SHRP-H-674

Fabrication and Testing of Automated Pothole Patching Machine

James R. Blaha

BIRL
Northwestern University
1801 Maple Avenue
Evanston, IL 60201

Strategic Highway Research Program
National Research Council
Washington, DC 1993

SHRP-H-674
Contract H-107B
Product Code: 3005

Program Manager: *Don M. Harriott*
Project Manager: *Shashikant Shah*
Production Editor: *Marsha Barrett*
Program Area Secretary: *Carina Hreib*

October 1993

key words:
asphalt pavement repair
automated pothole patching machine
hot air lance
pothole repair
robotics
spray patching
spray emulsion

Strategic Highway Research Program
National Academy of Sciences
2101 Constitution Avenue N.W.
Washington, DC 20418

(202) 334-3774

Acknowledgments

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

Contents

List of Figures

List of Tables

Abstract

This is the final report of a 28 month long effort sponsored by the Strategic Highway Research Program (SHRP) that had the objective to solve the pothole repair problem through complete automation of a repair procedure. The SHRP H107B research project was conducted by BIRL, the industrial research laboratory of Northwestern University. Conceptual designs and feasibility tests are described leading to fabrication of pothole repair equipment modules. The report describes how the modules were then computer controlled and mounted on a commercial truck chassis inside of a custom body shell. The fully automated system uses fewer laborers than manual pothole patching to reduce the cost of making repairs and to lessen the risk to the workers. Speedy and yet quality repairs are achieved in nearly all weather conditions, road configurations, and with a variety of materials. Furthermore, the system has shown strong commercial appeal because it can be operated at off-hours and at night, by one or two workers seated in the truck cab at all times. A computer vision system and robot is shown to perform the repair operations under computer control. The system can cut and shape a pothole in asphalt surfaced pavement, vacuum clean the cavity, heat and dry the bonding surfaces and spray an asphalt emulsion and rock aggregate patch material into the hole. A flat and dense patch is created with no additional roller compaction, with average repair lifetimes expected to last several years using standard.materials. Background information on pothole repair materials, procedures and economics is provided in appendices.

Executive Summary

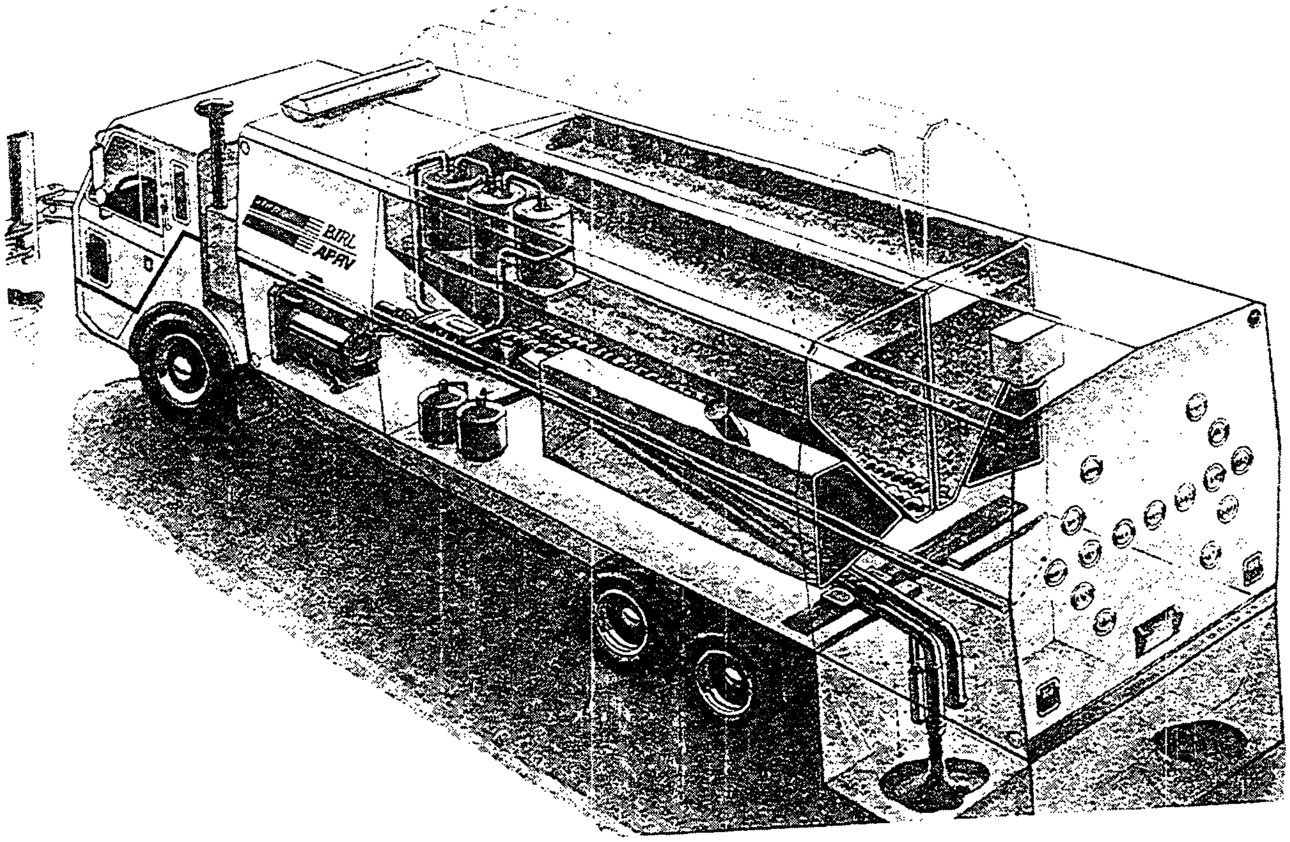
Hundreds of millions of dollars are spent annually on pothole repair, at the further cost of workzone casualties, loss of productivity, damaged goods and vehicles, and the accelerated deterioration of our road system. This 28 month long effort sponsored by the Strategic Highway Research Program (SHRP) had the objective to help solve the pothole repair problem through complete automation of a repair procedure. The goals of SHRP were set very high. An automatically made permanent repair was the ultimate goal, with a target lifetime of 3 to 5 years--better than manual procedures can typically achieve. The system was to use fewer laborers to reduce the cost of making repairs and to lessen the risk to the workers. Speedy and yet quality repairs were required to be made in nearly all weather conditions, road configurations, and with a variety of materials. Furthermore, the system had to be commercially appealing to satisfy the basic SHRP theme that research must be put into practice for the results to have maximum benefit.

The design had to overcome the problems of automating the pick ax and shovel type of repair that is common to pavement maintenance. Not only the tools had to be automated, but also an innovative repair procedure had to be developed to make a patch that would last longer than the most diligent crew would typically make. The procedure developed was a blend of tried-and-true techniques for pavement repair. First, establish a sound base to bond to the patch material. Second, clean all loose debris from the bonding surfaces. Third, dry all the bonding surfaces to promote adhesion of the new patch material. Fourth, apply exactly the right amount of quality patch material to construct a dense and flat patch that cures immediately. Last, leave the repair site perfectly clean because safety and appearance count. Feasibility testing demonstrated that this automated procedure could attain high levels of productivity without sacrificing quality.

The research study was conducted by BIRL, the industrial research laboratory of Northwestern University. Four phases of research were undertaken to develop an automated pavement repair vehicle that would satisfy SHRP requirements and lead to field testing and commercialization. The first phase developed and evaluated concepts for the equipment and repair procedure. System level design was followed by repair procedure design, and then design to the component level. Feasibility tests were used to validate the concepts. The second phase constructed equipment prototypes and validated their performance through testing. The third phase integrated the prototypes onto a vehicle base, automated them, and performed initial testing. Finally, the results were documented in this report and other training guides.

The equipment construction phase developed prototypes that would implement the best concepts, flexibly so they could be integrated onto a vehicle. Many commercial components were used to reduce cost, but complete repair systems were unavailable to serve the major repair functions. The major repair systems were custom designed using practical engineering principles founded on scientific experiment.

The design and performance goals have been reached, and in some cases exceeded, by the Automated Pavement Repair Vehicle (APRV) resulting from this effort. Although the vehicle only repairs potholes at present, other repair capabilities could be added in the future. The APRV offers the benefits of reduced labor costs, greater productivity, improved traffic safety, longer lasting repairs, with minimal material waste.

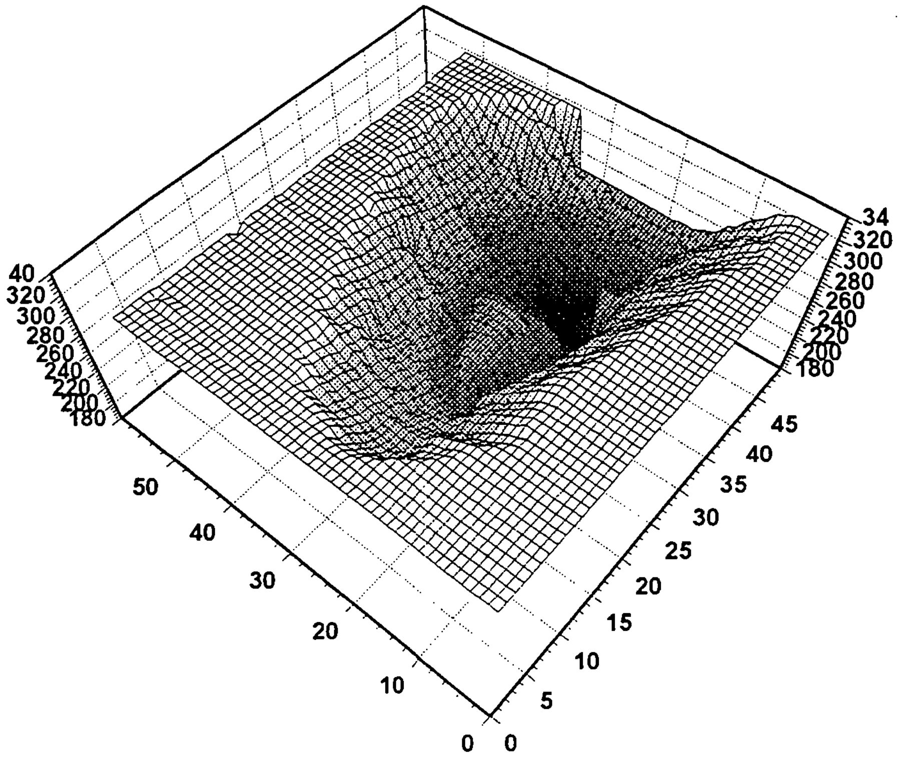


The APRV creates a "warm summer day" for pothole repairs; clean, warm, and dry conditions ideal for making a patch that lasts. Automated repair is done in several steps.

First the driver locates the hole to be repaired and optionally uses a pavement cutter operated by joystick to cut and shape the holes, to create a sound base for the patch. The best way of cutting irregularly shaped potholes, without wasting good pavement, uses a vertical-milling principle. Next, doors on the underside of the repair box at the back of the truck unfold down to the pavement to create a "warm summer day". A vision system scans the pavement area under the box to automatically tell the robot how to proceed. A telescoping robotic arm moves a vacuum nozzle into the pothole. The conceptual design study rated vacuum cleaning as the best way to remove water, mud, and debris from the hole. The prototype uses the inlet of a blower already installed on the truck to do the job at practically no additional cost using simple and compact filter design. The robot arm then moves a hot air lance across the pothole to heat the surface and bonding edges. The lance is a custom designed propane burner, known in the pavement maintenance community for repairing cracks and other pavement distresses without flames. After this very thorough preparation of the pothole, the vision system instructs the robot exactly how and where to forcefully spray a stream of asphalt patching compound into the hole to form a dense and flat patch. Commercially called spray patching, this well established process was researched and optimized to attain a new level of performance that should yield patch lifetimes of several years. Mechanical compactors are not required because the process is so effective at forcing the mixture into the hole and building the patch from the bottom up. Ongoing field studies show that spray patches can have excellent density at the moment of placement, with immediate drive-over capability. Spray patches have been installed and monitored all across the country showing years of lifetime. Although some of the sprayed material scatters over the pavement surface, the vacuum nozzle sweeps it up to leave a clean repair site. The doors of the workbox close, and the driver is signaled to move to the next repair site at highway speeds. The entire repair takes a few minutes depending on the size of the hole.

Significant innovations were responsible for making the automated vehicle possible. First, all but the cutting operation is done in a protective enclosure at the rear of the truck. Doors on this repair box drop down to the level of the pavement so that weather has no effect on the repair as it is being made. The traveling public is also protected from the repair operations and they should not be distracted by the operations. Since the truck is only stationary for a few minutes, the truck can perform repairs as a moving workzone, using the rear-mounted arrow board and perhaps a trailing shadow vehicle.

The second innovation was the use of computer process control to fully automate the material handling and each of the repair steps. The computer instructs a robot how to move the vacuum, heating, and spray filling nozzles over the pothole. The intelligence comes from video cameras that inspect the pothole before and after repair. More importantly, the computer vision system controls the repair process. The combination of computer process control, robotics, and machine vision yields consistent, high quality patches every time, faster than a manual crew. The vision system and robotics allow the truck to operate at off-hours (even at night). There are no delays in setting up or taking down equipment, and each step is rapidly performed in sequence, which maximizes the payback and minimizes the lane occupancy time. Recent demonstrations of the APRV show a pothole repair completed in a few minutes.



The vehicle will be further demonstrated and field tested under the sponsorship of the Infrastructure Technology Institute of Northwestern University. In parallel with the testing effort is a significant current effort to commercialize the vehicle so that the greater benefits of the SHRP development can reach highway use and public acceptance. The current goal is to have an arrangement for commercial production of the APRV in place by the end of 1993. Publicity to date has generated an enormous world-wide interest in purchasing or building the APRV.

With improved roads will come measurable benefits to motorist and trucking companies. Vehicle maintenance costs and liability claims may drop. Delays caused by pothole repair should decrease, thus lowering the cost of goods. The economy of a state depends on the quality of its transportation infrastructure. The APRV technology will directly improve the quality of roadway transportation, thus benefiting the economy of the state (and country) that uses it.

1

Research Program

Perspective

The deteriorated state of the US highway system leads to millions of potholes being created each year. Hundreds of millions of dollars are spent annually on pothole repair. They create traffic hazards, they damage trucks and cars, and the repair process ties up traffic causing the daily loss of tens of thousands of labor hours of drivers and passengers as well as increasing the cost of goods from their delay. Despite the best efforts of thousands of road maintenance workers, it is very difficult to keep up with the problem.

We estimate (in Appendix B) that a manually performed permanent pothole repair by a typical road crew of 5 costs about $80 on the average. Other estimates range from $30 to over $100.[1,2] Only about $2 to $5 of these costs are for the patch material placed in each hole. Most of the rest of the cost comes from under-utilized labor and inefficient repair procedures. Repairs can also be made quickly by a smaller crew using more expensive materials, but often the patches do not last long enough to justify endangering lives and delaying traffic. A way is needed for a small crew to quickly and safely make a patch that will last years and years.

Objectives

This 28 month long effort sponsored by the Strategic Highway Research Program (SHRP) had the objective to help solve the pothole repair problem through complete automation of a repair procedure. The goals of SHRP were set very high. An automatically made permanent repair was the ultimate goal, with a target lifetime of 3 to 5 years--better than manual procedures can typically achieve. The system was to use fewer laborers to reduce the cost of making repairs and to lessen the risk to the workers. Speedy and yet quality repairs were required to be made in nearly all weather conditions, road configurations, and with a variety of materials. Furthermore, the system had to be commercially appealing to satisfy the basic SHRP theme that research must be put into practice for the results to have maximum benefit.

Research Plan

A four-phased research and development program was undertaken under the guidance of SHRP and an Expert Task Group (ETG) specifically established to monitor the effort and recommend actions as needed. The ETG contained representatives from state highway agencies, the equipment construction industry, and the Federal Highway Administration.

At the conclusion of each phase, a decision whether to proceed with the next phase was made.

The four phases had associated tasks as follows:

Phase I: Development of Plans, Specifications and Drawings
    Task 1: Conceptual Design
    Task 2: Feasibility Testing
Phase II: Fabrication and Testing of First Generation Prototypes
    Task 3: Fabrication of Prototype Equipment Components
    Task 4: Conduct Component Test Program
Phase III: Fabrication and Testing of Second Generation Prototype
    Task 5: Modifications and Revisions of Components
    Task 6: Fabrication of Integrated Equipment
    Task 7: Field Testing, Evaluation, and Demonstration
    Phase IV: Prepare Documentation of Results
    Task 8: Documentation of Results

BIRL, the industrial research laboratory of Northwestern University was the prime contractor. Small subcontracts were used for some equipment construction, but nearly all engineering and integration was done with BIRL resources. BIRL staff on the project had over 100 years of expertise from the automotive and vehicle-related industries, 50 years of experience in manufacturing and process control, and 20 years of imaging and computer automation expertise. The design and fabrication teams had specific quality objectives throughout the program. The vehicle system was created using a technique called 'quality engineering'. The repair system was viewed as a manufacturing process control system on wheels. The system had the function to make a pothole patch. The team had to define what was a quality patch, and how to engineer a machine that would achieve this result. We went one step further and developed specific criteria and a rating procedure to do formal evaluation of alternative designs as shown in Appendix C.

Research Results and Benefits

The final deliverable result was the Automated Pavement Repair Vehicle (APRV), for repairing potholes and other road surface defects. According to our productivity estimates, the automated vehicle will create a permanent patch having years of life for less than $25 installed cost, including the amortized cost of the vehicle. Small patches could be placed for less than $10. It has been estimated that there are perhaps 16,000,000 to 50,000,000 potholes on the nations roadways at any given time. SHRP estimates that 25,000 tons of pothole repair materials are used annually in the US. The cost savings from automated repair is apparent in the difference of $80 - $25 = $55 per hole. This does not include possible savings of more than one hundred dollars per hole in less lost time to society from traffic tie-ups caused by slow pothole repairs. Potentially, hundreds of millions of dollars could be saved for the US highway system. Additional benefit would come from saved lives, reduced traffic delays, less automobile and truck maintenance, and lower transportation costs. Work-zone casualties for 1989 for example, show that 350 people were killed in roadway maintenance activities. The APRV has been designed to get the workers off the road and to perform the repairs very rapidly, doing it right the first time.

Problem Definition: The Hole Problem

Potholes are a prevalent problem, affecting every motorist or trucker at some time. Maintenance departments everywhere are plagued by this form of road defect most of the year. Potholes are also widespread across Canada and other parts of the world. This is due to the basic causes of potholes and the methods yet available to repair them. This section will provide background on potholes in asphalt-surfaced roads. Additional detail on their causes and repair techniques is available in Appendix A.

Good design requires a careful specification of the problem. At a high level, the problem definition affects the system design process. A few of these factors are discussed here, with more detailed requirements presented in later sections. A pothole must be specified in terms of its length, width, depth, and location on the road. Many sources were sought to provide a definition for the purpose of this program. Potholes can be found anywhere over the road surface. They may be closely spaced or infrequent over a road system. Pothole repair can be quite difficult to do in highway practice. A good definition was needed to set the requirements for the automated repair system. The definition was used to judge the practicality of some approaches. The definition was synthesized from many sources consulted early in the program:

- SHRP
- Asphalt Institute
- US Army Corps of Engineers
- American Public Works Association
- State highway district engineers
- Pavement engineering consultants
- Photo surveys and direct observation

State highway personnel and consultants point out that they usually occur in the wheel paths, particularly the outer path, and especially where a pavement has been widened. Often, such widening unfortunately results in a joint positioned directly in the outer wheel path. A joint is particularly vulnerable to pavement problems. Potholes also occur near the center-line of two-lane roads, where the lanes of asphalt overlays are joined. A reasonable definition of a pothole is a bowl-shaped (roundish) depression with sharp, broken edges, between 1 and 2 feet (30 to 60 cm) in diameter, with severe cases of 3 feet (1 m). The depth ranges from 2 to 6 inches (5 to 15 cm) generally, with the larger holes having greater depths. Figure 1-1 shows a representative pothole.

Potholes on state highways may be different and perhaps less severe than those found on local road systems. They are a relatively advanced form of pavement deterioration, often caused by a lack of preventative road maintenance. Poorly constructed roads can rapidly become riddled with them. State highways are more likely to have smaller and shallower potholes than local roads, although there are exceptions.

Figure 1-1. Representative Pothole.

Pothole Definition

SHRP established a basic requirement for the scope of potholes to be repaired. An expanded definition included other variations that would be encountered in practice.

> **Pavement Type:** The pothole would be in pancake pavement, flexible base, or rigid composite base. Pavement areas adjacent to the pothole might be asphalt or Portland cement concrete.
>
> **Pothole Size Limits:** 1 to 6 inches (2.5 to 15 cm) in depth, 1 to 10 square feet (.09 to .93 sq m) in surface area.
>
> **Pothole Frequency and Location:** Closely spaced or infrequent. Anywhere in 10 to 12 foot (3 to 3.66 m) lane width but usually in wheel paths assumed to be 7 feet (2.13 m) center-to-center, about 2 feet (.61 m) wide.
>
> **Repair Conditions:** It should be the objective to make repairs in virtually any weather condition, day or nighttime operation whenever potholes develop.

Pothole Location

The design requirements of an automated pothole repair vehicle are affected by the scope of pothole location and spacing. Potholes can be found anywhere on the road surface, and they may lie adjacent to non-asphalt paving materials or structures. Spacing between potholes may vary considerably, across the road (transverse spacing) and along the length of it (longitudinal spacing). The repair system must be extremely versatile in handling these variations. The system must help a skilled operator to handle unusual circumstances. Manual overrides can give the operator control at these times.

Pothole Spacing

Although most potholes occur in wheel paths (the most fatigued areas), our scope definition included their development anywhere in the lane. Particularly vulnerable areas are at the longitudinal joints, such as the centerline and near the edge of a pavement which has been widened. Shown in Figure 1-2, are four conditions for the spacing of potholes termed 'cluster', 'band', 'line', and 'sparse'. Optimally, the pothole repair equipment should be able to reach a pothole located anywhere in the lane without having to unnecessarily move the truck within the lane. It is desirable to keep the width of the truck to 8 feet (2.4 m) or less, so that special permits are not required. If a batch of holes occurs within a small area, then it is desirable to fix them all without moving the truck, and without having to take down and set up equipment for a short move. Setup delays are very costly to road maintenance productivity, so the total reachable area should be large at each stop.

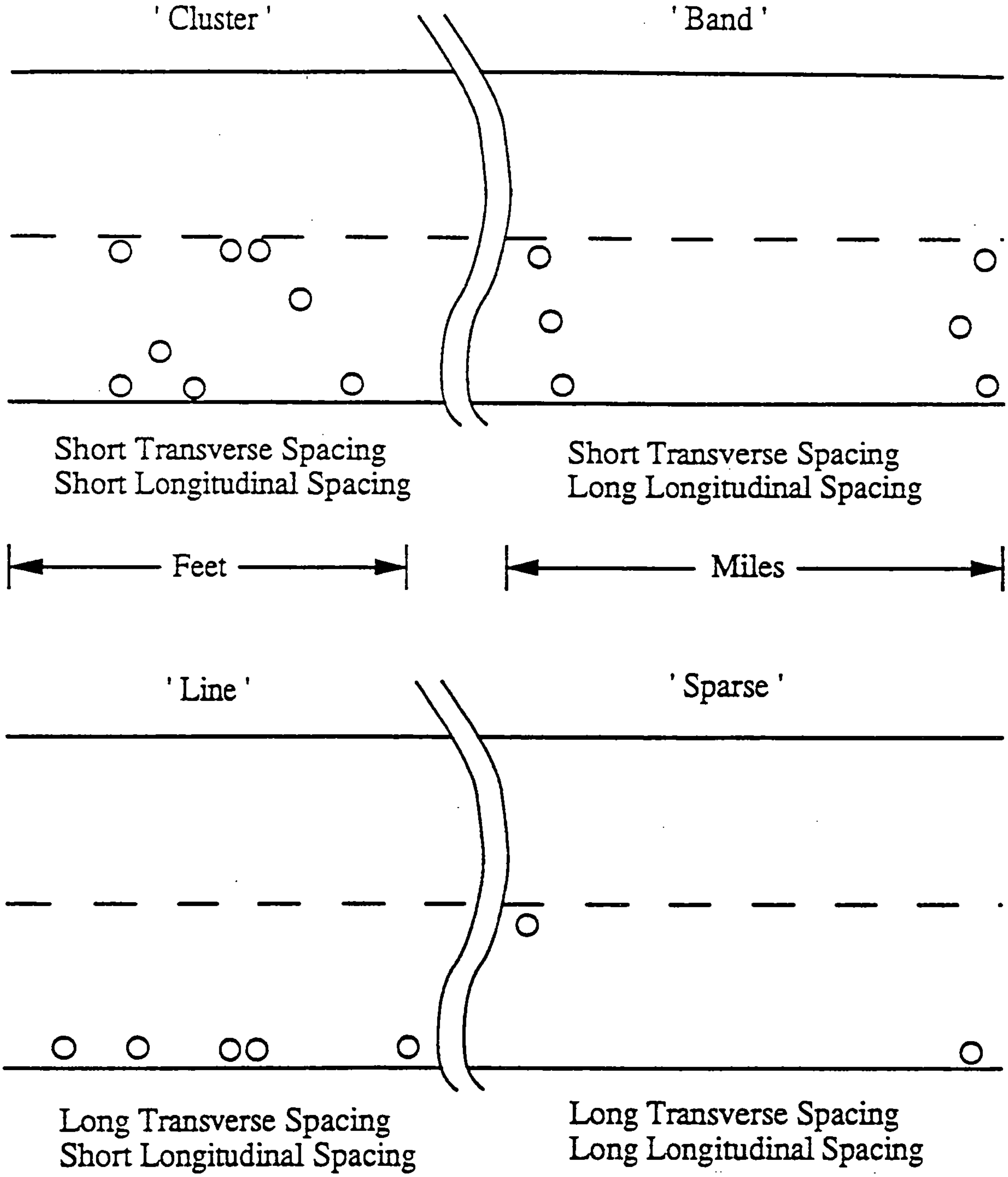
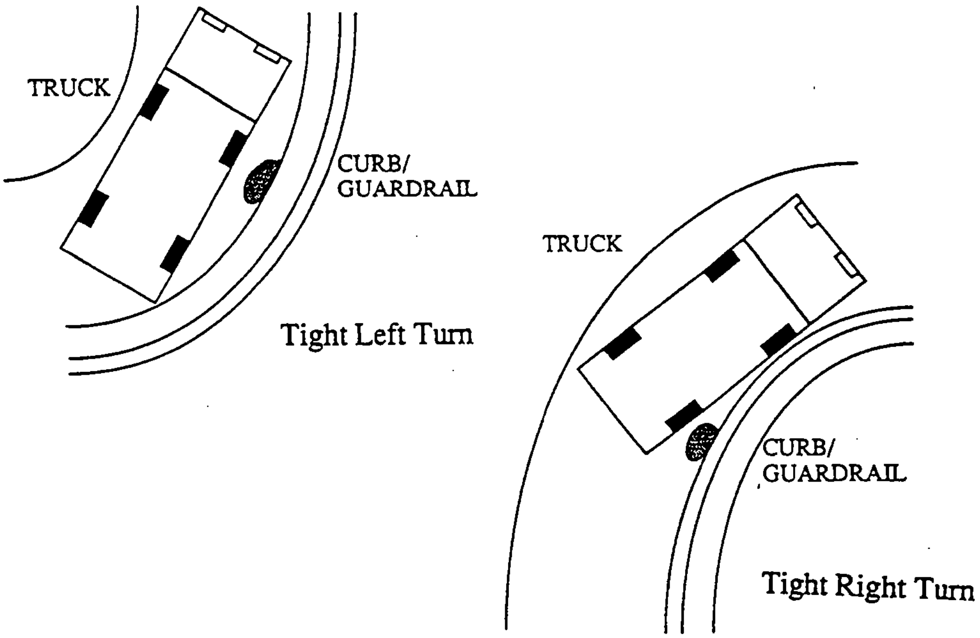


Figure 1-2. Pothole Spacing Along a Pavement.

Adjacent Surfaces and Structures

Access problems for a vehicle can also affect the design requirements of the automated repair system. Potholes often occur near curbs, drains, and manholes not always in wheelpaths. They often arise at the juncture of concrete and asphalt sections. Curbs can present problems for truck access as shown in Figure 1-3. When the road has a tight radius turning to the left, this presents a difficult reach problem for large trucks. The middle portion of the truck can never be close to the curb unless the wheels are allowed to ride up on the curb. On a tight turn to the right, with a guardrail close to the curb, the truck body may get in the way.

The design requirement for tools, controls, and sensing methods can be affected by the features present on the road. Nearby metallic structures such as drains and manholes affect the choice of pavement cutting tools used. They may also present problems for automated control. Cutter bits that are designed to cut asphalt must not be allowed to contact metal, concrete, or stone, otherwise severe wear or breakage may result. Sensors could be incorporated in the tool to detect this contact, but with some difficulty. There is the possibility of cutting down into the rigid concrete base of a pavement. This will lead to premature wear of the tool and it may damage the base itself (which is already weakened anyway). Older cities may have cobblestone base pavements at variable depths under the asphalt surface. Often an existing concrete patch may have failed, leading to potholes around the edges. These repair situations pose real problems for any cutter using abrasives or impact.



Tight Left Turn

Tight Right Turn

Figure 1-3. Curb/Guardrail Access Problem for a Pothole Repair Vehicle.

Repair Conditions

The prime time for potholes to develop is in the winter and spring months over most of the US. A map of the four US climactic regions is presented in Figure 1-4, that was developed under other SHRP program efforts. The worst problems occur in wet/freeze and wet/non-freeze regions. Warmer and drier weather is better for pothole repair. Usually, winter potholes are repaired with temporary measures that may be expected to last only until better weather permits concentrated effort to make a permanent repair. Ideally, every pothole repair should be done only once, to make a patch that will last the lifetime of the surrounding road. SHRP required that the automated repair system must tolerate winter operating conditions across the US and use materials and procedures that will perform well when applied in winter. The automated repair system should be designed to be relatively insensitive to cold and wet conditions, and the repairs should demonstrate long-life when made under these weather conditions.

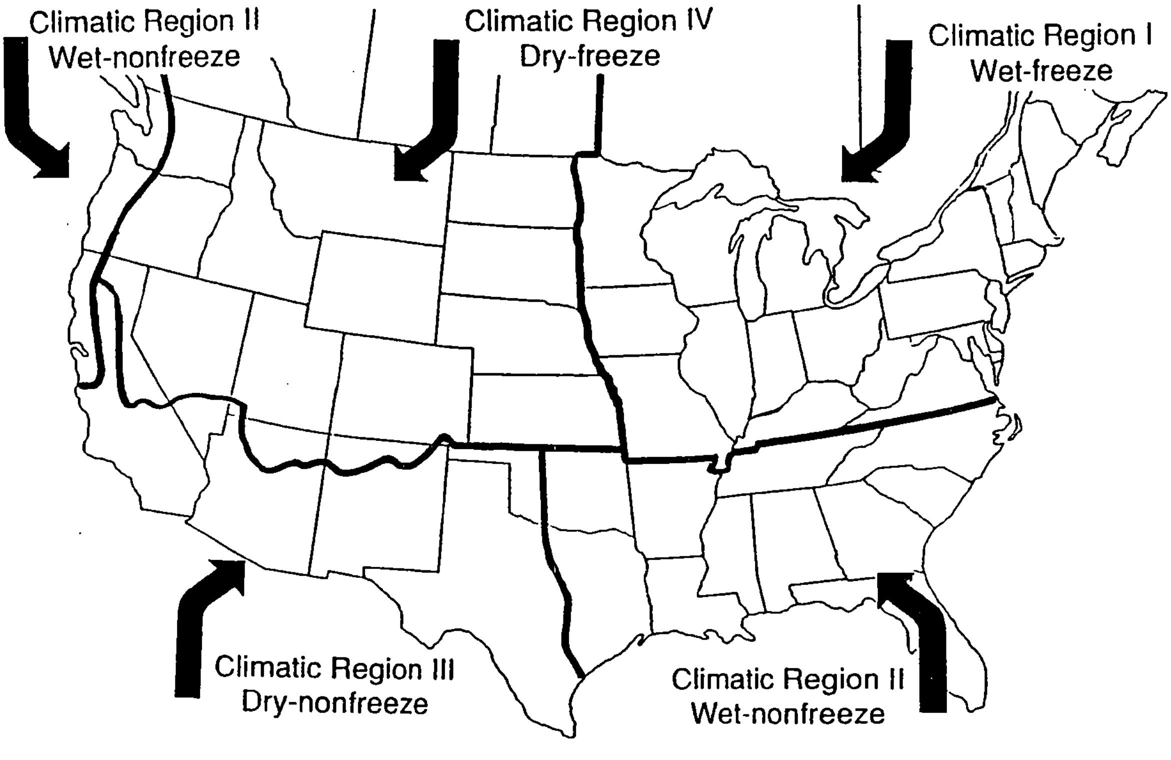


Figure 1-4. Four Principal Climactic Regions of the U.S.

Repair Materials

Other SHRP research project H105 specified a list of materials that would be selected from for use by this repair system.[3] Conventional repair is performed with either a hot bituminous (asphalt) material "hot mix", a cold emulsified (cutback-solvent or water based) "cold mix", or a cold mix that is created during dispensing called "spray emulsion" (also known as spray injection, velocity filling, or spray patching). Henceforth, in this report we will call it spray patching. Recently, two-component epoxy materials have been used also. There are many individual formulations and application procedures within these broad categories. Appendix A treats this subject in more detail.

The SHRP H-105 final report states that the "patching mixtures must develop certain properties in order to perform well. These properties include:

- Stability or resistance to shoving and rutting
- Stickiness or adhesion for bonding to the sides and bottom of pothole
- Binder resistance to stripping in the presence of water
- Durability or resistance to deterioration caused by traffic and climate
- Workability or ease of handling, shoveling, and compacting
- Storageability with no reduced workability"

The application methods differ for hot mix, cold mix, and spray patching. The SHRP H-105 report analyzed some performance factors in detail. Our design and engineering was primarily concerned with the repair procedures and how they could be automated. Initially, all materials and procedures were considered but Phase I of the study concluded by selecting spray patching as the material and procedure of choice.

Comparison of the Standard Repair Procedures

The most time consuming, and therefore costly, procedure to repair pothole is with hot mix. Typically, it is applied with steps of cutting, cleaning, tacking, filling, and compacting. It may have years of lifetime when applied with great care. Cold mixes are popular in the cold and wet climactic regions during the pothole seasons, and much time and effort have gone into their development. Since a crew of several is still required to make a patch, the repair cost is still mainly from labor rather than materials and equipment. Proprietary cold mixes were created to meet the needs of emergency wet and cold conditions where crew exposure to traffic and weather was a severe problem. Since this material seems to perform well in wet holes (water-emulsion based), they can be applied in very severe conditions with little or no hole preparation. This material is not a perfect cure-all, and the patches do not last as long as holes prepared well and patched with some other materials. Their high cost and regional availability eliminates them from some agency budgets. Another SHRP study (H106) has compared the field performance of these materials and procedures listing expected lifetimes and principal factors in their performance. A tentative conclusion of the of the study is that spray patching technique gives longer lasting patches in a variety of conditions, at low installation cost.

Economics of Manual Versus Automated Patching

An operational requirement was that the system be productive and place as much material per day as possible, with less labor, and at lower cost. The overall design of the system and many of the engineering decisions depend on calculated operational and maintenance costs. There are many sources of information for determining the cost of various patching operations. The primary economic drivers include: the cost of materials, labor rates, productivity of patching operations, costs of delays, and patch lifetimes. However, no single source was found that could bring all of these costs into a single comparison. For this reason, we developed a productivity model to analyze how pothole patching costs are related and used it as a tool to evaluate the impact of some engineering decisions on final patch cost . Various scenarios are analyzed in Appendix B.

One can look at pothole repair costs on a daily, seasonal, or yearly basis, but that only tells part of the story. To perform a fair cost comparison of different approaches, it is perhaps best to look at the cost of making a single repair, and assume equivalent patch lifetimes. When field data are available on actual lifetimes and other cost variables, the basic comparison can be adjusted.

The SHRP Focus Newsletter of May 1991 reports on SHRP research that compares the cost and productivity of pothole patching under different weather conditions. A conclusion is that the labor cost is a significant percentage of the repair cost, followed by materials, and then equipment. Patch lifetimes varied over a significant range for the procedures of conventional "throw and go," proprietary material "throw and go," and "Do it right/cut/dry/compact." In some circumstances, using the more expensive proprietary materials may result in a lower (annual) cost per patch because long lifetimes can be achieved.

These results were useful to the program, but a more detailed analysis was required so that specific design and engineering decisions could be made. Three cost areas were used in this program to estimate the cost of permanent pothole repair: labor, material, and equipment. These were broken down in detail and put into a spreadsheet as shown in Appendix B. Productivity is estimated from several important input variables: hole size, repair cycle time, delay times, days of operation per year, and percent patch failure rate. The spreadsheet calculates material usage, repairs per day and per year, and total costs. The best indicator of cost effectiveness is cost per pothole repair. Also of value is the total number of potholes repaired per year.

Three repair scenarios were analyzed: manually applied hot mix, manually applied cold mix, and automatically applied materials. The manual hot mix case assumes a repair crew of five, composed of one driver, two operators, and two highway maintenance workers. A truck and supporting equipment was assumed.

The manual cold mix case assumes a repair crew of three, composed of one driver, and two highway maintenance workers. Two different materials were analyzed. A truck and supporting equipment was assumed.

The automated case (the procedure had not yet been completely established) assumes a repair crew of one driver (acting as the operator). Potentially, a crew of two might be required by some states. A more expensive truck and supporting equipment was assumed. The spreadsheet varied the repair times, hole sizes, delays, days of operation, and material costs for all three repair scenarios.

Total cost estimates are presented in Figure 1-5. It shows that automated patching could be much less expensive and more productive than manual "Do it right" procedures (if the automated system was designed correctly). Shown on the graphs are cost per hole per year of life, as well as holes repaired per day (per crew) and man-hours per ton of material applied. The automated case uses fewer laborers, although the payscale for the automated operator is expected to be a bit higher. The repair times are 2 to 4 times shorter than manual methods as well. Amortized equipment cost is higher for the automated system, but, if spread over a period of years, this cost is very manageable. The automated system can operate more days per year, as well as day or night, since the vehicle would protect the crew from the weather and traffic. Material costs for the automated case are also low on the order of $20 to $25 per ton. Average patch life will be significantly longer than manually made patches in average conditions. This factor must be studied by long-term field testing. In terms of productivity, the automated case requires only 1.5 to 7 man-hours per ton of material placed, in comparison to 10 to 30 man-hours per ton for the "Do it right" case. Efficiency of labor use is a strong benefit of the automated patcher, and this is reflected in the very low cost of automated patching.

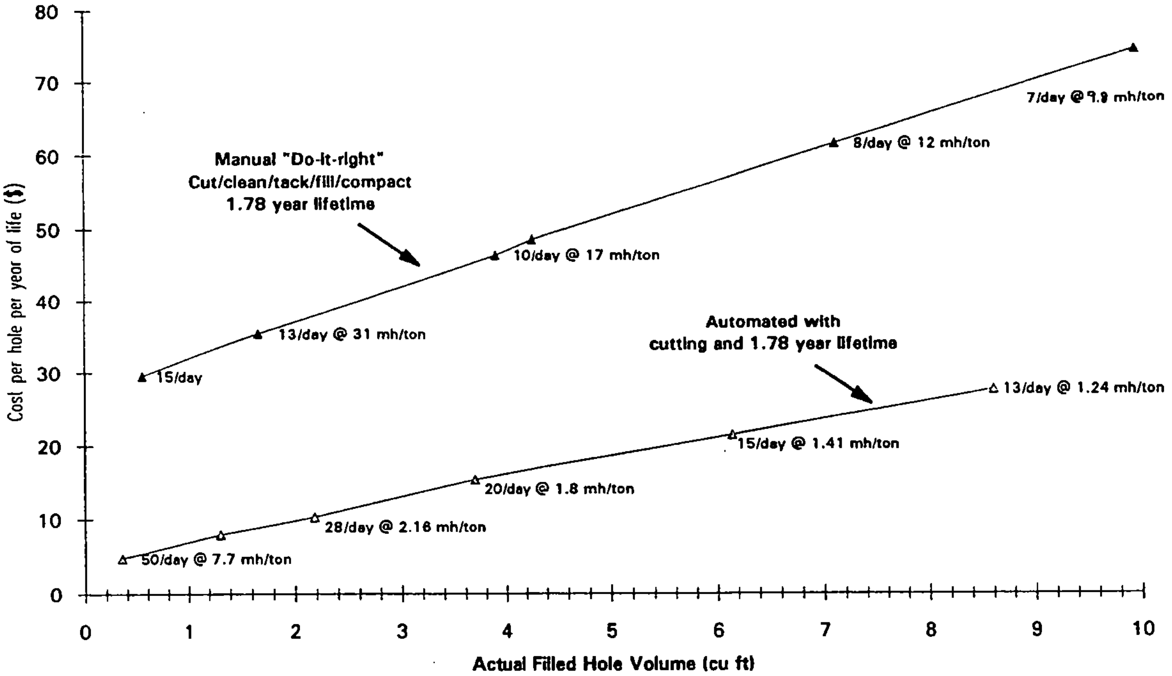


Figure 1-5. Estimated Economics of Manual Patching Versus Automated.

A conclusion of the productivity analysis is that automated repair would have these primary cost advantages over manual repair:

- One-fourth the cost for permanent pothole patches
- Productivity of two or three patching crews
- Enhanced safety for the automated crew (always in the cab)
- Less traffic tie-ups to the traveling public and faster repair of potholes during the spring and winter period when most are generated.

Payback would be very attractive to commercializers, contractors, state highway agencies, cities, and municipalities. We calculated the payback for two different scenarios of sparsely spaced small potholes (see Figure 1-2) and sparsely spaced large potholes in Appendix B. Since one automated system could have the productivity of two or three "Do it right" crews, cost saving accumulates quickly. Over $ 1,000 per day could be saved for a payback after less than one year. These are estimates that assume the same material costs per ton, and the same repair lifetimes. We expect the automated case to result in even longer patch lifetimes.

The Intermodal Surface Transportation Efficiency Act (ISTEA), passed in 1991, requires the state agencies (who obtain federal funds for highway maintenance) to calculate the cost of lost productivity to society caused by repair efforts. They are obligated to use this information to select the least costly (to society) method of repair. Manual repair during the dayshift on major roadways carries enormous costs in lost work hours. The automated vehicle developed in this program can repair in off-hours (even at night), with much less lane occupancy time. This cost advantage could serve to make this automated vehicle a viable alternative. A one-mile traffic back-up on a four lane expressway could well cost 200 person-hours lost productive work, worth a minimum of $2000 in a one-hour repair period, or $16,000 in one work shift. Clearly, the automated repair vehicle would be very cost effective in this environment.

Conceptual design took all of these cost factors and productivity models into account in an effort to satisfy SHRP objectives. As the system had not yet been designed, this data was used to guide a decision making process that was to occur over the next two years through phases of concept design, equipment construction, and vehicle integration.

2

Development of Concept Design

Phase I effort was conducted over the period December 1, 1990 to March 31, 1991; it consisted of concept design and feasibility testing in Tasks 1 and 2, respectively.

Design Methodology

The Automated Pavement Repair Vehicle (APRV) was designed in four stages. The overall system was designed, then a general repair procedure was designed, then each component was designed to meet specifications, and finally each component design was evaluated and revised to handle unexpected variations and problems.

Basic Design Objectives

The primary objective of the APRV was to produce a high quality permanent patch in asphalt-surfaced pavements. Patch quality (its performance) can be measured in terms of:

1. Patch lifetime.
2. Cost of making the patch.
3. Impact on the traffic, operators, and environment.

In the first stage, the system-level design was affected mainly by factors 2 and 3. The second stage of procedural design considered factors 1 and 3 of greatest importance. In the third stage, procedural and functional specifications were affected by all factors, but mainly by the impact on the operators and the public. The fourth stage highlighted operational requirements that were driven mainly by factors 1 and 2. This would ensure quality patches would be achieved even though the materials or procedures may vary for reasons that may not be under complete control.

System-Level Design

The team evaluated three viable system-level concepts, represented in Figure 2-1. One concept placed the materials on a separate trailer to be towed by the main repair vehicle. This allowed replenishment of materials over the course of a workday by using two trailers. It also allowed for the material trailer to be stored in a garage overnight without having to store the much larger main vehicle. Power take-offs and a material-conveyor system could accomplish the link between the trailer and main vehicle.

Another concept utilized two repair vehicles to handle cavity-preparation activities and filling activities separately. We see that dividing the procedural steps (of hot/cold mixes given in Appendix A) into two subsets (survey, cut, clean--in a 'cleaner vehicle') and (tack, fill, level, compact, seal in a 'filler vehicle') nicely balances the workload across the system components. The equipment will be better utilized, and any vehicle breakdowns will only impact one-half the functionality of the system. Coordinating the two vehicles could be difficult. The cost of the approach is in requiring two vehicle bases and two operating crews.

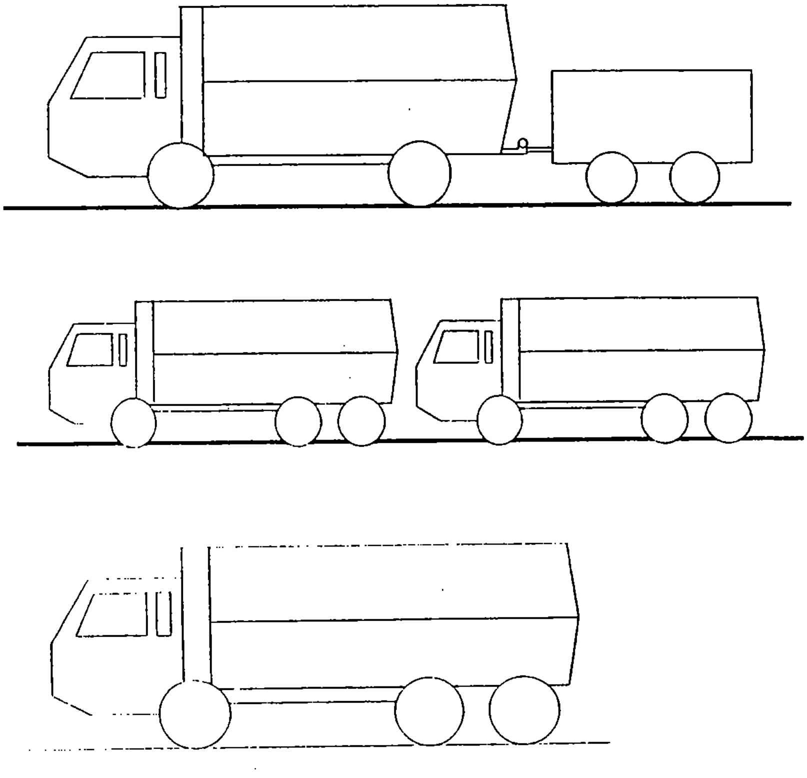


Figure 2-1. System-Level Vehicle Concepts.

The best concept was for a single vehicle to hold all of the materials and equipment for the patching operation. There were many advantages including less labor, lower cost, greater productivity, greater safety, and better potential for automation. This concept was eventually chosen for the APRV.

Automated Repair Procedure Design

Based on these system-level concepts, a set of general operational requirements was developed to meet SHRP requirements and to help guide the rest of the design stages. It was a given that the system should operate for a full day without replenishment of material or fuel, and that cutting spoil or debris would be dumped once per day. It was also important to keep the vehicle size within acceptable limits and operable at highway speeds when moving between repair sites. These general operational requirements are presented in Appendix D. Figure 2-2 shows a flow diagram for the entire automated pothole repair sequence for a workday. These steps satisfy the general operational requirements. The individual repair operations are broken down into two basic categories: cavity preparation and material placement. Pre- and post-inspections assure quality results. Specific decision points indicate where the operator is required to interact with the system. The final operating procedure is listed later in the report.

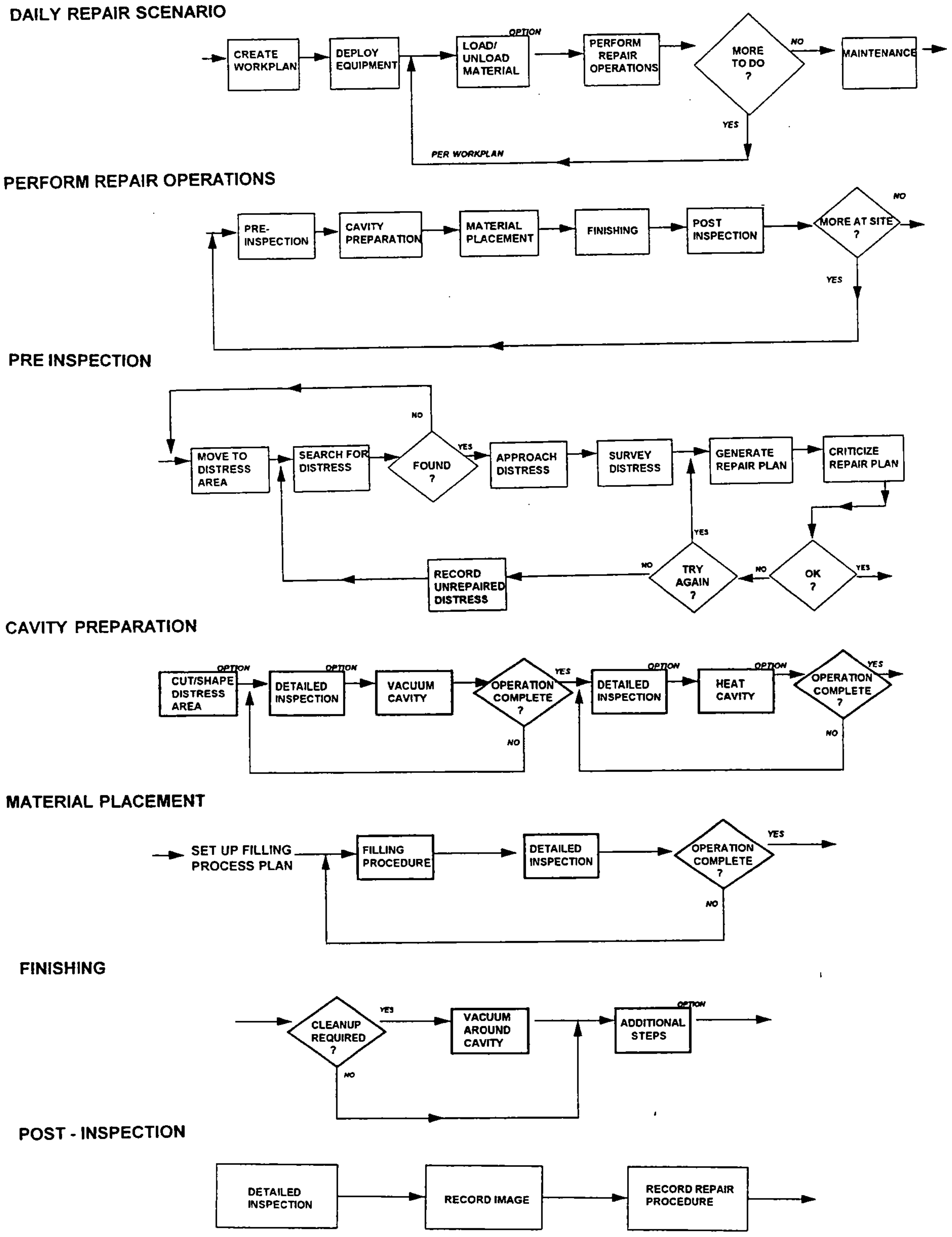


Figure 2-2. Automated Repair Sequence Flow Diagram.

Component Design

Design and development of the automated pavement repair system began with a system design, then followed with a repair procedure, and then a statement of objectives for each component. Minimal operational requirements were also established to meet SHRP requirements. In this section, the basic requirements for equipment components are explained and identified as shown diagramatically in Figure 2-3.

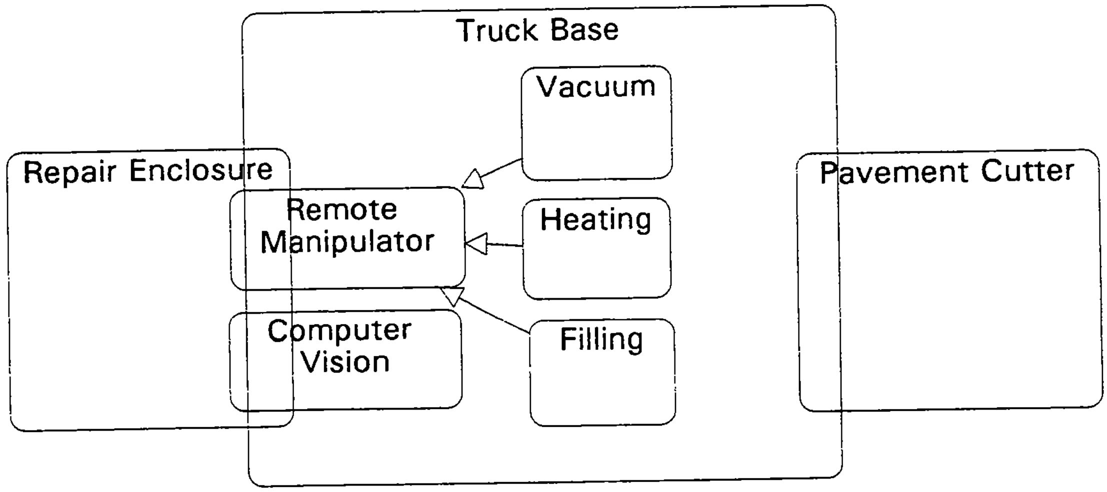


Figure 2-3. Major Equipment Modules of the Repair System.

Truck Base

The truck base had to allow for substantial material storage and weight, easy mobility in repair situations, excellent visibility for the operator, and flexibility in design features to accommodate the various repair equipment modules that would have to be mounted.

Repair Enclosure Module

Since poor weather affects the quality and durability of a patch, it was decided that an enclosed area would effectively screen the patching operation from ambient conditions. The enclosure was to be designed to hold in the warmth from the heating system, restrict the sunlight and headlights from the pothole area where the computer vision system was operating, and protect the public from the repair operation.

Pavement Cutter Module

Since some states require cutting and shaping pothole cavities prior to material placement, a cutting module was required. It was to be operated from inside the truck, to perform routing and shaping of the pothole cavity in asphalt to a depth of 6 inches (15 cm) or less, over an area estimated at 10 square feet (.92 sq m).

Vacuum System Module

This system needed to clean the pothole of water, mud, and small aggregate chunks after the cutting operation. A second function would be cleanup of the repair site after patching. It was required to hold the waste materials for later dumping. Additionally, it had to scrub the vacuum air clean so that clouds of dust would not be exhausted from the truck during operation.

Heating System Module

Pothole heating required a safe system of very low maintenance and high energy efficiency with no scorching. The heating source needed to be adjustable over a wide range so that heat could be applied to localized areas of the pavement only where the repair was being made.

Filling System Module

This system would fill the prepared cavity with selected and proven materials, under automatic control, to achieve a dense patch having a level surface that would last years. It had to be low maintenance and accommodate variations in materials, application temperatures, oddly shaped potholes of virtually any depth from 1 inch to 6 inches (2.5 to 15 cm). An objective was the system should use low-cost materials that could be easily obtained, and be adaptable to new materials under development in the industry. Selection of materials were made from those identified by SHRP H-105, with continuing study in H-106.

Computer Vision System Module

A vision system was needed to take images of the pothole being repaired. These video images would be used to automate the repair process. The imaging of the pavement surface and pothole had to be handled under a variety of lighting conditions. The automatic system had to recognize potholes as well as oddly shaped or colored defects on the pavement. The system would have to create the necessary information to run the remote manipulator under automatic control, and also help the operator monitor the repair process through a TV monitor.

Remote Manipulator Module

This system had the objectives to provide a way of moving vacuum, heating, and filling nozzles over a wide area of pavement to perform "hands off" pothole repair. It had to operate automatically, quickly, accurately, and safely. Additionally, it needed to be used by an operator holding a joystick and looking at a TV monitor.

Concept Design Evaluations

Over 100 concepts for automated repair were developed expressing alternatives of each functional element in the repair procedure. The design team used brainstorming and tradeoff evaluations as a method to achieve quality in the design. Experts having different perspectives were assembled and presented the problem. Many moderated group sessions examined initial concepts, and discussed alternatives. Alternatives for the automation approach were also developed.

Concept Design Areas

The team developed concepts in the areas listed below to support the preceding stages of design:

- Vehicle System
- Initial Marking/Survey
- In-process Inspection
- Computer Control
- Pothole Locating and Approach
- Cavity and Edge Preparation
- Cleaning
- Drying/Heating
- Tacking

- Bulk Material Handling/Storage
- Cold Mix Filling
- Hot Mix Filling
- Aggregate Binder Pressure Filling
- Leveling
- Compaction/Consolidation
- Stabilization Sensing
- Sealing
- Finishing/Top Coating
- Final Cleanup
- Tool Manipulation

Many of these ideas were described in short documents with explanatory figures so that they might be evaluated for their strengths and weaknesses. These ideas were evaluated by pavement engineers, highway maintenance foremen, the ETG and others outside of BIRL. Outside evaluation ensured that the design addressed all the practical problems expected for a pavement repair vehicle.

Concept Ranking and Selection Process

The design team and outside advisors defined a set of criteria shown in Table 2-1, which helped to formally express the meaning of quality in terms of the patch and in terms of the component repair equipment. The criteria were used to numerically rate each design concept to come to a selection of those to actually fabricate and test in later effort. The criteria had different levels of importance depending on whether it was essential, important, or beneficial. A weight of 5 signifies essential importance, 4 high importance, 3 moderate importance, 2 low importance, and 1 beneficial but low importance.

Table 2-1. Important Quality Criteria for the Patch and the System

Weight	Evaluation Criteria
5	Patch quality and performance (lifetime, annualized cost of repair)
5	Maintenance required (of production unit)
5	Safety feature to public and crew (obstruction, speed, etc.)
4	Operator difficulty of use (training requirements)
4	Cost of production unit (less important to prototype)
3	Versatility of unit (as opposed to narrow range of applications)
2	Technical difficulty in making prototype and production models
2	Supporting systems required (complexity of integrated system)
1	Other benefits/drawbacks (evolution to new materials/problems)

Patch Quality (5): Repair lifetime vs. cost of making the repair. This is the most significant quality criteria. It includes how well the procedure matches what was originally specified by SHRP, what is acceptable commercial highway practice, and what is the best that technology can achieve. The objective was a repair that would last the remaining life of the asphalt surface, in the range of 3 to 5 years, rather than a patch that may only last a single year. The machine's performance (as opposed to the patch performance) is covered by other criteria.

Maintenance Requirements (5): Low maintenance is essential for a commercial vehicle and for highway acceptance. Field breakdowns must be minimal. The design should allow simple maintenance to be accomplished without disassembly or exposing the crew to risks. Part wear must be strictly controlled and breakage avoided. Automated maintenance (such as self-cleaning) is desirable.

Safety (5): Several safety issues are covered by this criteria. Faster repair cycle times, smaller trucks, less post-repair debris, less explosive, flammable or toxic materials, and greater maneuverability all improve public safety. The crew's safety is improved by some of these and by avoiding repair techniques that have inherent danger, i.e. cutting, impact, or compressive operations. Low maintenance improves safety because many accidents with machinery happen when it is being repaired. Worker safety is greatly improved by getting them off the road and seating them in the repair vehicle, ideally in front.

Operator Difficulty (4): The repair system must be easy to use, particularly in cold and wet conditions. The emphasis must be to make it easy to use and let the operator feel confident that he/she is controlling the system to help do the repair. Automatic functions must have suitable manual overrides. The operator must be able to monitor all steps of the operation. Operator controls must be intuitive. They should not require a light touch or a steady hand that will strain the nerves of the operator over the course of a day.

Cost (4): The cost of operation and maintenance should be very low. Energy and labor efficiency are very important. The fabrication costs of the prototype may be fairly high, but the production model costs must be low enough so the system can be purchased by a range of users. The cost of a system can be offset with greater versatility or other long-term benefits.

Versatility (3): The design should accommodate all sizes and shapes of potholes, and similar distresses that the operator may want to repair. The machine must allow for this without breaking down. It is advantageous if a system can be used for multiple purposes besides pothole repair.

Technical Difficulty (2): Commercially proven equipment should be used to lower the difficulty of building a prototype as well as building production models. It is necessary to have a robust design that will not be overly complex. State-of-the-practice equipment is more reliable and should be emphasized over state-of-the-art technology.

System Demands (2): Computers, sensors, controllers and structural supports fall into this criteria. Size, weight and power requirements are also included. It is best to use a single component to perform multiple functions and to look for synergistic results.

Other Benefits/Drawbacks (1): There are advantages to a system that can be adapted to use new materials or techniques.

Based on all of these criteria, the Functional Specifications and Testing Plans (developed by SHRP H-105 for this program), and the set of operational requirements given in Appendix D, a final selection was made for fabrication and test.

A spreadsheet was developed (see Appendix C) to accept a person's ratings of the ideas on a 1-5 (drawback-benefit) scale, which were then multiplied by the weight (importance) of the criteria (from Table 2-1) to yield a numerical ranking of the ideas from best to worst. The spreadsheet allowed questions to be posed such as "What would the system contain if we wanted the safest possible system? What about the most versatile operation? Show me a configuration to obtain the highest quality repair using components of the least cost?" To answer questions like this, one would simply sort through the categories and pick the highest scores for components compatible with one another.

What followed from the formal evaluation (by picking the high scores in every category) was a system- and functional-level listing of the best equipment and methods for pothole repair and suggestions for their configuration in a vehicle system. The team identified critical issues for examination in feasibility testing of Task 2.

Vehicle System Concept Design

One arrangement for the equipment components onto a vehicle chassis was envisioned in Figure 2-4. This drawing shows that a repair enclosure off the back of the truck was an excellent way of protecting the pothole from weather. The principal components include: pavement cutter, vacuum system, heating system, filling system, robotic manipulator, and computer vision system. Other arrangements were seen to be possible. The next section describes the feasibility testing involved in making these judgments.

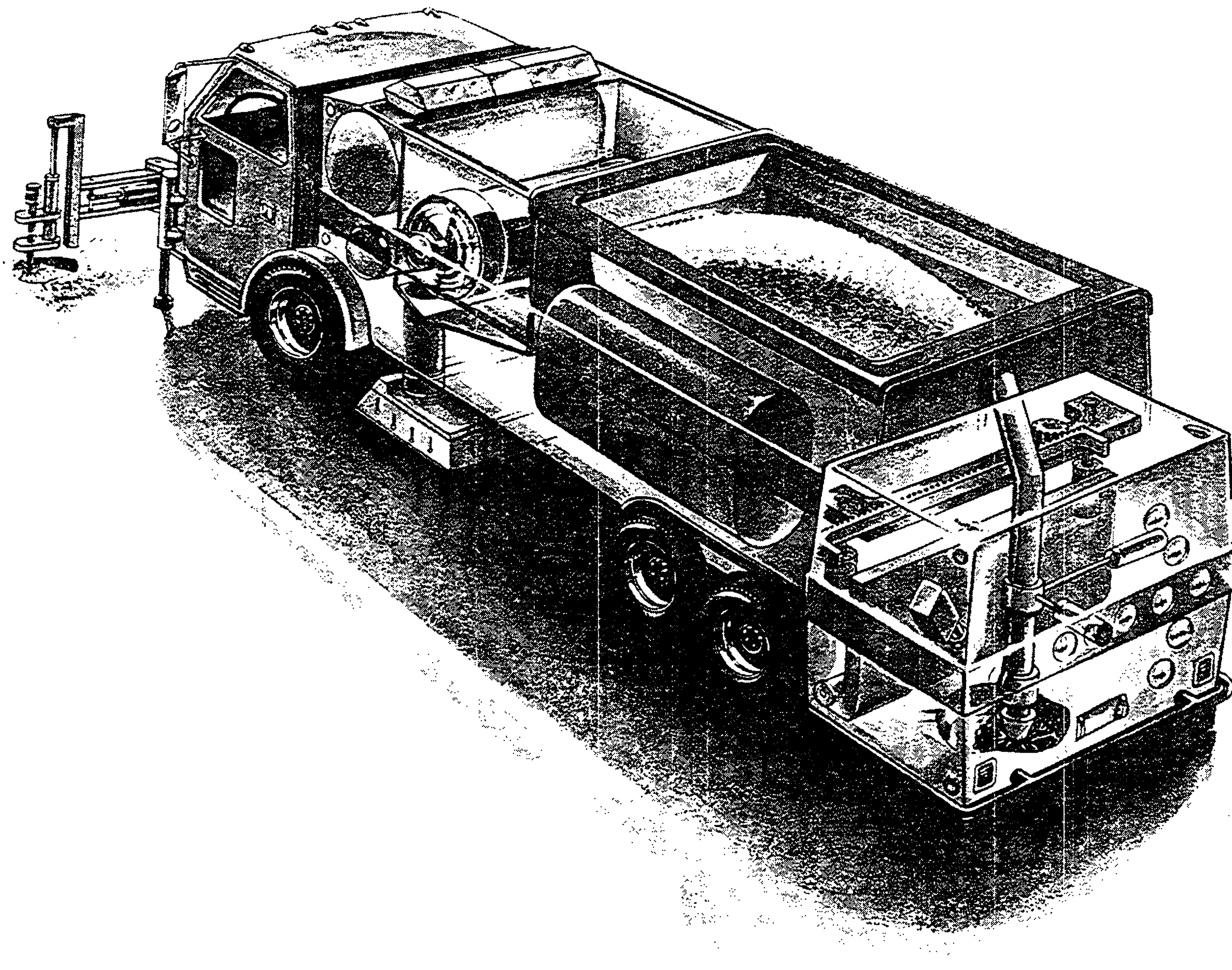


Figure 2-4. Early Concept Drawing of Repair Vehicle.

3

Feasibility Testing of Concepts

Task 2 feasibility testing was conducted in conjunction with the concept design mainly during the first quarter of 1991. The research examined and validated concepts that were selected by the team as having the highest value. Lab and field evaluations were conducted and presented as part of the Phase I research results to show that the equipment could be built in Phase II.

Cutting Evaluations

Pavement cutting and routing were studied by both BIRL and Crafco engineers (under a subcontract). Surveys of commercial systems and cutting bits were made, videotapes were analyzed, and engineering drawings were created to evaluate the concepts. Crafco designed a custom vertical milling cutter as required. BIRL engineers analyzed cutting forces and torques and evaluated the robotic control requirements.

Crafco showed that a custom vertical milling cutter could be made and articulated by three methods; XY table, drop-down platform, and scissor-type motion. A very heavy duty articulation unit and supporting structure would be required. These approaches also required that the unit operate underneath the truck and be limited in operation to slightly less than the width of the truck. Thus, to access a full lane width, the truck would have to be oversized, violating one of our main requirements. Alternative methods were sought.

BIRL engineers examined a commercial asphalt milling unit, the VACM by Roadbadger. Their videotape demonstration was analyzed for the operating characteristics and type of supporting structure required. It was shown mounted to a backhoe operated by a skilled worker. The unit performed well, plunging into asphalt or Portland cement roads easily. However, the backhoe itself was thrown from side-to-side as is was doing so. Clearly very high torques are involved in cutting pavement by this technique.

The VACM unit was nearly 6 feet tall, weighing nearly 1,000 pounds. We believe that this unit would have far exceeded the requirements to route and shape pothole edges, and so a custom solution was designed and built specifically to handle pothole edge shaping.

Other cutters considered included planers by Bobcat, ECON, and others. The planer can cut only 1 to 2 inches (2.5 to 5 cm) deep in one pass, so multiple passes would be required. The planers come in widths from 9 to 16 inches (22.5 to 40 cm), so moderately large potholes would require a sweep pattern and more time. The best approach for these methods is an XY table, similar to what Crafco originally designed for the milling unit. We were concerned that monitoring the planing operation should be an easy task. Planers have a shrouding, necessary to their operation, that would interfere with vision. Thus, the control of the cutter would have to rely on force sensing and hydraulic pressure sensing.

However, interpreting the signals from the cutter would be a challenge. If sensing was completely ignored, maintenance would be a problem. For example, if a cutter impacts a manhole, drain grate, or reinforcement bar, the bits may be sheared off. They are not designed to cut concrete effectively.

Water jet cutting is possible but very expensive. The commercial units are very large and they depend on high-quality filtration of the water for operation. Water on freezing pavement may leave ice patches for traffic. An innovative cutter using metal shot was examined, but it would have required excessive effort to manipulate it in a controlled fashion around the hole, and again vision systems will not be effective as a control method.

Method of Choice

A vertical milling type of pavement cutter was selected for prototyping because it offered the best tradeoff of flexibility, speed, and simple control. The articulation unit was a new swing arm design. It was to include joystick control in a design that could be adapted to the vehicle chassis at a later time. A vacuum collection system for the debris was also designed and built.

Vacuum Evaluations

As the first step in a repair, high-power vacuuming accomplishes several desirable things. Water, debris, rocks, and even large loose asphalt chunks can be removed from the hole very efficiently. A commercial unit by Elgin Sweeper was evaluated as a first step. It used a 12,000 CFM blower to develop a vacuum sufficient to pick up a brick. Elgin performed tests on water and debris removal from potholes in early spring of 1991. However, the unit is designed for dust and debris removal from large pavement areas rather than small potholes. The function and performance of the unit depends on a large hopper and tremendous blowers. In contrast, we had shown the feasibility of a low power (3 HP 'shop vac') vacuum to quickly empty a hole of water and small debris if the nozzle could be moved around the cavity. Crafco made a trailer-mounted vacuum unit used for debris removal after routing pavement. The nozzle of this system was 3 inches in diameter, allowing fairly large rocks to be collected. Field demonstration of the unit showed that vacuuming can remove debris and water from a hole effectively, although a higher power unit would be needed for an automated repair system. An industrial vacuum system by Hi-Vac was evaluated as well. Large horsepower electric blowers were used to develop a strong vacuum and a series of separators and filters captured the waste. The waste included water, dust, debris, and general foundry waste. However, the size, cost, and power requirements were seen as major drawbacks.

Method of Choice

There was strong consensus that vacuuming was a superior cleaning approach to blowing or sweeping, however a custom vacuum system had to be prototyped to handle wastes associated with pothole repair. A vacuum would be more effective than brooms, and less dirty than blowing. It would leave the repair site clean and free of loose rocks. The design would be small and inexpensive, with easy unloading, and very low maintenance.

Heating Evaluations

Heating of the pothole cavity and surrounding edges should provide better bonding to any patch material, according to many sources. From our inquiries of experts in the field, we received unanimously positive responses to the benefits of heating. Heating is not often done as part of manual repair procedures, however. Present commercial systems can be time consuming and require skill in judging the correct time of heat application to prevent damaging the road surface. However, we desired an automated method of heating mainly the pothole edges to the softening point, and drying and super-cleaning the cavity without scorching. To design the heating system, we needed to know the ambient temperature range of the pavement, air temperatures, time available to heat the area, and knowledge of the thermal properties of asphalt pavement. We investigated heat transfer through asphalt materials to determine a minimum operating temperature that would achieve softening, and a maximum temperature to prevent burning or other deterioration. The range of ambient pavement temperatures the system may encounter was assumed to be 20 to 150 degrees F (-6 to 66 C). Some studies have related air temperatures of 0 to 120 degrees F (-32 to 66 C) to pavement temperature. The time available to heat a given area was assumed to be 1 minute or less to remain productive.

To establish the last parameter for the design, the thermal properties of asphalt were tested in the lab. Furnaces and propane torches were used to heat core samples and large asphalt chunks, consisting of both old and new pavements. Thermocouples monitored heat flow through the material. Additionally, an infrared imaging thermographer was used to monitor the heat flow though the sample by observing infrared radiation emitted by the surface. A literature search conducted in this area helped in designing these experiments.

Asphalt pavement has thermal insulation properties, and it requires substantial time to heat asphalt to any depth. However, our main objective was to dry the pothole surface and achieve some softening so that a better bond with new patch material could be achieved.

The concept design was based on the idea of heating the pothole cavity while monitoring its surface temperature. A non-contact infrared pyrometer (single-point optical thermometer) can be used to continuously monitor the pavement temperature ensuring safe and adequate heating. Our results showed the pavement samples softening at 160 to 180 degrees F (71 to 82 C), and we calculated the necessary heat input to achieve this softening to a depth that would facilitate bonding of the patch material. The heat input required was estimated to be 200,000 BTU/hr (roughly twice the capacity of a home furnace). Several sources of heat were next considered.

Microwave heating has been done for asphalt pavements, but that technology is for deep and even heating, not just a surface effect as was desired.

Electric heaters were also considered using suitable reflectors to concentrate the heat. Low voltage, high current heating elements can be used to eliminate the danger to operators. To develop sufficient heat energy (200,000 BTU/hr), a very large generator would be required which would place a heavy demand on the power- take-off of the truck or require a dedicated generator. It was estimated that to achieve rapid heating from an electric unit would require about 58 kW of electrical power, too much to consider for a mobile vehicle.

Propane is used in commercial systems for pavement maintenance such as the handheld 'Hot Air Lance' or 'Air Propane Burner' manufactured by Napoleon Fabricators of Napoleon, Ohio and also in large radiant heat pavement recyclers. We examined the lance to determine if it could be adapted to wide spread heating of the cavity area. A 'hot air panel' concept could arrange several of these smaller units in a grid to provide individual control to heat only the repair area. A prototype unit was constructed using a 50-gallon drum sliced along it's length and fitted with a compact 8-inch-long lance fueled by liquid propane gas (LPG) and compressed air. It was shown to heat a 2-foot by 4-foot (60 cm by 120 cm) pavement area evenly without damage to the pavement. However, the drum enclosure prevented easy monitoring of pavement temperature by infrared pyrometer. The lance by itself was considered a good solution if it could be moved back and forth by the remote manipulator over the pothole surface. This would also solve problems with the arrangement of mechanisms in the repair enclosure. There is a restriction of propane from some state bridges and tunnels, so conversion to compressed natural gas (CNG) was investigated and determined feasible.

Method of Choice

The propane-fired lance offers the best combination of heating speed, controllability, low cost, and low maintenance. The technology had already been demonstrated in the highway field and was basically off-the-shelf although fail-safe electrical ignition had to be developed.

Patching Evaluations

Literature studies, site evaluations, and personal interviews with state highway engineers and workers have provided many insights into practical pothole repair methods. Over 90 vendor contacts were made in the areas of repair materials, equipment, and automated systems.

No vendor was found that could meet all of the requirements. The final report of SHRP H-105 also presented valuable statistics on the lifetime of patches made with different materials, temperatures, and moisture conditions. A general conclusion can be drawn that cold mix materials are more compatible with variations in application temperature and moisture presence in the hole. Permanent repairs with cold mix have an average lifetime of over one year, with some cases much longer. Temporary 'throw-and-go' repairs with high performance materials last longer than repairs done with hot mix under poor weather conditions. A strong case can be made for cold mix as being a more 'robust' material with less sensitivity to application procedures or conditions if proper cavity preparation is performed.

Our research into one of the materials identified by H-105, called spray emulsion (spray patching), revealed that it has excellent tolerance to weather conditions and the repair situation. This technology had already reached a high degree of automation with several commercial units available having some degree of remote control and material control.

Very little literature exists on the subject of spray patching, although the technology is over 15 years old. Some of our findings are presented in Appendix A. Consequently, we had to observe the systems directly and assess the patch performance. The systems show very cost-effective results across the country and overseas. To assess the performance of spray patching we selected representative systems for analysis and visited test sites located in wet/freeze climactic regions, during the late-winter and early-spring seasons on different pothole applications. Different crews and companies were interviewed with questions related to the evaluation criteria used during Task 1, i.e., performance, maintenance, safety, operator skills, cost, versatility, etc.

The overwhelming observation was that quality patches could be placed very rapidly with a minimum of labor. We witnessed patches on asphalt overlays, full-depth asphalt, Portland cement concrete, patches to existing hot/cold mix cut patches, shallow delaminations, bridge decking, and shoulder reconstruction. Spray patchers are very versatile tools in the hands of skilled workers. Some patches were over two years old, and looked quite new. Different materials were used with good success. In the site observations, we noted the use of wet pea gravel, dry crushed limestone, and granite. The vendors also claim that many emulsions are compatible with the equipment so long as it is properly matched to the aggregate. Discussions with the patching crews showed pride in their workmanship and a sense of trust in the performance of the machine. We have learned that inexpensive, trailer-mounted spray patchers are a favorite of state highways for customization and prototyping.

The Transportation Research Board Annual Conference of 1993 was host to a SHRP session on Maintenance Effectiveness, where the conclusion of the 2 year long SHRP H-106 program was reported . This program has studied the effectiveness of various pothole patching and crack sealing materials and procedures.[4] About 1200 pothole patches were installed in 8 test sites located across the U.S. and Canada.

The SHRP H-106 contractor reported at that time that after 18 months of testing spray patching had the lowest patch failure rate of all the tested materials and procedures, at all the sites. Two of the dramatic comparisons presented at the conference are shown in Tables 3-1 and 3-2 comparing materials and procedures.

Table 3-1. Spray Patch Materials Performance Studied by SHRP H-106

% Failure Rate of Patches	Patch Material
13	Spray Patch
18	Perma Patch
24	Penn DOT 485
26	Sylvax UPM
27	QPR 1000
36	High Float Med Set
36	Penn Dot 486
52	Local material

Table 3-2. Spray Patch Procedure Performance Studied by SHRP H-106

% Failure Rate of Patches	Patch Procedure
13	Spray Patch
15	Edge Seal
20	Semi-Permanent
31	Throw/No Roll
50	Other

Concrete spall patching was also studied and reported by H106. The spray patch method had 0 % failure over their experimental period, compared to several near 4 % and up to 11 % failure for one material tested. We believe concrete spall patching with spray patching technology would be a natural, and know that some states routinely specify it for spall repairs.

Spray patch materials are inherently low in cost, with rock aggregate costing from $7 to $12 per ton, and asphalt emulsions costing from $0.60 to $1.00 per gallon. It should be noted that a significant cost of more expensive cold mixes is due to the plant mixing. This step is eliminated in spray patchers, since the asphalt emulsion and rock aggregate are handled in bulk, and combined in the dispensing nozzle at the moment it is sprayed into the pothole. Thus, the lower material cost is a strong advantage, as well as the compatibility with newer materials.

Method of Choice

Our conclusion was that the spray filling concept was the best and most automatable approach of all the pothole repair technologies available. Commercial systems have demonstrated repair lifetimes equal or (in some cases) better than permanent repairs using hot or cold mix. None of the spray patching system vendors recommended cutting before filling. Neither was hot oil tacking, roller compaction, or sealing recommended as standard procedures. The simplicity of the spray patching concept offered tremendous advantages and the opportunity to reduce the size and complexity of the total system. Compared to many other approaches the team considered for filling with hot mix or cold mix, we felt that pothole filling with the spray patch concept would reduce system cost by at least one-half, speed repair operations by a factor of two or three, and eliminate most of the equipment maintenance problems for the crew.

Computer Vision Evaluations

The vision system had to determine a pothole's measurements, depth, and volume so that it can be repaired automatically by a robot.

These measurements can be made by a two step approach. In step one, a video system similar to a TV camera views the road area. A pothole can be located and its edges determined automatically by computer because it is darker than the surrounding pavement. A second method could use the spatial frequency of the surrounding pavement aggregate texture as an indicator of the cavity boundary. The cavity has less frequency-detail (lower contrast) because it contains rocks, dirt, and water compared to the black and white speckled image of the surrounding asphalt pavement. Both imaging methods can make mistakes if the surrounding pavement is not ordinary or if it is contains visibly distinct regions, such as concrete, manholes, oil spills, etc. From our experience in looking at, photographing, and analyzing pothole images, we conclude the two-dimensional imaging approach offers a potential solution for many cases, as long as the operator can override the computer. In general however, one can not determine depth information from this technique, yet depth is crucial to automated filling. Additional techniques are required.

Once the boundary is established, several methods of depth measurement are possible. One way is by ultrasonic range detection (similar to the autofocus feature of Polaroid cameras). A second way uses structured lighting to put together successive vertical profiles of the cavity into a depth contour map. Another way is stereo vision which uses two cameras (like our eyes) to determine depth from the difference between images. Yet another way uses laser imaging in a radar mode to create a detailed surface map of the road, potholes, cracks, and other features.

Each of these methods has benefits and drawbacks that were evaluated. The two-dimensional ultrasonic range detection idea presents an engineering problem in sweeping the sensor over the entire surface in a mechanical way. This approach is commonly referred to as a 'flying spot scanner'. This could present difficulties in keeping the range sensor clean and getting the necessary accuracy.

Another scheme of obtaining the length, width, and depth measurements comes from the technology of laser scanning and structured lighting. Laser scanning is presently used in many applications for highly accurate range and shape detection. It is used in one commercial pavement distress measurement vehicle for rut and cracking measurements. Laser scanning can be expensive if a great deal of accuracy is required. However, imaging potholes only requires a spatial accuracy of about 0.25 inches (6 mm) or less for practical automated filling procedures. Alternatively, instead of illuminating the target with laser light, ordinary collimated (focused) white light can be used if projected through a narrow slit across the pothole cavity. The light would come from above, but the camera views the cavity at an angle, thus a profile or 'slice' of the cavity is seen by the camera, as shown in Figure 3-1. When many adjacent slices are imaged and assembled on a screen, the complete topography of the cavity is immediately visible. This single display allows for the determination of length, width, and depth of the entire imaged area. All of the necessary information can thus be obtained from a single vision system if necessary.

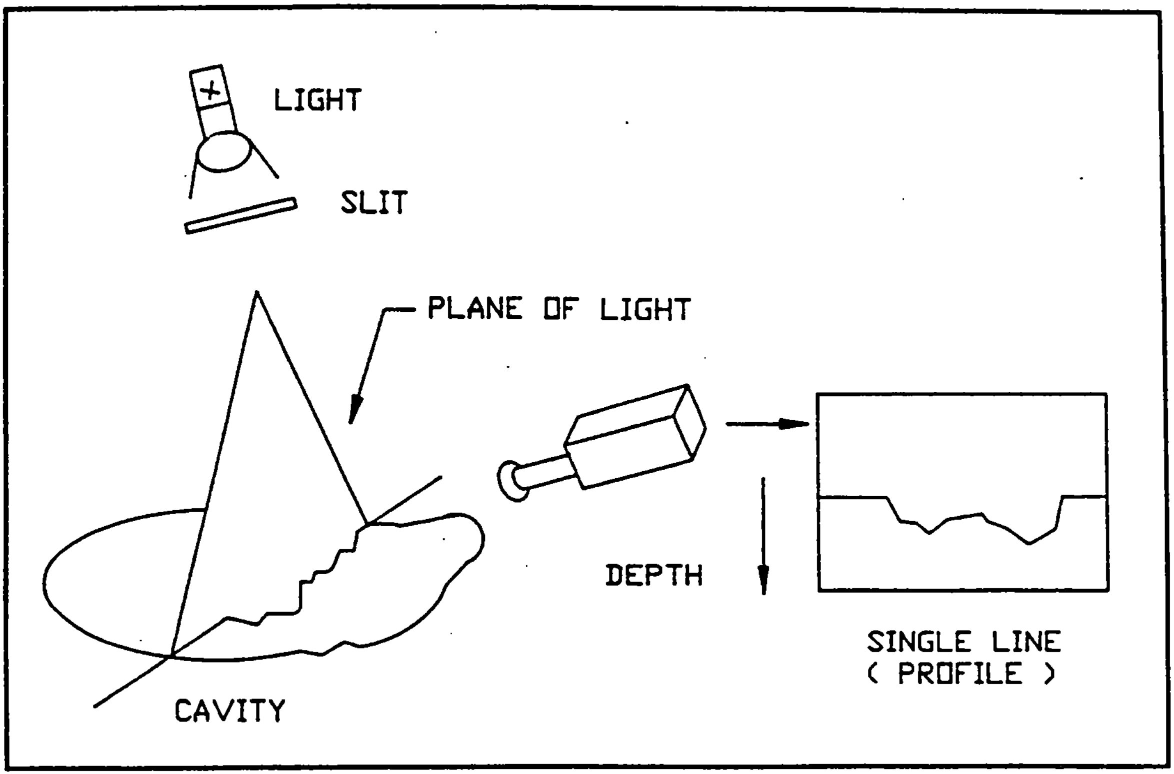


Figure 3-1. Structured Lighting Technique for Potholes.

A variation on this structured white light approach which is easily imagined is structured shadowing. In that approach, a sharply-edged shadow is passed slowly over the entire area, and a CCD video camera views the irregular shadow from an angle. The computer extracts the same information as was done for the slit approach. All that is required is a movable straight-edge close to the pavement surface, a bright point source of light, and a video camera with an angled view of the whole surface. Figure 3-2 shows a pothole with a shadow cast over the hole, and the output of an algorithm that follows this shadow. A preliminary estimate was made showing the approach could give about 0.25 inch depth accuracy over the whole area if several cameras were used. There are still mechanical problems with this approach that would ideally be eliminated.

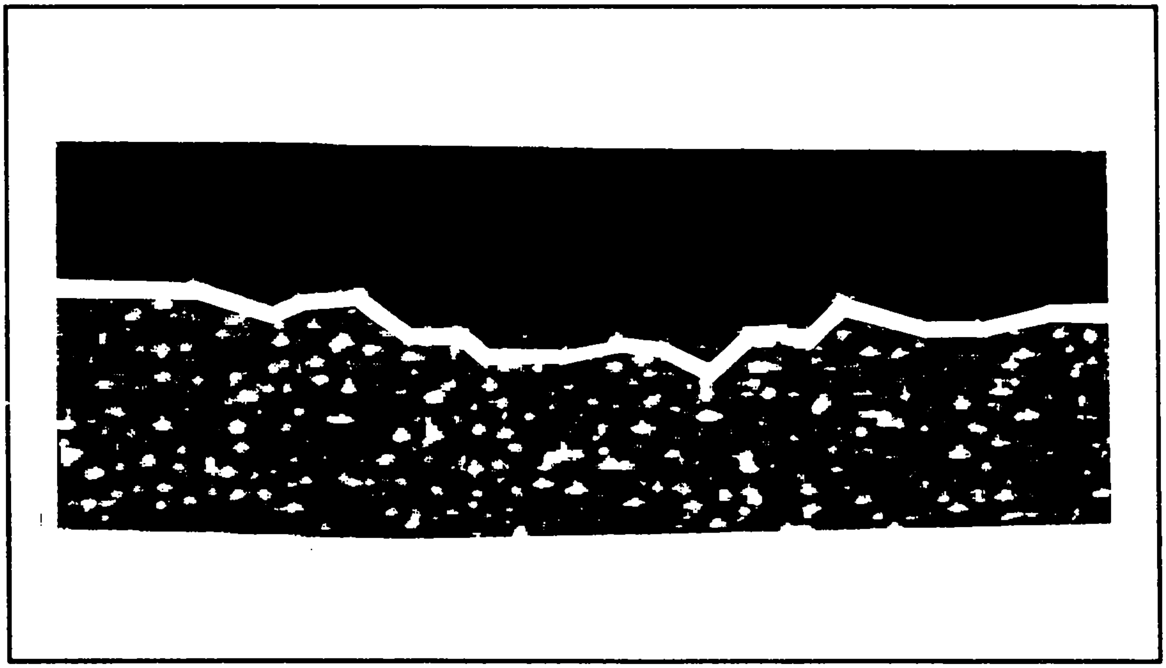


Figure 3-2. Results of Structured Lighting Technique.

A commercial laser scanning system based on radar principles was also evaluated. A single small box is the sensor 'head' containing the cameras, lasers, and optics. It could be mounted above the pothole in some protected enclosure so that it could view a large area of pavement at one time. The experimental image data from the box showed a 5 by 8 foot pavement surface could be sensed to very high accuracy in a few seconds. The major drawback is the cost and support electronics required to run the system.

Lastly, stereo vision presents another method for highly accurate depth perception. The pothole depth calculation is all done in software, which depends on exact camera alignment. Our feasibility test of this approach failed to accurately determine depth because the rough and jagged surface of the pothole was too confusing to the computer algorithm. We think this approach is not field-ready because it is also too sensitive to the cameras and optics. The approach is costly because two identical cameras, offset by a couple of feet (.6 m) horizontally, are looking down into the cavity with perfectly controlled lighting.

Neither of the above approaches was a clear winner until the cleaning, filling, and robotic technology was chosen and designed into a workspace that could include the vision system. However, structured lighting, shadowing, and laser techniques seem to offer the best tradeoff of accuracy and durability.

Method of Choice

The laser radar scanning approach was chosen as the ideal way to solve this problem because it was a commercially available package, it had very high accuracy, and it operated significantly faster than any other approach considered. We expect that the high cost of the electronics will drop dramatically (as all electronics does) over the next couple of years and if purchased in quantity. A close second is the structured lighting technique, as it offers enough accuracy at moderate cost.

Remote Manipulator Evaluations

Manipulation of the repair nozzles and tools, whether it be cutters, lances, or filling nozzles, requires a support system and a mechanical structure sufficiently strong to handle significant weight and impact forces. Since the road surface is basically planar, only two degrees of freedom (X and Y direction) are required for the remote manipulator. A third vertical axis of motion (Z direction) is needed if the tool must descend into the cavity in controlled fashion. It was our objective to find a commercial manipulator (robot) that had speed, strength, high payload capacity, tolerance to extreme shocks, and yet only require low maintenance in a dirty environment. None of these features is typically available in commercial robots, however.

We considered XY 'plotter type' tables during the cutter evaluations (see Figure 3-3) and find them subject to problems from dirt, spray, weather conditions, and small accidental impacts to the chassis. As noted previously, the XY table also must be well supported at all corners, forcing it to be located under or inside the truck.

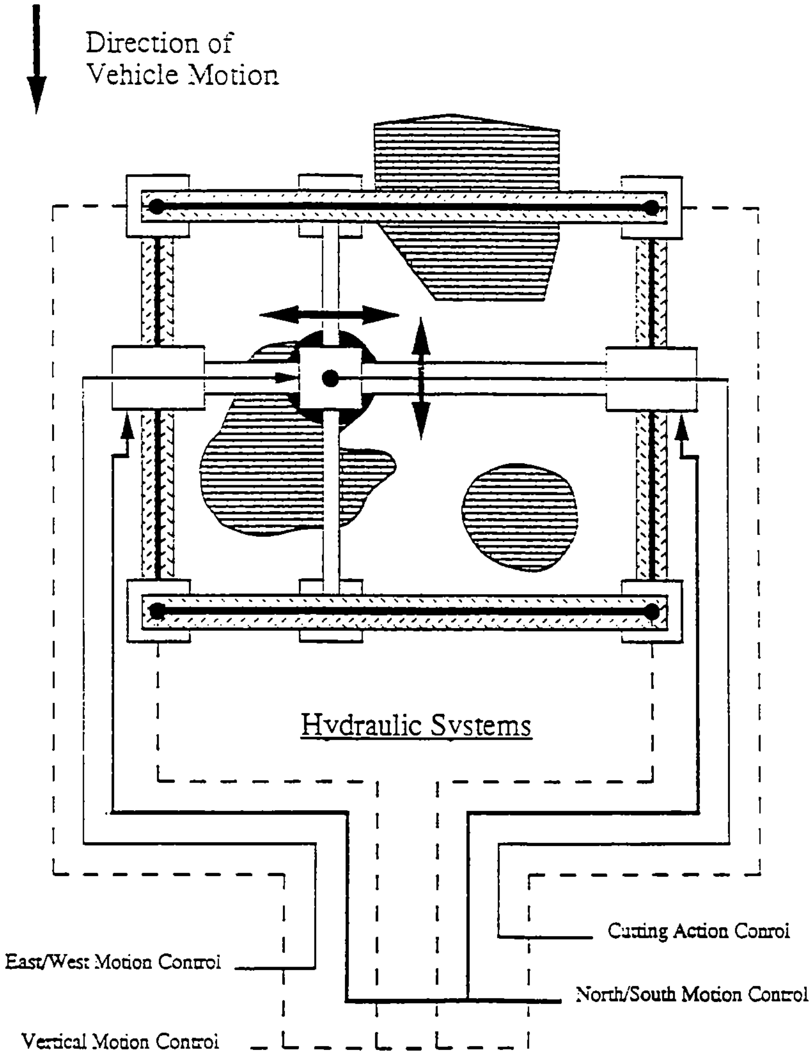


Figure 3-3. Remote Manipulator Using XY Table.

Three link manipulators, such as a backhoe, offer tremendous strength, but are difficult to control with computers. Similarly, multiple link swing arms moving in the horizontal plane (such as the cutter arm eventually developed by Crafco for the cutter) present automatic control problems.

From field observations of highway personnel using spray patchers it was noticed that the spray nozzle is not always held vertical. In fact, the operators often stand in one place and swing the nozzle through a considerable arc to shoot the material into any location on the road. At times, the angle of the nozzle was 30 degrees to vertical, yet the material was properly applied and it adhered to the road with little scatter. This observation was the origin of the idea for a telescoping robotic boom concept (developed in Phase I) that could be extended and sweep through an arc so that the attached nozzles could move over a large repair area. The hollow boom could also be used to convey the rock aggregate and hold the hoses, wires and other items as needed for the repair systems. A telescoping boom has been used on commercial spray patchers on the front of a truck, but these systems are very heavy, and hydraulically operated by joystick. They could not be easily adapted to computer control.

Method of Choice

An electrically-powered telescoping boom was selected as the best design for the system. None were commercially available however. It offered the advantage of carrying materials through the tubing of the arm, great stiffness and durability, and a very long reach to maximize the repair area. It was envisioned to have simple control through two electric motors run automatically by the computer or by joystick. Since it would have a minimum of moving parts and operate from a fixed position inside the truck, it would have great strength and durability. The cost of this solution was in the design and test of a new robot, not the parts. A simple design was needed to prevent difficulty of commercialization or maintenance.

4

Development and Testing of First Generation Equipment

Specifications for the equipment were established through the concept design Phase I, in particular by the operational requirements given in Appendix D, and the repair procedural diagram of Figure 2-2. The productivity analysis provided guidance as to the importance of speed and sequencing of the repair equipment. Section 3 feasibility testing validated the concepts and supplied performance goals for the equipment to reach.

Phase II effort conducted from May 1991 to March 1992 consisted of construction and testing of prototype equipment modules in Tasks 3 and 4, respectively. A synopsis of this development is included here, with additional detail presented in Appendices E through H.

Scale Model

A 1:8 scale model of the truck was created to experiment with different arrangements of possible equipment design as shown in Figure 4-1. The equipment had to be fabricated within the constraints of a commercial vehicle base, with a size and weight that would permit access to all highways of the US. The repair enclosure idea placed additional constraints on the arrangement of the systems. Practical issues were also addressed to ensure that the final vehicle would be road worthy and suitable for extensive field testing. Issues included: vehicle weight and balance, material loading and unloading, maintenance, access to pothole locations, turning angle, hose lengths, robot sizes, cab design, door design, and more. Small mockups of the equipment were built and positioned within the model to evaluate problems before construction.

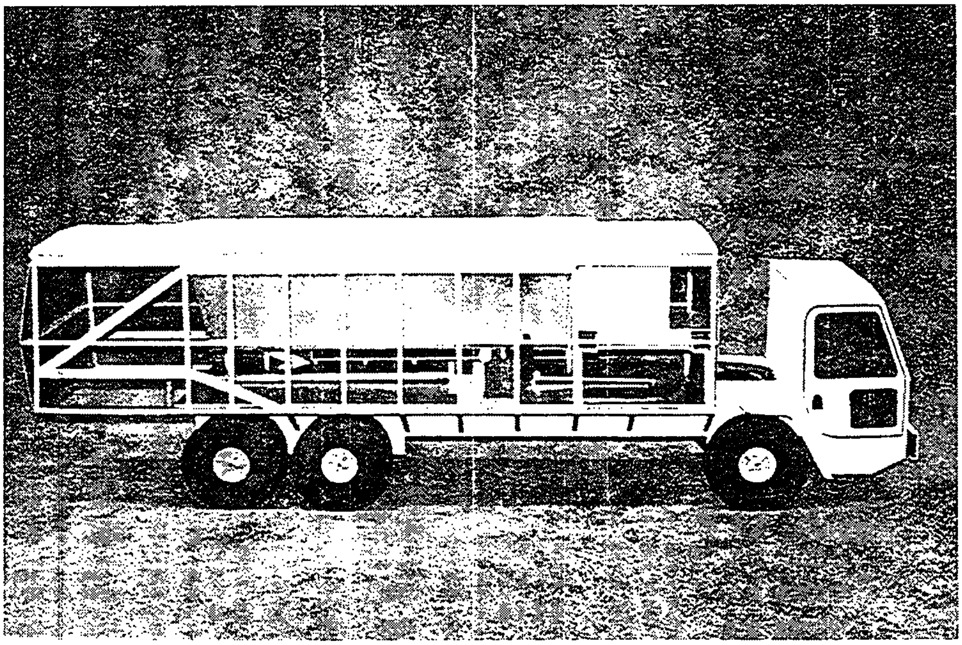


Figure 4-1. Scale Model of APRV.

Repair Enclosure

A mockup of the repair enclosure 'repair box' was made in the shop to serve as a base for installing the robot, vision systems, and repair nozzles. It was equipped with folding doors that would lower down to the floor as they would do on the vehicle. After construction, it was seen that an early idea to move the repair box up and down and side to side (shown in Figure 2-4) was not practical. It was pointed out that a large box hanging off the back of the truck could pose safety problems. Potentially, it might endanger the passing traffic if it extended into another lane. A stationary box still met all of the objectives. The robot and vision system could have excellent coverage of the road in a 5 by 8 foot (40 sq ft) area without the cost and risk of moving the box. The truck had a trim design that would not exceed 8 feet (2.4 m) in width, and a tight turning radius so that it could be maneuvered over nearly any pothole area.

Pavement Cutter

Crafco built, tested, and delivered the pavement cutter equipment module mounted on a trailer along with the first-generation prototype vacuum module so that it could suck up water and mud before cutting and sweep up the spoil after cutting. The cutter shown in Figure 4-2 was hydraulically driven from a power-take-off (PTO) of a 23 HP diesel engine and it was controlled by a joystick and toggle switches. The cutter head was mounted on a vertically-operated slide at the end of a two jointed arm. The arm was operated by 3 inch (7.5 cm) hydraulic cylinders for applying concentrated cutting force. The rotating cutter contains a spiral hub of carbide-tipped bits that dig into asphalt and break it up into small pieces. The bits are resistant to wear and they can be easily replaced in the field.

This system satisfied all design objectives. It was mounted on the front bumper of the truck in later effort. Appendix E contains additional detail.

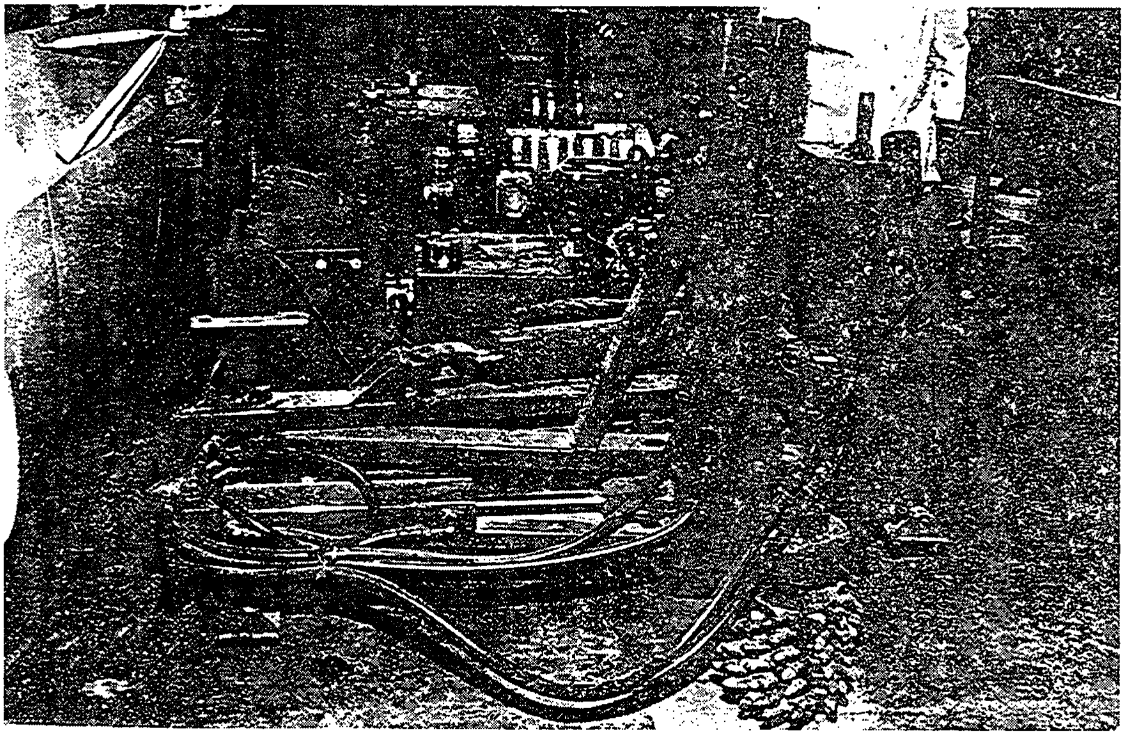


Figure 4-2. Prototype Pavement Cutter.

Vacuum System

Several vacuum designs have been considered over the course of this program. Recirculator types are used in some high-capacity road sweepers, such as Elgin, for dust and debris pickup over wide areas. Positive displacement types such as Hi-Vac are used in industries for scrap pickup, spill cleanup, bulk transfer of materials, etc. The positive displacement type matches the needs of pothole cleaning well since various-sized aggregate, debris, and water will be encountered. Figure 4-3 shows the initial prototype constructed by Crafco. After experimentation we revised the prototype design to incorporate the best features of both types.

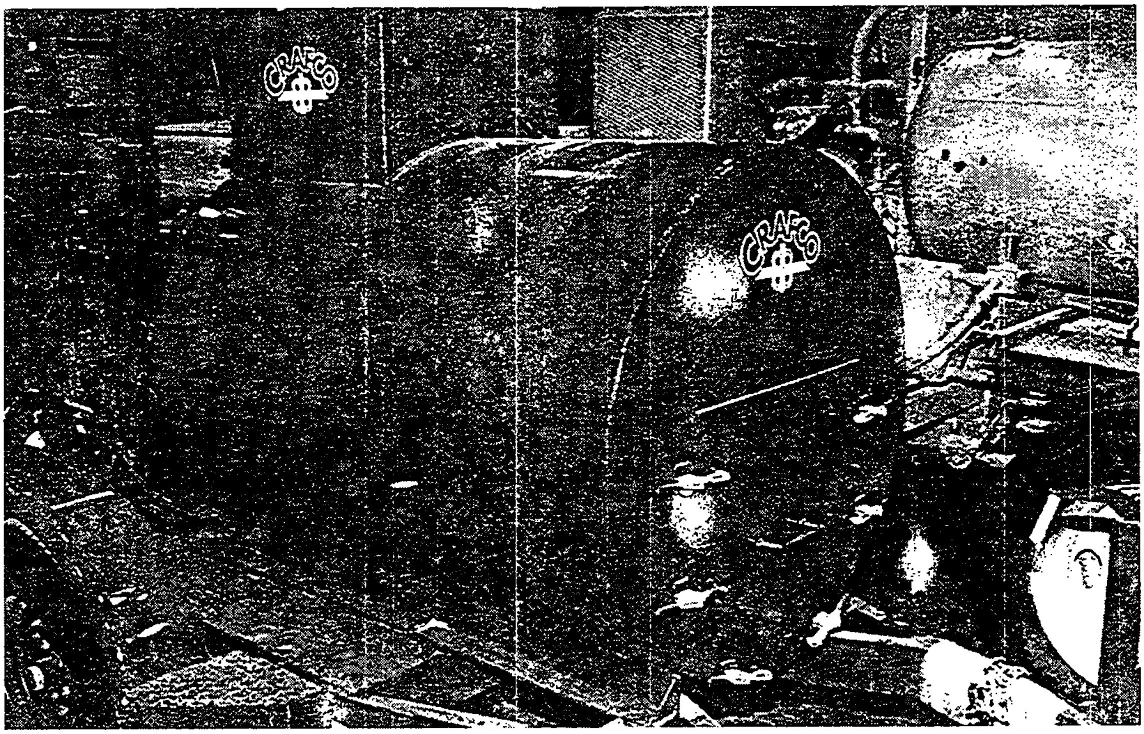


Figure 4-3. First Vacuum Cleaning Prototype.

The vacuum nozzle could be mounted on the cutter system off the front of the truck to rapidly remove water and large debris from the cavity before cutting, and spoil after cutting. Thus, when the repair box is brought over the hole, the hole will have already been cleaned. Heating, drying, and filling operations can then proceed normally. We knew that the spray filling operation would scatter some over-spray on to the surrounding pavement (but contained within the repair box). Further vacuuming would be required to leave the worksite completely clean. An 8 foot (2.4 m) wide, 2 inch (5 cm) long vacuum nozzle, specifically designed to pick up the over-spray, was prototyped and tested for this purpose. It was hoped that it could be mounted to the trailing edge of the repair box and descend to the road. As the truck would begin to drive forward, the over-spray would be vacuumed away in one pass, the nozzle would retract, and the truck would drive to the next pothole site. However, the vacuum power available from the 510 CFM blower we selected could not effectively remove debris and overspray from an 8 foot (2.4 m) wide path since the area of the nozzle was so large that sufficient air velocity at the nozzle could not pick up stones. A decision was made to use one vacuum hose attached to the manipulator for all vacuuming before repair and for cleanup. The final prototype is shown in Figure 4-4.

This blend of ideas from the best of the industrial systems and commercial sweeper vacuums ideally solved the pothole cleaning problem. Through careful design of the blower requirements we have created a system using the same blower driven from the transmission PTO, that will serve the vacuum system and the spray filling system. This prototype satisfied all design objectives. Additional detail is included in Appendix F.

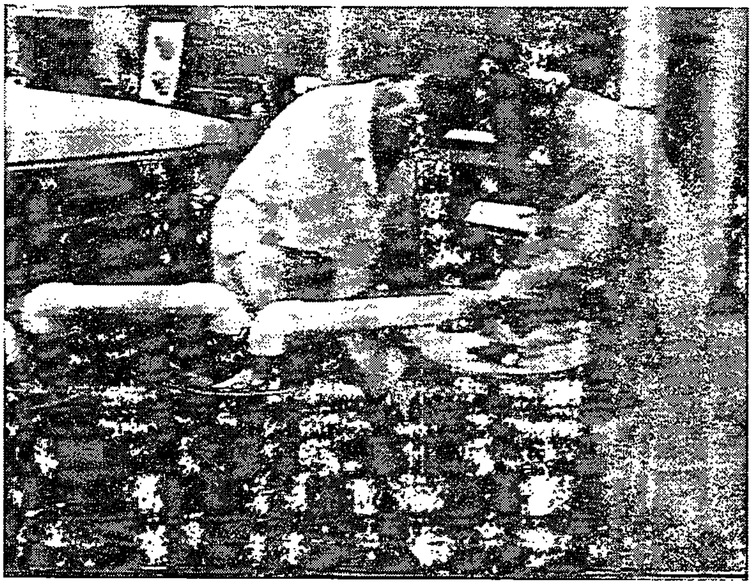


Figure 4-4. Revised Vacuum Cleaning Prototype.

Heating System

We revised the hot air lance prototype from broad coverage to a concentrated blast. Additionally, we designed and tested an electrical ignition system and gas flow control module that would allow computer control of the system when placed on the truck. Electronic fail-safe logic prevents a potentially dangerous situation of free-flowing propane gas. The electronics does this by sensing when the flame is on and controlling gas flow with solenoid valves. If the flame goes out or acts abnormally, for whatever reason, the propane is shut off.

We tested the lance at various distances and angles from asphalt pavement, using an infrared thermographer as shown in Figures 4-5 and 4-6. In the 1:8 scale figures, the lance is located at the top of the image with the hot air blast pointing down onto a cold pavement surface. The color spectrum at the bottom of the figures (color in the original) shows the temperature corresponding to a color. The temperature distribution of the hot air on the pavement during operation can be seen in Figure 4-5. The center 1 foot (30 cm) diameter area of intense heating shows temperatures from 120 to 200 degrees Fahrenheit (49 to 93 Centigrade) with the higher temperatures in the middle. This experiment was a 10 second blast at 18 inch (45 cm) distance from 50 degrees F (10 Centigrade) asphalt pavement. Figure 4-5 was taken just before shutting off the 10 second burst of heat. Note the time scale in the upper right corner. At 14 seconds later in Figure 4-6, the cross hairs (positioned to read the temperature at the center of the heated area) indicate "CRS= +154" a pavement temperature of 154 degrees F (68 Centigrade), ideal for drying and warming the pothole surface for filling with the patch material. Note that a temperature of at least 120 degrees (49 Centigrade) is maintained at a radius of 8 inches (20 cm) around this center point. From these experiments we estimate that typical pothole heating times will range from 10 seconds to 1 minute depending on the size and ambient conditions.

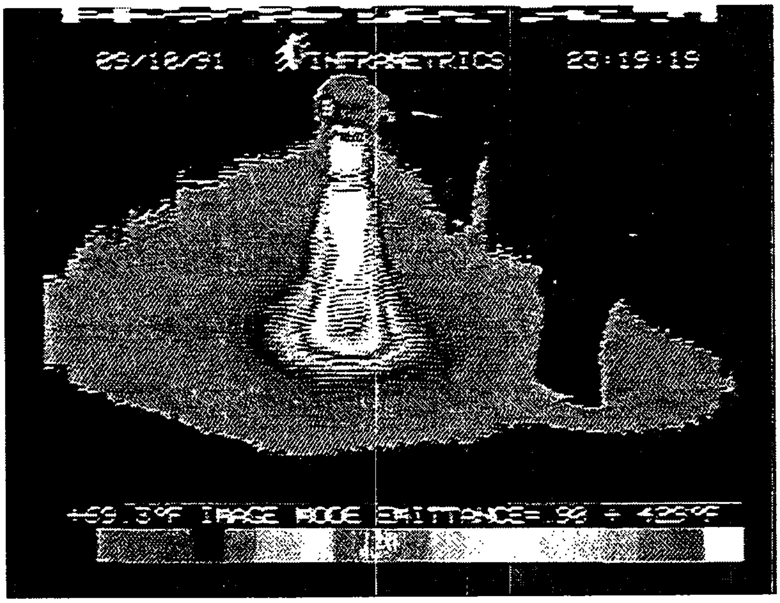


Figure 4-5. Infrared Images of Lance Heating Pavement.

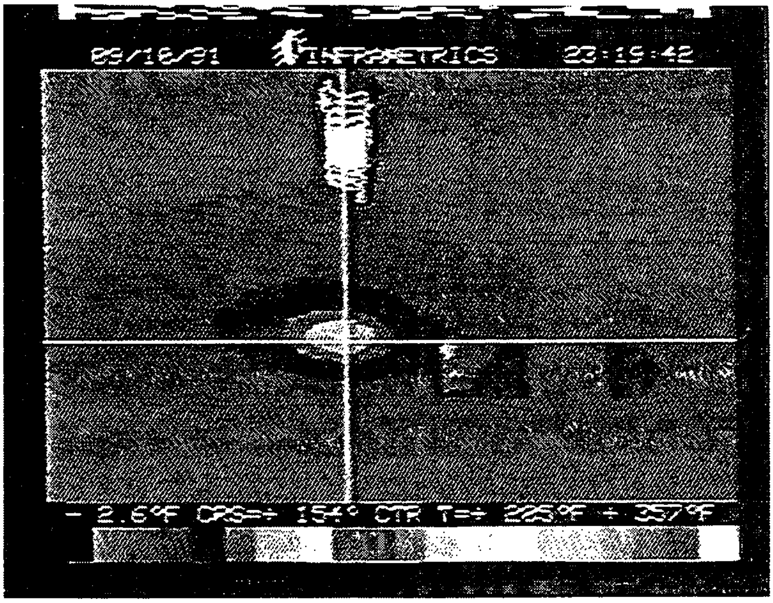


Figure 4-6. Temperature Measurement of Pavement After Heating.

The vehicle will be equipped with a non-contact infrared pyrometer to watch pavement temperature before, during, and after heating, thus assuring that no damage is done. Once the system has been field tested and we obtain information correlating time initial pavement temperature, and final temperature, the system can depend on a simplified timed heating cycle.

Additional development of an electrical ignition system resulted in a lance design that can guarantee a "flame-on" condition while the gas is flowing. The system only requires simple control of the gases and a computer generated (or push-button) "start" command to begin the ignition sequence. If combustion does not occur in a few seconds, the gas is shut down and the computer is informed. If the flame should go out during operation for some reason, the gas will be turned off and the computer informed of the problem.

Spray Filling

The prototype spray filling system has been designed to be automatically controlled on a vehicle. Some of the commercial systems we evaluated showed promise but none offered the required features for this task. The testing program clearly demonstrates that this design achieves very high rates of productivity, with a very simple approach having controls ideally suited to our automation needs. The computer can simultaneously control the aggregate feed rate, emulsion flow rate, temperature, aggregate coverage, and spray pattern. This is the surest way of achieving the most consistent patch performance.

The first prototype was constructed on a spray patcher vehicle rented for this purpose from Ridley Asphalite. This allowed detailed evaluation of the densities and impact pressures achieved during the process and gave us mobility to experiment on the road. From this experimental data we developed a better understanding of how and why spray patches last as well as they have been reported. Appendix A provides some details.

At the time of review, commercial spray patchers could output a maximum sustained rate of 1 cubic foot (.03 cu m) of aggregate per minute. The blower capacities were nominally in the range of 100 to 200 CFM (2800 to 5600 liter/min) at 5 to 10 PSI (.35 to .70 kg/cm^2). Hose sizes varied from 2.5 to 4 (6.3 to 10 cm) inches and the exit nozzles sometimes tapered down to concentrate the material flow. Patch material exits the nozzle at 35 to 55 mph (56 to 88 kph) as claimed by the vendors. These specifications are by no means meant to include all products, but serve to indicate general practice at the time of this evaluation.

Using our prototype, we determined that the velocity of the patch material striking the pavement is a significant factor in eliminating voids from a patch and in promoting the emulsion break (and therefore patch cure). Our experiments with a dynamic pressure sensor allowed us to determine the force of impact of a rock propelled by our prototype.

The measured impact forces were used to calculate that individual rocks impact the pavement at about 1,000 PSI (70 kg/cm^2) in our prototype. This pressure is several times greater than the mechanical pressure achieved by a 3-ton roller compacting hot mix.

Field testing of the prototype used standard emulsions and aggregates sprayed into potholes in the local area around BIRL. The prototype could produce over 1 cubic foot (.03 cu m) per minute of material, through a 2.75 inch (6.9 cm) diameter steel tubing (the telescoping robot boom), achieving exit velocities of 60 to 100 mph (96 to 160 kph). This is double the speed of the claimed commercial system range, which potentially could give the patch material 4 times the kinetic energy on impact (since kinetic energy is proportional to the square of the velocity). It still remains to be established by long-term field test if such velocities result in longer patch life. Higher velocities can also cause the aggregate to bounce out of the hole if sufficient emulsion is not present to cause adhesion.

The prototype excels in the criteria of maintenance. There are no moving parts that come in contact with the rock, aside from an abrasion resistant screw conveyor in the hopper and the slide extension of the robot boom. The elbow, were the rock is turned from horizontal to vertical, is wear coated to minimize the abrasive action of the rock and give longer life to this part.

Figure 4-7 shows one considered way to heat and agitate the emulsion. Electrical heaters can be arranged into independent heating zones. All of the emulsion lines and pumps should be insulated to reduce heat loss and prevent clogging. The desirable temperature range is from 100 to 160 degrees Fahrenheit (38 to 71 Centigrade), determined by experiment and as recommended by the Asphalt Emulsion Manufacturing Association.

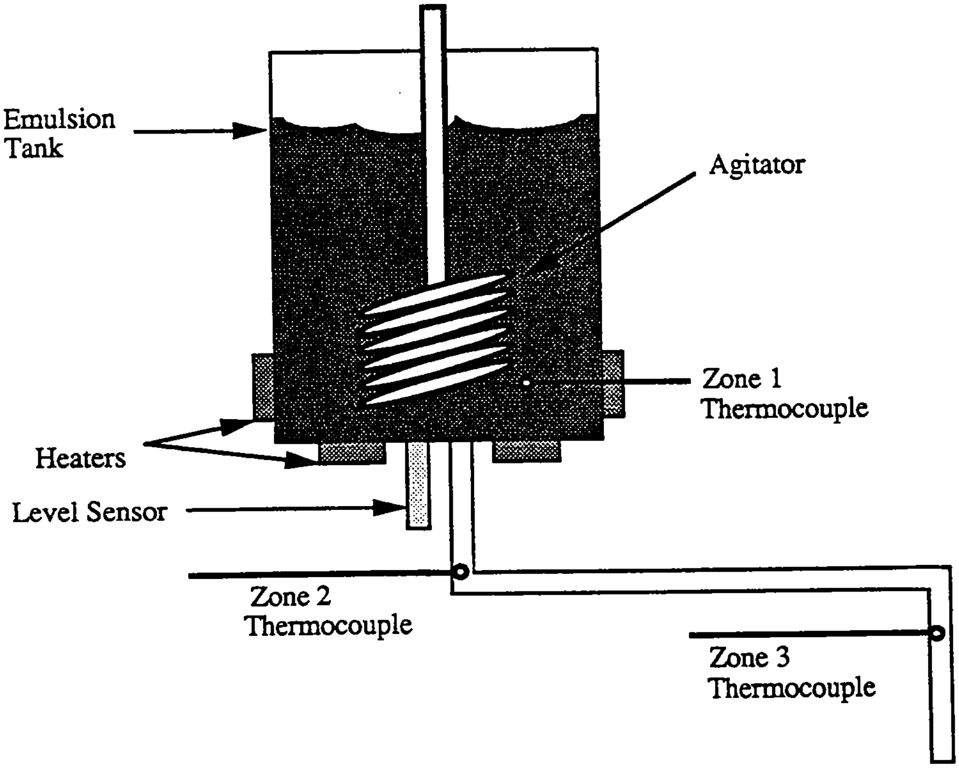


Figure 4-7. Emulsion System.

Some data provided under SHRP H106 shows that a spray patch can have about 95% density when placed *without post-compaction*, but it may show further densification over a 7 month time span (very similar behavior to the pre-mixed control patches placed *with post-compaction*). Our feeling is the much higher rock velocity will result in denser patches at the time of placement. As reported earlier, the lifetime of the spray patches monitored by H106 and other independent sources show that patches typically last years all across the country.

Computer Vision System

A prototype was made using the structured light technique for 3-D imaging because of its speed, cost effectiveness, and durability. This system was located in the repair box mockup and tested with the robot. The imaging system can present live video images, as well as stored images, and graphic overlays of depth and position information. Appendix G discusses some of the details of the 3-D system.

Figure 4-8 shows a "live" TV image of a pothole used for experiments. It is complex in shape and has depths down to 7 inches (18 cm) below the surface. A bump is also included in the middle to check for obscuration problems.

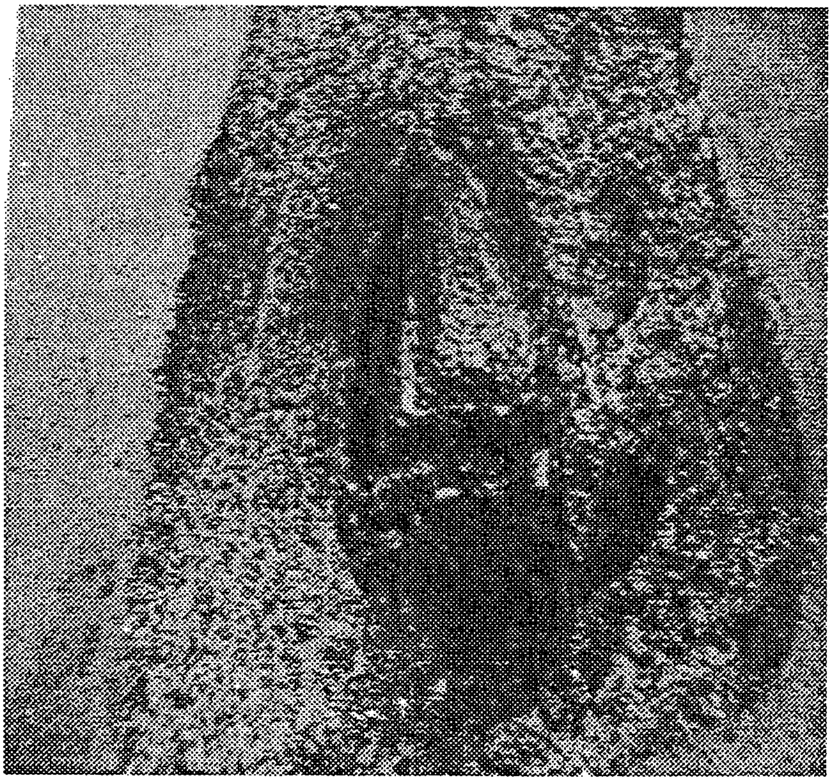


Figure 4-8. Example Pothole Used in Imaging Experiments.

The system scanned the light source and camera across the pothole area (across the 8 foot width of the repair box) and the imaging algorithm determined the depth profile from the contour of the stripes, as shown in Figure 4-9. Actual depth data is sent to the robot program. This display helps the operator monitor the repair operation and it can be used to help guide the robot arm by joystick.

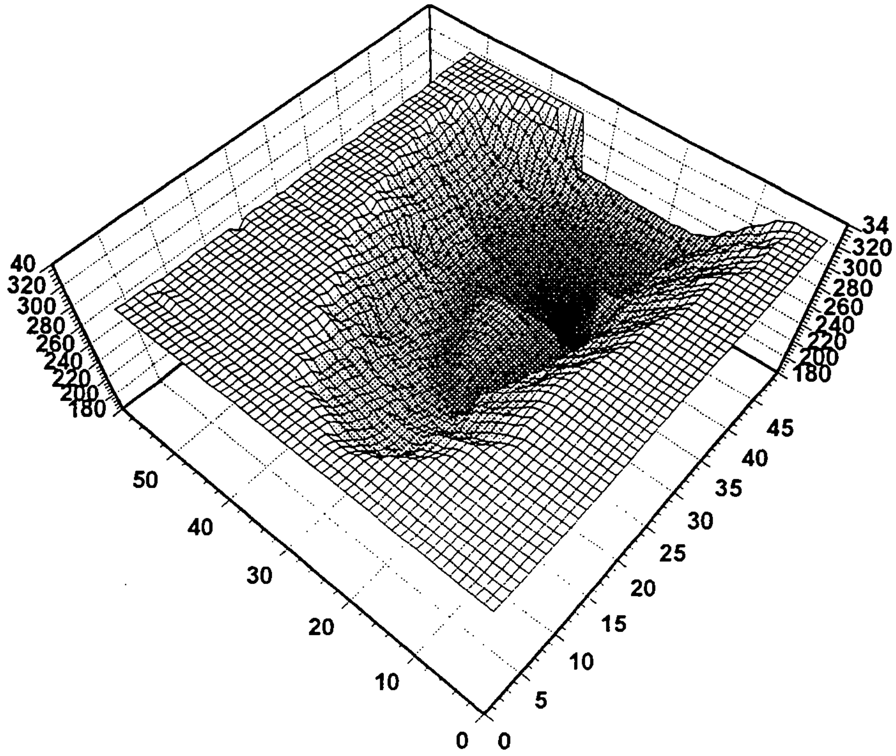


Figure 4-9. 3-D Surface Map of Pothole.

Robot Manipulator

Industrial robotic technology was used to build the robot manipulator prototype. Overall the operation will resemble a telescoping boom that can be swept through an arc inside the repair box, as shown in Figure 4-10. The boom is hollow and carries the rock aggregate under air propulsion from the hopper to the nozzle. At that time, it is sprayed with emulsion just before it exits and sprays into the hole. The boom was designed to move the hot air lance and vacuum nozzles. The motion of the boom is controlled by computer with input from the vision system. A joystick is also provided for some manual control by the operator. The prototype is shown in Figure 4-11.

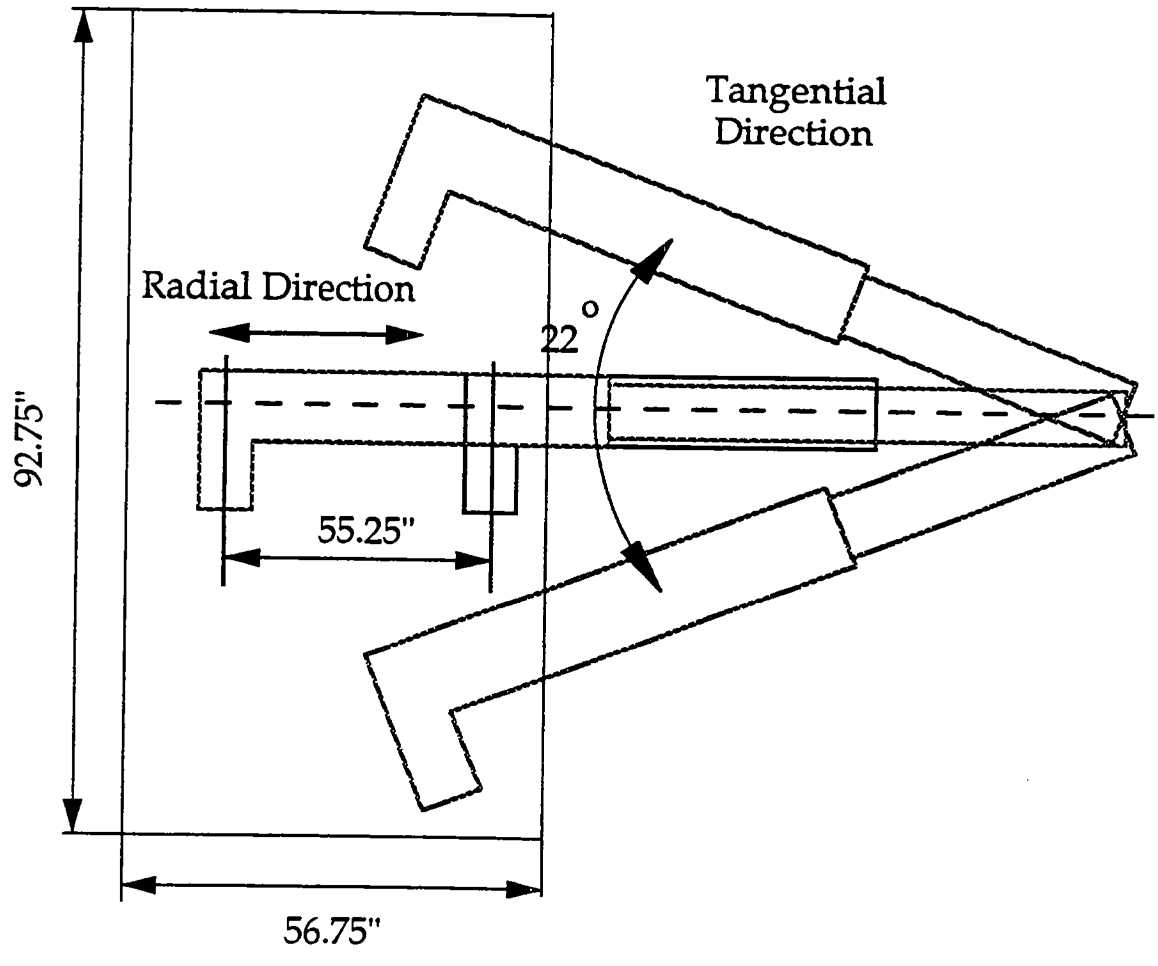


Figure 4-10. Telescoping Boom Robot Design.

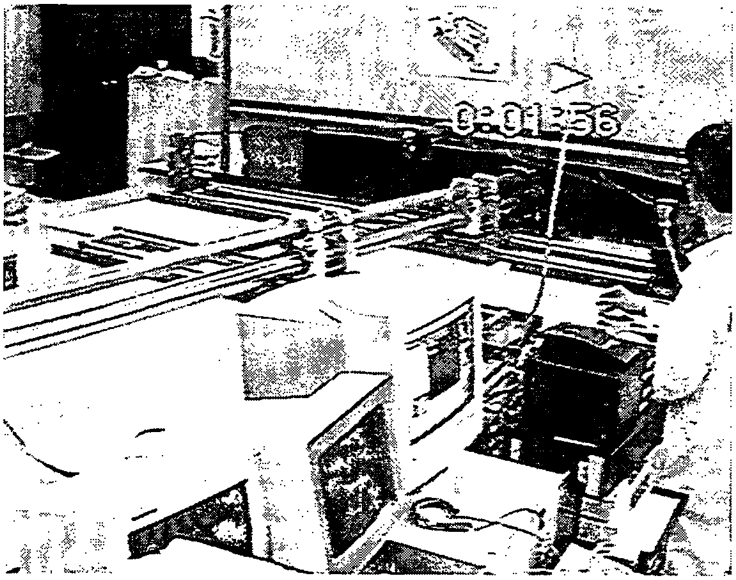


Figure 4-11. Robot Manipulator Prototype.

Adaptive software mechanisms permit the robot to function within specifications invariant to road conditions, the tilt of the truck, or wear and corrosion effects.

The telescoping boom is controlled by servo motors in a polar coordinate type of reference frame. The motors are capable of high accuracy and speed. The target speed is near 1 foot (30 cm) per second in any direction, with maximal coverage of the repair box working area. A payload of 50 lbs (23 kg) is easily accommodated on the end of the arm. Optical limit-switches prevent the operator from accidentally crashing the arm into the sides of the repair box. As the light beam is broken, the robot is stopped instantly.

5

Development of Final Vehicle Prototype

Phases III and IV of the program were conducted between May 1992 and March 1993 broken down into four tasks. Task 5 revised the design of the equipment modules so they could be integrated. Task 6 assembled the modules onto the vehicle prototype. Task 7 performed some testing of the equipment, and Task 8 documented the results and produced this report. This section will show how a commercial vehicle chassis was specified, purchased, and the equipment prototypes were installed and automated.

Vehicle Cab and Chassis

A detailed comparison of alternative truck models has been undertaken in this program. The results are presented in Table 5-1. Many factors were considered but the final choice made was Crane Carrier Company (CCC). One of the deciding factors was front-wheel turning angle. Testing of the turning radius of the potential truck choices was made. The CCC chassis had a much better turning angle (46 degrees) over the other choices. This makes it more suited to maneuvering for pothole repair or any maintenance activity. It may have been possible to modify the other models to improve turning angle, but a standard model was needed.

The CCC line is recognized in the industry as providing a chassis suited to many demanding applications. The "Low Entry Tilt" (Model LET), is often used in the refuse industry where gross vehicle weights can run high, and turning radius is critical. The CCC has the best turning angle of the 4 trucks we examined. At 46 degrees, the truck has a turning radius of 22.7 feet (6.9 m) for excellent maneuverability to reach potholes and pavement distresses wherever they are found.

The frame is structural steel ship channel of high modulus, heat treated and then straightened to eliminate racking and twisting problems. The 10 inch (25 cm) rails extend all the way from the front bumper to the tailboard. Heavy duty electrical systems and air brake systems are specified for this application.

Table 5-1. Vehicle Model Comparison

	WHITEGMC	PETERBILT	CCC
Engine	Cummins L10-260	Cummins L10-280	Cummins L10-260
AT	HT740P 4 SP	HT740RS (Shallow Pan) 4 SP	HT740RS 4SP
Front Axle#	20,000	20,000	22,000
Rear Axle(s)#	40,000	40,000	40,000
Tires - Front	365/80R20 Michelin 4ZA	385/65R22.5 XZ4	365/80R20 Michelin
Tires - Rear	11R22.5 Michelin	11R22.5 XDH-T	11R22.5 Michelin
Battery	4-2500CCA	4-2500CCA with Disc/Swt	3-2850CCA
Exhaust	Single Horz.	Single Horz.	—
FPTO	Yes	Yes with 9" extension	—
Drive Cont	6x4	6x4	6x4
Front Wheel Angle (Max.)	30°	40°	46°
Front Bumper to CL of Front Wheels	72.50"	67"	64"
CL of Front Wheels to Start of Body	17.50"	19.00"	20.0"
Front Bumper to Start of Body	90.00"	86.00"	84.00"
W.B. (Wheel Base)	200"	200"	200"
Body Length Including Work Box	288"	288"	288"
O.L. (Overall Length)	378"	374"	372"
Price** (Nearest 100)	$63,800	$69,200	$73,000

The CCC model features a prime mover of Cummins Diesel L10 260 horsepower which we use to drive the front-mounted power-take-off (PTO) that drives the hydraulic system for pavement cutting. An Allison automatic transmission equipped with an eight-bolt PTO powers the 510 CFM blower, which serves a dual purpose. Slight adjustment of the engine speed from normal idle of 700 RPM to 1100 RPM is all that is required to drive the blower and hydraulics efficiently and this is done under computer control through a high-idle governor.

A generator set by Kohler provides 15 kilowatts of 120v single-phase electrical power for the computer systems, lighting, vision systems, and sensors. The vehicle chassis will handle a gross weight of 62,000 pounds (28,200 kg) if needed, though we expect to operate at less than that with a full load. With a wheel base of 200 inches (5.08 m), body width of 8 feet (2.44 m), and height of 10 feet (3.05 m), the overall size has been designed to make it legal in every state.

Although a single driver is the only required operator, we provide a crew cab for additional crew or observers on day-long repair excursions. Typical cabs give seating for 1 or 2 but the crew cab gives air-cushion ride for 3 in air conditioned comfort. We tested an LET-model garbage truck to determine the amount of shock and vibration that may be present. The accelerometer recorded up to 6 g's of acceleration could be experienced in the cab in each direction (up/down, left/right, forward/back). The worst shock came when striking an unrepaired pothole at 60 mph (96 kph). Consequently, the computers and video displays are shock-mounted in the cab for extra vibration protection.

The LET was selected so that routine engine maintenance could be accomplished by tilting the cab forward. The cab also allowed ample room for computers and monitors. The monitors can be arranged so that either the driver could operate the system or a passenger. The cab-over-engine design made it possible for the operator to view the pothole in front of the truck easily. This was necessary for the operator to use a joystick to control the cutting operation. Figure 5-1 shows the vehicle design as it appears in transport between pothole repair sites.

Gull-wing doors over the dual 13 foot (4 m) aggregate hoppers permit a 12 foot (3.7 m) wide loader to dump a bucket directly into each of the 4 cubic yard (3 cu m) hoppers with minimal spillage as shown in Figure 5-2. The covers will keep the weather off the aggregate during storage and improve the aerodynamics and safety of the system in transport. Heavy-duty edges prevent accidental damage from the loader. The doors can raise to nearly vertical to allow the loader easy dumping. The dual emulsion tank systems each have a capacity of 180 gallons (680 liters). Each of the 6 tanks are heated electrically by 120 volts and they may also be kept warm with engine heat during operation. Keeping the emulsion heated prevents clogging, improves the flow, and speeds its cure time. Side panels of each tank can be removed for easy cleaning. A separate tank of diesel fuel can be pumped through the emulsion system for cleaning.

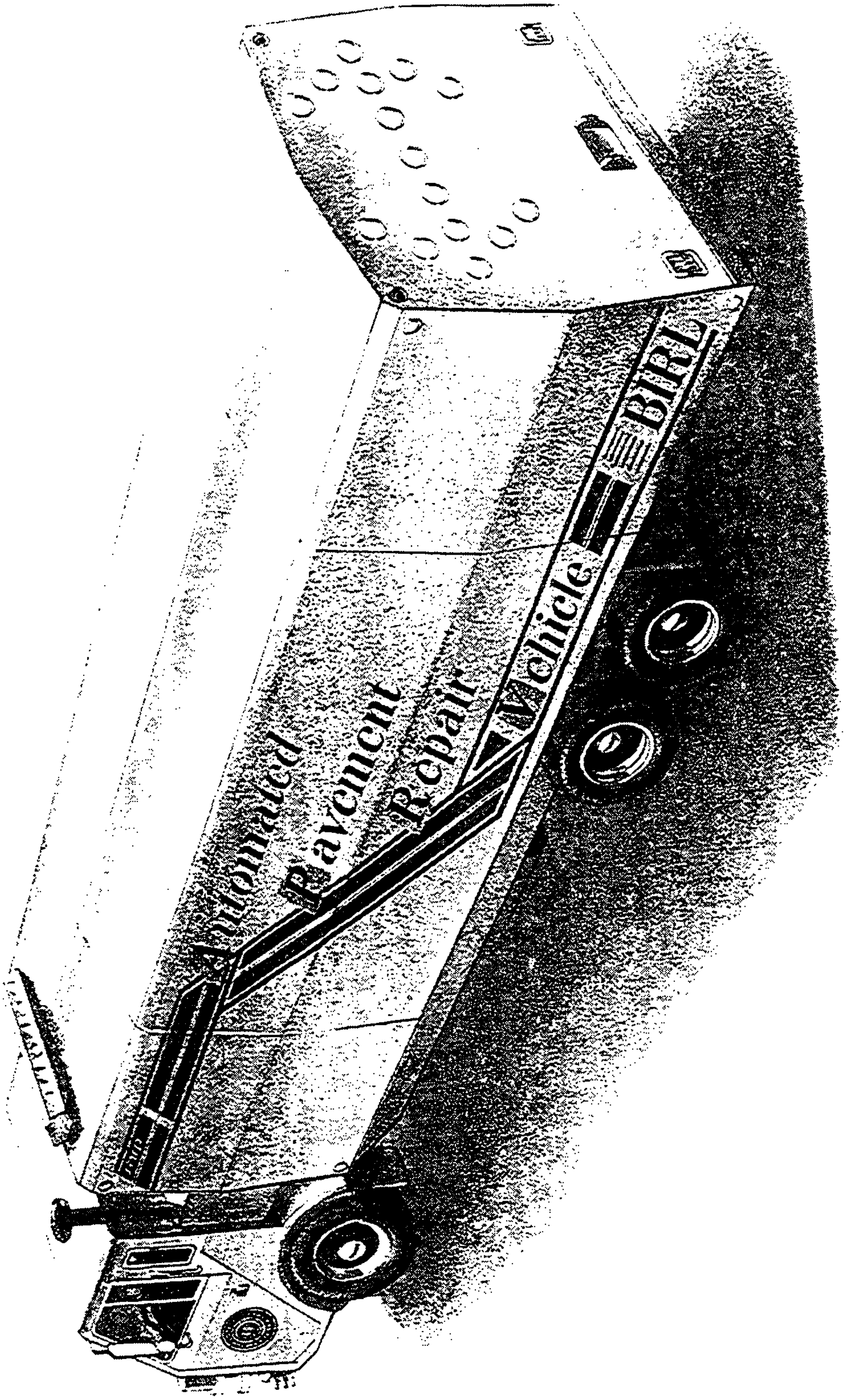


Figure 5-1. Exterior View of the Automated Pavement Repair Vehicle.

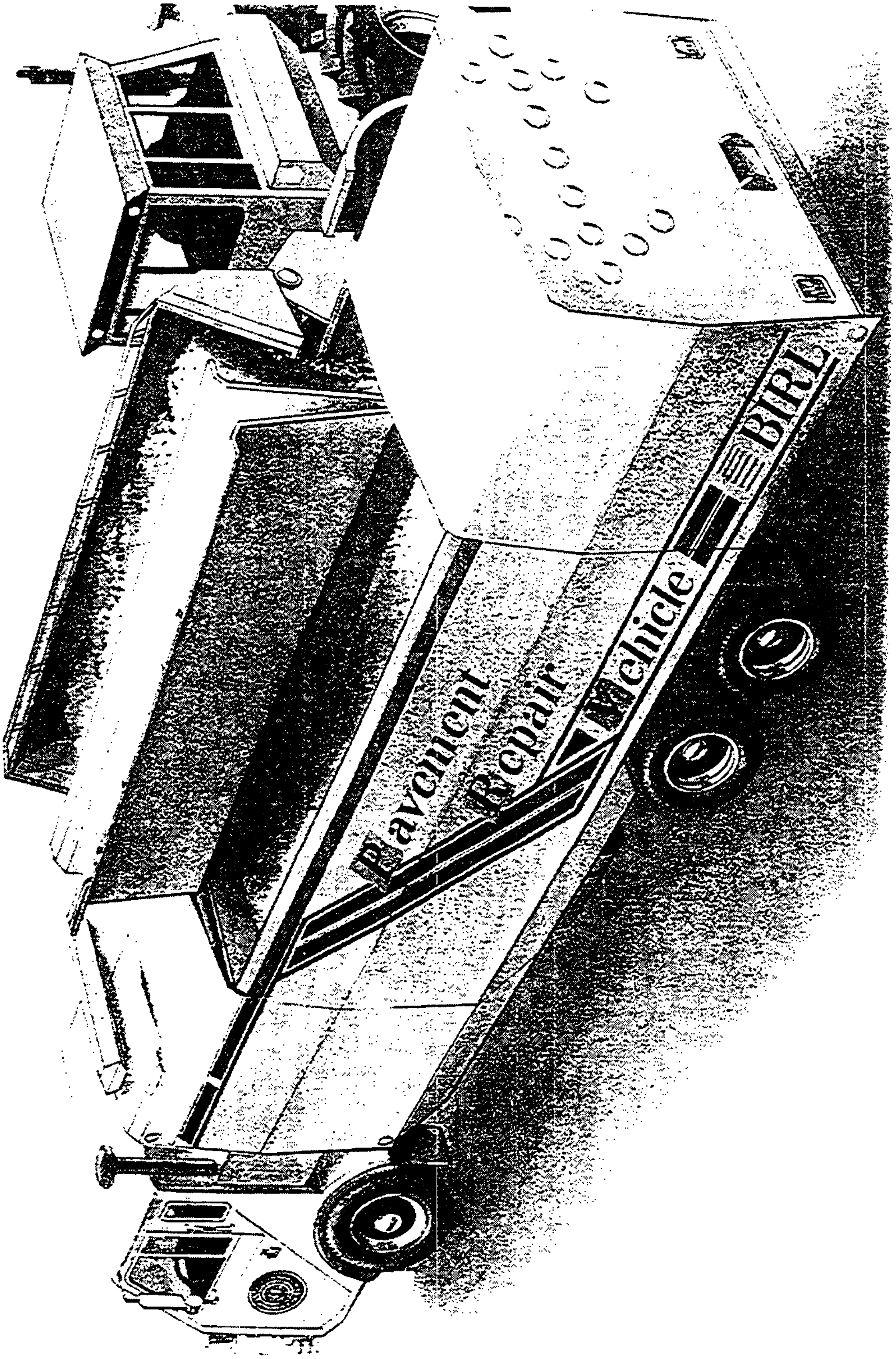


Figure 5-2. Loading Materials in the Automated Pavement Repair Vehicle.

Component Layout

Figure 5-3 on the following page shows the APRV in cutaway view, exposing one possible configuration of the principal equipment components. From front to back, the principal APRV components are:

- Pavement cutter (hydraulic, joystick operated)
- Computer system in truck cab (dual processors, optical disk drive)
- Generator set (15 kW)
- Vacuum filtration system and waste hopper
- High volume, dual purpose blower
- Liquid propane gas tanks for heating system
- Dual hoppers for rock aggregate storage covered by doors
- Dual emulsion tanks for liquid asphalt emulsion storage
- Repair box enclosed area (doors unfold down to pavement level)
- Vision system cameras to view pavement (CCD and 3-D laser scanning)
- Robotic arm manipulator (moves the three tools below)
- Vacuum nozzle with extension to descend into hole
- Hot air lance pavement heating system
- Patching material dispensing nozzle

The truck is self-contained (and holding enough patching materials for an 8 hour shift or more) and there is no equipment setup or take down time. The truck drives at highway speeds from pothole to pothole, with the ability to repair over a full lane width. It is not necessary to back the truck up or maneuver it precisely over the hole. Since the repair area is 5 feet long by 8 feet wide (1.5 m x 2.4 m), several closely spaced potholes can be repaired at a single time without moving the truck at all. Ideally, the APRV could be demonstrated to operate as a moving workzone requiring only minimal traffic control such as a trailing shadow vehicle equipped with an arrow board. Other configurations are possible. For example, if less rock was to be carried, the wheel base could be shortened. If cutting was not required, the requirements for the hydraulic system, bumper, and frame strength could be reduced. If a single rock and emulsion was to be carried, then dual hoppers and tanks would not be required. This arrangement optimized many factors for field test capability and a commercial production model could have different requirements.

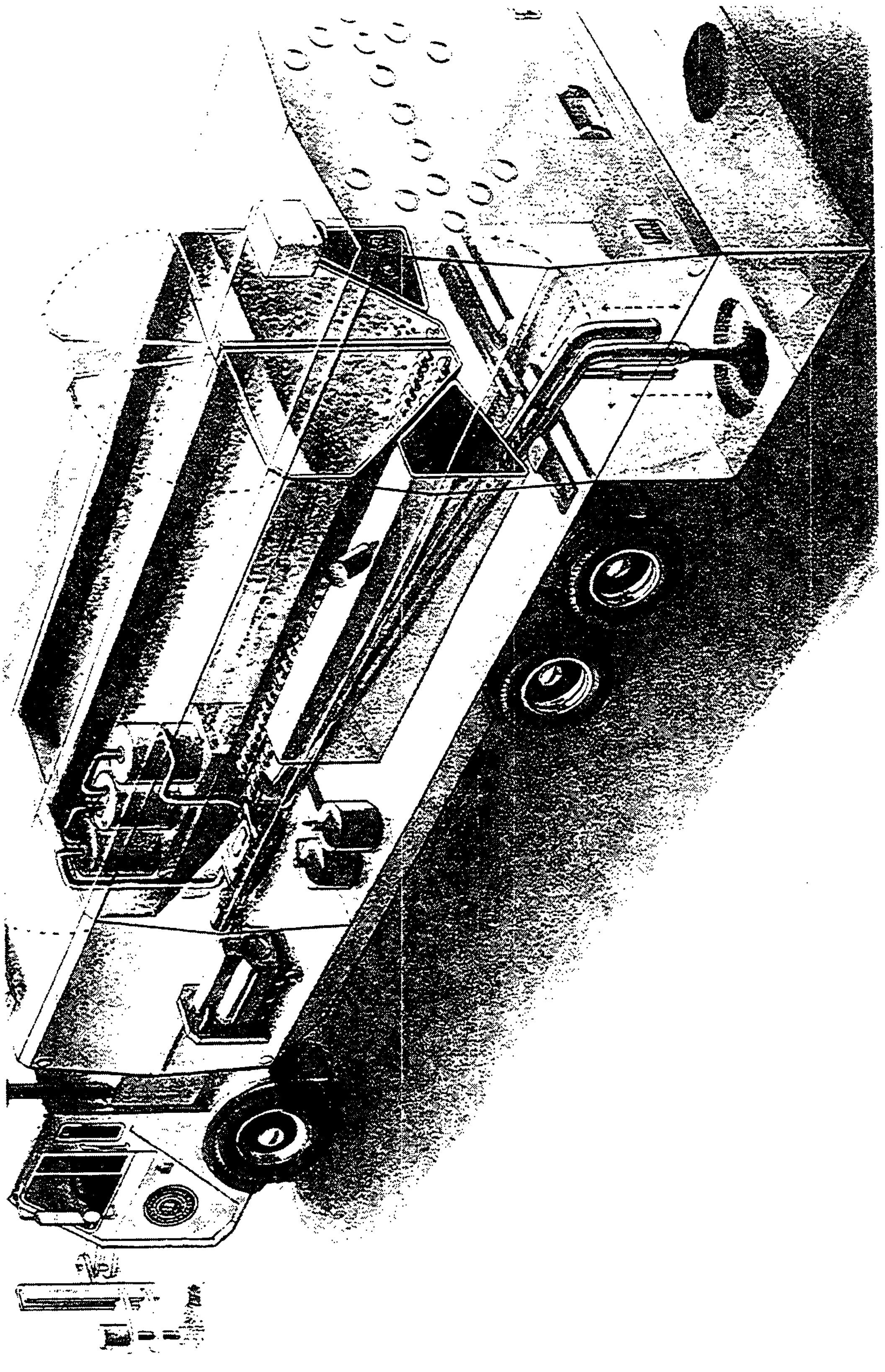


Figure 5-3. Internal View of the Automated Pavement Repair Vehicle.

Assembly and Integration

The APRV was assembled in five basic stages at a number of locations. The first stage constructed the equipment modules and tested them individually. The equipment was designed to allow easy integration onto a truck chassis, without having known beforehand which chassis would be used. The second stage specified and purchased the cab and chassis, and then designed and constructed a body shell separately that could later be mounted on the frame rails. An outside shop constructed the body to our design. In the third stage, the body was bolted onto the truck chassis and revisions were made to the mounting system. The body was painted with a tough Imron paint by an autobody shop and lettered by a professional sign painter. The fourth stage mounted all of the equipment inside the body and revised individual designs to accommodate the layout of the body. Finally, the equipment was wired together, lines, and hoses were added, and operational testing began. This work schedule permitted significant overlapping of tasks so that the labor force could be effectively used at all times, even when delays were encountered.

Review of Objectives

A detailed listing of operational requirements was presented in Appendix D. These requirements were considered our objectives for the development effort. Listed below in Table 5-2 are these objectives and how well the APRV satisfies them.

Table 5-2. Operational Requirements Satisfied by the APRV

Requirement	Satisfied/Not Satisfied	Comment
Repair Cycle Time	Satisfied	5 - 10 minutes
Pavement Type	Satisfied	All asphalt-surfaced
Pothole Size	Satisfied	Very wide range
Pothole Location	Satisfied	Anywhere on road
Lane Occupancy	Satisfied	No adjacent lane closure
Traffic Level	Satisfied	Very high traffic
Safety Provisions	Satisfied	Arrows and lights
Repair Procedure	Satisfied*	Enhanced Spray Patch
Survey / Marking	Satisfied	Computer vision
Cutter	Satisfied	Joystick routing/shaping
Spoil Handling	Satisfied	Cutter debris and more
Cleaning	Satisfied	Water, mud, chunks
Drying	Satisfied	Fast, heated air, no flames
Tacking	Satisfied	Optional step
Filling	Satisfied	Automatic spray patch
Material Capacity	Satisfied	11 tons (8 yards)
Repair Materials	Satisfied*	Emulsion and rock
Material Storage	Satisfied	Heated, pumped
Leveling/Compaction	Satisfied	Automatic during filling
Sealing	Satisfied	Optional step
Clean Up	Satisfied	Automatic vacuum
Vehicle Specs	Satisfied	Legal in all states
Weather	Satisfied	Nearly all weather
Productivity	Satisfied	11 tons/day @ 2 man-hr/ton

Note: * Some of the materials and procedures used from those specified for consideration. This satisfied the terms of the research scope.

A photograph of the final vehicle prototype is given in Figure 5-4, at a showcasing event for the construction industry, ConExpo '93 held in Las Vegas during March. The 4,000 mile (6480 km) round-trip from BIRL (Evanston, IL) through the snow-covered mountains of Colorado, to the exposition provided ample opportunity to test the road worthiness of the design and isolate problems before field testing. The APRV was displayed in the combined FHWA/SHRP booth for 6 days of public and industry scrutiny.

Figure 5-4. ConExpo Display of the Automated Pavement Repair Vehicle.

Automated Pothole Repair Procedure

Many states have specified pothole repair procedures. The states' repair procedures vary, as well as the equipment and materials used to perform them. Thus, we had to determine a generic procedure that seemed to satisfy all the states' requirements and that could be flexibly utilized by individual states. The APRV performs a repair procedure that can be controlled or sequenced by the driver, who is the assumed operator. Most of the steps are optional, and they may be done to the degree required by the conditions.

Step 1: The driver locates a pothole using his eyes and a downward-pointing CCD camera looking through the windshield. With a cab-over-engine design on the truck, he can see a point on the road 2 feet (.6 m) in front of the plane of the windshield--in fact he can see his bumper. He then points to the target hole on the touch screen of the display. A bumper-mounted light-bar can be used at night to sight the potholes. Incidentally, this system could be used to create a photo log for pavement distress recording.

Step 2: The driver uses joystick control to manipulate the bumper-mounted pavement cutter to clean and shape the edges of a pothole. Some states do not perform pothole cutting with some materials so this is an optional step. Although maneuvered by joystick located in the cab in this prototype, it could be fully computer-automated. It can shape the edges of a several square foot pothole in a few minutes. The truck is then driven forward slowly about 33 feet (10 m) until the pothole is positioned under the repair box area at the rear of the truck. Exact alignment is not required and the computer vision system located in the box shows a live TV image useful for positioning. Cutting can be continued as the pothole is repaired.

At the rear of the truck is an overhanging area called the repair box (actually a workspace enclosure) where most of the repair takes place. Essentially a robotic workcell, the repair box houses a 2-dimensional and a 3-dimensional vision system, pyrometer, robotic arm, vacuum system, and a hot air lance. Doors on the underside of the box unfold down to pavement level to keep weather conditions away from the repair as it is made. They also confine the repair process and materials to a local area thus minimizing the effect over the traveling public. Thus, the operator can bring a warm summer day to the pothole, day or night, rain or shine.

Step 4: A 3-dimensional laser vision system located inside the repair box scans the pavement area under the box to detect the depressed area of the pothole. This system shows the operator a 3-dimensional graphic display of the pothole surface, including accurate readings of the depths and overall dimensions. It sends this data to a computer program that calculates a motion sequence for the robot to do the vacuum, heating and filling operations. Upon approval of the operator, the robot begins its repair tasks. If desired, the operator can use a joystick to do the repair manually by watching the TV monitor.

Step 5: The telescoping robotic arm extends from its rest position and moves a vacuum nozzle down into the cavity. High power vacuum sucks out water, mud, and cutter debris very rapidly. Enough power is available to also suck up large asphalt chunks. The vacuum system empties the waste into a hopper which is dumped once per day or less frequently.

Step 6: The same robotic arm then ignites and moves a hot air lance across the pothole surface, to heat the surface and bonding edges of the cavity. The temperature of the pavement is closely monitored to assure that no overheating takes place. Final temperature readings indicate readiness for filling.

Step 7: The next step is the application of patch material now that the hole is shaped, clean, dry, and warm--ideal conditions for bringing out the best in a patch material. The overall filling rate can be controlled up to about one cubic foot per minute. The robot sprays the material in a sweeping pattern into the hole until it is determined to be properly filled and flat. The joystick can also be used for touch up if desired.

We use dual aggregate and emulsion systems that are independently powered and controlled. One hopper could contain a coarse aggregate for base material and the other a closed graded aggregate for surface patching. Or if desired, two different material systems could be carried on board to allow for experimental patching in the same location as a control patch.

Step 8: After the computer has controlled the filling of the pothole cavity, the robotic arm can vacuum away any over spray from the patching process, thus leaving the repair site perfectly clean. A video record of the process ensures that a quality patch was made. A computer data log documents the repair made and the procedure used. The doors of the workbox then close and on a signal the driver can move forward to the next pothole. Enough material and waste storage is onboard to allow all day operation.

The APRV should have a repair cycle time of 5 to 10 minutes, depending on the procedure used and the size of the hole.

6

Conclusions and Recommendations

This research has developed an automated solution to the problems of pothole repair. A vehicle has been designed and constructed to meet program objectives and operational requirements. We believe the end result of 15,000 person-hours of effort on this program satisfies our original design criteria (see Table 6-1 and Appendix C) established over 2 years ago in Task 1.

Table 6-1. APRV Design Score Quality Criteria

Weight	Score	Total	Evaluation Criteria
5	5	25	Patch performance
5	5	25	Maintenance required
5	5	25	Safety feature to public and crew
4	4	16	Operator difficulty of use
4	3	12	Cost of production unit
3	5	15	Versatility of unit
2	3	6	Technical difficulty in making production unit
2	3	6	Complexity of integrated system
1	5	5	Other benefits/drawbacks
		135/9	Design Score (15 out of 17.2 possible)

Patch Performance (5): Objective: An economical repair that would last the remaining life of the asphalt surface, in the range of 3 to 5 years. *Result: Initial field tests of the spray filling module indicate long life patches. The H-106 program is monitoring spray patch performance and finding multiple-year lifetimes. Further APRV field testing through another program will validate these claims. The in-place patch cost is lower than manual patching costs. Greater productivity and consistency can be achieved regardless of weather or road conditions.*

Maintenance Requirements (5): Objective: A low maintenance vehicle system designed for commercial use and for highway maintenance community acceptance. *Result: The design has good features for routine maintenance and cleaning according to our commercial feedback from demonstrations and expositions. We have a controlled part wear through hard coatings and by sensing the performance of the equipment modules to detect problems. Diagnostic capabilities are built in.*

Safety (5): Objective: Improve public safety through faster repair cycle times, less post-repair debris, less explosive, flammable or toxic materials, and greater maneuverability. Improve worker safety by getting them off the road and seating them in the repair vehicle, ideally in front. *Result: The APRV design offers a cycle time of a few minutes, using non-toxic materials. No open flames exist, nor are high pressures used. Only one or two laborers are needed, and they are always seated in the front cab. Day or nighttime operation is allowed.*

Operator Difficulty (4): Objective: The repair system must be easy to use, particularly in cold and wet conditions. *Result: The APRV has many automatic functions including manual overrides. The operator can be easily trained to monitor all steps of the operation and make adjustments if needed. Operator controls are built for rugged use and the displays are simple and easily understood.*

Cost (4): Objective: The cost of operation and maintenance should be very low. Production model costs must be low enough so the system can be purchased by a range of users. *Result: The APRV system should have payback in one to two years. Daily operating costs are very low, since the materials are inexpensive and little energy is required to control and apply them to the pavement.*

Versatility (3): The design should accommodate all sizes and shapes of potholes, and similar distresses that the operator may want to repair. *Result: The APRV allows for this without breaking down. The system could be used for multiple types of pavement repair. Different aggregates and emulsions can be handled, even two at a time.*

Technical Difficulty (2): Commercially proven equipment should be used to lower the difficulty of building a prototype as well as building production models. *Result: The APRV uses many off-the-shelf components. Some systems have been engineered from scratch to use fewer parts than those on the market, yet achieve higher performance. Standard computers and electronics are used as well. The cab and chassis are standard and different models could be used as the truck base. There is strong commercial interest in manufacturing and distributing the APRV internationally.*

System Demands (2): Objective: It is best to use a single component to perform multiple functions to save on weight, cost, power requirements and maintenance. *Result: The APRV uses the truck engine for most of the power requirements. A dual purpose blower serves vacuum and spray patch needs. The robot serves all three repair systems.*

Other Benefits/Drawbacks (1): Objective: There are advantages to a system that can be adapted to use new materials or techniques. *Result: The APRV could be adapted to use proprietary mixes, fibers, other types of aggregates, or even epoxies and sealants. The spray patch module and the robot give this flexibility.*

Commercialization Potential

Since the first newspaper and magazine articles on the APRV development appeared in the local Chicago area in the summer of 1991, there have been a flood of inquiries. Articles about 'the patcher' have appeared in nearly every major paper and international wire service. International manufacturers and distributors have responded to this publicity with phone calls and letters expressing the desire to commercialize the system. We have presented papers at the Transportation Research Board's Annual Conferences in 1992 and 1993, their Equipment Management Workshop in July 1992, and the 4R Conference in December 1992.

The truck itself was displayed at the world's largest construction equipment exposition (ConExpo) in Las Vegas from March 20 to 25, 1993 as evidence of SHRP research results. Hundreds of positive inquiries were made on the truck from all over the U.S. and many from representatives of foreign manufacturers, distributors, and users. Other countries having expressed interest to date include the following:

Japan
Canada
Mexico
Panama
China
Turkey
Germany
Israel
Brazil
West Indies
Saudi Arabia
Argentina
Ireland
Romania
Costa Rica

It is clear that potholes are a global problem and that a commercial solution is needed for their economical repair. This should help improve the commercial attractiveness by creating a larger market. A program sponsored by the Infrastructure Technology Institute (ITI) of Northwestern University is helping to commercialize the APRV for the international marketplace. The ITI has been federally funded with the mission to develop and commercialize technology for roads and bridges (among others) in critical areas that are seen to have high impact over the next few years. Part of this commercialization effort is the demonstration and display of the APRV truck or program at additional conferences in 1993. Another focus of the effort is to demonstrate the technology to companies that could play a role in its manufacture and distribution. The goal is to have a commercializer selected by the end of 1993.

We feel that the commercialization potential is very strong, and that it will peak shortly after full-scale demonstration and testing later in 1993.

Field Test Program

The ITI program also plans initial highway field testing to begin after full-scale demonstration. The ITI program will validate some of the results of this SHRP program. A number of states are expressing interest in providing a site and resources to conduct patching experiments. Since the objective of the effort was to produce a vehicle system suitable for operation in any climactic region under virtually any conditions, conducting an extensive field test is beyond the scope of the ITI program. The first tests will occur in midwestern states bordering Illinois, with additional states as time and funds permit. We will study some of the principal factors involved in the performance and lifetime of the repair:

- Aggregate / emulsion mixture ratios
- Repair size and depth
- General effects of drying the hole
- General effects of heating the hole
- Automation performance in achieving a good patch

The APRV is equipped with computers that will record the repair procedure performed, and also match it with images of the pothole taken before, during, and after the repair. Where possible, control patches (of standard materials and procedures) will be placed nearby to study the relative lifetimes and performance in traffic over a period of time.

We recommend that an extensive field test program be established by the Federal Highway Administration to study these additional factors:

- The effects of cutting and shaping the hole
- Specific aggregate / emulsion combinations
- Aggregate / emulsion handling and storage parameters
- The effects of fibers and other additives
- Alternative materials and procedures
- Minimum and maximum repair depths
- Patch density as a function of time
- Optimum pavement temperature for patching
- Optimum pavement surface moisture levels
- Performance benefits of different robotic motions for filling

The APRV is an ideal testing platform because of its dual material capacity, careful computer control of all the process variables, and the built in sensors and vision systems for recording the experiments.

Benefits

The technology developed and applied through this SHRP study will have lasting benefit to all roadway maintenance authorities and workers by making pothole repair safer for all, with greater performance and productivity than traditional methods.

Given a successful commercialization program and field testing, production models could start to become available for the benefit of the pavement maintenance community in 1994. We think that different configurations would be manufactured to maximize the benefit to state highways, districts, cities, and private contractors. Every group has special requirements as to size, maneuverability, level of automation, and material capability. Since the APRV was designed as a modular system, each of the components could be modified to suit the needs of the end user.

A single APRV should be capable of making two or three times the number of permanent repairs as a manual crew could do in a shift, particularly in poor weather conditions. In theory, the system could operate more than one shift per day. It can operate at times of lower traffic, such as night, where a manual crew would have great difficulty. The APRV is designed to stand ready for instant response to emergency pothole situations experienced in the winter and spring months. It can be radio-dispatched at highway speeds to make the repair, without exposing the workers or the public to unsafe conditions.

A fleet of APRV's could address the needs of a large city or a district. Equipment sharing across boundaries could add to the cost-effectiveness of the vehicle. Over a period of time, the sheer number of potholes on a roadway system might finally be reduced to a manageable amount. Rapid pothole repair will also slow down the deterioration of a pavement, and add life before an overlay is required. At the time of overlay, quality pothole repair is crucial to establishing a solid base before applying the new material.

With improved roads there will come measurable benefits to motorist and trucking companies. Vehicle maintenance costs and liability claims may drop. Delays caused by pothole repair should decrease, thus lowering the cost of goods. The economy of a state depends on the quality of its transportation infrastructure. The APRV technology will directly improve the quality of roadway transportation, and thus benefit the economy of the state (and country) that uses it.

7

References

1. Kulash, Damian J., "Curing Road Acne", SHRP Focus Newsletter, National Research Council, May 91.

2. Anderson, David A., H. R. Thomas, A Critical Evaluation of Pothole Repair Strategies, Final Report PTI 8017 to Pennsylvania Department of Transportation, Pennsylvania Transportation Institute, Pennsylvania State University, September 1980.

3. Crovetti, J. A., M. I. Darter, K. L. Smith, K. D. Johnson, M. C. Belangie, Synthesis of Operational Deficiencies of Equipment Used for Pavement Surface Repairs, Final Report H-105 to SHRP, ERES Consultants, July 1990.

4. Wilson, Thomas P., A. Russell Romine, SHRP H-106 Innovative Repair Materials and Methods -- Summary of Pothole Repair Project, ERES Consultants, Presented at 4R Conference and Road Show, December 6-8, 1992, pp 88-92.

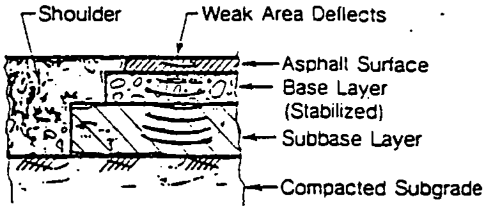
APPENDIX A

POTHOLES AND THEIR REPAIR WITH ASPHALT MATERIALS

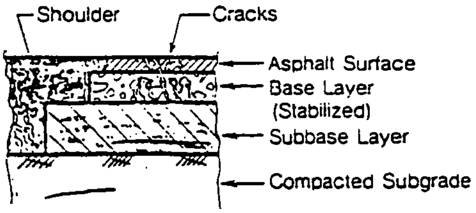
Pothole Formation in Asphalt-Surfaced Pavements

Potholes are structural failures in the road surface caused by loading and weakening of the base or subbase. Loading is due to traffic primarily, but weakening can be from several causes. Poor materials, poor compaction, poor drainage, or poor workmanship are usually at fault. Standing water has the potential to ruin a pavement in a short time. This is one reason why improving the drainage around a pavement can be so important to the life of the road. The complete process of pothole formation in flexible pavements is shown in Figure A-1 reproduced from an excellent 1984 report by the Pennsylvania Transportation Institute (PTI) of Pennsylvania State University called "Pothole Repair Management". The weakened areas bend more than normal, particularly with heavy loading, and this causes cracks to appear on the surface. Water enters the cracks and begins to saturate and further deteriorate the base. In freezing weather, the water may turn to ice and expand the cracks or separate the asphalt layer from the base. Traffic action, which exerts downward force (deflection) as well as to the side (shear), then dislodges pieces of the surface, exposing the base layer to the elements. Without the asphalt layer for protection, the base rapidly erodes and complete failure results.

A rigid base pavement develops potholes in a different way, but the results are similar as shown in Figure A-2. Since a rigid base flexes at joints and cracks, the asphalt surface may also develop a crack. When water or incompressible particles find their way into the crack and down into the base, the freedom of movement is hampered and concrete spalling can result. The additional stresses and strains cause further cracking which accelerates the problem. If the cracks are not cleaned and sealed quickly, sections of the asphalt may peel away exposing the base. Deteriorated concrete bases can also lead to potholes. Corroded reinforcement bars (from deicing chemicals or induced electric currents), poor materials, or poor construction, are often to blame.

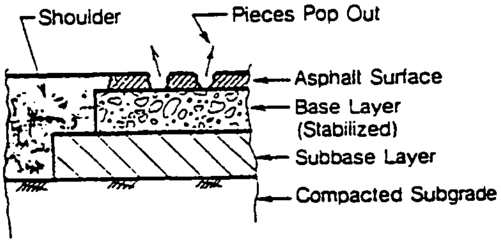


Step 1. Pavement Deflects Excessively

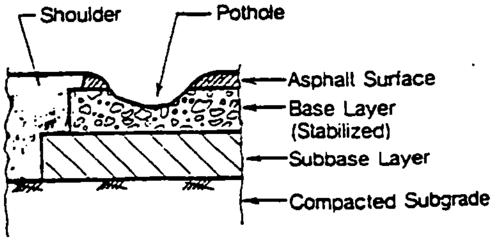


Step 2. Cracks Form, Water Enters

Pothole Formation in an Asphalt Pavement

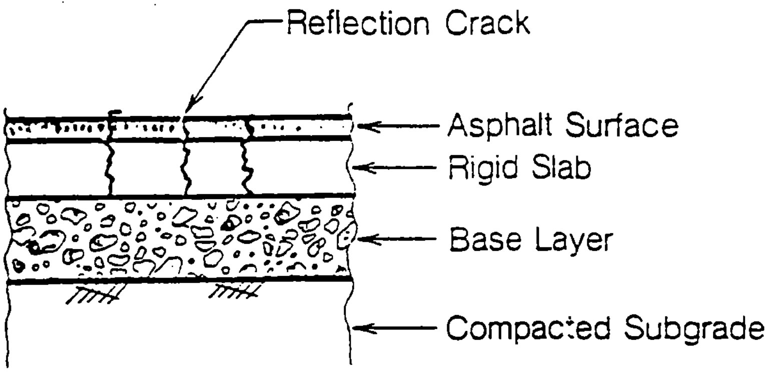


Step 3. Water Freezes, Pavement Pieces Pop Out



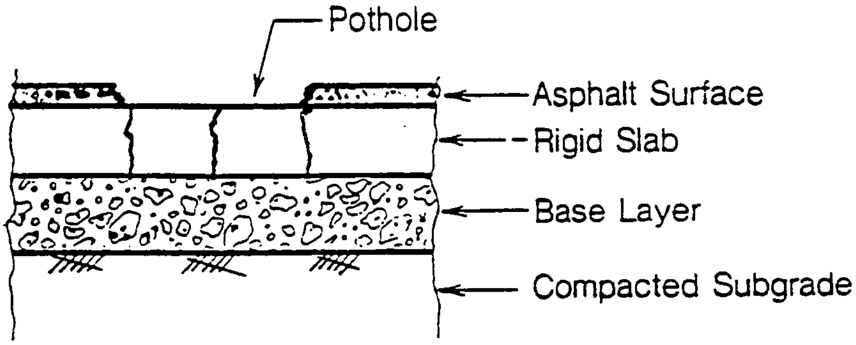
Step 4. Pavement Erodes Into Base Layer

Figure A-1. Pothole Formation in Flexible Pavements
(Source: Pothole Repair Management, PTI, March 1984)



Step 1. Reflection Cracks Form

Step 2. Water Between Layers



Step 3. Surface Peels Off

Figure A-2. Pothole Formation in Rigid Base Pavements
(Source: Pothole Repair Management, PTI, March 1984)

Pothole Definition

Many sources were consulted to determine a reasonable definition of a pothole that could be used as a specification for the automated repair system concepts:

- SHRP
- Asphalt Institute
- US Army Corps of Engineers
- American Public Works Association
- State highway district engineers
- Pavement engineering consultants
- Photo surveys

The "Distress Identification Manual for the Long Term Pavement Performance Studies, SHRP-LTPP/FR-90-001" defines potholes as "bowl-shaped holes of various sizes in the pavement surface". Severity is characterized according to depth and area, according to guidelines given in the report.

The photographs in that report clearly show the rounded nature of potholes and the table report suggests that many potholes are less than or equal to 3 square feet in area, and less than or equal to 2 inches deep. Potholes can be found with dimensions greater than these, but a large percentage fall into these limits. We also examined other sources of information to expand on this basic definition and made many direct observations of potholes in various state highway and local roadway situations.

The report "Asphalt in Pavement Maintenance, MS-16", by the Asphalt Institute similarly defines potholes as "bowl-shaped holes of various sizes in the pavement surface resulting from localized disintegration". No suggestion is made as to the extent of a pothole, but the accompanying photographs show a typical case including water, loose aggregate, foreign material, and edge cracking.

The US Army Cold Regions Research and Engineering Laboratory (CRREL) conducted a Pothole Workshop in 1980, which lead to a thorough report called "Pothole Primer: A Public Administrator's Guide to Understanding and Managing the Pothole Problem, Special Report 81-21". They cite that all potholes require two ingredients at the same time; water and traffic. "Since water and traffic must be present together, it can easily be seen that the most common location for pothole development is in the *wheel paths* of traffic". The mechanisms can be "fatigue failure caused by excessive flexing of the pavement which occurs most commonly...on thin pavements when excess water is in the base". Fatigue failure causes the classic pothole (bowl-shaped crater) particularly in thinner (less than 3 inch pavements), through the disintegration of the pavement into 1 or 2 inch pieces that are dislodged by traffic. While the thicker (3 to 4 inch) pavements may crack and deform, they tend to resist dislodging of the pieces and the formation of a crater. Another mechanism is "raveling failure...which occurs only when traffic is present and water actually washes away the adhesive asphalt films that hold the stone aggregate together". Raveling can occur on both thick and thin pavements with equal severity. A prime example of raveling can be seen in the failure of some existing pothole patches. A patch can ravel away very quickly under severe conditions forcing maintenance departments to patch the same hole several times per month in extreme cases.

The Construction Engineering Research Laboratory (CERL) "Asphalt Surfaced Roads and Parking Lots Field Manual" (June 1989), defines a pothole to be small bowl-shaped depression of less than 3 feet diameter, having sharp and nearly vertical edges near the top of the hole. It may result from mixture or subgrade problems.

A 1983 booklet published by the American Public Works Association "The Hole Story: Facts and Fallacies of Potholes", draws upon the CRREL study and research by the Asphalt Institute in defining potholes. The implication is that water and traffic (in the wheelpaths) are the causes of potholes, and the results are bowl-shaped depressions that collect water and lead to further deterioration.

State highway personnel and consultants point out that potholes usually occur in the wheel paths, particularly the outer path, and especially where a pavement has been widened. The seam is unfortunately positioned directly in the outer wheel path. Potholes also occur near the center line of two-lane roads, where the two lanes of asphalt overlays are joined. Their experience confirms the definition of a pothole being a bowl-shaped (roundish) depression with sharp, broken edges, between 1 and 2 feet in diameter, with severe cases of 3 feet. The depth ranges from 2 to 6 inches generally, with the larger holes having greater depths.

Finally, it must be mentioned that potholes on state highways may be different and perhaps less severe than on local road systems. Potholes represent a relatively advanced form of pavement deterioration, often caused by a lack of preventative maintenance. As such, state highways are more likely to have smaller and shallower potholes than a local road.

Pothole Repair Procedures

Hot Mix

Heated bituminous mixtures require intensive cavity preparation to ensure adequate patch life, and they are typically applied in warm and dry weather, not cold and wet conditions. While the material is less expensive than most available (about $16 ton), repairs may be more costly in the long run because of the labor required and the fact that an inadequately prepared hole (such as done in emergency conditions or in haste) may result in very rapid failure. Patch consolidation occurs with cooling of the mix and mechanical compaction. Generally, the following steps are performed by a foreman and a crew of 7 equipped with a dump truck holding the heated mixture (or a 'hot box'), an impact or abrasive pavement cutter, heated oil tanks, brooms, shovels and lutes, and a mechanical compaction device.

1. Foreman surveys and marks pavement surrounding pothole, identifying it for removal.
2. Cut the pothole with a jackhammer from the inside out to the marked outline, trying to cut vertical sides to a depth of solid pavement. If a saw is used, follow the outline. Note that a saw can only make straight cuts.
3. Clean out the cavity with brooms and then air blow pipe if available. Try to dry the surfaces.
4. Tack coat the cavity surfaces with heated tack oil for this purpose, using brooms or spray wand. Should achieve even coating of all surfaces and allow to set until tacky.
5. Shovel (or dump) hot mix into cavity and spread with shovels and brooms into all areas. Continue to apply hot mix and build up level of mix to 1 inch above surrounding pavement level for each 4 inches (approximately) of the cavity depth.
6. Level the mix off evenly with a lute or broom in preparation for compactor. Clean mix off the surrounding pavement.
7. Compact the filling with rolling compactor, by making passes along the outside edges, and then working into the middle. Final passes over the entire hole working transversely to road so that the wheel ruts do not cause bridging. Must accomplish these 10 to 15 passes quickly before mixture cools and hardens. Vibratory mode should be engaged when over hole. If plate compactor used, follow same basic procedure. The final passes should leave the mixture about 1/4 inch above surrounding pavement for resistance to water penetration and also allowing traffic to compact further without creating depression. If density gauge available, it should read at least 95% density. May need to repeat steps 5 through 7 for deep holes.
8. Seal coat the edges of the patch with a suitable compound applied with broom or spray wand.
9. Optional: Dust surface of patch with sand, fine aggregate or crushed rubber particles if immediate drive-over is required.

Cold Mix

Cold bituminous mixtures are designed for application in more adverse weather conditions. Patches can be made with less intensive cavity preparation but may result in shorter patch life in this case. While the material is moderately expensive of those available (about $20-40 ton) it may be more costly in the long run because the patches may last only a short time. Many different states have developed their own cold mixes that have good lifetime and storage properties. Patch consolidation occurs with compaction, time, and exposure to the elements. Generally, the following steps are performed by a foreman and a crew of 5 to 7 equipped with a dump truck holding the cold mixture, an impact or abrasive pavement cutter, heated oil tanks, brooms, shovels and lutes, and a mechanical compaction device.

1. Foreman surveys and marks pavement surrounding pothole, identifying it for removal.
2. Cut the pothole with a jackhammer or pick from the inside out to the marked outline, trying to cut vertical sides to a depth of solid pavement.
3. Clean out the cavity with brooms and then air blow pipe if available. Try to get water out of the hole.
4. Tacking not used.
5. Shovel (or dump) cold mix into cavity and spread with shovels and brooms into all areas. Continue to apply cold mix and build up level of mix to 1 inch above surrounding pavement level for each 4 inches (approximately) of the cavity depth.
6. Level the mix off evenly with a lute or broom and clean the mix off the surrounding pavement.
7. Compact the filling with truck tires or by striking repeatedly with back of shovel. If using tires, work from outside in as with rollers, by driving forward and backing up under supervision. The final passes should leave the mixture about 1/4 inch above surrounding pavement for resistance to water penetration and also allowing traffic to compact further without creating depression.
8. Seal coat not used.
9. Optional: Dust surface of patch with sand, fine aggregate or crushed rubber particles if immediate drive-over is required.

Proprietary Cold Mix

Proprietary cold emulsion-based mixtures are designed for application in a wide range of weather conditions. Patches can be made with little recommended cavity preparation but often result in shorter patch life in this case. While the material is the most expensive of those available (about $60-70 ton) it may be fairly economical for emergency patching because it can be applied with a minimum of labor. Patch life must be considered shorter term than permanent however. Patch consolidation takes place slowly due to compactive efforts of traffic and chemical changes. Generally, the following steps are performed by a foreman and a crew of 3 to 5 equipped with a dump truck holding the cold mixture, brooms, shovels and lutes.

1. Survey and marking unnecessary since there is no cutting.
2. Remove loose debris from hole.
3. Brush, blow, or shovel water out of the cavity if possible.
4. Tacking not used.
5. Shovel (or dump) cold mix into cavity and spread with shovels and brooms into all areas. Continue to apply cold mix and build up level of mix to 1 inch above surrounding pavement level for each 4 inches (approximately) of the cavity depth.
6. Level the mix off evenly with a lute or broom.

7. Compact the filling with truck tires or by striking repeatedly with back of shovel or hand tamper. If using tires, work from outside in as with rollers, by driving forward and backing up under supervision. The finishing passes should leave the mixture about 1/4 inch above surrounding pavement for resistance to water penetration and also allowing traffic to compact further without creating depression.
8. Seal coat not used.
9. Most products claim immediate drive-over, but the patch will remain soft for some time.

Comparison of the Standard Pre-Mixed Procedures

The most time consuming, and therefore costly, procedure is hot mix. It has the longest lifetime when applied in ideal conditions, so a careful annualized cost (or per patch) comparison is required to assess the economics. Cold mixes are quite popular in the cold and wet climactic regions during the pothole seasons, and much time and effort has gone into their development and comparison to other materials. Since a fairly large crew is still required for their application, their cost is still measured largely in terms of labor rather than materials and equipment. Proprietary cold mixes were created to meet the needs of emergency wet and cold conditions where crew exposure to traffic and weather had to be minimized. Since they are adaptable to wet holes (being water-based emulsions), they can be applied in moderately severe conditions with little or no preparation. However, the patches do not last as long as a holes prepared well and patched with the other materials. Their high cost and regional availability eliminates them from some agency budgets. They also expose the worker most to the hazardous conditions being fairly mobile.

According to SHRP Project H-106, pothole patching by conventional materials depends heavily on weather conditions at the time of placement and on the amount of preparation done to the pothole before filling. The graphs shown below summarize the effects of procedure, temperature, and moisture over the patch lifetimes of hot-mix, cold-mix, and the proprietary cold-mixes. The conventional system of filling with hot-mix asphalt is particularly sensitive to temperature, moisture, and proper application procedures (temporary versus do-it-right cut/fill/compact). The other conventional system of standard cold-mix (Penn DOT 485/486 for example) or the proprietary cold-mix "throw and go" is less sensitive to temperature and moisture, but the permanent compaction procedure is still required for a patch lifetime of one year or more. Interestingly, only the proprietary cold-mixes (Sylax UPM, Perma-Patch, QPR 2000, etc.) could achieve over one year of life in wet or cold conditions, which shows the importance of materials. The principal drawback to this system is the relatively high cost of the materials and their proprietary formulation. While hot-mix may sell for $16/ton, polymer-modified cold-mixes may sell for $80/ton.

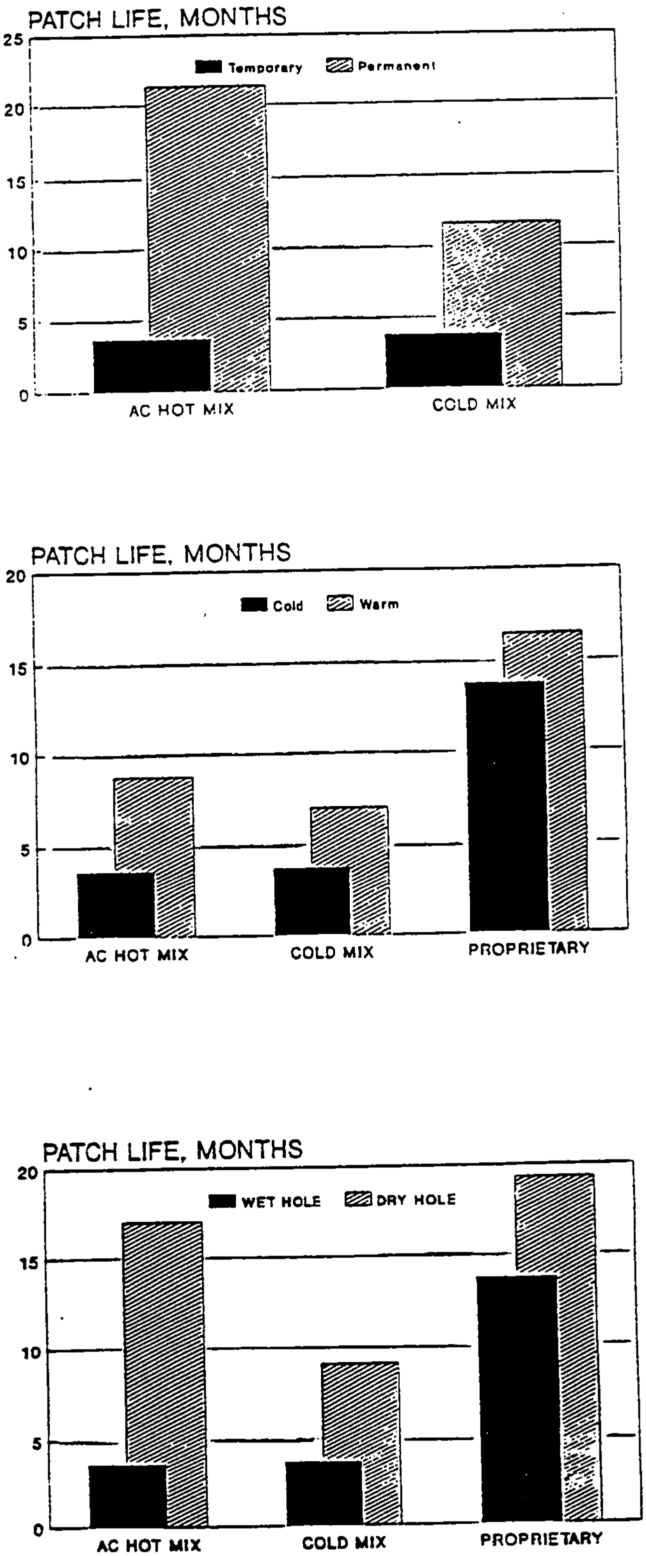


Figure A-3. Summary of Conventional Pothole Patch Lifetimes Reported by SHRP

Spray Emulsion Patching Procedure

Spray emulsion (spray patching, spray injection) technology is a widely used method of pothole repair being used in at least 25 states covering all four climactic regions of the US as shown by the shaded area of the Figure A-4.

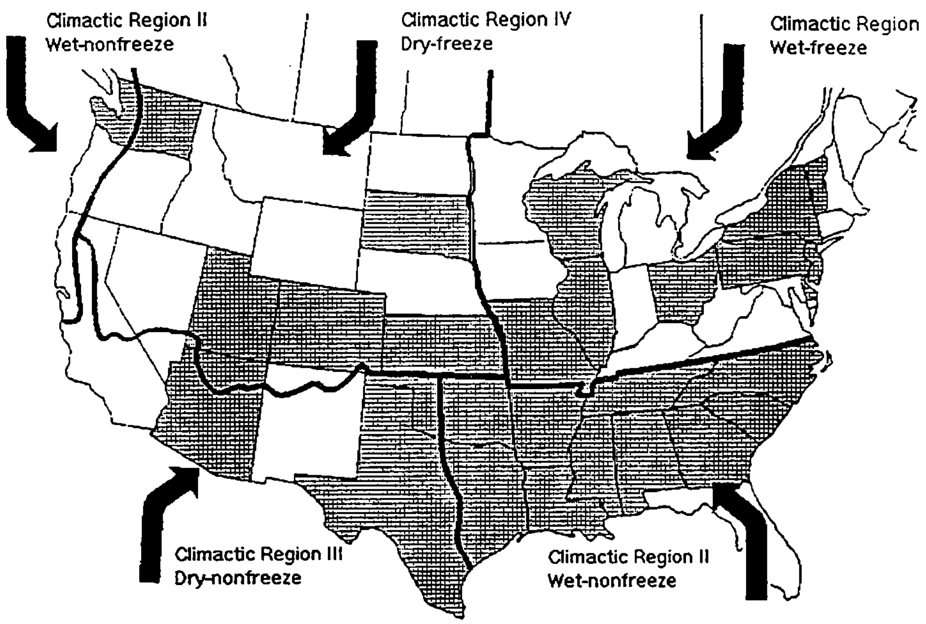


Figure A-4. Twenty Five Known States Using Spray Patching in Four Climactic Regions

Our user survey indicates that the patches last as long as, and in many cases longer than, other traditional methods. Our 25+ direct contacts have stated clearly that they have had "no patch failures to date" when properly using the equipment. These contacts from the above 25 identified states yielded average lifetimes over 3 years (to date), as the following Table A-1 shows.

Spray emulsion equipment is commercially available from a number of vendors, and it is owned and operated by state highway agencies, counties, cities, and private contractors. It is clear that the economics and reliability of this repair method is a driving factor in its growing acceptance across the US, Canada, England, Ireland, and Australia. Because the method is flexible, it is also frequently used for the correction of other road defects including, concrete spall patching, wide crack repairs, lane and shoulder repair, and bridge approach and deck repair.

Table A-1. Reported Life of Spray Emulsion Patches

Region	Users Reporting/ Life YTD	Users Reporting/ Life Avg.YTD
1. **Dry Freeze** (Northwestern U.S.)	1/2 2/3	3/2.66
2. **Wet Freeze** (Northeastern U.S.)	1/4 2/1	3/2.00
3. **Dry Non-Freeze** (Southwestern U.S.)	2/3	2/3.00
4. **Wet Non-Freeze** (Southeastern U.S.)	1/4 2/6 3/2 3/3	9/3.44
U.S. DOT - Unknown Region	1/6	1/6.00
Total Averages		18/3.17

The basic principal of spray emulsion is simple in concept as shown in the Figure A-5 below. A hopper contains a quantity of aggregate (3/8" diameter, crushed limestone is typical) that can be dispensed by some means into a feeder mechanism. From the feeder mechanism the rock enters an airstream where it is entrained and moved down a hose or pipe to a position near and above the pothole. As the aggregate is conveyed by the air, it picks up velocity until terminal speed is reached. Just before the aggregate is discharged from the hose or pipe at the delivery nozzle , it is sprayed with a mist or stream of liquid asphalt emulsion discharged from a heated storage tank.

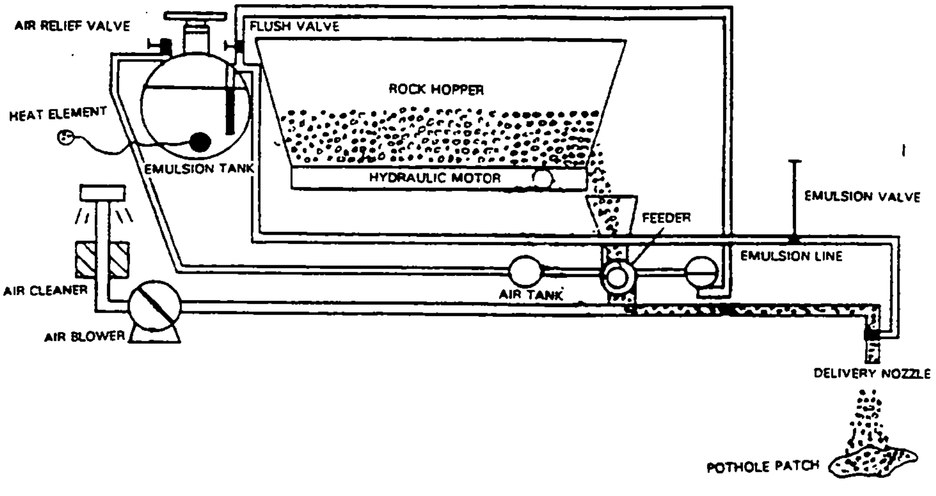


Figure A-5. Basic Concept of Spray Patching Equipment

The patch material is thus created on the fly as it is needed and its high velocity causes the individually coated rocks to impact the road surface with enough force to stabilize the patch as it is placed. Air voids are eliminated from the patch as it is built from the bottom up. The aggregate is bound and interlocked together by the matrix of the asphalt as it cures from the impact, temperature change, and exposure to the elements.

The commercial systems all employ variations on this basic design, yet none control the process to assure critical set points are maintained. The quality of the road repairs performed with this technology are still heavily dependent of the skill of the equipment operators holding the nozzle and moving it back and forth across the pavement. Some systems have an arm that can be moved by servo controlled hydraulics from the cab of the truck. The emulsion and rock flows are established by mechanical valves and electrical switches and their sequencing is critical as many things happen quite rapidly as the spray pattern is attained. Aggregate velocity is usually a fixed parameter of the design in spite of its importance in achieving tight spray patterns, minimizing bounce-back, and causing the initial cure of the patch material as it impacts the road. A two to three person crew is often used, with the equipment mounted on a trailer and hauled by a dump truck holding the aggregate. Integrated vehicles exist, but their capacity is quite limited and even though the operator does not leave the truck cab, most of the critical aspects are still manually controlled through banks of valves and switches located within reach of the operator. No sensors or computer control is yet available on any commercial system.

APPENDIX B

POTHOLE PATCHING COST COMPARISONS

There are many sources of information for determining the cost of various patching operations. The primary economic drivers include: the cost of materials, labor rates, productivity of patching operations, costs of delays, and patch lifetimes. No single source was found that could bring all of these costs into a single comparison, however. This document will analyze patching costs primarily with a spreadsheet that was developed using a model including the following factors:

- Repair Time
- Productivity
    - Hole Volume before and after optional cutting
    - Material usage
    - Work time available
    - Days of operation per year
    - Operational delays
    - Repair lifetime
    - Failure rate of patches
- Labor Costs
- Material Costs
- Equipment Costs

The aim of the comparison was to determine an approximate cost to make a patch and to relate that to the expected lifetime of the patch, giving a total cost per patch per year of life. The figures given are rough approximations only, and are not intended as a statement of actual costs for any given situation. They are useful to compare the different procedures and materials to show sensitivity to the above factors.

The graph later in this section shows the results of plotting 7 different patching scenarios, each of which will be explained by a representative printout of the spreadsheet. A number of example costs from each case are printed on the graph on the following page, which serves as a comparison between all the cases. Table B-1 shows the different cases that were evaluated, by varying the material and procedure, whether cutting was done or not, days of operation per year, and patch lifetime:

Table B-1 Cases for Cost Comparison

Case	Procedure	Cutting/No	Days/year	Lifetime (yrs)
1	Automated (1)	No cut (2)	230	3.2 (3)
2	Automated	No cut	300(4)	3.2
3	Automated	Cutting	230	3.2
4	Automated	Cutting	230	1.78 (5)
5	Conventional Throw and Go	No cut	230	0.31 (6)
6	Proprietary Throw and Go	No Cut	230	1.08 (7)
7	Do it right (8)	Cutting	230	1.78

NOTES:

1. Automated procedure developed for this program. Cutting, vacuum cleaning, heating, spray patch filling, cleanup. Times are estimates. Cost of truck and support equipment was estimated at $260,000. Vehicles amortized over 15 years (10% overhead). The driver was the only labor cost considered (50% overhead). Material $30/ton (10% overhead).
2. Cutting is an option of the automated case.
3. Estimated lifetime for automated patches based on phone survey with average reported lifetime of spray patches 3.2 years (to date).
4. Automated operation in all weather could be 300 days/year or more.
5. Average lifetime of a do it right patch, reported by SHRP in Focus Newsletter, May 1991. Used in this case for comparison to automated patching.
6. Average lifetime of a throw and go patch with cold mix, reported in SHRP Focus Newsletter.
7. Average lifetime of a throw and go patch with high performance cold mix, reported in SHRP Focus Newsletter.
8. Do it right procedure includes cutting, cleaning, tacking, filling, compacting, cleanup.

The graph (Figure B-1) compares the 7 cases on the basis of cost of a patch per year of life, versus the actual volume of a pothole at the time of filling (after cutting if necessary). There is no adjustment for the changing value of materials or equipment over the life of the patch. It was discovered that the hole size was a good independent variable. Each plot on the graph also notes:

- the number of holes repaired per day, and
- the performance (man hours/ton of mix placed).

The bottom four plots on the graph are the automated cases 1-4, which show the lowest costs per patch per year of life. The next lowest cost case (6) was proprietary throw and go, showing the benefit of using a material that yields a long patch life. The "Do it right" method (case 7) was more costly, with the most costly case (5) of conventional "throw and go" because lifetimes are so short according to SHRP and other sources.

The Table B-2 gives the estimated costs for:

Small holes
  before cutting: 6 inch radius, 2 inches deep (0.13 cubic feet)
  after cutting: 8 inch radius, 3 inches deep (0.35 cubic feet)
Moderate holes
  before cutting: 13.5 inch radius, 4 inches deep (1.32 cubic feet)
  after cutting: 15.5 inch radius, 5 inches deep (2.18 cubic feet)
Large holes
  before cutting: 24 inch radius, 4 inches deep (4.19 cubic feet)
  after cutting: 26 inch radius, 5 inches deep (6.14 cubic feet)

The costs are expressed in two ways. Cost per hole ($) at time of patching and cost per hole per year of life. This is done for the three sizes of holes and an average of these sizes is calculated.

Table B-2. Estimated Costs for Patching Cases

Case	Procedure	Small	Moderate	Large	Average
1	Auto	5.92 (1.85)	6.72(2.10)	20.44(6.39)	11.03(3.45)
2	Auto	6.66(2.08)	15.37(4.80)	21.93(6.85)	14.65(4.58)
3	Auto w/cut	8.46(2.64)	14.40(4.50)	38.29(11.97)	20.38(6.37)
4	Auto w/cut	8.46(4.75)	18.32(10.29)	38.29(21.51)	21.69(12.18)
5	Con. Throw & Go	10.90(35.15)	16.12(52.00)	29.66(95.68)	18.89(60.94)
6	Prop. Throw & Go	11.50(10.65)	22.14(20.50)	46.04(42.63)	26.56(24.59)
7	Do It Right	52.58(29.54)	72.27(40.60)	109.37(61.44)	78.07(43.86)

We want to calculate a payback for the automated case compared to a manual patching case. The productivity of the two cases must be made equivalent before performing the payback analysis, however. From the graph (and the spreadsheets) the "Do it right" crew can fix 8 to 15 holes per day, depending on their size (case 7). The automated crew of 1 (using cutting) can fix from 15 to 50 holes per day (case 3 or 4). The automated vehicle (using cutting) is approximately as productive as 2 or 3 manual "Do it right" crews of 5 laborers each. Also, to keep the patch lifetime out of the comparison, we will pick case 4 which assumes the same lifetime (1.78 years) as "Do it right", and we will use the installed cost (not the cost per year of life). Thus, the comparison to be made is case 4 to case 7 (small holes in Table B-3, large holes in Table B-4) to reveal the worst case payback for automating pothole patching.

Table B-3. Cost Comparison of Patching Sparsely Spaced Small Holes

Procedure/Case	Holes	Cost per patch as made	Total cost/day
Do it right/7	50 x	$52.58	= $2,629
Automated/4	50 x	$ 8.46	= $ 423

The daily difference is $2,626 - $423 = $2,206 savings per day.

Payback is the cost of going to the automated system (assume $300,000 for the truck and support), divided by the daily savings.

Payback period = $300,000 / $2,206/day = 136 days (less than one year)

Table B-4. Cost Comparison of Patching Sparsely Spaced Large Holes

Procedure/Case	Holes	Cost per patch as made	Total cost/day
Do it right/7	20 x	$109.37	= $2,187
Automated/4	20 x	$38.29	= $ 766

The daily difference is $2,187 - $766 = $1,421 savings per day.

Payback period = $300,000 / $1,421/day = 211 days (less than one year)

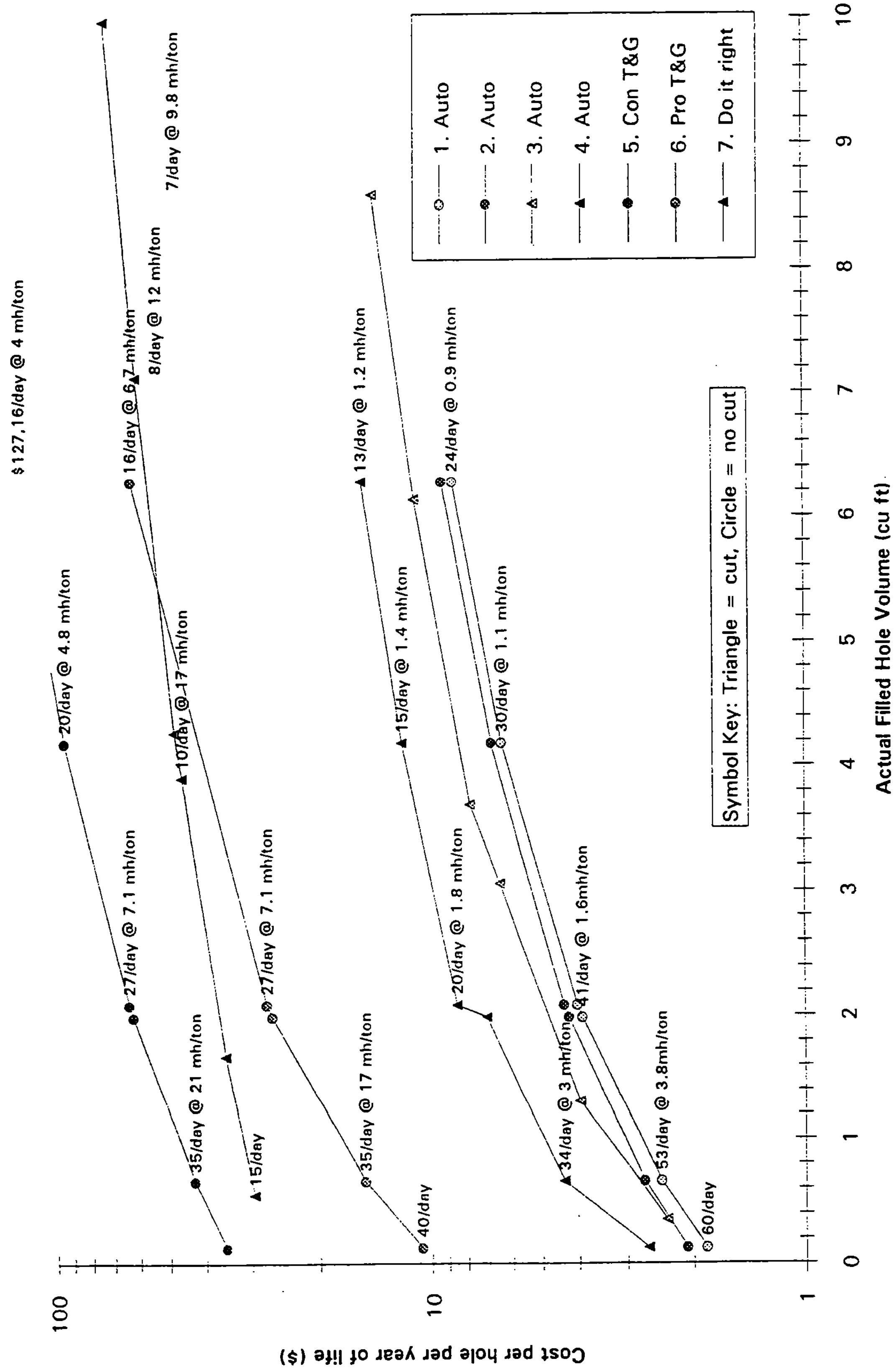


Figure B-1. Estimated Cost Comparison of Different Pothole Patching Cases

AUTOMATED **POTHOLE REPAIR COST ESTIMATION**

Repair Time:	Cubic ft	Minute	Procedure
Minimum Repair Time	0.15	5	(vac/heat/tack/fill)
Extra Time per Vol.	1	2	(vac/heat/tack/fill)
Cutting Used (Y/N)	N	6	(per cu ft enlargement)

Productivity:				
Orig. Hole Radius	6.00	(in)	0.50	(ft)
Orig. Hole Depth	2.00	(in)	0.17	(ft)
Orig. Hole Volume	0.13	(cu ft)		
Orig. Hole Area	1.31	(sq ft)		
Cut. Rad. Enlargemen	2.00	(in)	0.17	(ft)
Cut Depth Enlargemen	1.00	(in)	0.08	(ft)
Filled Hole Volume	0.13	(cu ft)	0.00	(cu ft enlargement)
Filled Hole Area	1.31	(sq ft)	0.00	(cu ft of cut spoil)
Material Weight	120	(lbs/cu ft)		
Material Used	16	(lbs/hole)		
Calc. Repair Time	5	(min)		**Required Capacities**
Between hole delay	3	(min)		
Work Time Available	8	(hrs)		**Material Capacity**
Repaired Holes/day	60		2700	(lbs/cu yd rock)
Fill Material Used	0.47	(tons/d	0.35	(cu yd/day)
Days of Oper./year	300			**Waste Capacity**
Repaired Holes/year	18000		0.29	(cu yd norm. waste/day max)
Ann. Fill Matl. Used	141	(tons)	0.00	(cu yd cut spoil/day)
Aver. Repair Lifetim	3.20	(years)	0.29	(total cu yd max vac vol.)
Total Cost per hole	5.92	($)		
Total Cost/Hole/year	1.85	($ per year)		

Labor Costs:	Persons	$/hour	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Driver	1	15	50	$382	$180	$54,000
Operator	0	12	50	$0	$0	$0
HMW	0	10	50	$0	$0	$0
Total Labor Cost				$382	$180	$54,000

Material Costs:	$/ton	tons/day	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Patch/ton	30	0.47	10	$33	$16	$4,663
Fuel/ton	3	----	10	$3	$2	$466
Daily Vehicle Fuel	10	----	10	----	$11	$3,300
Total Material Cost				$36	$28	$8,429

Equipment Costs:	Cost $K	Amort Yr	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Vehicles	250	15	10	$295	$139	$41,667
Support	10	7	10	$17	$8	$2,429
Total Equipment Cost				$312	$147	$44,095
Total All Costs				$731	$355	$106,524

Figure B-2. Example Spreadsheet for Patching Case 1.

AUTOMATED

POTHOLE REPAIR COST ESTIMATION

Repair Time:	Cubic ft	Minute	Procedure
Minimum Repair Time	0.15	5	(vac/heat/tack/fill)
Extra Time per Vol.	1	2	(vac/heat/tack/fill)
Cutting Used (Y/N)	N	6	(per cu ft enlargement)

Productivity:				
Orig. Hole Radius	6.00	(in)	0.50	(ft)
Orig. Hole Depth	2.00	(in)	0.17	(ft)
Orig. Hole Volume	0.13	(cu ft)		
Orig. Hole Area	1.31	(sq ft)		
Cut. Rad. Enlargemen	2.00	(in)	0.17	(ft)
Cut Depth Enlargemen	1.00	(in)	0.08	(ft)
Filled Hole Volume	0.13	(cu ft)	0.00	(cu ft enlargement)
Filled Hole Area	1.31	(sq ft)	0.00	(cu ft of cut spoil)
Material Weight	120	(lbs/cu ft)		
Material Used	16	(lbs/hole)		
Calc. Repair Time	5	(min)		
Between hole delay	3	(min)		
Work Time Available	8	(hrs)		
Repaired Holes/day	60			
Fill Material Used	0.47	(tons/d		
Days of Oper./year	230			
Repaired Holes/year	13800			
Ann. Fill Matl. Used	108	(tons)		
Aver. Repair Lifetim	3.20	(years)		
Total Cost per hole	6.66	($)		
Total Cost/Hole/year	2.08	($ per year)		

Required Capacities

Material Capacity

2700	(lbs/cu yd rock)
0.35	(cu yd/day)

Waste Capacity

0.29	(cu yd norm. waste/day max)
0.00	(cu yd cut spoil/day)
0.29	(total cu yd max vac vol.)

Labor Costs:	Persons	$/hour	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Driver	1	15	50	$382	$180	$41,400
Operator	0	12	50	$0	$0	$0
HMW	0	10	50	$0	$0	$0
Total Labor Cost				$382	$180	$41,400

Material Costs:	$/ton	tons/day	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Patch/ton	30	0.47	10	$33	$16	$3,575
Fuel/ton	3	----	10	$3	$2	$357
Daily Vehicle Fuel	10	----	10	----	$11	$2,530
Total Material Cost				$36	$28	$6,462

Equipment Costs:	Cost $K	Amort Yr	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Vehicles	250	15	10	$385	$181	$41,667
Support	10	7	10	$22	$11	$2,429
Total Equipment Cost				$407	$192	$44,095
Total All Costs				$826	$400	$91,958

Figure B-3. Example Spreadsheet for Patching Case 2.

AUTOMATED

POTHOLE REPAIR COST ESTIMATION

Repair Time:	Cubic ft	Minute	Procedure
Minimum Repair Time	0.15	5	(vac/heat/tack/fill)
Extra Time per Vol.	1	2	(vac/heat/tack/fill)
Cutting Used (Y/N)	Y	6	(per cu ft enlargement)

Productivity:				
Orig. Hole Radius	6.00	(in)	0.50	(ft)
Orig. Hole Depth	2.00	(in)	0.17	(ft)
Orig. Hole Volume	0.13	(cu ft)		
Orig. Hole Area	1.31	(sq ft)		
Cut. Rad. Enlargemen	2.00	(in)	0.17	(ft)
Cut Depth Enlargemen	1.00	(in)	0.08	(ft)
Filled Hole Volume	0.35	(cu ft)	0.22	(cu ft enlargement)
Filled Hole Area	2.44	(sq ft)	0.33	(cu ft of cut spoil)
Material Weight	120	(lbs/cu ft)		
Material Used	42	(lbs/hole)		
Calc. Repair Time	7	(min)		
Between hole delay	3	(min)		
Work Time Available	8	(hrs)		
Repaired Holes/day	50			
Fill Material Used	1.04	(tons/d		
Days of Oper./year	230			
Repaired Holes/year	11436			
Ann. Fill Matl. Used	239	(tons)		
Aver. Repair Lifetim	3.20	(years)		
Total Cost per hole	8.46	($)		
Total Cost/Hole/year	2.64	($ per year)		

Required Capacities

Material Capacity

2700	(lbs/cu yd rock)
0.77	(cu yd/day)

Waste Capacity

0.24	(cu yd norm. waste/day max)
0.60	(cu yd cut spoil/day)
0.84	(total cu yd max vac vol.)

Labor Costs:	Persons	$/hour	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Driver	1	15	50	$173	$180	$41,400
Operator	0	12	50	$0	$0	$0
HMW	0	10	50	$0	$0	$0
Total Labor Cost				$173	$180	$41,400

Material Costs:	$/ton	tons/day	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Patch/ton	30	1.04	10	$33	$34	$7,900
Fuel/ton	3	----	10	$3	$3	$790
Daily Vehicle Fuel	10	----	10	----	$11	$2,530
Total Material Cost				$36	$49	$11,220

Equipment Costs:	Cost $K	Amort Yr	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Vehicles	250	15	10	$174	$181	$41,667
Support	10	7	10	$10	$11	$2,429
Total Equipment Cost				$184	$192	$44,095
Total All Costs				$393	$421	$96,715

Figure B-4. Example Spreadsheet for Patching Case 3.

```
AUTOMATED                   POTHOLE REPAIR COST ESTIMATION

Repair Time:                Cubic ft   Minute           Procedure
                            --------  --------  --------  --------  -------
Minimum Repair Time           0.15         5  (vac/heat/tack/fill)
Extra Time per Vol.              1         2  (vac/heat/tack/fill)
Cutting Used (Y/N)               Y         6  (per cu ft enlargement)

Productivity:
Orig. Hole Radius             6.00  (in)          0.50  (ft)
Orig. Hole Depth              2.00  (in)          0.17  (ft)
Orig. Hole Volume             0.13  (cu ft)
Orig. Hole Area               1.31  (sq ft)
Cut. Rad. Enlargemen          2.00  (in)          0.17  (ft)
Cut Depth Enlargemen          1.00  (in)          0.08  (ft)
Filled Hole Volume            0.35  (cu ft)       0.22  (cu ft enlargement)
Filled Hole Area              2.44  (sq ft)       0.33  (cu ft of cut spoil)
Material Weight                120  (lbs/cu ft)
Material Used                   42  (lbs/hole)
Calc. Repair Time                7  (min)               Required Capacities
Between hole delay               3  (min)
Work Time Available              8  (hrs)               Material Capacity
Repaired Holes/day              50                2700  (lbs/cu yd rock)
Fill Material Used            1.04  (tons/d       0.77  (cu yd/day)
Days of Oper./year             230                      Waste Capacity
Repaired Holes/year          11436                0.24  (cu yd norm. waste/day max)
Ann. Fill Matl. Used           239  (tons)        0.60  (cu yd cut spoil/day)
Aver. Repair Lifetim          1.78  (years)       0.84  (total cu yd max vac vol.)
Total Cost per hole           8.46  ($)
Total Cost/Hole/year          4.75  ($ per year)

Labor Costs:                Persons   $/hour  Ovrhd %  Cost/ton  Cost/day  Cost/yr
                            --------  --------  --------  --------  --------  ---------
Driver                           1        15        50      $173      $180    $41,400
Operator                         0        12        50        $0        $0         $0
HMW                              0        10        50        $0        $0         $0
--------------------        --------  --------  --------  --------  --------  ---------
Total Labor Cost                                            $173      $180    $41,400

Material Costs:             $/ton    tons/day  Ovrhd %  Cost/ton  Cost/day  Cost/yr
                            --------  --------  --------  --------  --------  ---------
Patch/ton                       30      1.04        10       $33       $34     $7,900
Fuel/ton                         3      ----        10        $3        $3       $790
Daily Vehicle Fuel              10      ----        10      ----       $11     $2,530
--------------------        --------  --------  --------  --------  --------  ---------
Total Material Cost                                          $36       $49    $11,220

Equipment Costs:            Cost $K  Amort Yr  Ovrhd %  Cost/ton  Cost/day  Cost/yr
                            --------  --------  --------  --------  --------  ---------
Vehicles                       250        15        10      $174      $181    $41,667
Support                         10         7        10       $10       $11     $2,429
--------------------        --------  --------  --------  --------  --------  ---------
Total Equipment Cost                                        $184      $192    $44,095
====================        ========  ========  ========  ========  ========  =========
Total All Costs                                             $393      $421    $96,715
```

Figure B-5. Example Spreadsheet for Patching Case 4.

```
CONV THROW & GO             POTHOLE REPAIR COST ESTIMATION

Repair Time:          Cubic ft   Minute          Procedure
                      --------  --------  --------  --------  -------

Minimum Repair Time       0.15         5  (sweep/fill/level/truck)
Extra Time per Vol.          1         3  (sweep/fill/level/truck)
Cutting Used (Y/N)           N         0  (per cu ft enlargement)

Productivity:
Orig. Hole Radius         6.00  (in)         0.50  (ft)
Orig. Hole Depth          2.00  (in)         0.17  (ft)
Orig. Hole Volume         0.13  (cu ft)
Orig. Hole Area           1.31  (sq ft)
Cut. Rad. Enlargemen      2.00  (in)         0.17  (ft)
Cut Depth Enlargemen      1.00  (in)         0.08  (ft)
Filled Hole Volume        0.13  (cu ft)      0.00  (cu ft enlargement)
Filled Hole Area          1.31  (sq ft)      0.00  (cu ft of cut spoil)
Material Weight            120  (lbs/cu ft)
Material Used               16  (lbs/hole)
Calc. Repair Time            5  (min)              Required Capacities
Between hole delay           7  (min)
Work Time Available          8  (hrs)              Material Capacity
Repaired Holes/day          40               2700  (lbs/cu yd rock)
Fill Material Used        0.31  (tons/d      0.23  (cu yd/day)
Days of Oper./year         230                     Waste Capacity
Repaired Holes/year       9200               0.19  (cu yd norm. waste/day max)
Ann. Fill Matl. Used        72  (tons)       0.00  (cu yd cut spoil/day)
Aver. Repair Lifetim      0.31  (years)      0.19  (total cu yd max vac vol.)
Total Cost per hole      10.90  ($)
Total Cost/Hole/year     35.15  ($ per year)

Labor Costs:          Persons   $/hour    Ovrhd %  Cost/ton  Cost/day  Cost/yr
                      --------  --------  -------- --------  --------  ---------

Driver                       1        15        50     $573      $180    $41,400
Operator                     0        12        50       $0        $0         $0
HMW                          2        10        50     $764      $240    $55,200
--------------------  --------  --------  -------- --------  --------  ---------
Total Labor Cost                                     $1,338      $420    $96,600

Material Costs:       $/ton     tons/day  Ovrhd %  Cost/ton  Cost/day  Cost/yr
                      --------  --------  -------- --------  --------  ---------

Patch/ton                   30      0.31        10      $33       $10     $2,383
Fuel/ton                     0      ----        10       $0        $0         $0
Daily Vehicle Fuel           5      ----        10     ----        $6     $1,265
--------------------  --------  --------  -------- --------  --------  ---------
Total Material Cost                                     $33       $16     $3,648

Equipment Costs:      Cost $K   Amort Yr  Ovrhd %  Cost/ton  Cost/day  Cost/yr
                      --------  --------  -------- --------  --------  ---------

Vehicles                     0        15        10       $0        $0         $0
Support                      0         7        10       $0        $0         $0
--------------------  --------  --------  -------- --------  --------  ---------
Total Equipment Cost                                     $0        $0         $0
====================  ========  ========  ======== ========  ========  =========
Total All Costs                                      $1,371      $436   $100,248
```

Figure B-6. Example Spreadsheet for Patching Case 5.

```
PROP THROW & GO            POTHOLE REPAIR COST ESTIMATION

Repair Time:             Cubic ft   Minute          Procedure
                         --------  --------  --------  --------  -------
Minimum Repair Time        0.15          5  (sweep/fill/level/truck)
Extra Time per Vol.           1          3  (sweep/fill/level/truck)
Cutting Used (Y/N)            N          0  (per cu ft enlargement)

Productivity:
Orig. Hole Radius          6.00  (in)         0.50  (ft)
Orig. Hole Depth           2.00  (in)         0.17  (ft)
Orig. Hole Volume          0.13  (cu ft)
Orig. Hole Area            1.31  (sq ft)
Cut. Rad. Enlargemen       2.00  (in)         0.17  (ft)
Cut Depth Enlargemen       1.00  (in)         0.08  (ft)
Filled Hole Volume         0.13  (cu ft)      0.00  (cu ft enlargement)
Filled Hole Area           1.31  (sq ft)      0.00  (cu ft of cut spoil)
Material Weight             120  (lbs/cu ft)
Material Used                16  (lbs/hole)
Calc. Repair Time             5  (min)             Required Capacities
Between hole delay            7  (min)
Work Time Available           8  (hrs)             Material Capacity
Repaired Holes/day           40               2700  (lbs/cu yd rock)
Fill Material Used         0.31  (tons/d      0.23  (cu yd/day)
Days of Oper./year          230                     Waste Capacity
Repaired Holes/year        9200               0.19  (cu yd norm. waste/day max)
Ann. Fill Matl. Used         72  (tons)       0.00  (cu yd cut spoil/day)
Aver. Repair Lifetim       1.08  (years)      0.19  (total cu yd max vac vol.)
Total Cost per hole       11.50  ($)
Total Cost/Hole/year      10.65  ($ per year)

Labor Costs:              Persons   $/hour  Ovrhd %  Cost/ton Cost/day  Cost/yr
                         -------- -------- -------- -------- -------- ---------
Driver                          1       15       50     $573     $180   $41,400
Operator                        0       12       50       $0       $0        $0
HMW                             2       10       50     $764     $240   $55,200
-------------------- -------- -------- -------- -------- -------- ---------
Total Labor Cost                                      $1,338     $420   $96,600

Material Costs:            $/ton  tons/day  Ovrhd %  Cost/ton Cost/day  Cost/yr
                         -------- -------- -------- -------- -------- ---------
Patch/ton                     100     0.31       10     $110      $35    $7,944
Fuel/ton                        0     ----       10       $0       $0        $0
Daily Vehicle Fuel              5     ----       10     ----       $6    $1,265
-------------------- -------- -------- -------- -------- -------- ---------
Total Material Cost                                     $110      $40    $9,209

Equipment Costs:         Cost $K  Amort Yr  Ovrhd %  Cost/ton Cost/day  Cost/yr
                         -------- -------- -------- -------- -------- ---------
Vehicles                        0       15       10       $0       $0        $0
Support                         0        7       10       $0       $0        $0
-------------------- -------- -------- -------- -------- -------- ---------
Total Equipment Cost                                      $0       $0        $0
==================== ======== ======== ======== ======== ======== =========
Total All Costs                                       $1,448     $460  $105,809
```

Figure B-7. Example Spreadsheet for Patching Case 6.

DO-IT RIGHT

POTHOLE REPAIR COST ESTIMATION

Repair Time:	Cubic ft	Minute	Procedure
Minimum Repair Time	0.15	20	(cut/dry/fill/compact)
Extra Time per Vol.	1	3	(cut/dry/fill/compact)
Cut/compact (Y/N)	Y	3	(per cu ft enlargement)

Productivity:				
Orig. Hole Radius	6.00	(in)	0.50	(ft)
Orig. Hole Depth	2.00	(in)	0.17	(ft)
Orig. Hole Volume	0.13	(cu ft)		
Orig. Hole Area	1.31	(sq ft)		
Cut. Rad. Enlargemen	4.00	(in)	0.33	(ft)
Cut Depth Enlargemen	1.00	(in)	0.08	(ft)
Filled Hole Volume	0.55	(cu ft)	0.41	(cu ft enlargement)
Filled Hole Area	3.49	(sq ft)	0.62	(cu ft of cut spoil)
Material Weight	120	(lbs/cu ft)		
Material Used	65	(lbs/hole)		
Calc. Repair Time	22	(min)		
Between hole delay	10	(min)		
Work Time Available	8	(hrs)		
Repaired Holes/day	15			
Fill Material Used	0.48	(tons/d		
Days of Oper./year	230			
Repaired Holes/year	3404			
Ann. Fill Matl. Used	111	(tons)		
Aver. Repair Lifetim	1.78	(years)		
Total Cost per hole	52.58	($)		
Total Cost/Hole/year	29.54	($ per year)		

Required Capacities

Material Capacity	
2700	(lbs/cu yd rock)
0.36	(cu yd/day)
Waste Capacity	
0.07	(cu yd norm. waste/day max)
0.34	(cu yd cut spoil/day)
0.41	(total cu yd max vac vol.)

Labor Costs:	Persons	$/hour	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Driver	1	15	50	$372	$180	$41,400
Operator	2	12	50	$595	$288	$66,240
HMW	2	10	50	$496	$240	$55,200
Total Labor Cost				$1,462	$708	$162,840

Material Costs:	$/ton	tons/day	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Patch/ton	30	0.48	10	$33	$16	$3,675
Fuel/ton	1	----	10	$1	$1	$122
Daily Vehicle Fuel	5	----	10	----	$6	$1,265
Total Material Cost				$34	$22	$5,062

Equipment Costs:	Cost $K	Amort Yr	Ovrhd %	Cost/ton	Cost/day	Cost/yr
Vehicles	20	15	10	$30	$14	$3,333
Support	32	7	10	$70	$34	$7,771
Total Equipment Cost				$100	$48	$11,105
Total All Costs				$1,596	$778	$179,007

Figure B-8. Example Spreadsheet for Patching Case 7.

APPENDIX C

ALTERNATIVE CONCEPTUAL DESIGNS

Conceptual Design Evaluation Method

The following pages show the output of a spreadsheet created to help evaluate and score different concepts. The top row of the printout lists the criteria being evaluated, and its relative weight as shown in Table C-1 below.

Table C-1. Weighted Evaluation Criteria

Weight	Evaluation Criteria
5	Patch performance (lifetime, annualized cost of repair)
5	Maintenance required (of production unit)
5	Safety feature to public and crew (obstruction, speed, etc.)
4	Operator difficulty of use (training requirements)
4	Cost of production unit (less important to prototype)
3	Versatility of unit (as opposed to narrow range of applications)
2	Technical difficulty in making prototype and production models
2	Supporting systems required (complexity of integrated system)
1	Other benefits/drawbacks (evolution to new materials/problems)

The right hand column of the spreadsheet is a one line description of the concept, organized into categories. Each concept had an explanatory document describing the concept at the time of the evaluation, but they are not included here. The final score for a given concept is found under the column "Wtd Aver" (Weighted Average). The score for a concept was determined by multiplying individual scores for each criteria by its relative weight (importance) and they adding the results across the row and dividing by 9 (the number of criteria). The highest possible score was

$((5 \times 5)+(5 \times 5)+(5 \times 5)+(5 \times 4)+(5 \times 4)+(5 \times 3)+(5 \times 2)+(5 \times 2)+(5 \times 1)) / 9 =$

$155 / 9 = 17.2$

An average score was

$((3 \times 5)+(3 \times 5)+(3 \times 5)+(3 \times 4)+(3 \times 4)+(3 \times 3)+(3 \times 2)+(3 \times 2)+(3 \times 1)) / 9 =$

$87 / 9 = 9.7$

The lowest possible score was 0.

From the total scores for each concept, it is possible to order them from best (highest score) to worst (lowest score). Many fair and unbiased decisions were made using this analysis method. The highest scoring concepts were tested for feasibility, and in some cases prototyped. When these did not succeed as well as expected, or when one concept came into conflict with another, the second highest scoring concept was tried, etc.

CONCEPTUAL DESIGN EVALUATION MATRIX

Repair	Maint	Safety	Oper Dif	Cost	Versatile	Tech Dif	Support	Other	Wtd Aver	
5	5	5	4	4	3	2	2	1		
										Vehicle System
5	5	5	5	4	4	3	4	2	15.4	Single vehicle
4	4	4	4	4	4	4	4	1	13.4	Single-vehicle plus material trailer
4	4	4	3	4	3	4	4	1	12.7	Single vehicle plus equipment trailer
4	3	3	3	3	5	4	3	2	11.7	Two vehicles
4	4	4	4	4	4	4	4	1	13.4	Truck cab with equipment/material trailer
										Initial Marking/Survey
4	4	4	4	3	3	3	3	1	12.2	2-D gray level pothole locating
5	5	5	4	4	4	4	3	2	15.0	3-D profiling by shadow effect
4	4	4	3	3	3	3	3	1	11.8	3-D profiling using colored illumination
4	4	4	4	4	4	3	2	1	12.8	3-D profiling by focus mapping
5	3	4	3	2	4	2	2	1	11.2	Laser profiling
3	5	5	3	3	3	2	2	1	11.9	Acoustical distance mapping
3	5	3	1	5	4	3	4	1	11.8	Manual drawing of pothole and depth estimation
										In-process Inspection
3	4	3	1	5	3	5	4	1	11.3	2-D gray level/color closeup inspection
5	5	5	4	4	4	3	3	2	14.8	3-D profiling by shadow effect
										Computer Control
3	3	3	1	3	4	4	3	1	9.8	Joystick control of tool manipulation
4	3	4	2	2	3	3	3	2	10.4	Joystick control of tool manipulation with computer override
4	4	4	5	2	3	2	2	1	11.8	Computer automated tool trajectory
5	5	5	3	3	3	3	3	1	13.4	Computer assisted tool trajectory with manual override
5	5	5	4	3	4	3	3	2	14.3	Computer generated tool path display with manual override
										Pothole Locating & Approach
4	4	3	3	2	2	2	2	1	10.0	Automated selection of suitable potholes
5	5	5	2	5	5	4	4	1	15.0	Manual selection of suitable potholes
5	5	5	2	5	5	3	3	1	14.6	Manual alignment over pothole with computer guidance
5	5	3	4	2	2	2	2	1	11.6	Computer automated alignment over pothole

Figure C-1. Conceptual Design Evaluation Matrix (Page 1 of 4).

Cavity & Edge Preparation

2	3	3	4	3	2	3	3	1	9.7	Planer applied in the direction of vehicle travel
3	3	3	3	2	3	3	3	3	9.9	Planer attached to XYZ table
3	2	3	4	2	3	2	2	2	9.2	Array of multiple planers
3	2	3	3	2	3	2	2	2	8.8	Dual narrow planers on XZ axis
3	2	3	3	2	4	2	2	2	9.1	Assortment of planers on XZ axis
4	3	4	2	2	4	1	2	1	10.0	Vertical miller on XYZ table
4	3	4	2	1	4	2	3	3	10.2	Customized vertical miller on XYZ table
2	4	3	2	4	2	3	3	1	9.8	Rolling cutter
2	2	2	2	2	2	5	1	1	7.2	Jack hammer on XYZ table
3	2	3	3	1	3	2	2	1	8.2	Water-jet cutting
4	4	3	2	2	3	2	3	1	10.1	Hot-Air lance as cutter
5	5	5	5	5	3	4	4	2	15.8	Heating of edges and cavity
3	3	4	4	4	3	3	3	1	11.5	Brushing and blowing
3	3	3	3	3	2	1	3	1	9.3	Force sensor in bearings for detecting non-asphalt
3	3	3	3	3	3	2	2	1	9.7	Hydraulic pressure sensor/limits

Cleaning

5	4	4	4	3	4	3	2	3	13.1	Vacuum on XYZ table
5	3	4	4	3	4	2	2	2	12.2	Vacuum on cutter
5	5	5	5	3	5	3	2	3	15.0	Transverse vacuum nozzle under truck
3	5	4	5	4	3	2	3	1	12.9	Bank of pressurized air jets and collector
4	2	4	4	3	3	2	2	1	10.7	Array of oscillating brooms and collector
4	3	4	4	3	2	3	3	1	11.3	Rotating brush and collector
4	2	4	4	2	3	2	2	2	10.3	Array of brushes and collector

Drying/Heating

5	5	4	5	3	4	3	3	1		Electric heating panel
5	5	4	5	4	4	4	4	2	15.1	LPG or Nat Gas heating panel
4	4	3	4	4	4	4	2	1	12.4	Hot-Air Lance on articulated arm
4	3	3	4	4	4	3	2	1	11.7	Electric powered heat gun on articulated arm
4	2	3	4	2	3	2	2	1	9.7	Microwave
5	4	5	5	3	4	3	3	2	14.2	IR thermometer for control and protection

Tacking

4	3	4	4	4	3	4	4	1	12.6	Bank of nozzles
4	2	4	3	3	4	3	3	2	11.1	Nozzle on XYZ table

Bulk Material Storage and Handling

4	3	3	4	3	3	3	3	1	11.1	Hopper with rolling-toothed breakers
5	4	4	4	4	4	4	3	1	13.8	Gravity feed hopper with heat
5	4	4	4	4	5	4	3	2	14.2	Heated emulsion tank with agitation
3	3	3	3	4	3	4	3	1	10.8	Dump truck with adjustable sliding partitions
4	2	2	3	3	3	3	2	1	9.3	Trailer with conveyor system
4	4	4	4	3	4	3	2	1	12.3	Force sensor to determine amount of material
4	4	4	3	3	3	3	2	1	11.6	Ultrasonic material detector
5	4	5	4	4	3	4	3	2	14.1	Optical material flow detector
3	3	4	3	3	3	3	3	1	10.7	Pre-measured batch size for a particular hole
4	5	4	4	3	4	3	3	1	13.1	Continuous flow to prevent clogging

Figure C-2. Conceptual Design Evaluation Matrix (Page 2 of 4).

Cold Mix Filling

3	2	3	3	3	2	3	2	1	9.0	Transverse auger with gates
3	3	4	4	3	2	3	2	1	10.6	Heated hopper with gates and breakers
5	3	5	3	4	4	4	3	2	13.4	Pressure filling of heated mix
5	5	5	3	5	5	4	3	2	15.3	Pressure filling of separate materials

Hot Mix Filling

3	1	3	2	2	2	2	2	1	7.3	Transverse heated auger with gates
4	2	3	3	2	3	2	2	1	9.2	Pressure filling of hot mix

Aggregate/Binder Pressure Filling

5	5	5	4	4	5	4	4	2	15.6	Articulated aggregate/emulsion spray nozzle
4	4	4	4	3	3	3	2	1	12.0	Hopper with gates and banks of emulsion nozzles
3	3	4	3	3	3	3	2	1	10.4	Hopper with surface application of emulsion
4	3	4	3	2	2	2	2	1	10.0	Hopper with subsurface injection of emulsion

Leveling

4	3	4	3	3	3	2	2	1	10.8	Contourable scraper bar
3	4	4	4	4	2	3	2	1	11.6	Multiple discreet-sized scrapers
4	3	4	3	3	3	2	2	1	10.8	Vibrating scraper bar with adjustable height
4	3	4	4	4	2	3	3	1	11.8	Leveling by hopper contact with pavement
5	5	5	4	4	5	4	4	2	15.6	Controlled material flow rate

Compaction/Consolidation

3	3	3	3	3	3	3	3	1	10.1	Single, transversely-fixed vibratory roller
4	3	3	3	2	4	2	2	1	10.1	Array of transversely-fixed vibratory rollers
3	2	3	3	3	3	2	2	1	9.1	Array of vibratory plate compactors
3	2	3	3	3	4	3	2	1	9.7	Vibratory plate compactor on XYZ table
4	3	4	4	2	4	3	2	2	11.4	Rotating carriage of vibratory rollers
3	4	3	4	3	3	3	3	1	11.1	Pneumatic rollers
5	5	5	4	4	5	4	3	2	15.3	High velocity pressure filling

Stabilization Sensing

4	3	3	3	2	2	2	3	1	9.7	Real-time force sensing
3	3	2	2	2	2	2	2	1	7.9	Post-compaction density sensing
5	4	4	4	3	4	4	3	2	13.4	In Process material flow sensing

Figure C-3. Conceptual Design Evaluation Matrix (Page 3 of 4).

Sealing

4	3	4	4	4	3	4	4	1	12.5	Bank of nozzles after filling
4	3	4	3	3	4	3	3	2	11.7	Articulated nozzle

Finishing/Top Coating

4	4	4	4	3	3	3	3	1	12.2	Hopper for sifting of sand/rubber particles
4	4	4	4	4	4	3	4	2	13.3	Pressure application of fines/sand/rubber

Final Cleanup

4	4	4	3	3	4	3	3	1	12.1	Vacumming by articulated nozzle
4	4	4	4	4	3	4	4	2	13.2	Vacumming by transverse nozzle
4	3	3	3	3	3	4	3	1	10.9	Rotating sweeper and collector

Tool Manipulation

5	3	3	4	3	3	3	3	1	11.7	XYZ hydaulic table
4	3	3	4	4	3	4	3	1	11.8	XZ manipulation with stationary truck
4	3	3	3	4	4	3	2	2	11.3	XZ manipulation with Y truck
5	3	4	3	3	4	2	2	2	11.8	Two or three link swing arm
5	4	5	4	4	4	4	3	2	14.4	Articulated boom with nozzle
5	4	4	3	3	4	2	2	2	12.3	Automated backhoe arm
2	5	4	4	4	2	4	4	1	12.2	Truck motion only
4	3	4	4	4	4	4	3	2	12.8	Tool changing
4	2	3	2	2	4	2	3	2	9.4	Multiple arms/XY tables

Figure C-4. Conceptual Design Evaluation Matrix (Page 4 of 4).

APPENDIX D

OPERATIONAL REQUIREMENTS

A set of general operational requirements was developed to help guide the conceptual development. It was specified by SHRP that the system should operate for a full day without replenishment of material or fuel, and that spoil should be dumped once per day. It was also important to keep the vehicle size within acceptable limits and operable at highway speeds when moving between repair sites. Additional requirements are presented below.

Approximate repair cycle time: 20 minutes +/- 5 minutes for 5 cubic feet original hole size, depending on geometry and repair procedure.

Pavement type: Pancake, flexible base, or rigid composite base.

Original Pothole Size Limits: 1 - 6 inch depth, 1 - 10 square feet, 0.2 - 5 cubic feet volume. Optimized for 2 - 4 inch depth, 2 - 6 square feet, 0.5 - 2 cubic feet volume.

Pothole Frequency and Location: Closely spaced or infrequent. Anywhere in 12 foot lane width but optimized for wheelpaths assumed to be 7 to 8 feet center- to-center, 2 feet wide.

Lane Occupancy: If outermost edge of pothole (after cleaning) is within 1-2 feet of adjacent lane, then adjacent lane closure required.

Traffic Conditions: Assumed Average Daily Traffic (ADT) > than 300 with > 10% trucks. Emphasize application in heavy traffic areas > 10,000 ADT, under poor weather.

Safety Provisions: Arrow signs required and dump truck trailing vehicle if required of system. Dual rear view mirrors, temperature/pressure gauges in direct view of operator. All safety equipment to conform to OSHA and Manual on Uniform Traffic Control Devices (MUTCD) standards.

Overall Repair Procedure: Marking, cutting, cleaning, tacking, filling, leveling, compacting, sealing, clean up. Not all of these steps are required for all of the materials to be considered. Equivalent procedures to accomplish a permanent repair are acceptable.

Survey / Marking Capability: Upon positioning the vehicle for a repair, the system must locate and measure the pothole, present recommendations for the repair procedure, and automate the tracking of tools and procedures on the pothole.

Cutter Capability: Asphalt materials and existing pothole patching compounds to 6 inch depth maximum in one or more passes.

Spoil Holding Capacity: Approximately 2 cubic yards (3,780 lb. @ 50% density)

Spoil Unloading Frequency: At end of workday.

Cleaning Capability: Non-contact vacuum and blowpipes may be used, as well as high velocity heated air. No open flames applied to pavement surface. Contact devices such as brooms or squeegees may be used provided they can be automatically controlled.

Drying Capability: If required of the material, infrared methods or hot-air may be used in controlled fashion.

Tacking Capability: If required of the material, the tack coat will be sprayed into the hole automatically.

Tack Capacity: At least 50 gallons (heated as necessary).

Filling Capability: The system will be able to fill the prepared cavity automatically with one or more of the specified materials. This is discussed in detail below.

Total Material Capacity: Approximately 6 tons.

On-demand Repair Material Capacity: Approximately 1,000 lb. of material (heated if necessary), for a given hole.

Repair Materials: The complete system must be compatible with the materials specified by SHRP, but not simultaneously. A change of materials may require modifications to the system.

Material Heating and Storage: Material in tanks kept at 120 - 350 degrees F (+/- 25 degrees F) or as per material requirements, even at ambient temperature of 0 degrees F. Sufficient heating fuel for 10 hours operation. Ignition systems subject to outfire protection.

Material Loading Frequency: Once per day for maximum productivity rating.

Leveling Capability: If the material is not self-leveling, or if it is not leveled as applied, then it must be automatically shaped to match the level of the surrounding pavement, plus an overfill to account for any compaction requirements.

Compaction Capability: If required of the material, compact the filler to 95% density (ASTM D 1559), and match the level to the surrounding pavement. If a roller is used, its axis must be able to follow wheel ruts.

Sealing Capability: If required of the material, the edges of a filled pothole may be sealed with a material applied automatically.

Sealing Capacity: At least 50 gallons (heated as necessary).

Clean Up Capability: After repairs are completed, the system will drive away without leaving debris in the roadway, and the repair in drive-over condition.

Electrical System: Heavy duty and well regulated to supply automated components, computers, safety devices, and control systems with power.

Hydraulic System: Heavy duty as per automation and material handling requirements.

Vehicle Engine and Power Train: Assumed to be diesel and or propane powered with automatic transmission. Base and trailers restricted to be commercially available or customized and compatible with state highway pavement repair operations. Desirable to limit to 8 feet wide.

Power Take Off (PTO): Selected equipment modules will have PTO as well as any material trailer.

Weather Limitations: Moderate precipitation. Dense fog. Temperatures below 0 degrees F. Day or night operation required.

Estimated Performance Standard: Based on 8 hour shift, there are 420 minutes of net working time available. Assuming closely spaced potholes and an average repair cycle of 20 minutes, results in 21 holes of an average filled volume of 5 cubic feet compacted to 130 lb./cubic foot is 6.83 tons per day at 5.1 man-hours/ton (5 worker caravan) or 2 man-hours/ton (2 workers). Pothole size and labor force is a large factor in these calculations.

APPENDIX E

PAVEMENT CUTTER PROTOTYPE

Pavement Cutter Prototype and Test

The pavement cutter is shown in operation in Figures E-1, 2, and 3, taken from the videotaped testing. Shown in the footage is an approach to a cavity (E-1), cutting the cavity (E-2), and retraction away from the shaped cavity (E-3). After some design revisions, it passed all test requirements. The cutter head rotates at 290 RPM under a hydraulic pressure of 2200 PSI. The head is 10 inches in diameter overall, thus limiting its use to potholes larger than that. The cutting rate at the carbide tips is 760 feet per minute. Material removal rate depends mostly on the pavement structure and somewhat on the operator skill, but 0.2 to 0.5 cubic feet per minute is attainable. A two or three foot diameter cavity can be routed effectively in a few minutes. The lifetime of the carbide tips is not yet known (none have worn sufficiently to warrant replacement as yet). The hydraulic arm was mounted on the front bumper of the truck, near a central position. Power comes from the front PTO and a joystick in the cab controls motion through hydraulic servo valves.

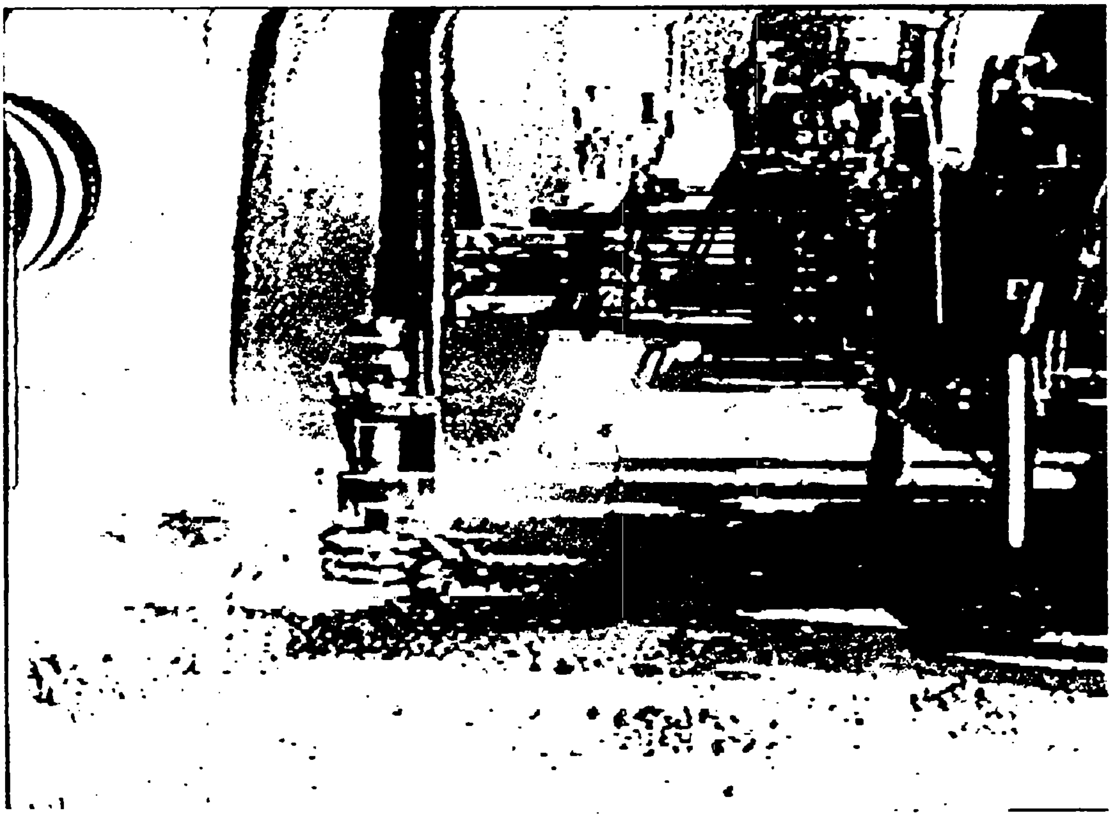


Figure E-1. Cutter Approaching Pothole

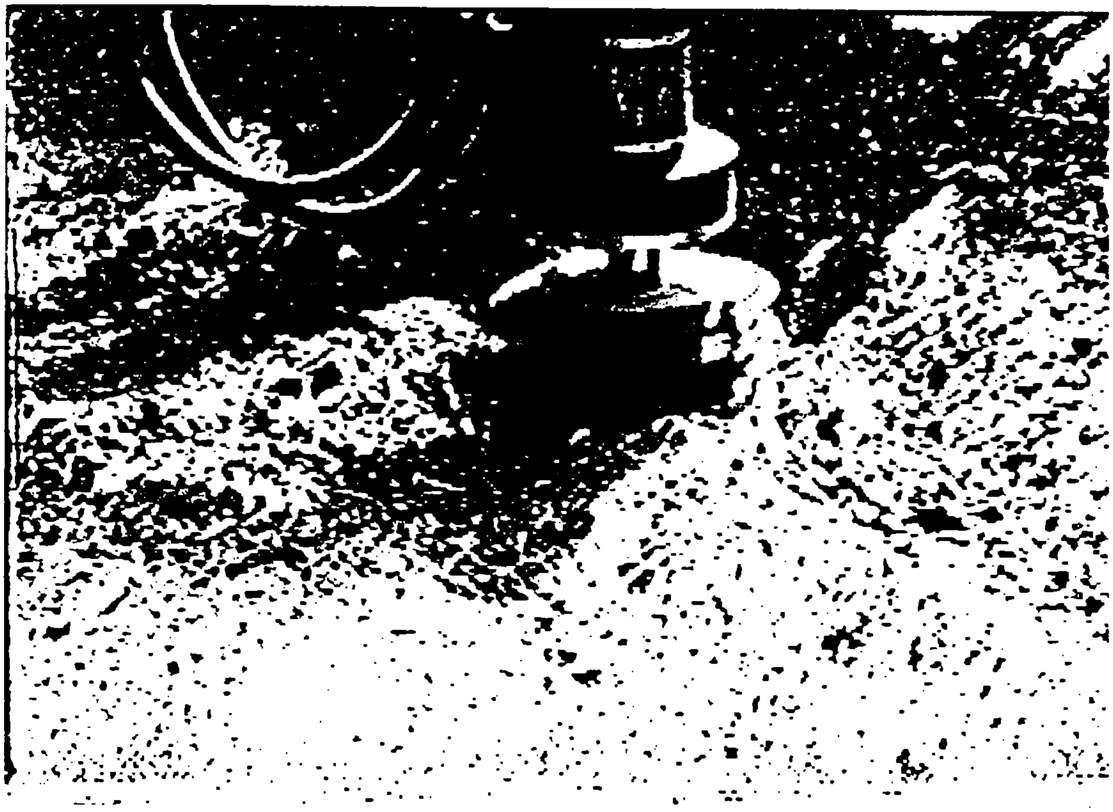


Figure E-2. Cutter Shaping Pothole

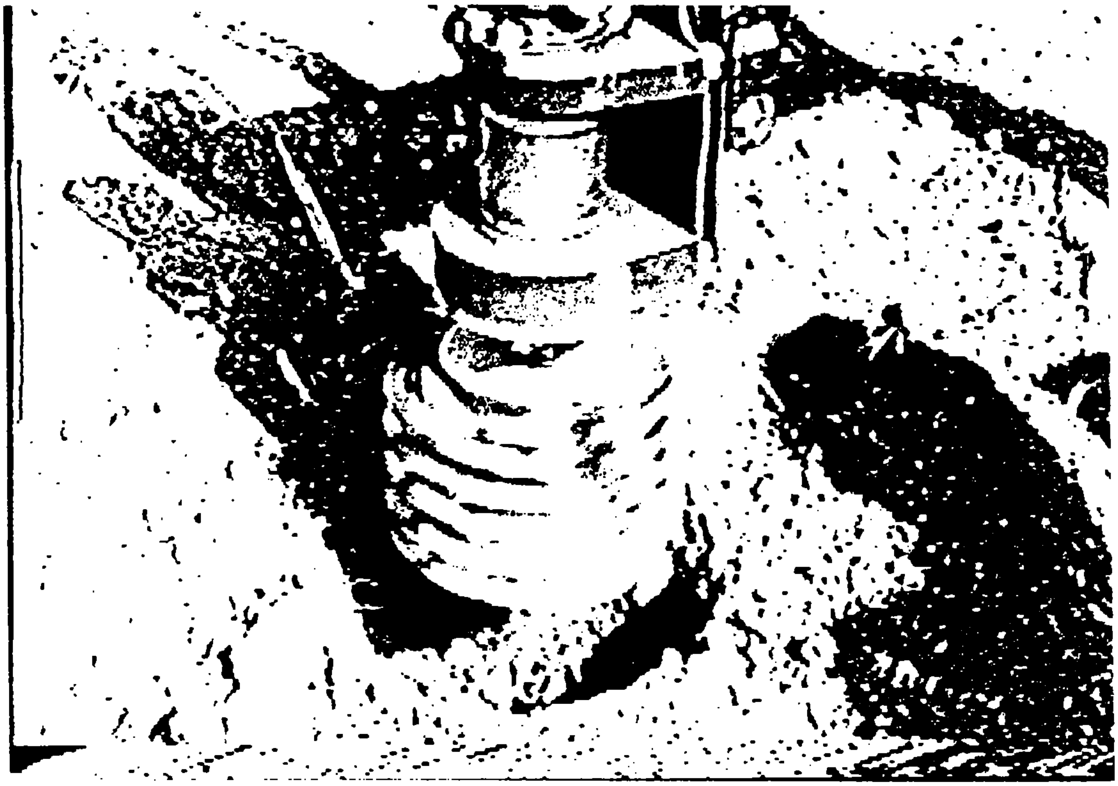
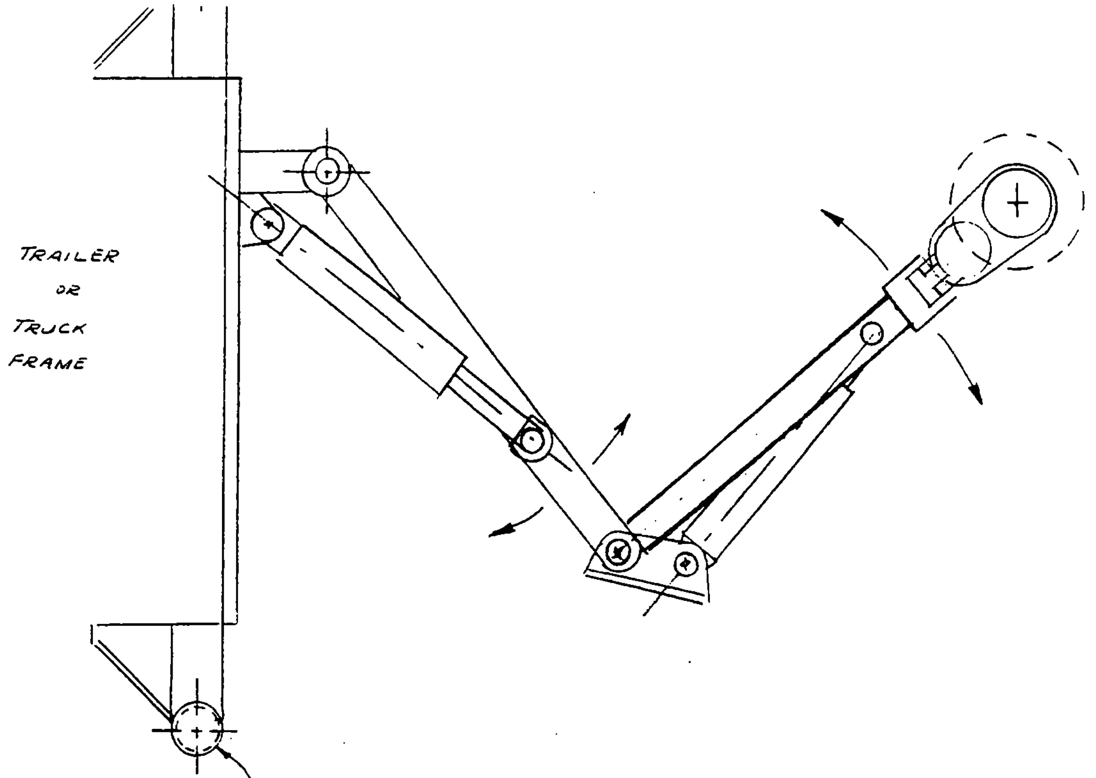
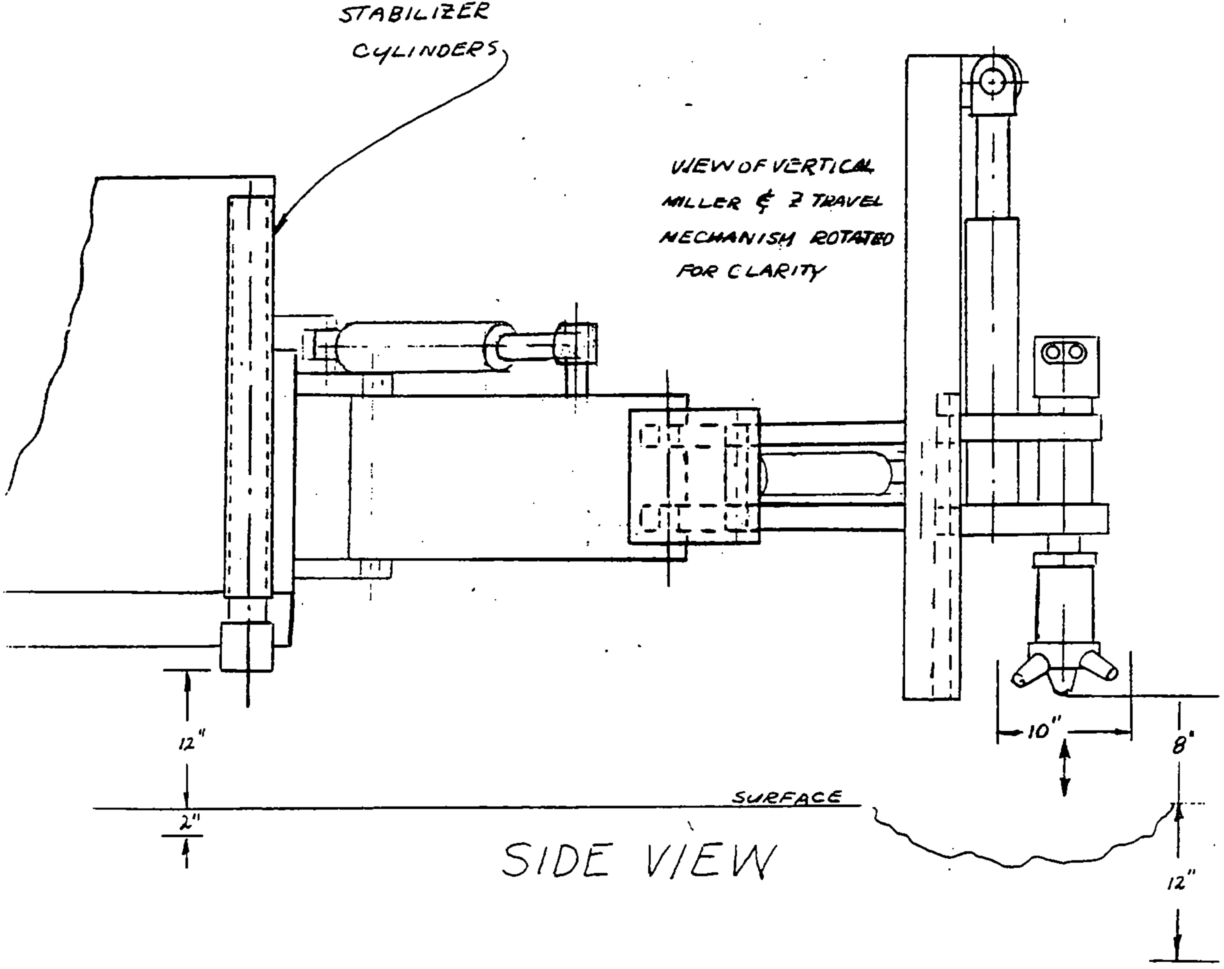


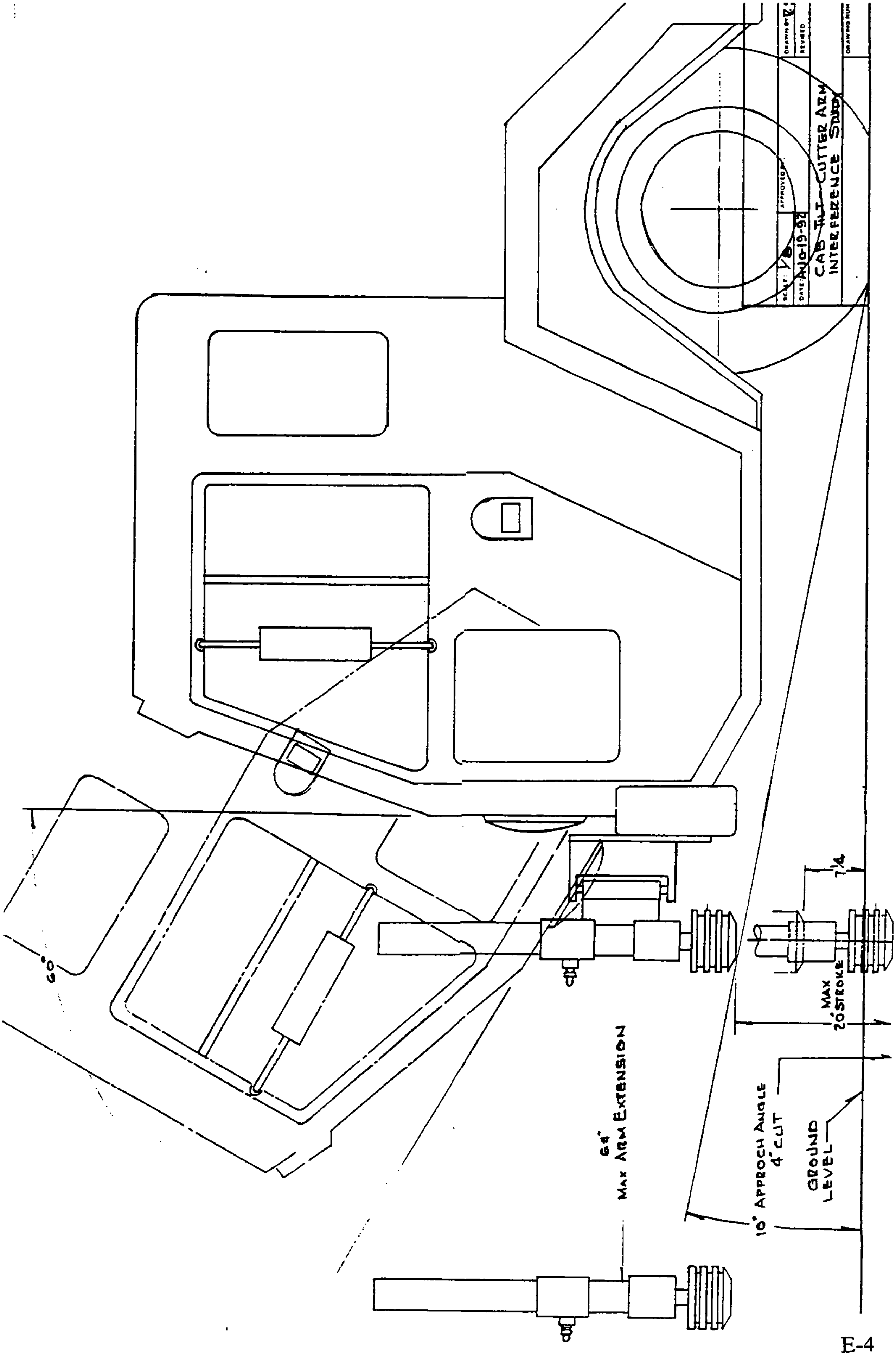
Figure E-3. Results of Cutter Shaping Pothole



TOP VIEW



SIDE VIEW


DRAWN BY R
REVISED
DRAWING NUM
APPROVED BY
SCALE: 1/8
DATE: AUG-19-92
CAB TILT-CUTTER ARM INTERFERENCE STUDY
60°
64" MAX ARM EXTENSION
MAX 20"STROKE
7 1/4
10° APPROCH ANGLE 4" CUT
GROUND LEVEL

APPENDIX F

VACUUM CLEANING PROTOTYPE

Vacuum Cleaning Prototypes and Testing

A positive displacement type of vacuum was tested in the first prototype built by Crafco. This unit employs a Paxton blower driven from a 23 HP diesel engine governed to a speed of 2800 RPM. The collection hopper is 200 gallons (27 cubic feet) and filtered by drum-type cylindrical filters. The trap door at the rear of the horizontal cylinder collection hopper allows simple drainage of water from the tank when vacuum is off. The 3 inch nozzle allowed a vacuum of 23 inches of water to be developed at the inlet. It was interesting to note that although the nozzle was 3 inches diameter, a rock measuring 3.5 x 2.5 x 2.0 inches was sucked up easily. It rotated in flight unfortunately and thus caused a blockage. The rock itself had a high specific gravity of 5.5 (with a weight of nearly 1 pound) demonstrating the strength of the prototype. The second generation prototype with a stronger blower and larger hose was stronger yet.

Another positive displacement system was tested. Hi-Vac makes an industrial vacuum cleaner of specification close to the pothole truck requirements. The unit is expensive however, and contains many additional features not required for our use. The blower size and capacity exceeds our requirements, however.

To summarize the findings, the large recirculator type systems are too large to include in this vehicle for pothole repair. However, pothole debris is handled very well by positive displacement type vacuums which are smaller with greater suction. In a recirculator design, when a blockage occurs the vacuum decreases. This is because the vacuum comes from the movement of air in the nozzle and filtration system. The design works best for dust collection.

In the positive displacement type, a blockage causes vacuum pressure to increase dramatically which acts to clear the blockage. The nozzle must not become blocked however, so a cross-hair over the front of the nozzle will help to prevent larger rocks from entering the system.

One approach considered was to use a small nozzle on the front cutter to remove water, cutting spoil, and other debris before the rest of the repair. A wide vacuum nozzle (coming from the recirculator concept) would then be ideal for sweeping up over spray from the velocity filling system. This material will be uniform in size (about 3/8 inch aggregate) and scattered over the width of the repair box. The actual quantity swept up would be small but spread out--ideal for a wide nozzle. The blower would have to be considerably more powerful than the Paxton used on the Crafco design. Calculations were made to choose one blower for the combined job of vacuuming (using the inlet side) and spray patching (using the outlet side). Our feeling after testing the wide nozzle was that the blower requirements could not be easily met within budget. An alternative was chosen to use a single nozzle on the end of the robot arm to do both vacuum cleaning before the repair and cleanup after. The filter used for the vacuum must remove even fine particulate from the vacuumed air to protect the blower. About 90% filtration at the 10 micron size should be sufficient and that makes the exit air of practically breathable quality.

APPENDIX G

COMPUTER VISION PROTOTYPE

Figure G-1 shows a pothole illuminated with a white strip of light obtained by a 3 inch long halogen lamp screened by a 0.25 inch wide by 10 inch long slit in a plate of metal, using the structured lighting technique shown previously in Figure 3-1.

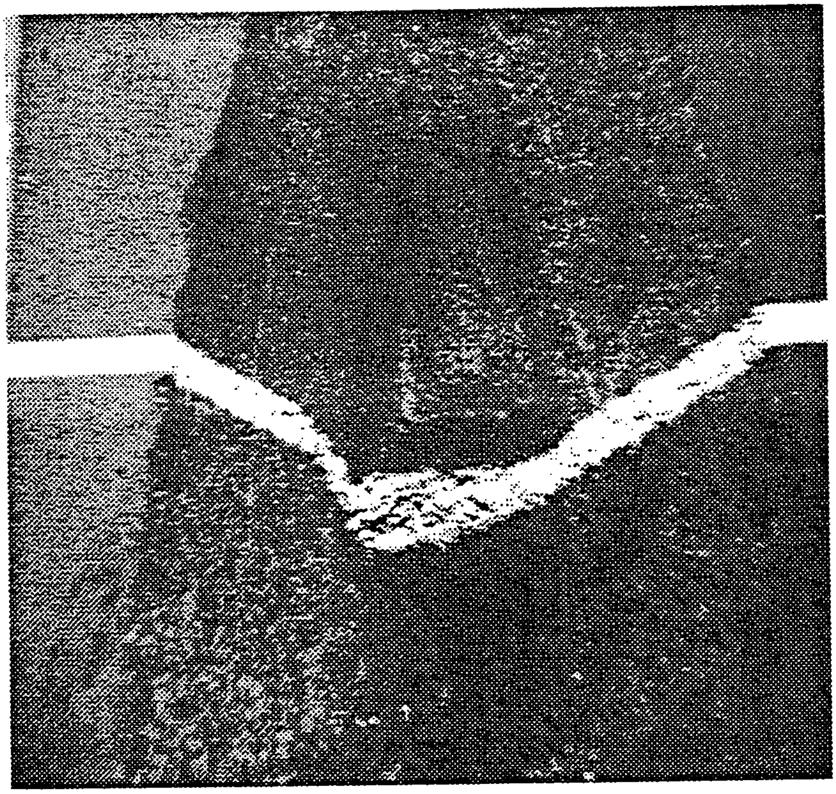


Figure G-1. 3-D Structured Lighting with White Light.

Clearly the strip of light shows the geometry of the pothole when viewed from a CCD (TV) camera at an angle. However, note that the pothole itself is visible to some extent and the strip of light varies in width as it intersects the surface of the cavity at different angles. An computer algorithm to calculate the depth profile is hampered by these problems.

Figure G-2 shows a laser light source (5 mW HeNe) spread into a line by a cylindrical lens. When projected onto the same pothole and viewed from the same angle, the results are dramatically improved. In this case, the line is about 0.1 inches wide and it shows up well even with ambient light. A laser interference filter over the CCD camera would virtually eliminate the background pothole image leaving only a clean line to be scanned by the imaging algorithm.

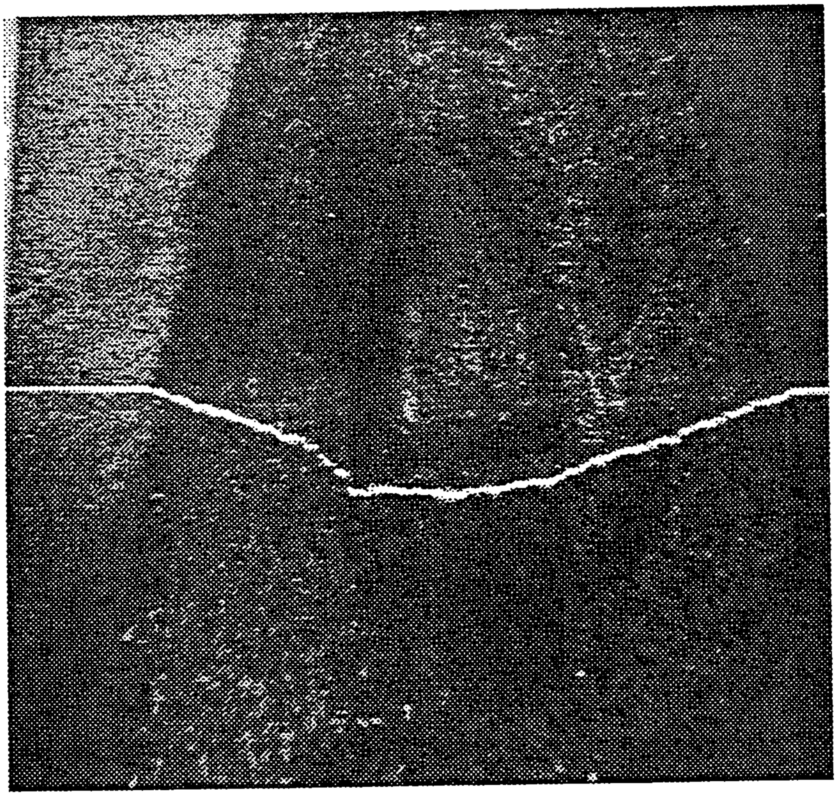


Figure G-2. 3-D Structured Lighting with Laser Light.

We also tested a commercial 3-D laser scanning system. Perceptron makes high performance 3-D depth sensors using laser light operating in a radar mode. The sensor unit measures about 6x9x9 inches and it can be located on the ceiling of the repair box out of harm's way. The sensing technology was developed for military application in tanks and has been in use for years in automotive manufacturing plants.

APPENDIX H

ROBOT MANIPULATOR PROTOTYPE

The robotic control system is comprised of a PID type controller, amplifier, motor and encoder as shown in Figure H-1. Key PID (proportional, integration, derivative) parameters were calculated. The horsepower of the motors was carefully chosen to handle worst case scenarios and gear reduced to match mechanical impedances. The robot control computer calculates trajectories (based on the 3-D vision input) and sends point coordinates and acceleration parameters to the controllers. The controller may also take external inputs from aggregate flow sensors or emulsion flow sensors to adjust filling speed based on the process. Thus, a closed-loop process control can be achieved. Filling rates of up to 1 cubic foot per minute can be achieved at travel speeds of 1 foot per second or more. Accuracy and repeatability should be better than required. These specifications meet the requirements of pothole repair, and other pavement repair.

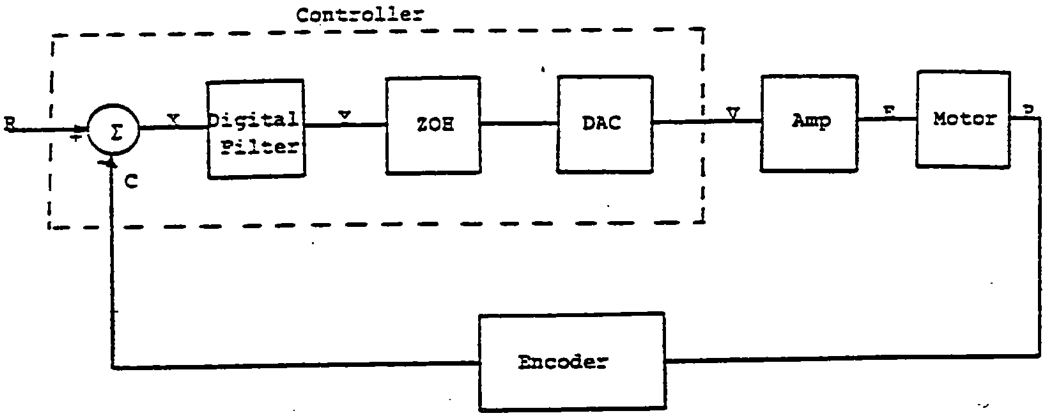


Figure H-1. Robot Control/System.

APPENDIX I

OPERATING PROCEDURAL GUIDE

TRUCK SYSTEM STARTUP/SHUTDOWN

Truck Startup
Place in Neutral.
Turn start key, press start button.
Wait for air pressure to build up.
Buzzer will sound until oil pressure is adequate.

Aggregate Loading
Key ignition must be on (for safety).
Press "raise" hopper door button to raise the desired side.
Loader can dump rock into hopper as desired.
Press "lower" button again to lower hopper door.
Repeat for other side if desired.

Emulsion Loading
Open side door near emulsion tank.
Open fill port on tank.
Pump in emulsion from asphalt supply tank.
Close port.
Close side door.

Start Genset
Press start switch located on the dashboard. Press "preheat" if cold weather.
Check instruments for proper operation.
Toggle the "start/preheat" switch to turn genset off.
Computer and controls will come on automatically.
Turn on computer/video monitors.
Watch computer monitor for proper operational status.

Truck Shutdown
Return truck to yard.
Select "shutdown" on computer.
Turn off genset.
Turn off truck.
Perform daily routine maintenance.

REPAIR SEQUENCE

Drive to Repair Site

On approach, select warning arrow to redirect traffic.
Approach pothole to within a few feet.

Cutting (optional)

Select "cut" option on computer screen.
Turn on power to joystick.
Using joystick, position cutter head near pothole.
Turn on cutter rotation.
Lower cutter head into pothole.
Move cutter around edges of pothole until sound edges are achieved.
Stop cutter rotation.
Raise cutter and retract to storage position.
Cutter can be left extended for next pothole if close-by.
Inform computer that cutting is complete.
This will inform computer to lower the repair box doors and turn on video camera.

Drive forward watching video camera for pothole to come into view.
Position repair box over pothole.

Select "3-D camera" measurement sequence.

Vacuum (optional)

Select "vacuum" operation if desired.
Automatic operation.
If vacuum selected, repeat "3-D camera" measurement sequence.

Heating (optional)

Select "heat" operation if desired.
Automatic operation.
In emergency condition, depress "stop" button on dashboard to halt propane flow.

Filling

Select "fill" operation.
Automatic operation.

Vacuum Cleanup (optional)

Select "vacuum cleanup" operation if desired.
Automatic operation.

Select "end sequence". Repair box doors will close automatically. Drive to next repair site or return to yard.

Highway Operations Advisory Committee

Dean M. Testa, *chairman*
Kansas Department of Transportation

Clayton L. Sullivan, *vice-chairman*
Idaho Transportation Department

Ross B. Dindio
The Commonwealth of Massachusetts Highway Department

Richard L. Hanneman
The Salt Institute

Rita Knorr
American Public Works Association

David A. Kuemmel
Marquette University

Magdalena M. Majesky
Ministry of Transportation of Ontario

Michael J. Markow
Cambridge Systematics, Inc.

Gerald M. (Jiggs) Miner
Consultant

Richard J. Nelson
Nevada Department of Transportation

Rodney A. Pletan
Minnesota Department of Transportation

Michel P. Ray
The World Bank

Michael M. Ryan
Pennsylvania Department of Transportation

Bo H. Simonsson
Swedish Road and Traffic Research Institute

Leland Smithson
Iowa Department of Transportation

Arlen T. Swenson
John Deere

Anwar E.Z. Wissa
Ardaman and Associates, Inc.

John P. Zaniewski
Arizona State University

Liaisons

Ted Ferragut
Federal Highway Administration

Joseph J. Lasek
Federal Highway Administration

Frank N. Lisle
Transportation Research Board

Byron N. Lord
Federal Highway Administration

Mohamed Y. Shahin
U.S. Army Corps of Engineers

Harry Siedentopf
Federal Aviation Administration

Jesse Story
Federal Highway Administration

8/16/93

Expert Task Group

E.B. Delano
Consultant

Peter A. Kopac
Federal Highway Administration

Frank N. Lisle
Transportation Research Board

Barry D. Martin
Saskatchewan Highways and Transportation

Richard Nicholson
QUIKRETE Technical Center

Leland Smithson
Iowa Department of Transportation

Arlen T. Swenson
John Deere

A. Haleem Tahir
American Association of State Highway and Transportation Officials

8/16/93