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Measuring Systems and Instrumentation for Evaluating the Effectiveness of Pavement Maintenance

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MEASURING SYSTEMS AND INSTRUMENTATION FOR EVALUATING THE EFFECTIVENESS OF PAVEMENT MAINTENANCE

Report to the Strategic Highway Research Program (SHRP)

by

Dr. Kenneth R. Maser and Michael J. Markow

1. OBJECTIVES AND SCOPE OF STUDY

1.1 Objectives

This study is a follow-up to SHRP project H-103 of the same title. The purpose of this study is to synthesize information resulting from the H-103 effort and from other sources, and to develop recommendations for SHRP regarding a future project H-104. The objectives of this study are as follows:

- To define pavement conditions that relate to maintenance effectiveness.
- To identify measurement and instrumentation systems that will enable maintenance forces to detect and correctly interpret these pavement conditions, to evaluate and select appropriate maintenance treatments, and to monitor the effect of this maintenance on subsequent pavement conditions.
- To prepare a draft RFP for SHRP research contract H-104 that builds upon the findings to the two objectives above and leads to a commercially viable prototype. This RFP will outline specifications for modifying existing equipment or developing new equipment to measure pavement conditions important for maintenance.

This report responds to the first two objectives. Earlier versions of this report were reviewed by the SHRP Executive Committee, the relevant Expert Task Group, and the Highway Operations Advisory Committee in considering options for project H-104. The suggestions of these committees are reflected in this final version of our report. Our findings and the deliberations by these committees have resulted in a Request for Proposals recently issued by SHRP that responds to the third objective above.

1.2 Scope

Focus on Maintenance

The scope of this project is limited to the measurement of pavement conditions important to maintenance. Measurements related to other aspects of pavement management (e.g., recording of pavement condition data to develop historical trends, to justify 4R projects, or to regulate vehicle or axle loads) are not included in this study. Measurements of other highway features besides pavements (e.g., bridges, culverts) are likewise not included in this study.

The SHRP announcement of project H-103 took definition of scope a step further, focusing on the role of preventive maintenance as being more "effective" than damage repair.[1] The program announcement contended further that to achieve the savings of a good preventive maintenance program "requires warning of impending problems, which in turn requires sensitive condition survey equipment and frequent condition surveys for early detection of problems. It may therefore often be too late for preventive maintenance if site selection [of maintenance performance] is based solely on [standard] pavement condition survey data."

This study therefore focuses on preventive maintenance in assessing what conditions and damage mechanisms must be measured by candidate equipment. Further discussion of the categories of distress of interest will be given in Section 4. Candidate equipment or technology for further development in project H-104 may be identified through one or more of the following ways:

- Commercially available equipment satisfying project criteria. (Criteria for evaluating equipment will be discussed in Section 5.)
- Modifications to commercially available equipment, including instrumentation, that would increase its usefulness and economy.
- New technology that could be developed to a pre-production stage under a later SHRP contract.
- Existing pavement measurement equipment that can be adapted to other measurements needed for preventive maintenance.

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[1]SHRP Program Announcement, 2nd Quarter FY 1988, issued Fall 1987, pp. 11-15.

Equipment Scale and Technical Sophistication

The SHRP technical statement of work for our study noted that the Expert Task Group and the Advisory Committee for projects H-101 and H-103 have recommended the following:[2]

- Equipment for use at the project level should be easily transportable, have a low first cost, but need not be operable at highway speed.
- Equipment for use at the network level should be operable at highway speed and offer a low operational unit cost.

These characteristics describe really two distinct classes of equipment, with significantly different implications for technology, cost, and level of sophistication. With respect to this choice of scale, the H-103 project file contains several indications of a leaning toward smaller, simpler, less expensive equipment that can be used by individual maintenance workers or crews, rather than large, expensive devices that may require extensive training in their use.[3] This direction has been continued in our study, specifically in the survey and evaluation of measurement approaches in Section 5. However, larger and generally more sophisticated and expensive devices are another potential solution, and SHRP may wish to explore this alternative at some point in the future.

Tasks and Method of Accomplishment

SHRP's statement of work described three tasks in our project:

1. Critically review the work conducted on SHRP project H-103. Synthesize the information available on the pavement measurements needed and the equipment and technology available to conduct maintenance-related measurements of pavement (whether through modifications to existing equipment, or development of available technology to a pre-production stage).

2. Appraise the technology identified in Task 1 with respect to technical feasibility, operational feasibility, and cost. From these appraisals, rank the candidate equipment or technology, and recommend those equipment modifications or technological developments to be pursued in SHRP contract H-104.

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[2]Letter from Don M. Harriott of SHRP to authors, July 25, 1989.

[3]An inclination toward equipment that can be used by maintenance personnel is expressed in several documents, among them the program announcement for H-103 (2nd Quarter FY 1988) and the minutes of the Highway Operations Advisory Committee meeting in November, 1988.

3. In cooperation with the SHRP staff, apply the information from Task 2 to the development of an RFP for research contract H-104 according to the standard SHRP format.

This report addresses Tasks 1 and 2. Task 3 has been addressed in the preparation of an RFP issued by SHRP in the Program Announcement for the 3rd Quarter of FY 1990.

This study has been accomplished under extremely tight deadlines. Therefore, no original research has been performed to investigate either the pavement conditions that should be measured or the equipment or technology most suitable for these measurements. Rather, the material in Sections 4 and 5 derives largely from the background and experience of the authors, supplemented by a brief review of the literature and assessments of material readily available to us. The references cited are examples of the literature in the field. They are not based on an exhaustive review, and while we have tried to cite current sources, in some cases other, more recent, articles may have been published which we simply did not have time to locate. Nevertheless, the conclusions and recommendations of this study should provide a valid comparison among proposed measurement approaches.

2. PERSPECTIVE AND APPROACH OF THIS STUDY

Different meanings may be ascribed to the title and objectives of this study, particularly as to what is intended by measurements of "the effectiveness of pavement maintenance." Our review of the H-103 record did not clarify this matter. On the contrary, it suggested at times that the contractor and various reviewers had somewhat different interpretations of how "maintenance effectiveness" should be translated into a meaningful set of requirements for measurement. One of the first topics that we addressed with the SHRP staff was this fundamental direction of this study with respect to the meaning of "maintenance effectiveness."

At least two perspectives can be taken on this subject. These perspectives are markedly different, lead to very different maintenance and inspection strategies, and implications for required equipment technology:

1. To consider those measurements that identify and locate conditions in the pavement, knowledge of which would help identify preventive maintenance needs. The intent of these measurements is thus toward management strategy: the definition of appropriate actions of preventive maintenance, when and where they should be undertaken, and perhaps why they should be performed.

2. To consider measurements directed toward quality control of pavement maintenance, assuming that the proper maintenance treatment was selected in the first place. Such measurements would help determine whether the maintenance was done correctly and whether it is fulfilling its intended purpose.

There are other possible interpretations: e.g., to develop inspection methods compatible with new maintenance materials and equipment being researched under other SHRP projects, or to define new measurements geared to totally new maintenance activities (or perhaps to new pavement designs and materials). Since these latter situations are still speculative, we have considered only the two alternatives above.

In consultation with the SHRP staff, we have adopted the first perspective as the motivation of this study, dealing with the identification of the need for preventive maintenance and the selection of the most appropriate maintenance treatment. This perspective puts a greater emphasis on arresting further damage than on repairing existing distress, and is therefore consistent with the statement of work in the H-103 project announcement. If these measurements are made periodically, they can be used to track changing conditions in the pavement that ultimately warrant preventive maintenance. Periodic measurements may also be used to evaluate the effectiveness of previous maintenance treatments (combining current measurements with previous measurements). Furthermore, a history of measurements can be applied to verify models of maintenance effectiveness anticipated to result from SHRP project H-101.

This approach has some implications for the type of equipment that might be appropriate. First, the concept of "portability" discussed in the records of H-103 committee meetings needs to be broadened beyond solely hand-held devices. This is not to rule such devices out; however, it is likely that at least some defects of interest will remain hidden from view for a period of time, at unknown locations, and therefore will require equipment that gives relatively broad, speedy coverage of a pavement. A piece of equipment on a trailer, able to probe a lane width at reasonable speed, might be understood to be portable in this context. Second, the equipment must be suitable to be used by field maintenance crews, without need for sophisticated training or interpretation of signals. Thus, some signal processing and interpretative capability may be built into the equipment. Also, the scale and cost of the equipment should be appropriate to decentralized operation in a highway maintenance organization.

3. REVIEW OF THE INTERIM REPORT FOR PROJECT H-103

We have reviewed the interim report and related documents submitted by the H-103 contractor to SHRP. Our belief is that some fundamental changes in direction of this study need to be made, in both the pavement- and the equipment- or technology-related sections. Therefore, rather than engaging in a lengthy review of technical details, we have restructured the premises of this study and the presentation of information entirely. Section 4 discusses pavement conditions and damage mechanisms relevant to maintenance effectiveness, and Section 5 describes measurement equipment and technology to detect these conditions or mechanisms. Section 6 presents our conclusions and recommendations.

4. PAVEMENT CONDITIONS AND DAMAGE MECHANISMS OF INTEREST

Mechanisms of pavement damage vary by pavement design and construction material, differ in their prevalence and importance throughout the country, and lead to somewhat different maintenance or rehabilitation treatments in each State. Nevertheless, it is possible to develop some general conclusions on pavement conditions that fall within the scope of this project, are of general interest to the highway community, and would form the basis to review candidate equipment and technology in Section 5.

Relevant pavement conditions will be identified through the following process. First, the criteria by which to consider pavement conditions (or the damage mechanisms by which they arise) for inclusion in this study will be discussed. Second, various categories of distress will be evaluated with respect to these criteria, to identify those conditions or mechanisms most important to consider for measurement. Third, the resulting list of specific pavement conditions, with associated maintenance treatments, will be summarized.

4.1 Criteria to Assess Conditions or Damage

The criteria governing which pavement conditions or damage mechanisms should be included in this study were inferred from several sources in project H-103, including the initial project announcement, the interim reports, and project correspondence and minutes. Where inconsistencies developed in the project record, discussions were held with SHRP staff to gauge current thinking and priorities among competing requirements for pavement measurement. Since it is difficult to provide hard and fast rules that govern every situation, the following criteria should be interpreted more as guidelines to help reduce the wide range of pavement conditions to a manageable set.

1. <u>Relationship to Maintenance</u>. Pavement conditions of interest should provide information useful to maintenance, especially in identifying the need for preventive maintenance. This criterion distinguishes the proposed measurements from those done for pavement management, where the set of relevant pavement conditions is virtually all-inclusive and may trigger responses ranging from routine maintenance to major rehabilitation or reconstruction. This approach also differs from that adopted in the H-103 report, which organizes pavement measurements by several "performance factors" related to each maintenance activity.[4]

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[4]The approach in the H-103 report is to identify the contributions of each maintenance activity to the performance of the overall pavement, expressed as "performance factors": e.g., the impermeability of the pavement surface, rideability, safety, vehicle operating costs, structural capacity, etc. The H-103 report then identifies technologies that measure these contributions. This is an entirely different problem from that being addressed in this report: measurements to identify the need for maintenance. These differences in philosophy highlight the importance of the discussion in Section 2.

Typical activities that constitute pavement maintenance (as well as rehabilitation) are illustrated in Figure 1.[Peterson, NCHRP Synthesis 77 1981; Epps and Monismith, NCHRP Synthesis 126, 1986] Figure 1 is particularly useful in that it further divides maintenance into corrective and preventive aspects. By relating these maintenance activities to the pavement conditions that they address, and more specifically to the damage mechanisms that they help arrest, one may identify the set of pavement conditions most important for measurement.

There are many sources in the literature that document highway practice in relating the maintenance activities in Figure 1 to the pavement conditions or damage mechanisms that they properly address.[5] As an example, Figure 2 displays California's guides for flexible pavement repair, citing many of the activities in Figure 1 (and variations thereof), and explaining those pavement conditions under which it is either proper or improper to apply each treatment. [Peterson, NCHRP Synthesis 77, 1981; Balta and Markow, 1985] For instance, many of the different seals listed in Figure 2 are intended to waterproof the pavement, suggesting that moisture detection within the pavement structure might be an appropriate condition to detect via measurement.

2. Visibility of Distress. This investigation has favored those conditions or damage mechanisms that are not easily visible or that cannot be measured on the pavement surface. For example, fine cracking is more difficult to detect than wide cracks, and would therefore be expected to benefit more from measurement equipment. (Furthermore, the detection and arresting of fine cracking is more closely allied with preventive maintenance than is the filling of wide cracks, which may already signal a maturing progression of failure.)

3. Non-Duplication of Current Measurements. Several categories of measurements are already made by many State highway departments to assist in their pavement management.[6] Briefly, these measurements may be organized within the following categories:

- Measurements of structural capacity (e.g., by static or dynamic deflections, and surface waves).
- Measurements of surface distress (e.g., by visual inspections, photologging, and image processing).

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[5] In addition to the source cited above, data relating maintenance activities to specific pavement conditions are available in the performance standards of States' maintenance management systems, and in FHWA and NCHRP studies of maintenance and rehabilitation.

[6] Surveys of measurements for pavement management are given, for example, in NCHRP Syntheses 76 [NCHRP, 1981] and 126 [Epps and Monismith, 1986], Balta and Markow (1985), and OECD (1987).

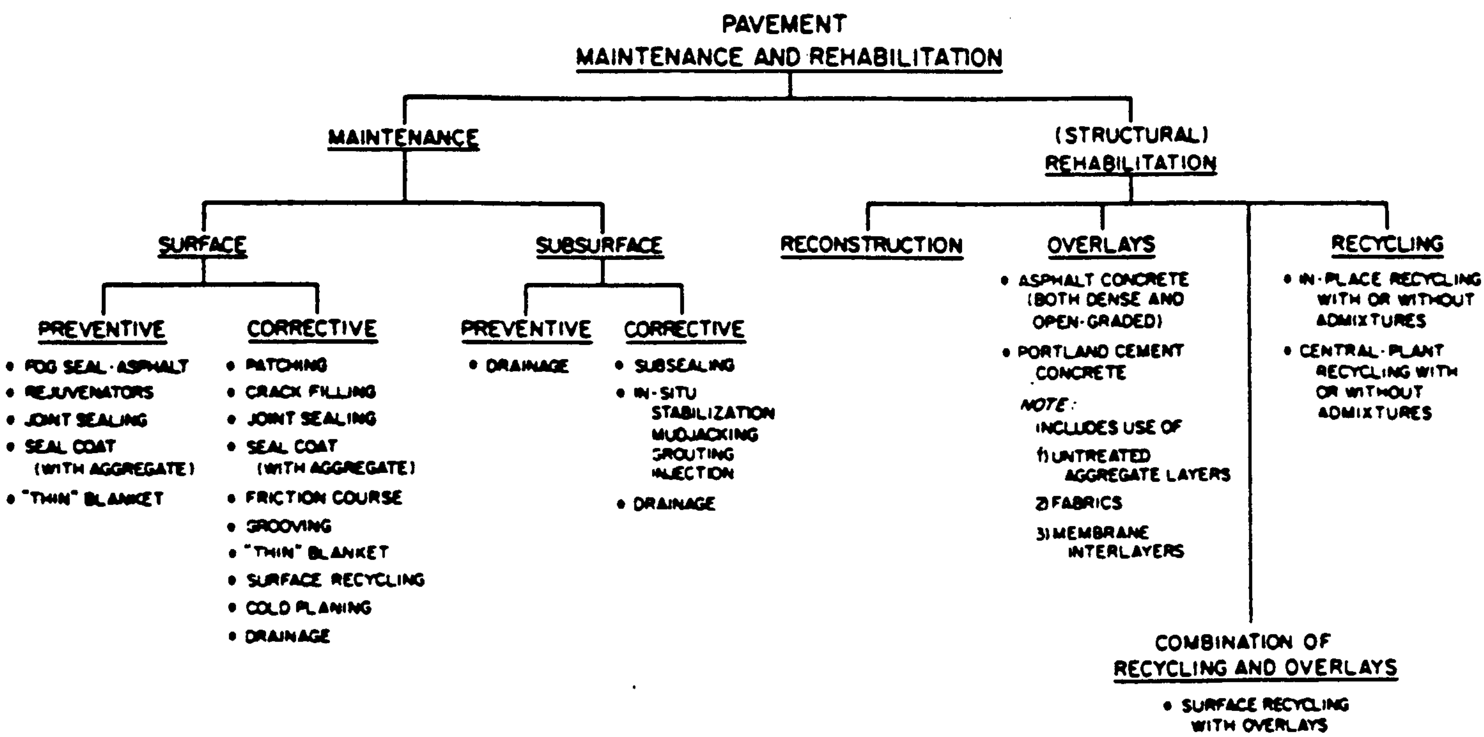

Figure 1. Typical Pavement Maintenance and Rehabilitation Activities

CALTRANS FLEXIBLE PAVEMENT REPAIR STRATEGY INFORMATION

REPAIR STRATEGY	FUNCTION (OBJECTIVE)	PROPER USE	IMPROPER USE	SERVICE LIFE	*1976/77 COST PER LANE MILE	CALIFORNIA'S EXPERIENCE
1. LANE RECONSTRUCTION	RESTORE STRUCTURAL ADEQUACY	A. WHERE MORE COST EFFECTIVE THAN ALTERNATES B. RIDE SCORE >45 C. VERTICAL GRADE CONSTRAINTS		20 YR	$90,000 (1)	EXTENSIVE
2. PCC OVERLAYS	RESTORE STRUCTURAL ADEQUACY	WHERE MORE COST EFFECTIVE THAN ALTERNATES (0.55' MINIMUM THICKNESS)	A. UNSTABLE TERRAIN B. VERTICAL GRADE CONSTRAINTS	10 YR	$65,000 (2)	LIMITED
3. AC OVERLAYS	A. RESTORE STRUCTURAL ADEQUACY B. REPAIR CRACKED PAVEMENT C. RESTORE SURFACE TEXTURE D. IMPROVE RIDE QUALITY	A. LOAD ASSOCIATED CRACKING B. RIDE SCORE >45 C. RUT DEPTH > 3/4" D. COARSE AGGREGATE RAVEL	A. VERTICAL GRADE CONSTRAINTS	10 YR	$12,500/0.10'	EXTENSIVE
4. INVERTED OVERLAYS	A. RESTORE STRUCTURAL ADEQUACY B. REPAIR CRACKED PAVEMENT C. RESTORE SURFACE TEXTURE D. IMPROVE RIDE QUALITY	A. WHERE MORE COST EFFECTIVE THAN CONVENTIONAL OVERLAY B. PROVIDE DRAINAGE BLANKET	FREEZE-THAW AREAS	10 YR TARGET	$35,000 (3)	LIMITED EXPERIMENTAL INSTALLATIONS
5. PAVEMENT REINFORCING FABRIC & OVERLAY	A. RESTORE STRUCTURAL ADEQUACY B. REPAIR CRACKED PAVEMENT C. RESTORE SURFACE TEXTURE D. IMPROVE RIDE QUALITY E. WATER RESISTANT MEMBRANE	A. WHERE MORE COST EFFECTIVE THAN CONVENTIONAL OVERLAY B. VERTICAL GRADE CONSTRAINTS		10 YR TARGET	$35,000 (4)	LIMITED EXPERIMENTAL INSTALLATIONS
6. RUBBERIZED ASPHALT INTERLAYER & OVERLAY	A. RESTORE STRUCTURAL ADEQUACY B. REPAIR CRACKED PAVEMENT C. RESTORE SURFACE TEXTURE D. IMPROVE RIDE QUALITY E. WATER RESISTANT MEMBRANE	A. WHERE MORE COST EFFECTIVE THAN CONVENTIONAL OVERLAYS B. VERTICAL GRADE CONSTRAINTS		10 YR TARGET	$35,000 (5)	LIMITED EXPERIMENTAL INSTALLATIONS
7. HOT RECYCLING	A. RESTORE STRUCTURAL ADEQUACY B. REPAIR CRACKED PAVEMENT C. RESTORE SURFACE TEXTURE D. CONSERVE NATURAL RESOURCES	A. WHERE MORE COST EFFECTIVE THAN ALTERNATES B. VERTICAL GRADE CONSTRAINTS	AIR QUALITY CONSTRAINT AT PLANT	10 YR	$24,000/0.10	NONE TO DATE
8A. HEATER REMIX 8B. CUTLER PROCESS	A. RESTORE STRUCTURAL ADEQUACY B. REPAIR CRACKED PAVEMENT C. RESTORE SURFACE TEXTURE	A. WHERE MORE COST EFFECTIVE THAN ALTERNATES B. VERTICAL GRADE CONSTRAINTS	AIR QUALITY CONSTRAINT AT SITE	5-10 YR	$25,000 (6)	HEATER REMIX-EXTENSIVE CUTLER PROCESS-NONE TO DATE
9. COLD PLANING	A. CONFORM TO ELEVATION CONTROL B. REMOVE DETERIORATED AND/OR CONTAMINATED LAYER	A. WHERE MORE COST EFFECTIVE THAN ALTERNATIVES B. PREPARE FOR OVERLAY C. AIR QUALITY CONTROLS PRECLUDE HOT PLANING D. VERTICAL GRADE CONTROLS		NOT APPLICABLE	$15,000 (7)	MODERATE

Figure 2. CALTRANS Flexible Pavement Repair Strategy Information

(Page 1 of 3)

REPAIR STRATEGY	FUNCTION (OBJECTIVE)	PROPER USE	IMPROPER USE	SERVICE LIFE	*1976-77 COST PER LANE MILE	CALIFORNIA'S EXPERIENCE
10. RUBBERIZED ASPHALT CHIP SEAL COAT	A. WATERPROOF PAVEMENT B. DECREASE CRACK SPALLING	A. SEAL DRIED OUT PAVEMENT B. STAGE CONSTRUCTION PRECEDING A PLANNED OVERLAY C. FINE AGGREGATE RAVEL	A. HIGH DEGREE OF ROAD CURVATURE B. HIGH VOLUME TURNING MOVES C. HEAL CRACKS D. >HAIRLINE CRACKS UNLESS FILLED E. RIDE SCORE >45	UNKNOWN ESTIMATE 2-5YR	$10,000	LIMITED EXPERIMENTAL INSTALLATIONS
11. ROCK SEAL COAT	A. WATERPROOF PAVEMENT B. DECREASE CRACK SPALLING C. TEXTURE SURFACE	A. SEAL DRIED OUT PAVEMENT B. FINE AGGREGATE RAVEL C. SKID RESISTANCE CORRECTION	A. HIGH DEGREE OF ROAD CURVATURE B. HIGH VOLUME TURNING MOVES C. HEAL CRACKS D. >HAIRLINE CRACKS UNLESS FILLED E. RIDE SCORE >45	1-3 YR	$ 3,000	EXTENSIVE
12. OPEN GRADED SEAL COAT	A. DECREASE CRACK SPALLING B. TEXTURE SURFACE C. CORRECT BLEEDING	A. SEAL DRIED OUT PAVEMENT B. COARSE AGGREGATE RAVEL C. SKID RESISTANCE CORRECTION D. CORRECT BLEEDING	A. HEAL CRACKS B. >HAIRLINE CRACKS UNLESS FILLED C. RIDE SCORE >45 D. FREQUENT TIRE CHAIN USE REQUIRED	5 YR	$ 5,000	EXTENSIVE
13. SLURRY SEALS	A. STOP RAVEL B. WATERPROOF PAVEMENT C. DECREASE CRACK SPALLING D. TEXTURE SURFACE	A. SEAL DRIED OUT PAVEMENT B. FINE OR COARSE AGGREGATE RAVEL	A. HEAL CRACKS B. RIDE SCORE >45 C. >HAIRLINE CRACKS UNLESS FILLED D. FREQUENT TIRE CHAIN USE REQUIRED	4 YR	$ 4,000	LIMITED
14. SEAL COAT WITH (SAND) COVER	A. WATERPROOF PAVEMENT B. DECREASE CRACK SPALLING. C. STOP RAVEL D. RESTORE BINDER FLEXIBILITY	A. SEAL DRIED OUT PAVEMENT B. FINE AGGREGATE RAVEL	A. HEAL CRACKS B. COARSE RAVEL C. RIDE SCORE >45 D. LOW TO MODERATE SKID NUMBER E. RUTTING F. HIGH. IMPER. PVMT.	1-3 YR	$ 1,500	EXTENSIVE
15. LIQUID SEAL COAT	A. WATERPROOF PAVEMENT B. DECREASE CRACK SPALLING C. STOP RAVEL D. RESTORE BINDER FLEXIBILITY	A. SEAL DRIED OUT PAVEMENT B. FINE AGGREGATE RAVEL	A. HEAL CRACKS B. COARSE RAVEL C. RIDE SCORE >45 D. LOW TO MODERATE SKID NUMBER E. RUTTING F. HIGH. IMPER. PVMT.	1-3 YR	$ 300	EXTENSIVE
16. BINDER MODIFIERS (REJUVENATING AGENT)	A. WATERPROOF PAVEMENT B. DECREASE CRACK SPALLING C. STOP RAVEL D. RESTORE BINDER FLEXIBILITY	A. SEAL DRIED OUT PAVEMENT B. FINE AGGREGATE RAVEL	A. HEAL CRACKS B. COARSE RAVEL C. RIDE SCORE >45 D. LOW TO MODERATE SKID NUMBER E. RUTTING F. HIGHLY IMPERMEABLE PAVEMENT	1-3 YR	$ 500	EXTENSIVE

Figure 2. CALTRANS Flexible Pavement Repair Strategy Information (Page 2 of 3)

REPAIR STRATEGY	FUNCTION (OBJECTIVE)	PROPER USE	IMPROPER USE	SERVICE LIFE	*1976-77 COST PER LANE MILE	CALIFORNIA'S EXPERIENCE
17. CRACK FILLING	WATERPROOF PAVEMENT	A. CLEAN CRACK ≥ ¼" WIDE B. APPROPRIATE SEALANT	A. DIRTY CRACKS B. < ¼" WIDE CRACKS	1-2 YR	$ 200	EXTENSIVE
18. MISCELLANEOUS (STONE DUST, METAL PLATES, EXPANDED METAL, CHICKEN WIRE, WELDED WIRE FABRIC)	REDUCE REFLECTION CRACKING	NOT WARRENTED	THESE EXPERIMENTAL MATERIALS DID NOT PERFORM BETTER OR AS WELL AS ADJACENT UNTREATED SECTIONS	POOR	N/A	LIMITED EXPERIMENTAL USE

* COSTS DO NOT INCLUDE TRAFFIC HANDLING

ASSUMPTIONS FOR FLEXIBLE PAVEMENT COST ESTIMATES

(1) 0.35' AC OVER 0.70' CLASS A CTB
(2) 0.55' PCC
(3) 0.08' O.G. with 0.20' AC
(4) REINFORCING FABRIC WITH 0.20' AC
(5) RUBBERIZED CHIP SEAL WITH 0.20' AC
(6) SCARIFY, ADD REJUVENATOR AND 0.08' AC
(7) 0.10' DEPTH

Figure 2. CALTRANS Flexible Pavement Repair Strategy Information (Page 3 of 3)

- Measurements of surface friction (e.g., by locked-wheel trailer, Mu Meter, and British portable tester).

- Measurements of pavement roughness (e.g., by response-type road meters, and profiling equipment, including models with non-contact sensors employing light, ultrasound, or lasers).

- Measurements of traffic volume and weights.

The intention of this study is to avoid duplicating either the purpose or the content of these measurements. Not only are States now conducting these measurements for pavement management, but there are also publicly and privately sponsored research organizations already investigating new technologies to address these needs. The guidelines of this SHRP study therefore lean toward new types of measurements with pavement maintenance specifically in mind.

This does not preclude, however, the adaptation of pavement management equipment to new types of measurements or to new purposes encompassing maintenance. For example, it is possible that zones of subsurface moisture or of fine cracking might be detected by deflection measurements. This possibility is indeed addressed in Section 5, and is regarded as an extension of pavement management equipment to additional applications for maintenance. Apart from this interpretation, however, the types of measurements and technologies listed above are already being used or under consideration, and are not addressed further in this study.

To summarize, we are interested in new types of measurements that yield new information about the pavement not otherwise apparent. This information should be of value in identifying the need for maintenance and the appropriate treatment, especially with preventive maintenance that can arrest further damage. Moreover, even if maintenance cannot completely forestall progressive deterioration, such information would be useful as a warning of future problems.

4.2 Pavement Damage Mechanisms or Conditions of Interest

General Catalog of Distress

In this section we identify those damage mechanisms or pavement conditions of prime interest in this study. The complexity of the problem must be acknowledged: Pavement damage arises through the combined effects of traffic loads, environmental influences (e.g., moisture, temperature, and temporal variations in these factors), pavement design characteristics (including layer thicknesses and materials properties, spatial variation of materials properties, and drainage characteristics), and time-dependent evolution of materials properties. Nevertheless, by keeping the discussion somewhat general, we hope to focus on fundamentally important conditions that affect pavements of various designs.

Pavement damage mechanisms and resulting surface distress have been well discussed and cataloged in the literature for many years.[7] A very general breakdown is as follows:

- Cracking or other fractures or discontinuities, whether due to traffic loads (e.g., fatigue cracking in both rigid and flexible pavements, slippage cracking from braking on flexible pavements, and corner breaks in rigid pavements), non-load-related causes (e.g., thermal or moisture changes, opening of construction joints, surface layer shrinkage, and problems with materials reactivity or durability, as in rigid pavement D-cracking), or combinations of these effects.

- Distortion of the pavement surface, including load-related distresses such as longitudinal roughness, flexible pavement rutting, rigid pavement faulting, and shoving; and non-load-related problems such as heaving (as due to frost or swelling soils, for example), rigid pavement blowups, curling of rigid pavement slabs, depressions, and subsidence.

- Surface disintegration or degradation, such as raveling, weathering (i.e., aging of the asphalt), polishing of aggregates, bleeding of asphalt, spalling, popouts or punchouts of rigid pavement, potholes, loss of skid resistance, joint deterioration (from fouling with incompressibles), and scaling or crazing of a rigid pavement surface. (Many of these problems are related to materials.)

- Subsurface problems, including inadequate drainage, pumping under rigid pavement joints, loss of support (whether due to contamination of base materials or to formation of voids), and delamination or debonding of pavement layers or overlays.

Several forms of distress listed above may be related to one another, either because they arise from common causes, or they are part of a progressive sequence of damage mechanisms. For example, loss of joint seals in rigid pavements may lead to water infiltration, causing pumping and loss of slab support, resulting in faulting and cracking of the slab. Similarly, cracking in a flexible pavement may allow water infiltration, leading to localized depressions, roughness, or potholes.

This linkage among damage mechanisms suggests different approaches that could be taken to their measurement. A measurement may be able to detect a damage mechanism or the resulting distress directly: e.g., to locate zones of cracking before they progress to wide fractures. Another approach is to rely on indirect measurements of such damage: e.g., rather than searching for a crack, to locate zones of moisture in the pavement that result from these

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[7]Examples of distress listings are given in NCHRP Synthesis 116 [Finn and Monismith, 1984] and OECD, Maintenance Techniques (1978). Catalogs of distress, with definitions and pictures, are given in HRB Special Report 113 (1970) and OECD, Catalog of Road Surface Deficiencies (1978).

fissures. Another indirect approach is to identify and measure changes in materials properties that favor the initiation of damage.

Selection of Pavement Conditions for Study

The primary consideration in selecting pavement conditions for study in Section 5 is their relevance in identifying the need for pavement maintenance, especially preventive maintenance. Reference to Figures 1 and 2 (supplemented by background knowledge of the authors) indicates the following:

- Preventive maintenance activities are centered around surface seals, rejuvenators, joint seals, and thin blankets or surfacings.
- The purposes of such activities are to accomplish one or more of the following:
    - To waterproof the pavement by sealing fine cracks or fissures, or restoring joint seals.
    - To restore proper materials characteristics of an asphalt surface (e.g., to counteract weathering, aging, hardening, or raveling, or to restore surface texture).
    - To prevent further deterioration of the cracks themselves (through contamination with incompressibles that lead to spalling and crack enlargement, and through hardening and raveling of the exposed crack surfaces).
- Maintenance activities, and especially preventive maintenance activities, are not intended to increase the structural capacity of the pavement.

Let us expand upon the functions of preventive maintenance above with respect to the catalog of general pavement distresses in the preceding section and the criteria for assessing their importance for measurement. Preventive maintenance addresses three basic problems in pavements: to restore the impermeability of the pavement surface, to forestall further deterioration of cracks, and to rejuvenate asphalt surface properties:

- The impermeability of the pavement surface is to preclude moisture infiltration. Pavement conditions related to this mechanism that could signal a need for maintenance include the following:
    - Zones of subsurface moisture, as might occur under cracked or porous asphalt surfaces.
    - Locations of subsurface moisture at incompletely sealed joints in rigid pavements.

- Moisture within the asphalt itself, due to cracks or voids in the asphalt layer, which can lead to stripping and raveling.

These conditions were therefore identified as candidates for measurement in Section 5.

- The prevention of further deterioration in cracking relates specifically to the presence of fine cracking within the pavement structure. Once such cracking progresses to wider, more extensive fractures, the damaging process has matured, and the maintenance response differs (i.e., crack filling or patching, rather than pavement sealing, becomes important). Fine cracks are more difficult to detect than an established pattern of wide cracks; furthermore, the latter are already addressed by current procedures in pavement management. Therefore, fine cracks were identified as a candidate for measurement in Section 5.

- The several materials-related benefits of preventive maintenance are associated with asphalt surfaces. One related measurement has already been discussed: the detection of moisture within asphalt layers, which is a precursor to further deterioration of the surface. The problem of asphalt aging is another, encompassing changes in materials properties leading to embrittlement and cracking. Aging can be arrested by the preventive maintenance activity of rejuvenation, and is thus also a candidate for measurement to be addressed in Section 5. Measurements of other conditions (e.g., skid resistance, surface texture, raveling) were considered, but not judged to be as important for measurement in this project, for one or more of the following reasons: they are already addressed through surface measurements in pavement management; they are the subject of much past or current research by others; they are readily visible or observable; or they indicate a type of damage not readily addressed by preventive maintenance.

With respect to the general catalog of distresses, the following points were considered:

- The various mechanisms of cracking have already been discussed above. Priority was given to the detection of fine cracks rather than coarse or wide cracks as being more relevant to the need for preventive maintenance, more difficult to detect visually, and a problem not well addressed by current measurements in pavement management.

- Problems of pavement distortion, while important to broader issues of pavement serviceability and performance, are not well addressed by preventive maintenance other than indirectly, at very early stages (e.g., by preventing moisture infiltration that may lead to distortion). Proposed measurements of moisture infiltration and fine cracking that could lead to distortion have already been discussed. (A further measurement that could add to the warning of distortion, that of voids at rigid pavement joints, is considered below.) Once the mechanisms of damage have progressed to actual pavement distortion, the results are quite visible and beyond the roles of conventional maintenance treatments, and measurements of such distress are already accounted for by data collection for pavement management.

- Measurements of surface characteristics (e.g., loss of skid resistance, changes in pavement texture, materials degradation, etc.) have already been discussed. Such problems are important to pavement performance and serviceability. However, they are quite visible, and many of these categories of distress are already detected by monitoring for pavement management. With the exception of asphalt weathering or the onset of raveling, which may be arrested for a while by sealing, such damage mechanisms are beyond the help of preventive maintenance.

- Subsurface problems are of interest, because conditions are not visible and there is great value in preventing further damage that will later affect the pavement surface. Subsurface moisture detection has already been discussed as a priority in this area.

  - Rigid pumping is a problem that entails several coordinated maintenance actions, both preventive and corrective: e.g., restoration of the damaged base, provision of better drainage, and sealing of the overlying joint (to prevent further infiltration). Although the evidence of pumping may be apparent (through the presence of ejected material at the edge of the pavement), the result of pumping (or of other moisture-related mechanisms) may not be. Therefore, detection of voids under rigid pavement joints was added as another condition to be considered in Section 5.

  - Loss of support of a pavement slab (e.g., through contamination of base materials) is a related problem. This situation will be addressed in conjunction with the measurement of moisture at a pavement joint.

  - Delamination of thin overlays was discussed with SHRP. Some importance was assigned to this problem because the early stages of damage are not visible. If localized weaknesses can be detected and corrected early, much greater deterioration of the surface can be prevented. Detection of delaminated zones was therefore included as a problem to be considered.

4.3 Pavement Conditions Selected for Measurement

The pavement conditions selected for measurement, with their associated maintenance activities, are summarized in the following list:

	Selected Pavement Conditions	Related Maintenance Activities
a.	Moisture infiltrating to base or subgrade	Seal coat, slurry seal, thin overlay, joint sealing

b.	Moisture under joints	Joint seals, improvements in subsurface drainage
c.	Fine cracking	Seal coat, slurry seal, thin overlay
d.	Subsurface voids at pavement joints	Undersealing, slab jacking; accompanied by joint sealing and improvements in subsurface drainage
e.	Overlay delamination	Patching or grinding
f.	Moisture in asphalt layer	Problem with initial construction or materials quality; sealing might help
g.	Asphalt aging	Surface rejuvenation

Candidate equipment and technology to detect these pavement conditions are presented in Section 5.

5. MEASUREMENT EQUIPMENT AND TECHNOLOGY

5.1 Technology Identification

The following list presents each of the pavement conditions discussed above, along with a selection of measurement technologies which are generically capable of detecting these conditions. All possible technologies are considered at this point, without regard to cost, convenience, required development, etc. These factors will be discussed later. Following the list is a brief description of each of the measurement technologies given.

Damage Condition	Measurement Technology
moisture in asphalt	Radar, EM Conductivity, Nuclear Magnetic Resonance, Continuous Microwave, Commercial Moisture Meters, Infrared Thermography
moisture entering base or subbase	Radar, EM Conductivity, Mechanical Surface Waves (SASW), Mechanical Impedance, Dynamic Deflection Measurements, Continuous Microwaves
moisture under joints	Radar, EM Conductivity, Mechanical Impedance

asphalt aging	Surface waves, Mechanical Impedance, Ultrasound
fine cracking	Infrared Thermography, Mechanical Surface Waves, Compressional and Shear Waves
overlay delamination	Infrared Thermography, Mechanical Surface Waves, Ultrasound, Microwaves
subsurface voids	Radar (large voids); Microwaves (small voids); Mechanical Surface Waves (SASW); Mechanical Impedance

5.2 Description of Technologies

The following paragraphs briefly describe the various technologies listed above. Particular attention is given to the principle by which each of the identified failure conditions are detected.

Radar

Radar is the electromagnetic analog of ultrasound. Short pulses of electromagnetic radiation are emitted by an antenna, propagate through the air and into a material. These pulses are reflected back to the antenna by interfaces and objects in the material which represent discontinuities in the electrical properties. The antenna receives these "echoes". The echo pattern, called the "waveform," is analyzed to determine the thickness of layers, and the properties of the materials within each layer. Commercial equipment for pavement application typically generates a broadband transmit pulse with a center frequency of about 1 GHz.

The basis for proposing radar for moisture detection in and under asphalt and concrete is the strong sensitivity that radar has to moisture. The dielectric constant of pavement materials and dry soil ranges from 4 to 10, whereas the dielectric constant of water is 81. Thus, the presence of moisture will have two effects: significant reduction in the radar velocity, and higher attenuation through moist materials.

High moisture in the asphalt might be detected by an anomalous delay in the reflected arrival from the bottom of the asphalt. High moisture in the base or subbase materials, or directly under joints, might be detected by noting anomalous increases in the amplitude of the reflection from the interface above the moist layer.[Maser, 1986, 1989] Radar is commercially used as a subsurface exploration tool for identifying the location of water tables using the above principles.

The basis for proposing radar for detecting subsurface voids is that the reflection from the pavement/base interface is disturbed by the presence of an intervening air (or water) void. This capability has been reported in a number of technical papers and reports, and is currently being implemented on a commercial basis by Donohue and Assoc., and Pulse Radar, Inc. This disturbance can be seen directly in the waveform [Steinway et al., 1981] and indirectly in the radar graphic output.[Kunz and Eales, 1985; Clemena, 1982, etc.] As noted in the H-103 report, research studies have shown that the void has to be sufficiently thick (e.g., > 1 inch) to be reliably detected (Bomar et al., NCHRP 304, 1988; Clemena et al., TRB 1109).

One point to note here is that radar might be far more sensitive to the contamination of the gravel base with fines and the increase in moisture content associated with the fine material. Therefore, a radar anomaly at a joint may be revealing a significant condition even if an actual void is not detected. Research to date has focused primarily on void detection, and has not considered this more general capability.

Infrared Thermography

Thermography is the science of evaluating materials by measurement of their surface temperature. Infrared thermography is a particular implementation of thermography in which an infrared camera is used as the means for making surface temperature measurement. An infrared camera detects the infrared radiation emitted by a material surface. With appropriate calibration for material properties and background radiation, this radiation can be converted into a direct measurement of temperature of the material surface.

Infrared thermography can detect horizontal delaminations in pavements and bridge decks.[Clemena, Kunz, Manning et al., etc.] This capability is currently being commercial provided by EnTech Engineering and Donohue and Assoc. The basis for this capability is the fact that the delamination introduces a thermal discontinuity in the pavement. Under the influence of solar radiation, the surface areas above a delamination will become hotter during the day, and cooler at night. This "thermal anomaly" can be directly seen on an infrared image. This capability requires the presence of solar input (and therefore won't work on cloudy days) and relatively dry pavement conditions.

The presence of moisture in a material will influence the amount of infrared absorption and radiation. It is possible that this property can be used to detect moisture in the asphalt. A similar capability has been developed for remote sensing of near-surface moisture in soils.

The presence of fine vertical cracks in the pavement produces localized heat transfer anomalies. Experience with infrared has shown that these cracks can appear more prominent in an infrared image than they might in a visual image, particularly under moist conditions.[Maser, 1989]

Mechanical Surface Waves

These are waves that propagate along the boundary between a semi-infinite solid and air, and are normally called "Rayleigh waves". These waves can be introduced into pavement just by hitting the pavement with a hammer. The velocity of these waves will depend on the mechanical properties of the pavement, and to a lesser extent on the properties of the base, subbase, and subgrade materials. The sensitivity to depth is proportional to their wavelength.[Nazarian and Stokoe, 1985; Heisey et al., 1982].

Fine cracking in the pavement may not be seen, but is will certainly disrupt the local mechanical properties. A surface wave passing through an area of cracked pavement should experience high attenuation and a delay in arrival. These characteristics can be detected with geophones placed on the pavement surface.

Aging of the asphalt results in the embrittlement of the asphalt at the surface layer. This embrittlement is associated with an increase in elastic modulus. Surface waves with wavelengths less than the pavement thickness will be sensitive to this change in elastic properties. The depth sensitivity noted above will reveal higher velocities for the shorter wavelengths (which are more sensitive to the near surface modulus increase) and lower velocities for the longer wavelengths.

Moisture in the subgrade will (depending on the soil type) change the shear wave velocity in the soil. The velocity of surface waves of long enough wavelength will thus be affected by this moisture. A delaminated overlay will change the mechanical structure of the pavement, and will therefore change the surface wave velocity. The presence of a subsurface void will have a similar effect.

Spectral Analysis of Surface Waves (SASW)

SASW is a particular implementation of surface waves which permits the determination of shear wave velocity vs. depth from the surface wave velocity vs. wavelength characteristics.[Nazarian and Stokoe, 1985; Heisey et al., 1982]. It can be used to determine the shear wave velocity of the pavement, the base, and the subgrade. It can thus be utilized for identifying all of the conditions described above for surface, but perhaps with a greater degree of detail.

Mechanical Impedance

Mechanical impedance involves striking or shaking an object or structure and determining its response vs. frequency. This frequency response reflects the material properties of the structure, including modulus, layer thickness, etc. Resonant frequencies are often simple indicators of anomalous structural conditions. The response of a concrete pavement with a void underneath it should be different from that of a pavement with good contact with the base material. The thickness of the void should make no difference. The response of a pavement with moisture in the subbase material should be different than for the same pavement without moisture. In either case, the technique can be implemented with a hammer and a dynamic motion sensor (e.g., geophone).

A variety of off-the-shelf equipment exists for implementing mechanical impedance methods. The H-103 report (Table 6-B) suggests that specific systems have been developed in Sweden for pavement evaluation ("The Measuring Vibrating Wheel" and "Road Bearing Classification System"). The H-103 report also mentions a Transient Dynamic Response technique which has been implemented in France and the U.K. However, no further information is provided about these European systems.

Dynamic Deflection

This technique is similar to that above. It is often implemented with several geophones in order to determine the deflected shape of the pavement surface. Utilizing various finite element models, the pavement layer properties can be back-calculated. These calculations would represent absolute values of pavement properties, as opposed to the relative changes predicted by the mechanical impedance measurement.

Direct compression and Shear Waves (Sonic Range)

These measurements involve propagation of direct P or S waves in the top pavement layer [see, for example, Kolsky, 1963; Manning, 1985]. The waves are initiated with a hammer blow, and measured with an array of geophones or accelerometers. Anomalous decreases in wave velocity measured in this fashion will indicate some reduction in the average moduli of the pavement, which should be an indicator of cracking and other deterioration in the pavement materials (e.g., stripping, freeze/thaw damage).

Ultrasound

Ultrasound is a well developed commercial technique for evaluating thickness and properties of materials, and for identifying and locating voids and cracks.[see Malhotra, 1976; Bungey, 1980] Pulsed ultrasound involves transmitting short, high frequency (> 20 kHz) mechanical pulses into a material using a variety of transmitting devices. These pulses propagate through the material, and reflections are generated at discontinuities in the material such as cracks and layer boundaries. If access to the other side of the material is available, the transmitted pulse can be received and analyzed. In the case of pavements, downward travelling pulses can only be sensed as reflections which return to the surface where the source is located.

The timing and amplitude of these reflections depends on the distance of the reflector from the source, and on the acoustic velocity of the material between the source and the reflector. For a reflector at a known distance, the acoustic velocity is an indicator of the material's elastic modulus, and represents a measure of material integrity. For a material of known velocity, the arrival time is an indication of thickness or the presence of flaws.

Applications of ultrasound in construction materials have focused primarily on transmission techniques for evaluation of the properties of materials such as wood and concretes.[Manning, NCHRP 118] Commercial equipment is available for these applications (eg., James "V-Meter"). Reflection ultrasound, as would be required for pavements, has not been commercially applied. A technique for ultrasonic determination of delaminations in concrete is currently in the research and development stage.[SHRP H-101] The H-103 report (Table 6-B) suggests the existence of such equipment in Denmark for pavement layer thickness determination (called "Geosonar"). No further details are provided.

EM Conductivity

This technique measures the conductivity of the earth by applying a magnetic field, inducing eddy currents, and measuring the secondary magnetic field produced by the eddy currents.[McNeil, 1980] The equipment involves two coils, and a field detector. Depth of investigation is proportional to the spacing of the coils. For the pavement application the coil spacing need only be equal to or a bit greater than the depth to subgrade.

Since moisture has a strong effect on the conductivity of earth materials (including asphalt and concrete), this technique should in principal be applicable to all moisture evaluations.

Continuous Wave Microwaves

These are similar in principal to radar. Radar is based upon sending out pulses and receiving echoes. In the CW Microwave technique, waves are sent out continuously. The typical frequency range is 0.2 to 8.0 GHz.[Koerner and Lord, "Electromagnetic Methods in Subsurface Investigations", 1982] The characteristics of different depths in the material are determined using frequency modulation. The higher frequencies allow for the detection of small voids, delaminations and small flaws, but they are accompanied by a reduced depth of penetration. These techniques are standard in non-destructive evaluation, but have seen little application to pavements.[Koerner et al., "CW Microwave Location of Voids Beneath Paved Areas", 1982]

Nuclear Techniques

Backscatter

This technique involves transmitting radiation into the material to be evaluated, and monitoring the rate of arrival of backscattered energy. The rate of backscattered gamma rays is directly related to the material density, and the rate of backscattered neutron particles is proportional to the material moisture content. This principle is exploited by a number of commercial nuclear moisture/density gages, such as Troxler, Humboldt, and CPN. They are capable of detecting moisture to within +/- 0.25 lbs/cu.ft. with a measurement depth up to 8 inches. Application of this technology to the detection of moisture in asphalt could be complicated by the fact that the rate of neutron backscatter is related to the presence of hydrogen, which is found in asphalt and in water. It is not clear that these two sources of backscatter could be separated.

Nuclear Magnetic Resonance (NMR)

This technique involves the application of a strong static magnetic field to a material, and sensing induced changes in atomic spin orientation using a pulsed oscillating magnetic field acting orthogonal to the static field (see Paetzold, et al.). The sensitivity of this measurement to hydrogen atoms provides the basis for measuring moisture content. Application of NMR to construction materials has been limited. FHWA sponsored the development of a prototype piece of equipment for determining moisture content in concrete.[Matzkanin et al., 1982] According to Manning [NCHRP 118] the developed equipment demonstrated the feasibility of the concept, but indicated that the equipment would ultimately be cumbersome, slow, and would require skilled operators. Commercial equipment for this application is not available.

Commercial Moisture Meters

There are a number of commercial devices on the market which can be used to detect moisture in construction materials. The principle of operation of these devices varies, and their resolution and depth of penetration are not generally made clear in the manufacturer's literature. One application, for example, is for the detection of moisture in roofing materials. One set of commercial devices for this application is made under the name of TRAMEX Non-Destructive Roof Moisture Detection Instruments. One of their devices, the Dec Scanner is a wheel mounted instrument which they claim can detect moisture to a depth of 5 1/2 inches through gravel. The applicability of this type of equipment to other materials and depths is not clear, but worth investigating.

5.3 Comparative Analysis of Alternative Technologies

Tables 1 - 6 present a comparison of each technology in terms of its application to the measurement of each of six damage conditions identified in Section 4. The technologies are evaluated in terms of the factors believed to be the most critical for the proposed application. It should be noted here that these summaries have been prepared solely on the basis of the experience and judgement of the authors and on information which was quickly available in our files and in the H-103 documents. The analysis is by no means exhaustive. The evaluations presume a method of implementation for each technology which has not been discussed. A further discussion of methods of implementation will ultimately be presented after the most attractive technologies have been identified.

A number of evaluation criteria have been identified for this evaluation. "Commercial availability" refers to whether or not the necessary equipment can be purchased from a manufacturer. Specific manufacturers have been mentioned as examples. Others may exist, and mention of specific names is not intended to imply an endorsement of these suppliers or their equipment. "Required development" identifies the issues which must be addressed in order for the technique to successfully measure the condition being considered. "Chance of success" rates the probability that this development work will succeed in producing a useful and desirable product. "Strengths/limitations" is self explanatory. "Usable by maintenance staff" assesses the potential simplicity and ease of operation that could be achieved with the proposed technology. This implies minimum training and operator sophistication. This criterion is significant if we believe that the equipment must be usable by maintenance personnel as part of local maintenance operations. This is the perspective that has been adopted in this study. This criterion is not significant, however, if the equipment is maintained and operated by central office personnel providing measurement services to the individual maintenance districts. The final item, "cost," is the projected cost of a completely developed piece of equipment ready to serve the intended measurement function.

5.4 Identification of Candidate Technologies for Further Evaluation

A qualitative review of the data in Tables 1 - 6 reveals certain technologies which stand out in terms of a number of evaluation factors. Below is listed those technologies which appear to be most attractive for each specified condition. Note from the discussion in Section 1 that the perspective taken here is that an attractive technology is one which can be easily used by maintenance personnel. Along with each technology is a rating (in parentheses) and a description of the rationale for its selection.

MOISTURE IN THE ASPHALT (Table 1)

EM Conductivity (1) This technology is a top candidate because it is already available commercially for conceptually similar evaluations. The key issue is to determine whether it can be implemented in the highway environment, since the equipment is very sensitive to the presence of nearby metal. Conceivably it could be suspended by a non-metallic boom from a survey truck, at a sufficient distance to eliminate this problem. In congested or urban areas, the presence of passing vehicles in adjacent lanes might have an adverse effect. These are transients which could possibly be eliminated by signal processing. Some simple field evaluations could resolve these issues.

Commercial Moisture Meters (2) These could be even more attractive than the nuclear technology since there is no problem with nuclear sources and licenses. However, it is not clear that a device exists that will work properly for this application. Some further investigation of

Table 1

Condition - Moisture in the Asphalt

Measurement Technology	Commercial Availability of Equipment	Required Development	Chance of Success	Strengths/Limitations	Usable by Maint. Staff?	Est. Cost ($K)
Radar	Yes, from Geophysical Survey Systems, Inc., Pulse Radar, Inc., Oyo Corporation, and Penetradar	Automated data interpretation	moderate	high-speed, non-contact	maybe	50
EM conductivity	Yes, from Geonics, Inc.	adaptation to highways	high	non-contact; must operate away from metal	yes	15
Nuclear Magnetic Resonance	none	must be considerably simplified and reduced in cost	moderate	direct measure of moisture; equipment bulky and expensive;	doubtful	100
Continuous microwave	none for pavement application	concept and equipment must be developed	moderate	non-contact; personnel would have to avoid exposure to high frequency microwaves	maybe	50
Neutron Backscatter	yes. from Humboldt, CPN	Need to distinguish moisture measurement from asphalt content measurement	moderate	measurement takes time; good for spot checks rather that continuous measurement;nuclear source requires caution and licensed operator.	yes	5
Infrared Radiation	yes, from Agema and Inframetrics	confirm reliable relationship between IR radiation and asphalt moisture content	moderate	non-contact; full lane survey possible; equipment requires operator expertise; limited by weather conditions	maybe	100
Commercial Moisture Meters	yes, from James, United Construction Products, etc.	confirm that they provide adequate resolution and depth of penetration for asphalt.	moderate	not clear	yes	<5

Table 2

Condition - Moisture entering base or subgrade

Measurement Technology	Commercial Availability of Equipment	Required Development	Chance of Success	Strengths/Limitations	Usable by Maint. Staff?	Est. Cost ($K)
Radar	Yes, from Geophysical Survey Systems, Inc., Pulse Radar, Inc. and Oyo Corporation	Automated data interpretation	high	high-speed, non-contact	maybe	50
EM Conductivity	yes, from Geonics	adaptation to highways	high	non-contact: must operate away from metal	yes	15
Mechanical Surface Waves	components are available, but user must integrate the system	establish correlation between moisture and changes in velocity and attenuation; automate data interpretation	moderate	spot measurements, not continuous (unless a continuous technique is developed)	yes	20
SASW	same as above	same as above	high	same as above	doubtful	50
Mechanical Impedance	same as above (Collograph? mentioned by VTI looks similar, but no info provided)	establish correlation between moisture and changes in impedance; automate data interpretation	high	simple: same disadvantage as above	yes	15
Dynamic Deflection	yes, from Dynatest, KUAB, PCS, etc.	none	high	complex data collection and interpretation	doubtful	80
Continuous Microwaves	not for pavement this application	must be completely developed - hardware, interpretation, etc.	moderate	non-contact	maybe	50
Static Deflection	Benkelman Beam, etc.; some development on making measurement from rapidly moving vehicle	none for existing equipment	high	equipment slow and cumbersome; high speed technology would be useful if available	doubtful	1-166

Table 3

Condition - Moisure Under Joints

Measurement Technology	Commercial Availability of Equipment	Required Development	Chance of Success	Strengths/Limitations	Usable by Maint. Staff?	Est. Cost ($K)
Radar	Yes, from Geophysical Survey Systems, Inc., Pulse Radar, Inc., Penetradar, Inc. and Oyo Corporation	Automated data interpretation	high	high-speed, non-contact	maybe	50
EM Conductivity	Yes, from Geonics	adaptation to pavements	moderate	non-contact; might be adversely affected by dowels	yes	15
Mechanical Impedance	Collograph? mentioned by VTI- looks similar, but no info provided	establish correlation between moisture and changes in impedance; automate data interpretation	high	simple: not continuous, good for spot measurements	yes	15

Table 4

Condition - Fine Cracking

Measurement Technology	Commercial Availability of Equipment	Required Development	Chance of Success	Strengths/Limitations	Usable by Maint. Staff?	Est. Cost ($K)
Infrared Thermography	Yes, from Inframetrics and Agema	interpretive techniques	moderate	non-contact, visual-like survey	maybe	100
Mechanical Surface, Compression, and Shear Waves	components available, but system must be integrated	need to develop relationships between signals and cracking	moderate	direct measurement	maybe	20
Mechanical Impedance	Collograph? mentioned by VTI- looks similar, but no info provided	establish correlation between cracking and changes in impedance; automate data interpretation	high	simple: not continuous, good for spot measurements(unless a continuous technique were developed)	yes	15
Static Deflection	Benkelman Beam, etc.; some development on making measurement from rapidly moving vehicle	none for existing equipment	high	equipment slow and cumbersome; high speed technology would be useful if available	doubtful	1-166

Table 5

Condition - Overlay Delamination

Measurement Technology	Commercial Availability of Equipment	Required Development	Chance of Success	Strengths/Limitations	Usable by Maint. Staff?	Est. Cost ($K)
Infrared Thermography	Yes, equipment from Agema or Inframetrics; services from Donohue or EnTech.	none	high	non-contact; entire lane scanned at 5 mph; must be operated and interpreted by trained personnel	doubtful	100
Mechanical Surface Waves	components are available, but user must integrate the system	establish correlation between delamination and changes in velocity	moderate	spot measurements, not continuous (unless a continuous technique is developed)	yes	20
SASW	same as above	same as above	high	same as above	maybe	50
Mechanical Impedance	same as above	establish correlation between delamination and changes in impedance	high	simple: same disadvantage as above	yes	15
Dynamic Deflection	yes, from Dynatest, KUAB, PCS, etc.	none	high	complex data collection and interpretation	doubtful	80
Chain Drag	equipment is home-made	none	high	reliable for thin concrete overlay; does not work for asphalt overlay; slow and time consuming	yes	0
Delamtech	yes, from SIE Corp (?)	none	high	same as above	yes	?

Table 6

Condition - Voids Under Pavement Joints

Measurement Technology	Commercial Availability of Equipment	Required Development	Chance of Success	Strengths/Limitations	Usable by Maint. Staff?	Est. Cost ($K)
Continuous Microwaves	not for pavement this application	must be completely developed - hardware, interpretation, etc.	moderate	non-contact	maybe	50
Radar	yes, from GSSI, Pulse Radar, Oyo, and Penetradar	none	high	non-contact; limited to large void sizes	doubtful	50
Mechanical Impedance	same as above	establish correlation between presence of void, thickness of pavement, and changes in impedance	high	simple; independent of void size; spot measurement at each joint	yes	15

commercial devices and their inherent capabilities would clear up this issue.

Continuous Microwave (3) This is a good concept, but nothing appears to exist commercially (unless it has already been incorporated into one of the above devices). Otherwise, it would have to be developed entirely from scratch. Once developed, it has a good chance of being a practical field tool. Note that prototype equipment for microwave heating of asphalt pavement has been developed and tested (Al-Ohaly and Terrel, TRR 1171). The proposed equipment would be lower power.

Radar (4) This is a viable technique, and commercial equipment is available. The main problem is data interpretation. It is not clear that asphalt moisture can be unambiguously inferred from the radar data. Some research and experimentation would be required to study this. If the capability is verified, it must be implemented in an algorithm which is built into the equipment. To date, all commercial ground penetrating radar applications involve subjective interpretation of the data, so this application would have to break new ground.

MOISTURE ENTERING BASE OR SUBGRADE (Table 2)

EM Conductivity (1) Same reasoning as above.

Mechanical Impedance (2) Moisture in the base and subgrade weakens the pavement, and this weakening will affect the pavement's dynamic response. This principle is indirectly employed by standard pavement capacity equipment, but with greater forces and lower frequencies. Chances for success are good. The primary hurdle is to identify the element(s) of the response signature that will serve as indicators of moisture, and to automate their identification. Ordinarily this would be hand carried, spot measurement equipment. It could possibly be automated in some manner similar to the Dynaflect, so that it could be applied from a moving platform. This would require further developmental effort.

Radar (3) Radar's capability for detecting subsurface moisture is well established. The key issue again is data interpretation. In this application it would have to be automated so that the results are presented unambiguously. This would require some developmental research, and the final system would have to be packaged for use by maintenance personnel.

Mechanical Surface Waves (4) Demonstrated capability for detecting subsurface variations in shear wave velocity. This correlates with soil moisture for fine grained and cohesive soils. The full applicability of this would have to be studied further. Secondly, a method of implementation which is simple and straightforward would have to be developed, and some type of automated data interpretation would have to be included.

MOISTURE/CONTAMINATION UNDER JOINTS (Table 3)

Mechanical Impedance (1) Same rationale as above. Higher priority here because dowels will adversely affect EM conductivity.

EM Conductivity (2) Same rationale as above. Affect of dowels could be subtracted out, since they are well defined, regularly spaced subsurface objects. Some research would have to be carried out to investigate this possibility.

Radar (2) Same rationale as above. Higher probability of success, since for joints you know exactly where you are looking. Some success with void detection, part of which might actually be in locating moisture which precedes the formation of voids. Once again, some means of automating the interpretation of the data needs to be developed.

FINE CRACKING (Table 4)

Mechanical Waves (1) This includes surface, shear, and compressional waves. All of these should be directly sensitive to the presence of fine cracking in the pavement. The key issues are (a) is the level of sensitivity adequate to make the technique useful, and (b) can it be implemented in a reasonably convenient and practical way. The answer to (a) will require some further definition of what exactly a "fine crack" really is (i.e., how deep, how long, how wide, etc.)

Mechanical Impedance (2) Fine cracking in the pavement definitely diminishes its structural capacity, and will alter its mechanical impedance. Issues are same as for moisture under pavement. "Fine cracking" will also need further definition.

OVERLAY DELAMINATION (Table 5)

Mechanical Impedance (1) Same rationale as discussed above. Automation, data interpretation are the key issues.

Infrared Thermography (2) This technology requires training in the use of equipment and in the interpretation of data, beyond what may be expected of maintenance personnel. Yet the capability for detection of delamination in pavements is proven, and it is being commercially applied in many states for bridge decks. If delamination detection is important enough for maintenance effectiveness, then infrared services should be contracted. Alternatively, the state can buy the equipment and train one or two operators who would centrally support local maintenance needs.

VOIDS UNDER PAVEMENT JOINTS (Table 6)

Radar (1) Radar has had some demonstrated success in identifying voids under pavements. Conceptually, it is limited to larger voids. Practically, it might be capable of detecting smaller voids and pre-void conditions since it is sensitive to the moisture and contamination that precedes pumping and void development. Field evaluations to date have not adequately evaluated the capability of radar for this application. Also, in the maintenance application, it may be possible to scan the pavement transversely across each joint to obtain more detail than previous longitudinal surveys have provided. Once again, the key issue with radar is automating the interpretation of the data. This task is more straightforward for the joint application, since the measurement is focussed on a localized area which occurs repeatedly along the pavement.

Mechanical Impedance (1) The void under the pavement changes the support condition, and will affect the dynamic response. This effect should begin to show up even before the void occurs, due to contamination and weakening of the base. A key issue here is whether or not the change is readily measurable and detectable. Some further study, coupled with field using prototype equipment on joints in various conditions could help answer this question.

6. CONCLUSIONS AND RECOMMENDATIONS

It is clear from the discussion in Section 5 that a number of possible measurement technologies are available for meeting the requirements outlined in Section 2. In some cases existing equipment is available, and its capability has been demonstrated in a setting very similar to that of pavements. In other cases, suitable equipment or generic technological capability exists, but its application to pavement maintenance needs to be verified. Overall, the various possibilities described above suggest a good chance that equipment to address pavement maintenance needs can be successfully developed. It is also clear what some of the technological directions and issues involved in bringing these possibilities to the pre-production stage might be.

Given the short period of time during which this report was prepared, we would defer on making any final recommendations regarding specific technological directions, or on what the scope of an H-104 RFP might be, until these findings are presented and discussed before appropriate SHRP committees. However, we do feel that such an RFP can be prepared, and that it has a good chance of leading to a successful outcome.

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