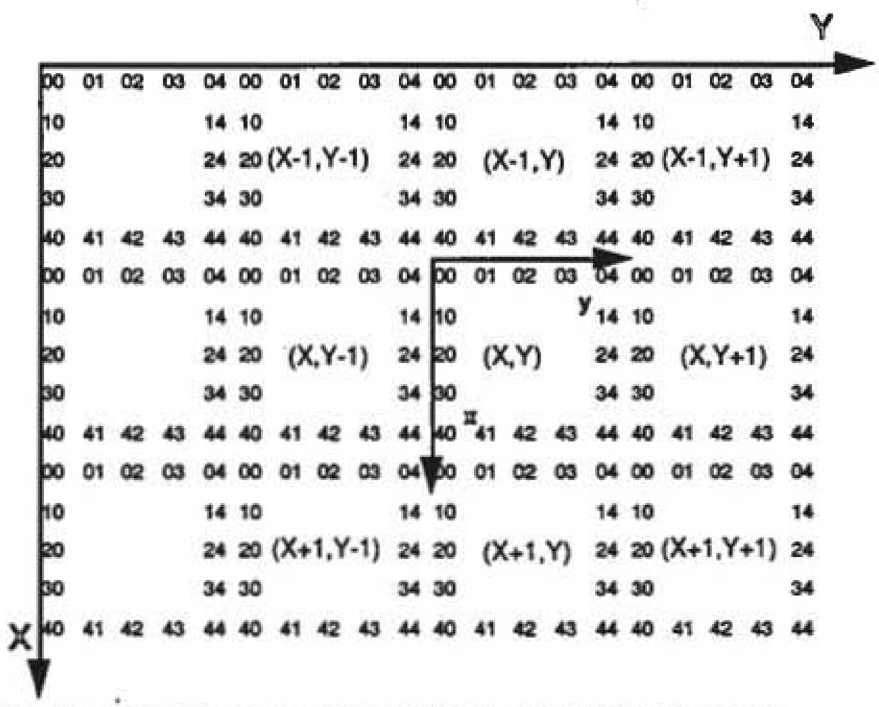
The field of view of the camera is to be divided into 3" by 3" grid elements. Since the resolution required is 1/8" or 8 pixels per inch, the required number of pixels should be 1.6*8 or 13 pixels per inch. An example of a grid element is shown below:



A border of a grid element has 16 representative pixels at 3/4" intervals. These representative pixels have coordinates as shown below:



This next picture shows how the grid elements fit within the grid and the reference frame for each:



The image is expected to have 52 by 52 grid elements.

DIGITAL FILTERING

Once the grid is established, a 13 column/13 row kernel is to traverse the horizontal or vertical lines within the grid. The kernel will be such that it will represent the local area of a representative pixel. After the filter is placed at each representative pixel, the surrounding pixels (1-6,8-13) will be set to 0 (black). See pictures below for what vertical and horizontal kernels might look like before and after filtering.

VERTICAL

	before	after	
1	1	0	
2	1	0	
3	1	0	
4	1	0	
5	1	0	
6	1	0	
7	1	#	$=\Sigma(1\text{-}13)$
8	1	0	
9	1	0	
10	1	0	
11	1	0	
12	1	0	
13	1	0	

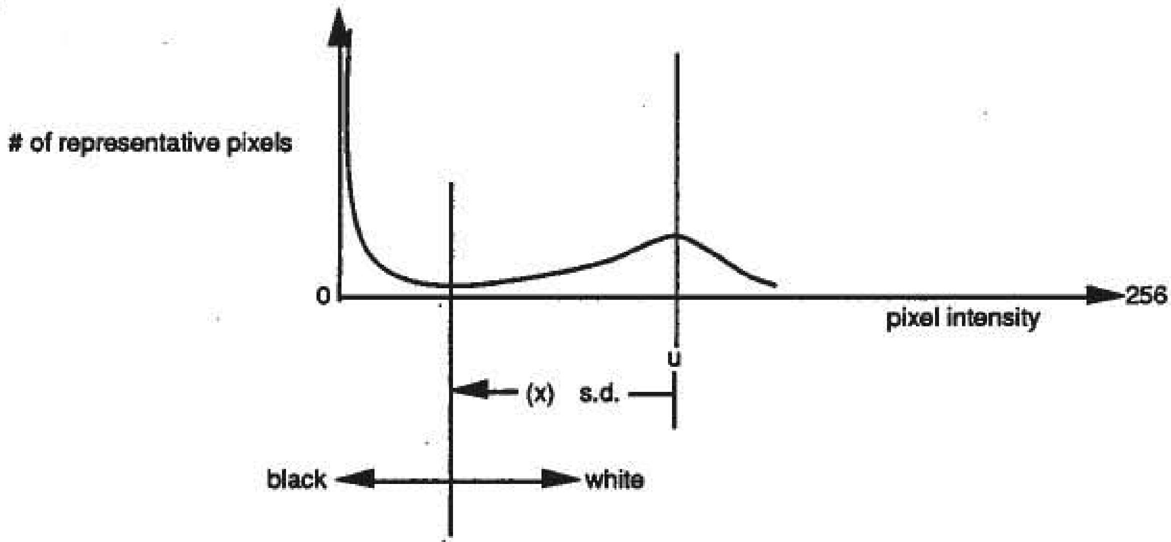
HORIZONTAL

	1	2	3	4	5	6	7	8	9	10	11	12	13
before	1	1	1	1	1	1	1	1	1	1	1	1	1
after	0	0	0	0	0	0	#	0	0	0	0	0	0

$=\Sigma(1\text{-}13)$

FINAL THRESHOLDING

Due to he presence of noise, some kernels with no cracks present will produce non-zero values. These must be thresholded again as shown in the following figure:



The final image is a binary one with determined cracked points as white and background as black.

CONNECTIVITY (RELAY RACE)

The first step to determine connectivity is to search the data structure for a grid element with only 2 representative pixels showing a crack. The grid element found is determined to be (X,Y) with two "local" coordinates of (x,y) within it. An analogy for the strategy used to determine connectivity is a relay race. Each representative pixel value in order to travel through an adjacent grid element must **"take"** a difference from the grid element it is leaving, **"jump"** to an adjacent grid element, and **"pass"** the difference on to a representative pixel element in that adjacent grid element.

The "Take"-

1. In the grid element with two "local coordinates", one pixel is arbitrarily taken as the "runner".
2. The remaining pixel coordinate is then subtracted from the chosen one (this gives a slope value of ($\Delta x,\Delta y$))
3. If neither Δx nor Δy is zero, then the absolute value of Δx and Δy is decremented until one of the absolute values becomes equal to 1

The "Jump"-

1. The Jump soley depends on the local coordinate value of the runner. The possible jumps are shown by the following table.

GIVEN	GO TO (X,Y)	GO TO (x,y)
x=0 (side)	X-1,Y	x=4,y(X,Y)
y=0 (side)	X,Y-1	x(X,Y),y=4
x=4 (side)	X+1,Y	x=0,y(X,Y)
y=4 .(side)	X,Y+1	x(X,Y),y=0
x=0,y=0 x=0,y=4 x=4,y=0 x=4,y=4 or,..abs(x-y)=0,4	permutation on above x= and y= values, except for the combination X,Y	permutation on above x= and y= values, except for the combination X,Y

The "Pass"-

1. Add the slope value from the "take" to the new local coordinate value until either a zero or a four occurs as an x or y coordinate.
2. Subtract the difference of the coordinate found from the "jump" coordinate
3. Search the current grid element for representative pixels.
4. Once one is found subtract from it the "jump" coordinate.
5. Treating the results from step 4 and step 2 as vectors, compute their dot product.
6. If the dot product is greater than 10 then you have successfully passed the difference on in step 2. <u>Note: This has the effect of allowing a representative pixel in an adjacent Grid element to carry on the line if it lies within +/- 45 degrees of an approximate continuation from the previous grid element.</u>
7. continue with the difference from step 4 as the new "take"

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

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10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04 00 01 02 03 04

10 14 10 14 10 14 10 14 10 14 10 14 10 14

20 24 20 24 20 24 20 24 20 24 20 24 20 24

30 34 30 34 30 34 30 34 30 34 30 34 30 34

40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44 40 41 42 43 44

Appendix 6

Report on the Testing of Road Surface Heat Lances

In addition to the computer based AC heat transfer model, the analysis of crack preparation has extended to the possible use of existing hot air lance technology. Recently the staff had the opportunity to perform simultaneous real time testing of three hot air lances. The purpose of these tests was to determine how effective existing technology could meet the needs of the crack sealing research group. The tests were designed to evaluate the efficiency of each hot air lance in the area of surface heating, moisture and aggregate removal, and operating noise. Due to nature of the hot air lances themselves, and the cost and sophistication required to measure the high temperature, high velocity exit gases testing both temperature gradients and velocity profiles were not performed. It was felt that a videotaped comparison between the lances on similar crack configurations may provide sufficient real time information which could lead to a better understanding of the dynamics of entrained aggregate and moisture removal, and surface heat transfer.

Three manufacturers furnished essentially two types of lances. Both L/A Manufacturing and Seal All Marketing use separate combustion and heat exchanger chambers, while Thorpe Manufacturing utilizes a propane fired Ram-Jet engine to generate both heat and high velocity air. The Thorpe lance had a significant advantage over the other style of lances in the area of heat transfer to the pavement; however, both L/A and Seal All Lances had a tightly directed stream of high temperature and velocity compressed air which was more effective in removing most of the entrained aggregate and moisture. One significant detractor of the Thorpe lance is its undesirable tendency to burn the asphalt as opposed to heating. This is largely a function of the nature of the Ram-Jet engine which allows combustion to take place externally rather than internally as is the case the other two lances.

In the second phase of testing, the lances were held approximately 3' from the ground while operating at maximum capacity. Sound level readings were taken at intervals of 5, 15, 25, 50, and 100 ft. both directly in front of the lances and 90° to the side. The dB readings generated are shown on Fig. A1. As can be expected the Thorpe lance is considerably louder than either of the other two lances. The reason for this is the cyclic nature of a Ram-Jet engine and the large air mass which is moved during the combustion process. Although both the L/A and Seal All lances are appreciably quieter than Thorpe's, the dB readings are well in excess of that level which can be considered safe or acceptable for daily use.

The construction of the two types of lances varies considerably. While the construction material for the Thorpe lance is unknown, both L/A and Seal All use 316 Stainless for the combustion chamber and critical heat exchanger tubes. Valve assembly selection varies from excellent to adequate with Thorpe leading the way with a well constructed modular control box to L/A Manufacturing whose gas valves are not designed for the volatile gas it requires. Ignition sources for all three lances vary from primitive to elegant. Igniting the L/A lance requires the use of a oxy-acetylene sparker. The Thorpe lance uses a commercially available standard spark plug and dry cell powered signal generator. By far the most elegant and simple solution to the ignition problem comes from Seal All Mfg. Seal All uses a standard piezoelectric ignitor which is permanently and unobtrusively attached to the lance. The system is rugged and requires no external mechanical or electrical power source.

Engineering characteristics, and corresponding heat output, of the three lances varies markedly with the each manufacturer. The Thorpe lance was designed by Merle Thorpe, who studied the effects of Ram-Jet engines during his Masters Degree program. Thorpe's adaptation of the Ram-Jet engine to the process of crack preparation may have been accidental. The Thorpe lance uses an existing device, the Ram-Jet engine, in a manner for which it was not designed. The high temperature combustion gas is quite effective at heating up the road surface; however, the device has demonstrated a limited ability in removing entrained aggregate and moisture. The lance doesn't merely heat up the road, it burns the lighter oils in the asphalt, leaving the surface in an undesirable scorched and blackened condition.

The lances manufactured by both L/A and Seal All have similar origins. Both lances were designed and originally built by Lewis Clark of Seal All Mfg. The L/A lance represents an early attempt by Mr. Clark and his partner Arv Sestrap to design an effective lance. The early limitations of the L/A lance have been corrected by Mr. Clark and his present lance is significantly more effective at achieving the desired crack preparation than L/A's lance. It should be noted that although the Seal All lance is significantly better than L/A's lance, it's design suffers from a glaring and fundamental lack of knowledge of fluid mechanics. Both Seal All and L/A lance's share similar choked flow restrictions which are sharply limiting the potential of both lances.

Although flow restrictions are limiting the output of both lances, material selection is also hampering the durability of the combustion chamber and heat exchanger tubes.

The selection of 316 Stainless steel is used extensively and was chosen for cost considerations and chemical corrosion resistance primarily; however, this particular alloy has a lower Chromium content 16-18% thus making it susceptible to high temperature corrosion. This is corroborated by Lewis Clark's own account of MTBF for his lance as being 500 hours of operation. This failure rate could be markedly reduced by selecting either a 310 or 314 stainless steel or for maximum life the selection of a 403 stainless. Heat exchanger affiance is limited by the use of a single tube placed axially in the combustion chamber. The tube is smooth surface thick wall 316 stainless with no interior convolutions to accentuate the heat transfer efficiency.

Conclusion:

All of the lances tested represent the most initial phase of surface heating analysis. It should be noted that all of the manufacturers represented are currently marketing these lances commercially with varied success. In addition, all manufacturers graciously volunteered their devices on trial basis for our tests. The ultimate outcome of these tests have shown that none of the lances tested will adequately meet all the requirements for heating efficiency, durability, and operating noise.

Appendix 7

Advantages/Disadvantages of the Preliminary Concept Machine Configurations

<u>ARRAY SYSTEM:</u>

ADVANTAGES

- relatively small number of moving parts
- relatively "simple" system to design and build
  a) software is generally built on the concept of on/off switches rather than on/off switching plus coordinate positioning (as with other designs)
  b) no problems created due to applicator assembly inertial forces since the assembly is fixed to the machine frame
- machine expansion is not a significant difficulty
- speed is limited only by pump and compressor outputs and sealant melting capabilities

DISADVANTAGES

* may provide an inadequate seal (due to non-ideal patch configuration)
- design of system could create inherent demands such as "instantaneous" sealant flow and possibly very large pump and compressor output requirements

* blowing out crack in transverse direction may not provide acceptable results
  a) air nozzle may not have adequate intensity and focus
  b) directional control of loosened debris may not be easily controlled
- requires a large number of output heads

* NOTE: Preliminary testing is required before it can be determined whether this is a significant problem.

<u>CARTESIAN COORDINATE SYSTEM:</u>

ADVANTAGES

- no need for complicated coordinate transformations to calculate the end effector position
- velocity of the end effector is constant for a given input (velocity is independent of the end effector position)
- inertia of the end effector is independent of its position
- potential speed of operation is increased due to decreased inertia of the end effector
- design of the drive system is simplified (as compared to an robot arm manipulator)
- actuator is simply supported
- load carrying capacity is increased (as compared to a robot arm manipulator)
- machine can be easily expandable (by adding additional end effectors) once the concept has been proven

DISADVANTAGES

- machine will require a relatively large number of moving parts (as compared to an array system)

ROBOTIC ARM MANIPULATION SYSTEM

ADVANTAGES

- robotic arm is self supporting
- arm is readily able to extend beyond the width of the support vehicle
- design of system would be more "open"; the internal components of the machine would be more accessible as compared to other systems due to lack of outer frame.

DISADVANTAGES

- more complicated coordinate transformations (for the end effector position) would be required (as compared to a cartesian coordinate system)
- high inertial properties of the end effector would reduce the overall system speed and performance
- a separate arm system must be provided for each end effector.
- system would require a relatively large number of moving parts (as compared to an array system)
- expansion by the addition of several end effectors is relatively complex (as compared to a cartesian or array system)
- robot arms would apply much more bending stress to the machine frame (as compared to a cartesian or array system)