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Cost-Effective Use of Manpower for Manual Pothole Repair

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ABSTRACT

The Pennsylvania Department of Transportation annually spends more than $30 million for repairing potholes. The production and productivity of pothole repair crews during 1980 and 1981 were compared with the department's performance standard. Crews were observed using an air compressor or a gasoline-operated tool for cutting. For compaction, either a 4- to 6-ton roller or a walk-behind vibratory roller was employed. Delays in crew deployment and during the repair operations were responsible for low production and productivity. Major delay categories were analyzed in detail and were found to be associated directly with ineffective management on the part of the crew foreman. Realistic reduction of the frequency and duration of delays through the exercise of leadership and effective management is discussed. The resulting time savings are incorporated into productive time to compute the production and productivity potential of five-person, six-person, and seven-person crews. It is shown that a crew of five, equipped with the slower (gasoline-operated) cutting tool, can achieve the recommended performance standard.

Productivity of pothole repair crews is a state highway agency objective that must be balanced against the need to produce a long-lasting repair. To achieve durable repairs, the repair crew must be provided with high-quality material and adequate equipment. Repairs must be made according to the proper procedure (1-3). Even with the right material and equipment, however, many repair crews are underachievers with respect to productivity (manhours per ton) and production (tons per day) (4,5).

The objectives of this paper are to isolate the significant factors that inhibit production and productivity of pothole repair crews and to describe the steps that can be taken by the crew foreman to increase output. Throughout this paper, comparisons are made to the Pennsylvania Department of Transportation performance standard for manual repair of flexible and rigid base pavements (6). The standard includes a planning unit of 6 tons per day and a productivity target of 4.73 manhours per ton. The crew should consist of a foreman and four highway maintenance workers. Safety personnel must be added.

STUDY PARAMETERS

The recommendations in this paper are the result of a comprehensive pothole research program sponsored by the Pennsylvania Department of Transportation (5). The productivity analysis presented herein represents a portion of the overall study. The evaluation of pothole repair practices is based on numerous production studies of field operations conducted during the spring of 1980 and of 1981. The data collection techniques were as follows:

- Field documentation of pothole repair,
- Time-lapse photography,
- Supplemental film notes,
- Stopwatch studies, and
- Debriefing reports and field notebooks.

A total of 56 days were spent studying repair operations in eight Pennsylvania counties. Thirty-eight legislative routes, with moderate to high average daily traffic (ADT), were included in the studies, resulting in the observation of 462 pothole repairs.

The crews that were observed used conventional repair equipment. All repairs were in flexible-base and rigid-base pavements. Both cold mix and hot mix were used as repair materials. Crew sizes ranged from five to nine, including the foreman but excluding personnel needed for traffic control.

CATEGORIES OF POTHOLE REPAIR

The production studies indicate that there are two distinct categories of pothole repair operations. The first category is characterized by highly deteriorated pavements exhibiting a large number of potholes. Highway maintenance workers (HMWs) walk from one pothole to another. Except for traveling to the work location at the beginning of the day and returning to the maintenance shed at the end of the day, little vehicular travel is required. When there are numerous potholes, each HMW can perform the same function on each hole. The performance standard in Pennsylvania covers this type of operation (6). Organizing the crew in this manner is referred to as "productionizing the work." This paper is limited to the characterization of this type of pothole repair operation.

The second category of repair operation is one in which the frequency of potholes is very low. This means that the work crew must regularly load its equipment on the truck, retrieve safety devices and personnel, and drive to another work location. Much of the day is therefore consumed by travel and setup time. Obviously, the production rate (tons per day) defined in the performance standard cannot be realized under these circumstances.

ANALYSIS OF OPERATIONS ON ROADS WITH A HIGH FREQUENCY OF HOLES

To be productive, a pothole repair crew must be aware of the operations that control the overall repair process. In addition, the time required to perform each of the steps in a repair must be determined, and an analysis of the delays associated with each step must be made.

Times for Basic Operations

A durable repair requires that the work be divided into several basic operations: cutting, cleaning, tacking, filling, leveling, and compaction (6 and Anderson and Thomas, unpublished data). Using time-lapse photography and stopwatches, the average times required to complete these operations were documented. These are given in Table 1 and are the result of numerous studies conducted under a variety of job and management conditions. It should be noted that all delays have been excluded. These times, therefore, represent ideal times for completing the work.

TABLE 1 Ideal Time for Pothole Repair Processes (excluding delays)

Operation	Probable Time[a] (Minutes)
Cutting	
Air Compressor	4.66
Pionjär[b]	7.26
Cleaning	
One HMW[c]	7.61
Two HMWs	5.58
Tacking	0.77
Filling	
One HMW	3.72
Two HMWs	2.22
Leveling	1.90
Compaction	
4-to-6-Ton Roller	8.64
Essick Roller[d]	4.79

[a] Weighted average based on the pothole volume distribution.

[b] Gas-operated pavement breaker.

[c] Highway maintenance worker.

[d] Walk-behind vibratory roller.

Data for the cutting operations were collected for the air compressor and the gasoline-operated cutting tool. Both old and new air compressors were included in the study. Although all the gasoline-operated cutting tools were relatively new, several were not properly adjusted, so their efficiency was reduced. Sharp and dull bits were noted for both types of pavement breaker. Experienced and inexperienced operators were observed. The data from Table 1 indicate that the gasoline-operated cutting tool took about 56 percent longer than the air compressor to cut a hole; however, the cutting advantage of the air compressor was partly offset by the greater mobility of the gasoline-operated tool (7).

Cleaning was performed by one or more HMWs with a shovel and broom. Cleaning time with the air hose of a compressor was treated as a delay and was not considered. The time required to clean a hole was a function of hole size and the number of HMWs performing the task. Usually no more than two HMWs performed this task simultaneously. The times required to clean an average-size hole using one and two HMWs are given in Table 1. Two points are worth noting. First, contrary to what might be expected, the addition of an extra HMW did not proportionately reduce the time required to clean the hole; in fact, the time was reduced by approximately one-fourth instead of one-half. This illustrates the inefficiency of adding extra HMWs to the crew. The second point is that cleaning is not necessarily the most time-consuming operation in the total process. The idea that cleaning controls the rate at which potholes can be repaired is only partly correct, because most of the cleaning operations observed were basically disorganized. The number of HMWs assigned to cleaning varied from pothole to pothole, and when two or more HMWs were deployed at a pothole, they often worked in an erratic fashion.

The filling operation, like cleaning, was performed by one or more HMWs. Although the introduction of a second HMW significantly reduced the filling time, it was not considered to be cost-effective because filling takes much less time than either cutting or cleaning.

The compaction operations were performed with a walk-behind vibratory roller or a 4- to 6-ton roller. In general, the production studies showed that compaction times were highly variable; this indicates the need for the state highway agency (SHA) to provide more explicit guidelines for the compaction procedure.

The data given in Table 1 illustrate the effect that failure to "productionize" the work has on crew productivity. Assume that a five-person crew is equipped with an air compressor and a walk-behind vibratory roller. The crew repairs one hole completely before moving to the next hole. Thus, two HMWs can be used for both the cleaning and the filling operation. The total ideal time can be calculated from Table 1 as 19.92 min. By assuming a density of $135\ \text{lb/ft}^3$ and an average hole volume of $3.60\ \text{ft}^3$, the ideal daily production (assuming 335 min of productive work time) and productivity can be calculated as follows:

$$\text{Ideal production} = \left\{[(60/19.92)(135)(3.60)]/2{,}000\right\}(335/60) = 4.09\ \text{tons/day}$$

$$\text{Ideal productivity} = [5(335/60)]/4.09 = 6.83\ \text{manhours/ton}$$

This ideal rate is, of course, unattainable because no delays have been considered. Nevertheless, it serves to illustrate that even under perfect conditions it is impossible to achieve the planning unit of 6 tons per day or the productivity target of 4.73 manhours per ton unless the operation is productionized (1,5).

Delays and Inefficiencies

Operational Delays

Delays are an inherent part of any operation. Although they cannot be avoided entirely, many can be controlled--controlling and avoiding delays are at the heart of the management effort. Foremen must exercise leadership in this area. In the absence of leadership, delays will be uncontrolled.

The production studies identified the delays that affected pothole repair on a daily basis. These have been categorized (Table 2) according to each basic operation. The delay times were determined from more than 95 hours of observation of 48 repair operations on roads with a large number of holes. Although all

TABLE 2 Percentage of Total Delay Time for Each Operation

Activity	Cutting		Cleaning	Filling	Compaction
	Air Comp.	Pionjar[a]			
Receive Instructions	3	1	1	0	0
Wait for Instruction/Observe	29	33	3	10	3
Wait for Another Operation	4	1	2	7	9
Wait for Mix to Arrive	-	-	-	9	-
Wait for Pothole	4	-	39	37	59
Move to Another Pothole	2	2	0	3	2
Change Tools	-	-	1	-	-
Start/Refuel/Adjust Equip.	6	2	-	3	1
Clean Hole with Air Comp.	5	-	2	-	-
Wait for Traffic	0	0	0	-	0
Personal Delays	4	1	1	2	-
Undetermined Delays	3	9	2	3	2
Productive Work (Efficiency)	40	51	49	26	24

[a] Gas-operated cutting tool.

repair operations will not necessarily be performed at the same level of efficiency as those studied, the data do reflect a typical crew that was organized to work on three to five potholes at once.

The data in Table 2 highlight what is perhaps the most difficult task in controlling the productionized operation: the challenge to the foremen to keep the various operations progressing. In the 48 repair operations studied, this was achieved with only marginal success, as evidenced by the fact that approximately 31 percent of the time available for cutting the hole was spent waiting for instructions. Marking the holes would certainly contribute greatly to reducing this lost time. Improving the efficiency of the cutting operation would have a positive effect on the other operations because the major source of lost time is waiting for a hole to be available to work on. The cleaning, filling, and compaction operations had production time losses of 39, 37, and 59 percent, respectively.

How common are the delay times that are given in Table 2? This can be answered, at least in part, by examining the data given in Table 3. It should first be noted that the number of times an HMW was delayed, either by waiting for instructions or waiting for work, was roughly equal to the number of times an HMW moved to another hole. For the cutting operation, this suggests that the operator was waiting for instructions after completing each hole. For cleaning, filling, and compaction, delays due to lack of work occurred at a rate approximately equal to delays due to moving to a new hole. It can be concluded that the failure to keep the cutting operation progressing, which subsequently slowed the remaining operations, was a continuous problem and was not limited to a small number of crews. Delays of short duration can seem quite insignificant at the time, but the cumulative effect can be dramatic.

Controlling Operation

One of the time-tested principles of management is that equal energies and attention cannot be devoted to all of the tasks and subtasks constituting an

TABLE 3 Frequencies of Occurrence of Selected Types of Delays

Operation	Number of Times Observed		
	Wait for Instructions/ Observe	Move to Another Pothole	No Pothole Available
Cutting	70	65	2
Cleaning	22	19	47
Filling	76	94	53
Compaction	21	51	63
Total	189	229	165

operation. This principle holds true for pothole repair. It is therefore important for the foremen to know which operation controls the level of crew output, for it is there that foremen should concentrate their managerial efforts.

Analytic calculations supported by visual observations indicated that when the gasoline-operated cutting tool was being used, the cutting operation controlled the daily production rate because it took longer to cut a hole than to perform any of the other operations. When the air compressor was used, calculations showed that the cleaning operation took longest. It should be recognized that cutting and cleaning operations are performed in close proximity to each other. When the cleaning controls production, the pavement breaker operator tends to slow down so that he or she will not get too far ahead. If some distance is not maintained between the two operations, the cleaning will be delayed occasionally because there is no hole available to work on. If too much distance is maintained between the two operations, the cutting operation tends to slow down and the cleaning operation tends to accelerate. Contrary to the analytic results, it is believed that in all but very unusual situations the cutting operation will establish the pace of the work. Because each operation affects subsequent operations, foremen should concentrate most of their managerial efforts on keeping the cutting operation from slowing down.

Deployment Delays

A crew cannot achieve high levels of production unless the work is productionized and continuous throughout the day. Delays in deployment, which reduce crew efficiency, have a great effect on production.

Foremen need to be aware of the average amount of time that should be spent at the work location and the average time at which work should commence for the day. The following represents a realistic distribution of time for the total 7.5-hr shift:

Task	Time (min)
Travel to job site, deploy safety devices	30
Organize and start equipment	10
Coffee break, a.m.	15
Start up after lunch	5
Coffee break, p.m.	15
Clean up and put away tools	10
Retrieve safety devices, travel to maintenance shed	30
Productive work time	335
Total	450

Having the crew arrive at the job site on time is only one aspect of crew deployment. For the operation to run smoothly, the material should arrive no later than 15-20 min after the crew begins work. The filling of holes should begin almost immediately, because the crew is waiting and the holes have been prepared.

During the spring of 1980 the time parameters noted were recorded for 13 patching operations in four counties. Summaries are given in Table 4. Note that the filling began more than 1 hr after the holes had been prepared. This delay affected the cutting and cleaning operations. There should not be too much time between the cleaning and filling operations because this could create safety problems. The longer the crew waits to begin the filling operation, the greater is the likelihood that the cutting and cleaning will be interrupted to allow the filling to catch up.

Crew Size

What effect does crew size have on production and productivity? Table 1 shows the relative ineffi-

TABLE 4 Time Data on Crew Deployment

Work Location	Work Began	Material Arrived	Delay	Filling Began	Delay	Material
1	8:45	9:35	50	9:45	10	Cold Mix
2	8:35	9:15	40	9:20	5	Cold Mix
3	9:15	9:41	16	10:53	72	Cold Mix
4	9:53	Before 9:53	0	11:36	103	Cold Mix
5	9:00	10:00	60	10:57	57	Cold Mix
6	12:55	Before 12:55	0	2:00	65	Cold Mix
7	9:18	10:20	62	10:28	8	Hot Mix
8	10:07	9:50	0	10:15	25	Hot Mix
9	10:00	Before 10:00	0	10:30	30	Hot Mix
10	8:47	10:05	78	10:15	10	Hot Mix
11	8:10	9:15	65	9:25	10	Hot Mix
12	8:40	10:15	35	10:55	40	Hot Mix
13	9:11	10:40	89	10:40	0	Hot Mix
Average[a]	9:13	9:52	39	10:25	33	

[a] Excluding work location no. 6.

ciency of using more than one crew member in the cleaning and filling operations. Although total production may be increased slightly by adding an additional HMW to the cleaning operation, this will have an adverse effect on productivity.

Sample data on crew size gathered during 1980 and 1981 indicated that, for 18 crews involved in repair operations on roads with a high frequency of holes, the average crew size was seven. (The performance standard specifies five.) Both figures include the foreman but not those HMWs required for traffic control. The size of 15 of 18 crews (83 percent) exceeded the performance standard.

PRODUCTION AND PRODUCTIVITY CALCULATIONS

Upper Limit on 1980 and 1981 Operations

The calculation of the upper limit on production and productivity for the 1980 and 1981 pothole repair seasons was based on the time data given in Table 5. A seven-person crew using a walk-behind vibratory roller was assumed. Delays within and between operations were determined from the production studies (5).

With a seven-person crew, two HMWs could be used for both the cleaning and filling operations. Thus, for the air compressor the total time needed to complete a hole was 56.01 min. With a gasoline-operated cutting tool the total time was 58.75 min. Based on actual observations, the productive time available for repair operations to be performed averaged 285 min. In reaching this figure it was noted that on the average the crew arrived at the work location, deployed safety devices, and was ready to begin work by 8:55 a.m.

The data in Table 4 indicate that cutting typically started at 9:13 a.m., so that the net work time available (NWTA) for a single workday was 267 min (285 - 18). Furthermore, a seven-person crew using a compressor needed (56.01 - 11.80) 44.21 min to complete a pothole after it had been cut. Thus, a crew of seven equipped with a compressor could have a maximum production of

$$[267 - (56.01 - 11.80)]/11.80 = 18.88 \text{ potholes/day}$$

If the compressor were replaced with a gasoline-operated cutting tool, maximum production could be

$$[267 - (58.75 - 14.54)]/14.54 = 15.32 \text{ potholes/day}$$

Measurements taken with a nuclear gauge showed that operations achieved an average compaction density of 120 lb/ft^3. Because an average pothole has a volume of 3.60 ft^3, the seven-person crew employing a compressor could place a maximum of

$$(18.88) \times (3.60) \times (120)/2{,}000 = 4.08 \text{ tons/day}$$

With a gasoline-operated cutting tool, the same crew could place

$$(15.32) \times (3.60) \times (120)/2{,}000 = 3.31 \text{ tons/day}$$

Thus, a seven-person crew could have an average production of

$$(4.08 + 3.31)/2 = 3.70 \text{ tons/day}$$

Personal observations during the two pothole repair seasons indicated that a patching crew typically placed one truckload of approximately 4 tons. The computed production of 3.70 tons per day was therefore compatible with field observations. On the basis of these computations, it was concluded that during 1980 and 1981 patching crews were not achieving the 6 tons per day recommended in the performance standard.

TABLE 5 Actual Times for Component Operations, 1980-1981

Operation	Ideal Time (Minutes)	Time Taken by Delays Between Operations (Minutes)	Time Taken By Delays Within Operation (Minutes)	Actual Total Time (Minutes)
Cutting				
Air Compressor	4.66	5.57	1.57	11.80
Pionjär[a]	7.26	6.78	0.50	14.54
Cleaning				
One HMW[b]	7.61	7.31	1.10	16.02
Two HMWs	5.58	5.36	0.79	11.73
Tacking	0.77	--	--	0.77
Filling				
One HMW	3.72	9.49	1.67	14.88
Two HMWs	2.22	5.58	0.98	8.78
Leveling	1.90	--	--	1.90
Compaction				
Essick Roller[c]	4.79	14.08	2.16	21.03

[a] Gas-operated cutting tool.

[b] Highway maintenance worker.

[c] Walk-behind vibratory roller.

By applying the deployment data in Table 4 and assuming a daily production rate of 4 tons per day, crew productivity could be calculated as 9.42 manhours per ton. This is double the 4.73 manhours per ton recommended in the performance standard.

Production and Productivity Potential

Table 6 gives a summary of the target delay times that can be achieved through the application of improved management skills at the foreman level (1,5). These were subsequently used to compute the times needed to complete each phase of the repair. Summaries of these times are given in Table 7. Cleaning controls production when a compressor is used for cutting, and cutting controls production if a gasoline-operated cutting tool is employed.

Computations of potential production and productivity are based on the assumptions that (a) net work time available for a day's operation is 335 min, (b) the crew is properly deployed in a productionized fashion, (c) the foreman controls work flow and minimizes delays, (d) a walk-behind vibratory roller is employed, and (e) a compaction density of 130 lb/ft^3 is achieved. With this compaction density, an average patch (volume = 3.60 ft^3) will contain 0.234 ton of material.

Under these conditions, a seven-person patching crew equipped with an air compressor can achieve

$$[335 - 5.55 - (0.77 + 2.81 + 1.90 + 8.05)]/6.00 \times (0.234) = 12.32 \text{ tons/day}$$

Notice that cleaning has been considered the controlling operation. Potential productivity of this crew will be

$$7\,(335/60)/12.32 = 3.17 \text{ manhours/ton}$$

The same crew, using a gasoline-operated cutting tool, can place

$$[335 - (28.28 - 8.75)]/8.75 \times (0.234) = 8.45 \text{ tons/day}$$

The corresponding productivity will be

$$7\,(335/60)/8.45 = 4.63 \text{ manhours/ton}$$

Similar computations were made for a crew of six and a crew of five. Results are summarized in Table 8 and graphically illustrated in Figure 1. In Figure 1, a median performance line is shown. This curve represents potential departmentwide performance if half the crews are supplied with air compressors and the other half have gasoline-operated tools. As can be seen, both production and productivity can exceed the performance standard by a considerable margin for all crew sizes examined.

Manhours per ton will increase at a modest pace as crew size increases. It is evident that six- and seven-person crews offer no advantage over the five-person crew from the productivity viewpoint. As more HMWs are added, daily production must also increase if the target productivity of 4.73 manhours per ton is to be maintained. For example, a seven-person crew would need to place 8.4 tons per day. This fact offsets the apparent production advantages of larger crews. The potential production exceeds the minimum daily production by 2.66, 3.12, and 1.98 tons per day for the five-, six-, and seven-person crews, respectively, suggesting a slight advantage to the six-person crew. On a percentage basis, the potential production exceeds the minimum by 44.3, 43.3, and 23.6 percent. Thus, the choice of a five- or six-person crew seems to be a matter of preference based on other nonquantifiable issues.

From this analysis it can be concluded that the

TABLE 6 Target Delay Times for Pothole Repair Operations

	Delay Times as a Percentage of Total Delay Time				
	Cutting		Cleaning	Filling	Compaction
	Compressor	Pionjar[a]			
Communication					
Receive Instructions	4.4	1.0	0.0	0.0	0.0
Wait for Instructions/Observe	13.2	22.7	0.0	0.0	0.0
Equipment Utilization and Maintenance					
Start/Refuel/Adjust Equipment	4.4	4.1	---	14.9	0.0
Compressor Blows Holes	0.0	0.0	0.0	---	---
Move to Another Pothole/Location	15.4	12.4	4.9	14.9	15.8
Work Flow					
Wait for Another Operation	0.0	0.0	0.0	3.3	7.9
No Pothole Available	24.2	22.7	48.8	49.6	65.8
Other Delay Situations					
Traffic	4.4	4.1	0.0	0.0	0.0
Talk/Personal/Look Around	24.2	6.2	19.5	9.9	2.6
Undetermined	9.8	26.8	12.2	7.4	7.9
Change Tools	---	---	14.6	---	---
Wait for Mix to Reach Site	---	---	---	0.0	---
Total Delay Time (minutes)	45.5	48.5	20.5	60.5	38.0
(% of NWTA)[b]	16	17	7	21	13
Productive Time (minutes)	239.5	236.5	264.5	224.5	247.0
(% of NWTA)[b]	84	83	93	79	87

[a] Gas-operated cutting tool.

[b] NWTA = net work time available.

TABLE 7 Improved Times for Operations in a Pothole Repair Cycle

Operation	Ideal Time (Minutes)	Total Time[a] (Minutes)	Time Taken by Delays (Minutes)
Cutting			
Air Compressor	4.66	5.55	0.89
Pionjar[b]	7.26	8.75	1.49
Cleaning			
One HMW	7.61	8.18	0.57
Two HMWs	5.58	6.00	0.42
Tacking	0.77	0.77	--
Filling			
One HMW	3.72	4.72	1.00
Two HMWs	2.22	2.81	0.59
Leveling	1.90	1.90	--
Compaction			
Essick Roller[c]	7.00	8.05	1.05

[a] Ideal time divided by efficiencies obtained from Table 6.

[b] Gas-operated cutting tool.

[c] Walk-behind vibratory roller.

performance standard with respect to crew size, production per day, and manhours per ton is realistic and can be achieved regardless of the cutting tool used. The attainable rates exceed the minimum values by a sufficiently large amount that five- and six-person crews should be expected to meet or exceed the performance standard fairly consistently.

RECOMMENDATIONS FOR PRODUCTIVITY IMPROVEMENT

There are numerous steps that can be taken to improve both the production and productivity of pothole repair. Underlying these improvements is the effective leadership that must be exercised by the foreman and the assistant county manager. Specific recommendations resulting from the study are summarized.

1. Improving deployment: On the average, the crew should arrive at the job site within 30 min of the beginning of the work shift. Cutting of potholes should begin within 10 min. The crew should not leave the job site less than 30 min before the end of the shift. This time frame should provide a minimum of 335 min (5.58 hr) of actual work time and 390 min (6.5 hr) of time at the job site.
2. Organizing and controlling the work: Work must be organized in a production-line fashion with each HMW assigned to a specific task or operation. Failure to do so will limit the crew output to about 3 tons per day. The foreman must keep the repair process moving and remove obstacles that can delay the work. Waiting for instructions, observing other work, and waiting for potholes to work on will significantly delay the repair process.
3. Crew size: Except with a five- or six-person crew, it is unlikely that daily production rates needed to ensure satisfactory productivity can be

TABLE 8 Patch Completion Times and Potential Production/Productivity

	Seven-Person Crew		Six-Person Crew		Five-Person Crew	
	Cutting Equipment		Cutting Equipment		Cutting Equipment	
Operation	Air Compressor	Pionjar[a]	Air Compressor	Pionjar[a]	Air Compressor	Pionjar[a]
Cutting	5.55	8.75	5.55	8.75	5.55	8.75
Cleaning (2 HMWs)	6.00	6.00	6.00	6.00		
(1 HMW)					8.18	8.18
Tacking	0.77	0.77	0.77	0.77	0.77	0.77
Filling (2 HMWs)	2.81	2.81				
(1 HMW)			4.72	4.72	4.72	4.72
Leveling	1.90	1.90	1.90	1.90	1.90	1.90
Compaction	8.05	8.05	8.05	8.05	8.05	8.05
Total Time (Minutes)	25.08	28.28	26.99	30.19	29.17	32.37
Production (Tons/day)	12.32	8.45	12.25	8.39	8.98	8.33
Productivity (MH/ton)	3.17	4.63	2.73	3.99	3.11	3.35

[a] Gas-operated cutting tool.

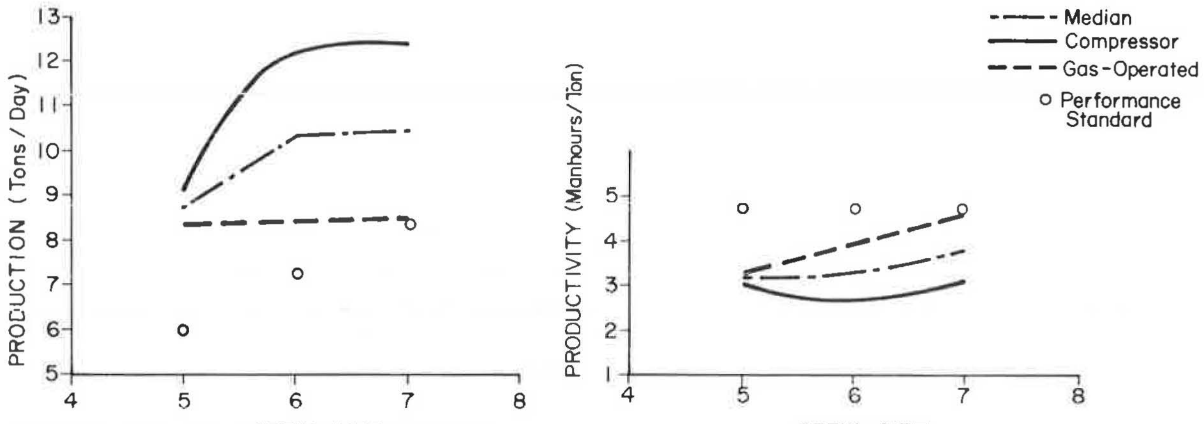

FIGURE 1 Potential production and productivity versus crew size.

achieved routinely. The most efficient crew size (exclusive of traffic control personnel) is a foreman and four HMWs.

4. Improving the cutting operation: Cutting is the most important operation in the overall repair process from the standpoint of productivity and production. The most significant delays that affect efficiency are waiting for instructions and blowing debris from holes with compressed air.

5. Communication: Waiting for instructions accounts for 30 percent of the available work time. Marking the boundaries of holes is especially important on badly deteriorated pavements where it is difficult to determine where the edge of the repair should be.

6. Improving repair quality and durability: The crew should be provided with specific guidelines for the compaction procedure required for pothole repair.

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Evaluation of Equipment Used for Localized Repair of Pavements

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ABSTRACT

Pothole patching for most highway agencies consumes a considerable portion of available highway maintenance funds. In Pennsylvania, pothole patching expenditures increased from $19 million in 1975-1976 to more than $30 million in 1977-1978. This prompted the Secretary of Transportation to launch an investigative research effort to evaluate the department's pothole repair strategies. As an outgrowth of this evaluation, a research project was awarded to the Pennsylvania State University to review current pothole patching technology of the remainder of the nation with the objective of recommending materials, equipment, and repair techniques that would be compatible with Pennsylvania's program. As a result, approximately $200,000 was expended for some of the more promising patching-related equipment to be field evaluated. This equipment was evaluated in terms of Pennsylvania Department of Transportation's pothole patching policy procedures, standards, and materials only and may not be relevant to other agencies. The equipment that was reviewed and evaluated was related to three equipment-dependent elements of pothole patching: cutting, filling, and compaction. Many of the various pieces available are very specialized and, for various reasons, were not determined to be cost-effective.

A major consumer of maintenance funds in Pennsylvania, as in most other states, is the patching of the ever-present, proliferating pothole. In 1982-1983, the Pennsylvania Department of Transportation expended approximately $37.4 million for the repair of potholes and, of this amount, 26 percent or $9.6 million was expended for equipment rental (outside and departmental). A breakdown for 1982-1983 follows.

	Cost ($000,000s)	Percentage of Total
Contract services	0.8	2
Material	7.2	19
Equipment	9.6	26
Personnel	19.8	53
Total	37.4	100

Because equipment selection has a considerable effect on the efficiency of pothole repair, it must be realized that direct expenditures for equipment are not the total picture and that in the selection of patching equipment life-cycle costs, productivity, crew acceptability, maneuverability, and logistics, among other things, should be considered.

In Pennsylvania, pothole patching expenditures increased from $19 million in FY 1975-1976 to more than $30 million in FY 1977-1978. This prompted the Secretary of Transportation to launch a quasi-investigative research effort to evaluate the department's pothole repair strategies. This research (1), in essence, confirmed the department's repair methods but indicated a need for additional training and possibly for more or different equipment.

As an outgrowth of this evaluation, an additional research project (2) was awarded to the Pennsylvania Transportation Institute, Pennsylvania State University, to review current pothole patching technology in the rest of the nation with the objective of recommending materials, equipment, and repair techniques that would be compatible with Pennsylvania's program.

As a result of this research, approximately $200,000 was expended for some of the more promising patching-related equipment to be field evaluated. The equipment was evaluated in terms of the Pennsylvania Department of Transportation's pothole patching procedures, standards, and materials only, and, because procedures vary considerably among states, the evaluation should be considered appropriate only to Pennsylvania.

PURPOSE

Equipment is an important component of the pothole repair process because it must not only be cost-effective but compatible with manpower availability and the type of material used. A search of the available literature indicates that little published information exists on the performance of various pieces of equipment. The purpose of this paper is to describe some of the equipment and to indicate the limitations and advantages of the equipment. Tables 1 and 2 give a summary of the important characteristics of the equipment considered appropriate for pothole repair.

EVALUATION

The basic equipment-related elements of pothole patching are (a) cutting, (b) filling, and (c) compaction. Equipment needs can be closely identified with these elements. Cutting (pavement breakers) requires

- Air compressors (pneumatic breakers),
- Gasoline-powered breakers,
- Hydraulic compressors and breakers,
- Milling machines, and
- Saws.

Filling requires

- Heated boxes,
- Portable mixers, and
- Recyclers-reheaters.

Compaction requires

- Static rollers,
- Vibratory rollers,
- Vibrating-plate compactors, and
- Tamping-foot compactors.

TABLE 1 Summary of Pothole Repair Equipment

Product Manufacturer, Model	Capacity	Approximate Cost (1983 dollars)	Record of Use	Dwell Time	Method of Feed	Method of Removal	Production Information	Method of Transport
Heated boxes								
Aeroil	2 tons	5,860		Indefinite	Top loaded	Shoveling door at rear		Towed
Aeroil	4 tons	9,993	Ill.	Indefinite	Top loaded	Shoveling door at rear		Towed
Poweray Infrared 2TSU	2 tons	4,809			Top loaded	Rear hopper-20 in. high		Towed
Poweray Infrared 4TSU	4 tons	11,400	Pa.	48 hr	Top loaded	Rear hopper-24 in. high		Towed
Poweray Infrared 4TCM	4 tons	7,618	Pa.	48 hr	Top loaded	Rear hopper		Mounts permanently on chassis behind cab
Poweray Infrared 6TDM	6 tons	7,956	Pa.	48 hr	Top loaded	Dump bed has to be raised	Propane	Mounts on dump truck
PB Loader Asphalt Patcher, B3-SM	4 tons	13,000-18,000	Pa., Wash., Calif., Ariz., Oreg.	Indefinite	Top loaded	Rear dump doors	Propane/butane	Slip in-slip out
Midland Warming Box	8 tons	12,000	N.Y., Wis., Ark., Pa.	8 hr	Top loaded	Rear hopper	Electric heated	Mounts on bed
Recyclers								
Aeroil AR-1000	2 t/hr	8,480	Kans., N.J.		Material thrown in drum	Drum rotates and dumps material in hole	Process ≈ 10-12 min	Towed
Bomag AR-5	5 t/hr	10,975			Shovel loaded	Discharge chute	Process ≈ 6-8 min	Towed
Brown Porta-Patcher	6 t/hr	20,000			Shovel loaded	Rear hopper	300 lb/min recycling, 400 lb/min cold mix	Towed
In-place heaters								
Poweray Heat and Serve	3 tons	24,645	Pa., N.Y.	48 hr	Top loaded	2 doors (on sides)	Propane	Towed
Patchmaster PM 5036	2.5 tons	56,925	Calif., N.Y., Mich.		Top loaded	Auger	Propane	Towed
Mixers								
McConnaughay HTD-F10T	10 ft^3 aggregate	17,000-25,000	Ky.	1 hr	Aggregate shoveled in	Shoveling tray	5 t/hr manual loader, 10 t/hr automated loader	Towed
HTD-10	200 gal asphalt							
McConnaughay HTD-6	6 ft^3 aggregate	13,000	Ky.	1 hr	Aggregate shoveled in	Shoveling tray	Rated 6 t/hr	Towed
McConnaughay HTD-4-T		8,000	Ky.	1 hr	Aggregate shoveled in	Shoveling tray	3 t/hr	Mounted on rear
Barber Greene Asphalt-Mobile		110,295	Pa.		Material self-contained	Discharge chute	12-15 t/hr	Mounted
Multiple purpose								
AMZ		40,000	Tenn.		Screw feeds aggregate into hopper	Compressed air	1-2 t/hr	Towed
RGS Thermo Lay	6.5 tons	18,950	Del. is testing Mo. approved		Top loaded	Hydraulic screw conveyor		Permanently truck mounted
Cutting tools								
Berema Pionjar 120/130	250 rpm	3,190	Pa., Wis.					Carried on truck
Racine Hydraulic MB-600		11,250	Pa.					Mounts on truck
Racine Hydraulic HB-75		2,095	Pa.					Carried on truck
Ingersoll Rand Air Compressor P100 WW	100 cfm/100 psi	10,000	Pa.					Towed
Compactors								
Wacker Vibroplate VPG-160 R		1,385	Pa.					Carried on truck
E-Z Patch Roller			Pa.					Mounts to rear of dump truck
Essick V-30W-R		7,455	Pa.					Carried on tail gate
Gallion 4-6 ton		31,000	Pa.					Towed

TABLE 2 Further Summary of Pothole Repair Equipment

Product Manufacturer, Model	Method of Transport	Temperature Information	Emissions	Mix Types	Comments
Heated boxes					
Aeroil	Light		No problem	Hauls hot mix	Includes portable infrared patcher and heated asphalt roller
Aeroil	Light	Maintains hot mix	No problem	Hauls hot mix	25-gal heated tank for tack material
Poweray Infrared 2TSU	Pickup		No problem	Hauls hot mix	Fuel consumption: one 100 lb cyl/8 days
Poweray Infrared 4TSU	Small	Maintains hot mix, heats cold mix to 180°F	No problem	Heats cold mix to 160°F overnight	25-gal heated tank for tack material
Poweray Infrared 4TCM	Dump	Maintains hot mix, heats cold mix to 180°F	No problem	Maintains hot mix, heats cold mix to 180°F overnight	
Poweray Infrared 6TDM	Dump	Maintains hot mix, heats cold mix to 180°F	No problem	Maintains hot mix, heats cold mix to 180°F overnight	Bed of dump truck has to be raised to deliver mix
PB Loader Asphalt Patcher, B3-SM	Truck with: Width: Min 78 in., Length: Min 120 in.	Maintains hot mix, heats cold mix to 120°F in 3 hr	No problem	Maintains hot mix, heats cold mix overnight	Optional 24-gal emulsion tank with heated spray wand and hand torch
Midland Warming Box	Dump	Maintains hot mix, heats cold mix to 225°F in 6-10 hr		Heats cold mix overnight (6-10 hr), maintains hot mix (8 hr)	Material cannot be heated in the field
Recyclers					
Aeroil AR-1000	Light	Heats mix to 325°F	Potential	Old plant or cold mix; reclaims planed asphalt	Auxiliary heating torch; potential asphalt damage
Bomag AR-5	Light	Heats mix to 300°F	Questionable		
Poweray Heat and Serve					Infrared heaters soften pavement before pavement is added; no need for cutting or tacking; no waste materials remain; potential asphalt damage
Brown Porta-Patcher	Dump		Potential	Recycled or cold mix	
Mixers					
McConnaughay HTD-F10T HTD-10	Truck		Potential	Heating and reconditioning, hot or cold mix	Kentucky uses mixers for reclaiming; not recommended by manufacturer
McConnaughay HTD-6	Truck		Potential	Heating and reconditioning, hot or cold mix	Kentucky uses mixers for reclaiming; not recommended by manufacturer
McConnaughay HTD-4-T	Standard dump truck		Potential	Heating and reconditioning, hot or cold mix	Kentucky uses mixers for reclaiming; not recommended by manufacturer
Barber Greene Asphalt-Mobile	Truck		Baghouse collection system		Optional truck-mounted unit
Multiple purpose					
AMZ	Towed behind dump truck that carries the aggregate			Cold mix produced at site	
RGS Thermo Lay	Conventional 84 in. tilt–90 in. cab-to-axle				Uses a hydraulic system; 220-V heater for cold mix (185-200°F in 8-10 hr); installation at site (1 day); can be used in winter as a sander (30-40 min changover)
Cutting tools					
Berema Pionjar 120/130	Pickup		Potential		Can be used to cut bituminous concrete
Racine Hydraulic MB-600	Truck mounted				Can be used to cut PCC and bituminous concrete
Racine Hydraulic HB-75	Pickup				Can cut bituminous concrete
Ingersoll-Rand air compressor P100 WW	Towed				Can be used to cut both PCC and bituminous concrete pavements
Compactors					
Wacker Vibroplate VPG 160 R	Pickup				Has maintenance problems; takes a long time to provide adequate compaction
E-Z Patch Roller	Mounts to rear of dump truck				Slows patching operation if same dump truck carries patching material
Essick V-30W-R	Mounts on tail of dump truck				Good compaction device
Gallion 4-6 ton	Mounts on tail of dump truck				Inadequate compaction for pothole repair

Cutting Equipment

The selection of equipment for the cutting operation is an important consideration because the cutting tool affects both quality and productivity. Production studies have identified cutting as the most important operation in achieving high production rates. A number of cutting tools are available.

Hand Tools

The advantage of hand tools is the low capital investment. There are no other advantages to their use. Hand tools are detrimental to the quality of the repair because it is difficult to remove all of the loose material from the edge or bottom of the distressed area. Also the hole cannot be cut with vertical edges, so the patch may fail by rutting or shoving.

Cutting a pothole with hand tools is very fatiguing and time consuming. It takes 30 min or longer to cut an average-size pothole. At this rate, it is impossible to achieve even minimal levels of production, hence the use of hand tools in Pennsylvania has been largely abandoned.

Air Compressor

Undoubtedly the most efficient pavement breaker in terms of productivity is one powered by compressed air. Air compressors have the advantage of operating multiple breakers in high-density pothole areas; compressed air is available for cleaning debris from the hole and can power a variety of tools. The compressor can also be used for other activities such as painting and sandblasting. It is the only unit recommended for use on concrete pavements.

An average-size pothole can be cut in less than 5 min. Flexible 50-ft hoses enable several holes to be prepared before the compressor must be moved to a new location. The only disadvantages that were noted are (a) high capital investment of $14,500 or more, (b) high energy consumption, and (c) towing vehicle is required.

Hydraulic Pavement Breakers

The hydraulic-powered tools provide many of the advantages of the air-operated tools for less cost. The models tested in Pennsylvania are skid mounted, can be carried in the bed of a pickup truck, and cost approximately $4,500. The hydraulic pump can also power a variety of tools including forestry tools (chain saws, pruners, and chippers) that are used by roadside crews. The quality of the pothole repair is equal to that of the air compressor provided the bit is sharp. However, no compressed air is available for cleaning.

Hydraulic-powered tools are not as efficient as air-powered tools, requiring approximately 10 percent longer to prepare an average-size hole. Nevertheless, a pothole can be completely cut in less than 6 min. Flexible hoses should be 50 ft long to provide maximum coverage at each location before moving to a new location.

Gasoline-Operated Pavement Breakers

The only gasoline-operated pavement breaker evaluated in Pennsylvania was the Pionjar model 120. It is a versatile tool that comes with a variety of attachments. The primary advantage of the Pionjar over air or hydraulic tools is superior maneuverability characteristics; it is not attached to a power source and requires no special transport equipment. The Pionjar costs approximately $3,000 and must be properly maintained for maximum efficiency.

The advantages of cost and maneuverability are offset by reductions in production. For example, when compared to an air compressor, the Pionjar will take approximately 50 percent longer to cut an average-size hole (about 7 1/4 min). The Pionjar cannot be used on concrete pavements. Nevertheless, the Pionjar is capable of achieving daily production rates in excess of 6 tons of asphaltic concrete or composite pavements. The department of transportation owns approximately 270 Pionjar pavement breakers that are used primarily as supplemental cutting tools.

Milling Machines

Milling machines, although not evaluated and not widely used for pothole repair per se, have seen limited use in one of the commonwealth's engineering districts. The Barco-Mill 100 has been used on some contracted pothole repairs with apparently encouraging results. It has also been used to cut extensive areas of deteriorated pavement at reflective and widening cracks in preparation for overlaying. On this type of operation, productivity far exceeds that of all other cutting devices. Although the use of milling is discouraged for small pothole repair, it will be further evaluated in preparing pavements for overlay.

Saws

The department of transportation owns or rents a few gasoline-operated saws for concrete pavement patching and, occasionally, for pothole repair; however, these were not specifically addressed in the Pennsylvania State University study (2). Despite the attractive feature of low cost, there are numerous disadvantages to saws. First, they leave a smooth vertical edge that is semipolished. This surface makes it difficult for the new patch material to adhere and may cause early patch failures. Where water is used to cool the saw blade, it will partly fill the hole causing additional cleaning problems. The depth of cut cannot be readily adjusted, and the production rate is slow compared to that of the other tools that are available. Furthermore, a pavement breaker will still be needed to loosen the material inside the perimeter of the cut. Also, saws lack versatility because they cannot be used in other applications. Considering the overwhelming disadvantages, the use of saws is not recommended.

Cleaning Equipment

Cleaning must be accomplished by hand, although it may be augmented with compressed air. The first step in cleaning is to remove the chunks of asphalt from within the perimeter of the cut. This is done with a conventional shovel. One with a long handle will minimize worker fatigue. Most of the small loose debris and stones can also be removed with the shovel.

It the hole is wet, most of the water can be removed with a broom. In some states a butane torch is used to further dry the hole; however, the practice is not followed in Pennsylvania. Studies by Pennsylvania State University indicate that the hole need not be totally dry to provide a permanent repair.

Loose debris that builds up in the corners must be removed. This can be done either with a stiff long-handled broom or with compressed air. Cleaning with compressed air is the easiest and most effective method. A blow tube should be used and the pressure should not exceed 30 psi. Compressors should be equipped with two lines the second of which is used for cleaning purposes only. To achieve high production rates, the cutting operation should not be stopped to allow cleaning to be done.

Tack Equipment

The most common tack materials used are emulsions and synthetic resins; each is used only with hot mix patching materials and requires different application equipment. To be successful, the tack must be applied in a thin coating, which can only be accomplished by brushing or spraying. Pouring from a pot or kettle is not acceptable. The resins are sufficiently fluid to be pumped through garden-type sprayers, but the resins are very volatile and safety concerns about using this material in an unapproved pressure vessel eliminated this method from consideration. Synthetic resins are normally brushed onto the surfaces.

To date, suitable equipment to apply tack material, other than the integral systems contained on the sophisticated patching equipment, has not been found. Experimentation on pressurized spraying containers is continuing with a few promising products.

Mixing and Filling Equipment

There are many devices manufactured for the heating and mixing of bituminous patching material. These vary from sophisticated mobile plants to simple reheaters. For the purpose of this paper, they are classified as (a) portable mixers, (b) reheaters-recyclers, and (c) reconditioners. Portable mixers vary widely in size and capacity and are generally used to combine virgin components (some in a more controlled manner than others) to produce a patching material. Reheaters-recyclers are generally used to reheat cold patch material or, in some cases, to reheat and recycle reclaimed asphalt pavement. Reclaimers are capable of heating distressed pavement areas with either radiant or infrared heat and adding material from self-contained heated storage units.

Portable Mixers

Four types of portable mixers were evaluated:

Asphalt-Mobile Mixing Plant

The Asphalt-Mobile mixing plant is a completely self-contained asphalt plant mounted on a truck chassis or semitrailer. The plant is capable of producing high-quality hot mixes of any design. It combines all drying, heating, and mixing operations and operates on volumetric control; it has a two-bin aggregate system (one fine, one coarse) each bin of which holds approximately 100 ft^3 and a 320-gal insulated, heated tank for asphalt supply capable of maintaining temperatures of 350°F. The unit is equipped with a baghouse-type dust control system that meets Environmental Protection Agency emissions standards. Each aggregate bin, complete with scalper screen, has an apron feeder underneath that moves the material through calibrated gates to a bucket elevator (38 tons per hour capacity) to the dryer. A counter-flow rotary dryer-heater system dries the material at a rate of up to 25 tons per hour depending on moisture removal requirements. Heated liquid asphalt is metered into the mixer in the desired proportion. Manufacturer's literature claims production capacities of up to 25 tons per hour; however, the department is generally finding an average of approximately 10 tons per hour to be more practical.

Because this unit is very expensive and produces at least 11 times the amount of material expected to be used by a patching crew in a day's production, it would be grossly inefficient to assign to an individual crew. Its use as a stationary plant to supply heated storage units at a central location was also considered and tried, but because of logistic problems of supplying and storing raw material and the traveling distances of crews, this idea was not thought to be cost-effective.

The unit produced material of very high quality, was well received by crews, and is well engineered. Nevertheless, it is very expensive, approximately $170,000 (1979 dollars) for the trailer model and approximately $230,000 (1979 dollars) for the truck-mounted model. With the emphasis in the department on treating the present high-quality cold mix (485) as a permanent repair material, there appears to be little justification for purchasing any additional Asphalt-Mobiles.

McConnaughay Mixer Model HTD-10T

The McConnaughay mixer is a towable mixer used to produce hot mix patching material. It operates on a drum-dry principle and combines, mixes, and heats components to approximately 300°F in 2-3 min. The mixer is equipped with a 10 ft^3 aggregate bin and an optional 200-gal heated asphalt supply tank. The manufacturer claims production capacities of up to 10 tons per hour, which, on the basis of field observations, seem to be optimistic.

It is not a self-contained unit because blended aggregate must be charged into the hopper. There are no quality control features associated with the HTD-10T. Aggregate blending is external to the operation and the proportioning of aggregate and asphalt is done manually. Although there is a timer, the mixing time is controlled exclusively by the operator and, in part, is determined by the moisture content of the aggregate. There are no controls or meters and there are no emission controls. Because of the volatile nature of cut-back asphalts, the unit can only be operated as a mixer if asphalt cements or emulsions are used. Both must be stored in insulated, heated tanks in order to maintain the proper viscosity. This aspect greatly limits the use of the HTD-10T in the winter. Experience in Cambria and Westmoreland counties indicates that a satisfactory temperature for asphalt cements cannot be maintained. Also, the asphalt supply lines are not insulated, hence extreme care must be exercised in cold weather to prevent material from solidifying in the lines.

There is no automatic ignition system; the unit must be ignited with a match and a rag on a stick. Control valves for the asphalt are surrounded by heated pipes and are not easily reached. There are two control valves for the heated asphalt located on opposite sides of the unit; because they are manually controlled, they cannot be operated concurrently.

A.M.Z. System

The A.M.Z. system is a pneumatically operated pothole repair system that can be operated with a two-man crew (not including traffic control). The equipment is basically self-contained; it needs only a truck to tow the equipment and to haul the aggregate. It is equipped with a high-volume lobe blower, a 120-gal asphalt storage tank, an aggregate hopper and supply system, and an applicator hose system including a lightweight nozzle equipped with controls. The operator controls the total operation at the nozzle and is capable of blowing the hole clean, tacking, and filling by a simple maneuver of the control valves. The A.M.Z. system is capable of providing a skin patch (a thin application of asphalt followed by a one-layer depth of aggregate) or a deep patch where the aggregate is coated (mixed) with asphalt within the nozzle and directed into the hole at a velocity of 60 mph (97 km/hr). According to the manufacturer, this adequately compacts the material.

Although the claims of the manufacturer must yet be evaluated in a field test, this equipment does show considerable potential especially for lighttype flexible pavements on which skin patching is most prevalent. Contrary to the manufacturer's claims, cutting to sound material, as with all other repairs, should be done ahead of this operation. One obvious drawback to this system is lack of quality control of the mixed material. The operator controls the ratio of asphalt to aggregate by manipulation of the controls. An attempt to evaluate this system will be made by the department during the spring of 1984.

Reheaters-Recyclers and Reconditioners

Reheaters-recyclers and reconditioners for the purpose of this paper are separated into two groups. The reheaters-recyclers are those that operate on a drum-dryer mixer principle. Included in this group are the Brown Porta-Patcher, the Bomag AR-5, and the Aeroil reclaimer AR-100. The Poweray Infrared Heat and Serve and the Patchmaster are representative of the reconditioners that rely on infrared or radiant heat to recondition pavement surfaces in place.

Brown Porta-Patcher

The Brown Porta-Patcher is one of several drum-type reheaters designed to recycle asphaltic material and to heat cold mix. The manufacturers claim that the heating process drives off the volatiles, leaving a quality hot mix. Laboratory tests of material samples run through the Porta-Patcher indicate that some of the volatiles are removed and that the material quality may be somewhat enhanced. The heat source for the Porta-Patcher is liquid propane. There is an electric spark ignition system and adjustable temperature control. Cold mix is manually fed into a hopper at one end of a revolving drum. The material is gravity fed through the drum while it is simultaneously exposed to the heat from the burners. It takes approximately 2-3 min for the material to be processed.

Production capability seems to be adequate, but productivity would be reduced because of the need to have an additional crew member feed the material into the hopper. There might be times when the crew would have to wait for more material to be processed, but, with proper instructions from the foreman, such delays could be minimized.

The Porta-Patcher is trailer mounted and can be towed by a dump truck. It weighs 3,900 lb with a tongue weight of 320 lb. There are no unusual maneuverability or logistic characteristics.

There are no special training requirements for operating the Porta-Patcher. However, it takes a while to learn how to tilt the drum properly. If the drum tilts too low, it is possible to burn the asphalt. No safety hazards were noted except that the workers were often irritated by the fumes coming from the rear of the drum.

The 485 cold mix used in Pennsylvania does not seem compatible with the Porta-Patcher. During the studies conducted in Allegheny County, air pollution problems resulted because of the high asphalt content of the 485 mix. A special mix would probably need to be designed for the Porta-Patcher and similar types of reheaters.

Bomag AR-5

The Bomag AR-5 is a portable drum-type reheater similar to the Porta-Patcher but smaller. The rated production capacity is 5 tons per hour, about half of the Porta-Patcher's capacity. Nevertheless, production appears quite adequate. The Bomag AR-5 weighs 1,350 lb with a tongue weight of 120 lb and can be towed by a crew cab. Problems with pollutants and fumes were not documented.

Aeroil Reclaimer AR 1000

The third type of reheater is similar to a small concrete mixer and if necessary can be used as such. Material is manually charged into the drum, is heated with propane burners directed into the opening of the drum, and is then discharged by tipping the drum.

Manufacturers of all of the equipment discussed normally promote their equipment to reheat milled, cold planed, or cold patch material. The equipment requires an additional crew member to operate and also requires double handling of material, both of which seriously decrease productivity.

In view of these comments and the concentrated effort Pennsylvania has made to develop a high-quality cold patch material to perform as a permanent patch and when one considers that material cost only accounts for approximately 20 percent of the patching cost, these units are not considered compatible with the department's philosophy. These units appear to be more compatible in the municipal area.

Poweray Infrared Heat and Serve

The Poweray Infrared Heat and Serve unit incorporates an infrared heater to heat a 6 ft x 8 ft area of existing pavement. New hot material stored in an integral heated box is added to and blended with the reheated pavement. There is no need to cut vertical edges with a pavement breaker or to apply a tack coat. Material can be blended at the edges, and there is no need to dispose of waste materials. The infrared radiation is created by premixed propane gas and air delivered under pressure to energy converters. No flame is produced that may alter the binding characteristics of the asphalt. The unit has two energy converters rated at 15 000 Btu each.

The quality of the repair produced by the Heat and Serve unit is limited in certain respects. Where several layers of overlays exist, the softening only penetrates the first layer; thus the effective depth may only be an inch or two. Heating is not effective where pavement markings exist or on heavily oxidized pavements, and moisture and dirt slow heat penetration. In a department evaluation, the Heat and Serve unit heated asphaltic pavement to 300°F at a depth of 1 1/2 in. in approximately 4 min. It seems unlikely that depths much greater than this can be softened as rapidly as needed. Table 3 gives the results of five holes repaired during 1979-1980. As

TABLE 3 Temperature Characteristics of Heat and Serve (1979-1980)

Hole Number	Heating Time (min)	Temperature (°F)		
		Pavement	Mix (surface)	At 1 in. Penetration
139	4	90	245	
140	4	93	223	150
141	7	98	300	156
142	7	102	300	200
143	7.5	104	280	

can be seen, the heated temperature diminished rapidly as a function of depth.

The Heat and Serve unit does not seem applicable to pothole patching except on a very limited scale. It is perhaps better suited to the repair of alligator cracks, bridge approaches, and the like; like the reheaters-recyclers, this unit may have considerable potential in the municipal area primarily for repairing utility cuts that have settled.

Patchmaster

The Patchmaster operates on the same principle as the Heat and Serve except that it uses radiant heat instead of infrared. It is a well-engineered device but expensive ($42,000 in 1981). The heating limitations of the Patchmaster are similar to those of the Heat and Serve.

The radiant heaters have approximately 50 000-Btu capacity, and in a field demonstration the asphalt was burned and a rejuvenator was necessary. Because of the potential harm to the pavement and the very high cost, this unit is not recommended for pothole repair work.

Heated Boxes

Heated boxes consist of insulated metal containers mounted on trucks or trailers. The boxes are heated in various ways and are used as storage vessels to transport and make possible the use of hot patching material by patching crews during the entire workday. The boxes are generally used to retain the heat of hot plant mix or to elevate the temperature of stockpile patching material to improve handling characteristics.

Thermo-Lay Pothole Patcher

This patcher is manufactured in three models: The Thermo-Lay model TM375-200 is a heated box mounted on a truck chassis. The model TRL 375-200 is a comparable trailer model and a slip in-slip out unit; model DM 375-200 is also available. This must be mounted on a truck bed or chassis, and for all practical purposes it is a permanent installation. Each comes with a variety of optional accessories. Model TM375-200 was evaluated.

The primary feature of model TM 375-200 is the insulated storage box. It is a combined heater and dispenser system. The insulated box has 3 3/4 yd^3 capacity. A 350 000-Btu propane burner is designed to heat cold mix overnight or to maintain hot mix temperatures. The burner system seems to be adequate. The material is dispensed via a 10-ft screw auger powered by a reversible 11-gal/min, 2,000-psi hydaulic motor. Early experience with the Thermo-Lay suggested that in traveling to the work site some compaction takes place around the auger. A larger hydraulic pump (18 gal/min, 2,000 psi) was installed that eliminated the problem. The material is discharged into a chute that can rotate 180 degrees. The chute eases the difficulties of shoveling the material, but positioning the truck so the material can be discharged directly into the hole is a problem. Typically, the material is discharged onto the pavement before it is shoveled into the hole. Other standard features of the Thermo-Lay include

- Heated asphalt system: 235-gal capacity, 20 gal/min, 1,200 psi reversible pump;
- Electrical heating system for overnight heating: 230 volt, 6 kw with thermostat control unit;
- Propane hand torch: 200 000 Btu with 10-ft hose;
- Diesel fuel storage for flushing asphalt pump: 18-gal capacity; and
- Hydraulic pavement breaker: 37 lb (67 and 85 lb sizes are optional).

Several optional features are also available. These include

- Hydraulic tamper, Stanley TA55112;
- 24-in spoils bin;
- Sanding attachment;
- Side board brackets to increase material capacity to 5 yd^3; and
- Vibratory plate compactor, model AP 2000, 4 hp.

The Thermo-Lay appears to be well engineered. Satisfactory temperatures were maintained. The hydraulic conveyor system was adequate when the larger pump was installed. The heated tack oil system used for tacking purposes was probably the best system observed. The tack material was discharged in a fine mist. Unlike nozzles of other heated systems, the nozzle did not become clogged after intermittent use. This is because the asphalt pump is reversible and the lines can be cleaned with the diesel fuel flushing system. The electrical heating system was not used during the study.

Several comments about the tack oil system are worthwhile. The need for such a system cannot be entirely justified at this point. A previous study has shown that there is little evidence to suggest that the tacking operation increases patch longevity. Further, departmental policy is not to tack cold mix. Thus, a pressurized tacking system may be considered an unnecessary expense. If tacking proves to be beneficial, an effective tacking program requires the use of different tacking materials, depending on moisture and weather conditions, time of year, and material availability. It is not known if the tack oil system on the Thermo-Lay will function properly with emulsions, synthetic resin, and cutbacks. A final drawback of the tack oil system is its effect on productivity. Certain tack materials, such as synthetic resin, may require a curing period of 10-20 min. An unattached tacking system is desirable to permit tack coating the holes well in advance of the filling operation; otherwise the filling operation will be delayed or curing requirements will be ignored.

Vibratory plate compactors and hydraulic tampers and pavement breakers will be discussed later. The 67-lb hydraulic pavement breaker is recommended in lieu of the 37-lb one. Also, a 50-ft hose should be specified instead of the standard 25-ft one.

High production levels will not be attainable with the Thermo-Lay for several reasons. First, production is limited by the 3 3/4 yd^3 hopper. If the truck returns for more material, it takes away the cutting capabilities. Returning for more material seems impractical. Even the increased 5 yd^3 capacity is below the departmental production goal.

The crew cannot be dispatched in an assembly-line fashion ("productionized") because the cutting, filling, and compaction operations are tied to a single unit. Productionizing the crew is a prerequisite to high daily production. A 50-ft hose on the hydraulic pavement breaker and a detached compaction device would help, but the improvements seem superficial.

P.B. Patcher Model B-3

The P.B. Patcher is a heated storage unit similar to the Thermo-Lay. The unit is manufactured as a unitized model (B-4) mounted on a truck chassis and a slip in-slip out model (B-3) to be used in conjunction with a dump truck. The model B-3 has a 3-yd^3 (4-ton) capacity and the B-4 has a 4-yd^3 (5-6-ton) capacity. The heat is provided by a thermostatically controlled propane or butane heater. The B-3 slip in-slip out model was evaluated.

Loading of hot mix at the asphalt plant is facilitated by hydraulically operated doors on the top of the box. The self-contained hydraulic system also controls individual dump doors. During the study, considerable difficulties were encountered with this system. Discharge of material is accomplished by raising the bed of the dump truck. The asphalt is discharged onto an optional shoveling apron that has a 1/4 yd^3 capacity. The P.B. Patcher is equipped with an emulsion tank and hand spray wand attached to a 25-ft hose. A diesel flushing system is included. An optional hand torch is also available. The heating, hydraulic, and emulsion spray systems are activated by an electronic ignition system. The starter switch caused considerable problems during the evaluation.

The overall performance of the P.B. Patcher was not good. The problems with the hydraulic system and ignition switch were not resolved during the evaluation.

The model B-3 has a 4-ton capacity, which is considerably short of the daily target value of 6 tons. There is no way of achieving this 6-ton goal unless the truck leaves the work area for more material or a second dump truck loaded with cold mix is used. Either approach is costly in terms of delay time and equipment costs. Thus, the P.B. Patcher does not appear adaptable to high production needs.

At first, the logistic features of the P.B. Patcher appear good, because it is easily hauled to the work area. However, the shoveling apron prevents the towing capabilities of the dump truck from being used. If an Essick roller is being used, it must be attached to the snow plow attachment or to the tailgate of another truck. Furthermore, there is no place to put the old pavement that has been cut out unless a second dump truck is used.

The cost of the P.B. Patcher is $8,000-$10,000. This is quite expensive in light of the fact that similar systems are available without the unnecessary accessories or required features such as hydraulic doors.

For productivity reasons, the only time when these units seem to be acceptable is when holes are widely distributed. Perhaps the best use for them is, again, in the municipal sector. Acceptable production levels cannot be achieved with the Thermo-Lay, the P.B. Patcher, and most other self-contained repair systems.

Poweray Model 4TSU

The Poweray model 4TSU is a low-cost, towed, heated box. It is the same type of insulated storage unit as the Thermo-Lay and the P.B. Patcher but without the added accessories and systems. The loading doors and shoveling doors are manually operated. There is no hydraulic system and the liquid asphalt system is optional. The heat source is propane gas, and the temperature control is manual. The material capacity is 4 tons. A 24-in. shoveling apron reduces spillage. The quality of the 4TSU is quite good, largely because there are few systems (only the burner system) that can malfunction. These units have been used by the department for a number of years and seem to be durable.

The production capacity of the 4TSU is less than the daily 6-ton goal. However, this apparent deficiency is not as acute as it is with the Thermo-Lay and P.B. Patcher. Because the 4TSU is towed, the bed of the dump truck can be used to carry additional unheated cold mix. When empty, the 4TSU can be parked at a convenient location while the unheated cold mix is being used. Also, there should be room in the dump bed for the old pavement material, thus eliminating the need for another truck. Another advantage of the 4TSU is the relatively low initial cost. Operating and maintenance costs are also favorable.

Poweray also manufactures a truck-mounted slip in-slip out unit (model 6 TDM) that has basically the same features as the 4TSU except a slightly larger capacity (6 tons). This unit, because it is truck mounted, has several drawbacks:

- Loading height is approximately 12 ft, which practically limits loading to a plant;
- Shoveling aprons are too high;
- The unit is secured to the truck by bolting, which, for all practical purposes, makes the 6 TDM a permanent unit; the unit is not easily installed or removed; and
- The changing of propane tanks was very difficult and required a loader to lift them from the truck.

Midland Warming Box

This unit is similar to the Poweray 6 TDM and has the same general disadvantages but one significant disadvantage, namely the unit is heated electrically, requiring 240-volt alternating current, which prevents the application of heat when on project and requires the unit to be parked at a location with an adequate power source.

Wylie TMH 250

This unit is a towed unit similar to the Poweray 4TSU; it has the same general advantages but it also has a few significant disadvantages. The propane system has no automatic tank-switching capabilities. The tongue seemed to be too short, which made maneuvering more difficult, and the thermostat is electrically operated requiring a battery to be connected to keep material at a workable temperature and prevent overheating. The thermostat and lights are on the same circuit with no switching capability. This makes it necessary to leave the lights on or remove the bulbs when heating overnight.

Compaction Equipment

The compaction of patch material is perhaps the most critical step in the repair process. Four basic types of compaction equipment were considered: vibratory plate, steel-wheeled vibratory rollers, two-wheeled static rollers, gasoline-powered breakers and hammers, and tamping-foot compactors.

The Pennsylvania State University recently undertook a comprehensive study of the department's pothole repair policy and procedures (2). Four types of compaction equipment were studied:

1. The vibrating plate (Wacker VPG-160R) is a small hand-operated device consisting of a gasoline engine that vibrates a flat plate. The device is often used for patching operations but its principal use is as a soil compactor.
2. The vibrating roller (Essick V30W-R) is a small roller of the walk-behind type. It has a vi-

bration capability that is combined with the weight of the machine to create the compactive effort. This roller is very maneuverable and can be towed on a flatbed trailer behind a small truck, or it can be carried on the tailgate of a dump truck.

3. The 4-6-ton roller is a static steel-wheel roller that can be towed behind a small maintenance dump truck. The roller has rubber tires that can be raised or lowered. The roller is usually operated at 5 tons. It does not have vibration capability.

4. The gasoline jackhammer (Pionjar model 120) is a hand-held, gasoline-operated cutting tool. The cutting tool can be removed and replaced with a small tamping foot. Compaction is achieved by the up and down action of the device.

Hot mix and cold patch were compacted with this equipment into holes of varying sizes and depths, and nuclear density and core density measurements were taken (Kilarski and Anderson, unpublished results).

Hydraulic tampers, truck-mounted rollers, and tamping-foot compactors were not considered satisfactory for various reasons and were not studied.

Study variables included hole size, hole depth, number of lifts, and number of passes. Densities were measured after each set of passes with the equipment. After the hot mix patch material was compacted, cores were taken at the center and corner of each hole. It was not possible to core the holes filled with cold patch.

Discussion of Results--Cold Patch Material

Some of the results of the evaluation of the cold mix material are shown in Figures 1 and 2. These figures show the compaction growth curves for the material with respect to hole size and the type of compaction equipment used.

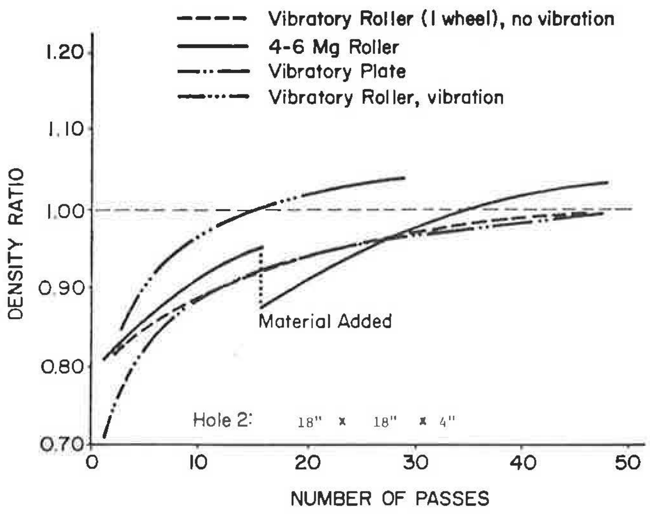

FIGURE 1 Cold mix growth curve—hole 2, 4 in. deep.

It can be seen that, for the majority of the holes, 95 percent Marshall density was achieved with the vibratory roller (with vibration) after approximately 10 passes of the device, whereas the small vibratory plate must make about 20 coverages for 95 percent density. A coverage is defined for the vibrating-plate compactor as the movement of the plate across the entire surface of the patch. This may take several back-and-forth or side-to-side passes with the device. Approximately 25 min were required to obtain 20 coverages on 3 x 5 ft holes. The 4-6-ton roller also needs about 20 passes to obtain 95 percent density, but it should be noted that for two of the larger holes, density was not achieved even after 25 passes. These results indicate that the small vibrating roller achieves the best compaction of the cold mix. The vibrating plate does an adequate job, but it takes longer to achieve compaction, and, in some cases, the 4-6-ton roller does not perform adequately.

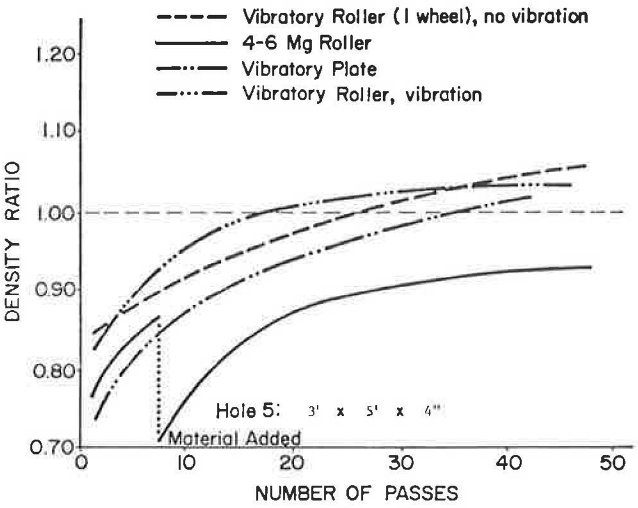

FIGURE 2 Cold mix growth curve—hole 5, 4 in. deep.

Discussion of Results--Hot Patch Material

The results of the evaluation of the hot mix material are shown in Figures 3 and 4, which show the number of passes needed to achieve 95 percent density. For the small holes, about 20 passes of the vibrating roller were required, whereas only 10 passes were needed for the large holes. The small vibrating plate did as well as or better than the vibrating roller in most cases. For two of the small holes and two of the large holes it took only about

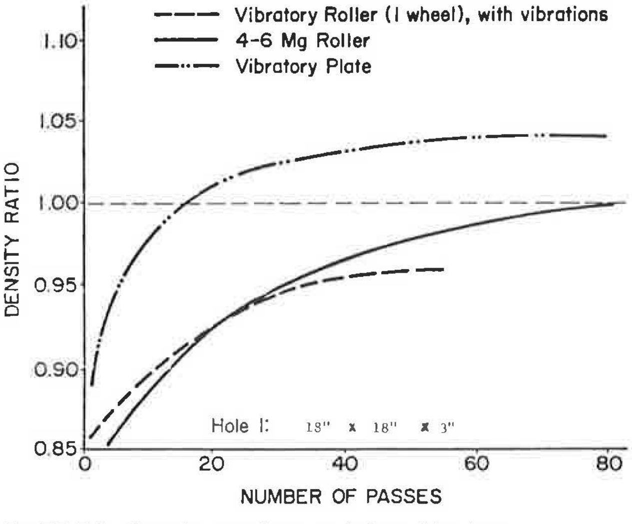

FIGURE 3 Hot mix growth curve—hole 1, 3 in. deep.

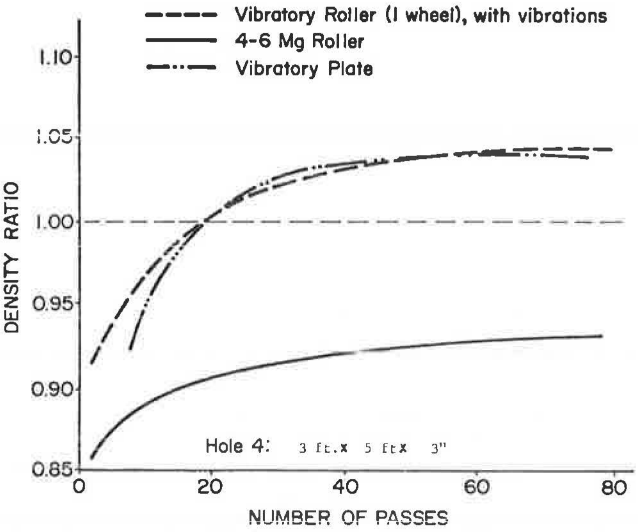

FIGURE 4 Hot mix growth curve—hole 4, 3 in. deep.

5 passes of the vibrating plate to achieve 95 percent density. The 4-6-ton roller took 40 or more passes to achieve 95 percent density on the large holes. This makes the 4-6-ton roller an ineffective compaction device for pothole repairs with both cold and hot material.

As with the cold mix, the vibrating device will overcompact the material in both the small and large holes. In particular, the vibrating plate shows a very steep growth curve on the small shallow hole, which indicates that overcompaction can occur quickly.

Comparison of Compaction Devices

Surprisingly high levels of compaction were obtained with the vibrating-plate compactor when it was used to compact hot patch material. However, the department has had problems maintaining this equipment and the crews do not like to use it. The device is heavy; it cannot be easily moved along the pavement; and it requires long periods of time to obtain proper compaction. In practice, the compaction obtained by crews using the vibrating-plate compactor may be much lower than indicated by the growth curves reported in this paper, especially for larger holes, because the time required to obtain proper compaction is considerably longer than that currently used by the crews.

The single-wheel vibrating roller is by far the most satisfactory of the compaction devices. It is mobile, can be mounted on the tailgate of a truck, and provides excellent levels of compaction. However, for the equipment to be effective it must be used in the vibratory mode. One or two passes must be made initially without vibration. Additional passes without vibration should be avoided because this inhibits further compaction when the vibration is applied.

Finally, regardless of the demonstrated effectiveness of the compaction device, its effectiveness is lost if the hole is underfilled. In the past department policy was to fill the hole so that after compaction it was flush with the pavement. This practice is not acceptable for holes that the compactor can bridge. Slight overfilling is needed to ensure that the compactor is bearing on the patch material and not on the surrounding pavement.

SUMMARY

Of the varied pieces of equipment available for pothole repairs, many are specialized and were not determined to be cost-effective for organizations that have large-scale pothole problems and that are production oriented. Some of this equipment may, however, have an application in the municipal sector.

This evaluation has generally served to confirm, and in a few areas enhance, the department's philosophies about patching equipment.

The typical patching crew equipment recommendation is

- One air compressor or Pionjar breaker,
- One Essick vibratory roller,
- One Poweray 4TSU heated transport (hot box),
- One small dump truck (approximately 33,000 lb GVW), and
- One crew cab pickup truck (Foreman).

This complement does not include any specialized equipment and is considered cost-effective for the majority of the department's organizations.

ACKNOWLEDGMENTS

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Analysis of Pavement Routine Maintenance Activities in Indiana

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ABSTRACT

An analysis of pavement routine maintenance costs for the state highway system in Indiana is presented. The data base includes pavement maintenance records for 4 years, 1980-1983. The results include a trend analysis as well as a correlation analysis. First, the total cost trends as well as individual activity costs are examined. Then the resource consumption trends are analyzed in terms of labor and materials use. Finally, a statistical correlation analysis is presented in order to examine the relationship of maintenance expenditures in the earlier years and the level of maintenance expenditures in subsequent years. The analysis showed high correlation between maintenance expenditures in a given year and the expenditures of the previous 2 or 3 years. The results of this study should be of direct use in the planning and management of annual pavement maintenance programs.

Pavement maintenance activities constitute one of the major parts of highway routine maintenance. In Indiana the share of pavement maintenance in the total highway routine maintenance expenditures was about 18 percent for FY 1979. This share is now about 24 percent for FY 1983 (1,2).

A study is being conducted at Purdue University to develop prediction models for pavement routine maintenance needs. These models can be used for making decisions about pavement maintenance management and cost control. A summary of the first phase of this study is presented. The first phase includes a historical data analysis of pavement maintenance costs and resources used as well as an examination of possible relationships between expenditures from year to year.

The data used in this study included detailed records of highway routine maintenance activities from the Indiana Department of Highways (IDOH) for FY 1980-FY 1983. These records are the compiled form of actual field information on all maintenance activities, which are recorded on field crew day cards.

TRENDS IN PAVEMENT MAINTENANCE COSTS

Pavement maintenance costs were computed for each highway section in terms of dollars per lane-mile. To avoid changes in unit prices from year to year, all costs were converted to 1982-1983 dollars. Of the total 874 sections, 768 sections [62 in the Interstate system (IS) and 706 in other state highway system (OSHS)] were found to have received one or more maintenance activities during the last 4 years. The remaining sections did not receive any pavement maintenance during the last 4 years.

It was observed that, in general, the average total cost of pavement maintenance of the IS is less than that of the OSHS. The average total cost on the OSHS is 30-120 percent higher than that of the IS. For instance, 10 percent of the total IS lane-miles received maintenance at an average cost of $295 per lane-mile per year, whereas 10 percent of the total lane-miles of the OSHS received an average of $547 per lane-mile per year in the last 4 years. The reason the IS sections have lower maintenance costs per lane-mile can be traced to the fact that the IS receives more dollars per lane-mile of major maintenance activities such as resurfacing and rehabilitation, which reduces the need for more frequent routine maintenance activities.

The major activities contributing most to the total maintenance costs are patching (activities 201 and 202 in Table 1) and sealing (activities 206 and 207 in Table 1). About 85 percent of the total cost of IS pavement maintenance was spent on these four activities during 1980, and 87, 82, and 90 percent were spent during 1981, 1982, and 1983, respectively. For the OSHS, these figures were 66, 69, 66, and 66 percent for 1980, 1981, 1982, and 1983, respectively (3-6).

TABLE 1 Pavement Routine Maintenance Activities *(7)*

Activity	Code No.	Production Units
Shallow patching	201	Tons of mix
Deep patching	202	Tons of mix
Premix leveling	203	Tons of premix
Seal coating	205	Lane-miles
Sealing longitudinal cracks and joints	206	Linear miles
Sealing cracks	207	Lane-miles
Cutting relief joints	209	Linear feet
Joint and bump burning	214	Bumps removed
Other	219	Man-hours

The single activity with the highest portion of pavement routine maintenance cost is shallow patching (activity 201). The share of this activity in the total cost was 27, 28, 38, and 30 percent during 1980, 1981, 1982, and 1983, respectively, for the IS. The corresponding figures for the OSHS were 32, 31, 40, and 29 percent, respectively.

The implication of these results is that, in developing routine maintenance prediction models, separate consideration should be given IS and OSHS. In addition, the results clearly show that the accuracy of prediction models would depend largely on the accuracy of the prediction of patching and sealing activity needs.

TRENDS IN LABOR CONSUMPTION

To analyze the labor requirements of pavement maintenance activities, average labor consumption rates in terms of man-hours required to produce one unit of a particular activity were calculated for each of the highway systems separately for each of the 4 years (3,4,7).

A review of the average labor consumption rates revealed that patching activities (201 and 202) on the IS required more labor than did those on the OSHS. On the other hand, the labor consumption rates of sealing activities (206 and 207) on the IS are less than those on the OSHS. This apparent discrepancy can be explained by the fact that both activities on the IS require more elaborate safety arrangements during maintenance operations causing a larger number of man-hours to be spent. However, the relative magnitude of cracks sealed per lane-mile in the OSHS is much higher than that in the IS and this is causing a higher net need for man-hours for sealing activities on the OSHS.

TRENDS IN MATERIALS USE

The rates of materials consumption in various activities were analyzed by examining the average rates of consumption of different material types by highway system for each of the 4 years.

A definite trend was observed in the use of bituminous mixtures in patching activities (activities 201 and 202). A significant increase took place in the use of salvage and cold bituminous mixtures to replace the conventional hot bituminous mixtures. For example, in 1980 for shallow patching activity (201), salvage bituminous mixtures were used rarely; they were not used at all on the IS and were used in only 1 percent of the OSHS jobs. However, in 1983, salvage and cold bituminous mixtures were used in 89 percent of the shallow patching jobs on the IS and in 100 percent of the OSHS jobs. At the same time, a gradual decrease took place in the use of conventional bituminous mixtures and bituminous materials. For example, bituminous mixtures were used in 100 percent of the shallow patching jobs on the IS during 1980 compared to 90 percent in 1983. The corresponding figures for OSHS jobs were 100 percent in 1980 and 82 percent in 1983.

The use of bituminous materials was also reduced during this period. In 1980, 77 percent of the shallow patching jobs on the IS used bituminous materials and in 1983 only 51 percent did. The corresponding figures on the OSHS were 65 percent in 1980 and 46 percent in 1983.

The same type of trend was observed in the materials use for deep patching activity (202). Furthermore, it was observed that the rates of consumption of both bituminous materials and conventional hot bituminous mixtures for patching were also reduced during the later years. For example, consider activity 201 (shallow patching). In 1980 the rate of consumption of hot bituminous mixtures for IS jobs was 1.0 ton per production unit, and in 1983 this rate dropped by about 40 percent to 0.61 ton per production unit. Similarly, for the OSHS jobs, the consumption rate was decreased from 0.95 ton in 1980 to 0.61 ton in 1983.

On the other hand, sealing activities (205, 206, and 207) showed different trends. While an increasing rate of bituminous materials consumption can be noticed for activity 205 (seal coating), a decreasing rate of consumption for the same material is observed for activities 206 and 207 (crack sealing). The reason for that increase in bituminous materials use in seal coating activity (recorded for OSHS jobs only) is due to the fact that this activity could be considered the only major maintenance activity applied on most of the OSHS (in the last few years, most of resurfacing and rehabilitation work was directed toward the IS). Thus the increase in the use of bituminous materials was to compensate for OSHS repair needs.

Finally, the other consumption rates and frequencies indicated a stable trend with only slight variations from year to year.

CORRELATION ANALYSIS OF PAVEMENT MAINTENANCE COSTS

Statistical correlation was performed between the pavement maintenance expenditures of a given year against the maintenance expenditures of a past year or number of years. Because the available data concerned 4 years, 1980-1983, three cases of correlation were applied: Case 1, correlation between each 2 successive years, that is 1980 with 1981, 1981 with 1982, and 1982 with 1983; Case 2, correlation between the average of 2 years' expenditures with the third year, that is the average of 1980 and 1981 with 1982, and the average of 1981 and 1982 with 1983; and Case 3, correlation between the average of 3 years' expenditures with the fourth year, that is the average of 1980, 1981, and 1982 with 1983. The results of the three cases are given in Table 2. As may be seen from Table 2, there is a general trend for higher correlation values between total costs for the IS than between those for OSHS. For example, in Case 2 (average of 2 years with the third year), the average correlation coefficient is 0.77 for the IS and 0.705 for OSHS, and in Case 3 these values are 0.82 and 0.72, respectively. The results also showed that the correlation coefficient is improved with the increase of number of past years considered. For instance, 0.65 was the correlation coefficient in Case 1 for both IS and OSHS, whereas the correlation coefficients in Case 2 were 0.77 and 0.705 for the two systems, respectively, and in Case 3 they were 0.82 and 0.72, respectively.

TABLE 2 Correlation Analysis of Total Costs

Pearson Correlation Coefficient					
Case 1[a]		Case 2[b]		Case 3[c]	
Interstate	Other State Highways	Interstate	Other State Highways	Interstate	Other State Highways
0.58	0.64	0.72	0.70	0.82	0.72
0.65	0.67	0.81	0.71		
0.73	0.65				
Average					
0.65	0.65	0.77	0.705	0.82	0.72

[a] Each 2 successive years, 1980 with 1981, 1981 with 1982, and 1982 with 1983.
[b] Average of 2 years with the third year, 1980-1981 with 1982, and 1981-1982 with 1983.
[c] Average of 3 years with the fourth year, 1980-1982 with 1983.

A second set of analyses was carried out to investigate the correlation between individual activity costs to determine if a relationship exists between expenditures of a past year or years and those of a following year. As in the previous analysis, the three correlation cases were applied for each individual activity. The results of the three cases are given in Table 3. The most important result is that patching and sealing activities (activities 201, 202, 206, and 207) showed the highest correlation values particularly when the expenditures of the past 2 or 3 years are considered (Case 2 or 3). It is believed that this is a good indication, because these activity costs represent more than 85 percent of total costs for the IS and more than 65 percent for the OSHS, which means that a good estimation of these activity costs using previous expenditure records can lead to a good overall estimation of total maintenance expenditures. Also, for these activities as well as most of the other activities, the IS correlation values were higher than those of the OSHS.

TABLE 3 Correlation Analysis of Individual Activity Costs

	Pearson Correlation Coefficient					
	Case 1[b]		Case 2[c]		Case 3[d]	
Activity No.[a]	Interstate	Other State Highways	Interstate	Other State Highways	Interstate	Other State Highways
201	0.73	0.69	0.82	0.71	0.82	0.72
202	0.63	0.24	0.76	0.27	0.76	0.33
203	0.16	0.06	0.21	0.04	0.23	0.02
205	NA	0.04	NA	0.06	NA	0.08
206	0.33	0.38	0.39	0.44	0.51	0.55
207	0.19	0.23	0.32	0.32	0.20	0.43
209	0.21	0.20	0.27	0.19	0.02	0.22
214	0.17	0.17	0.32	0.32	0.24	0.40
219	0.37	0.08	0.45	0.09	0.37	0.17

Note: NA = not applicable.

[a] Refer to Table 1 for activity names.

[b] Each 2 successive years, 1980 with 1981, 1981 with 1982, and 1982 with 1983.

[c] Average of 2 years with the third year, 1980-1981 with 1982, and 1981-1982 with 1983.

[d] Average of 3 years with the fourth year, 1980-1982 with 1983.

To summarize, the two correlation studies showed that the past expenditures could be of significant importance when used in maintenance prediction models for both total costs and individual activity costs. It should be noted here that the results give a general indication of the possible use of past records to predict future maintenance needs; however, no specific relationships could be derived from this analysis. The precise nature of these relationships merits further investigation.

CONCLUSIONS

On the basis of the findings of this study, the following conclusions can be drawn:

1. The accuracy of pavement maintenance cost estimation depends largely on the accuracy of predicting the cost of patching (shallow and deep) and sealing activities. These two activities constitute more than 85 percent of the total IS pavement maintenance costs and more than 65 percent of the total OSHS pavement maintenance costs.
2. The single activity that contributes most to total pavement maintenance costs is shallow patching activity, for which about 30-40 percent of the total pavement maintenance expenditures are made.
3. There is a significant difference in the use of labor and materials for the same pavement maintenance activities applied to IS and to OSHS. This is because maintenance practices are different for these two systems. In addition, the maintenance needs of these two systems are different. Consequently, the prediction of pavement maintenance costs should be undertaken separately for these two systems.
4. High correlation values were found in analyzing the year-to-year pavement maintenance expenditures, indicating the necessity of including past expenditures as a variable in maintenance cost prediction models. The average of the expenditures during 2 or 3 years showed better correlation values than were obtained when only 1 year was used to predict the following year's expenditure.
5. The results from disaggregate analysis of pavement maitenance costs can reveal much useful information that can be used in developing systematic maintenance management programs and in controlling maintenance costs.

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Abridgment

Introduction to Fuzzy Sets in Pavement Evaluation

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ABSTRACT

The theory of fuzzy sets is introduced to assist pavement evaluation. Many of the phenomena that control the performance of highways are not precisely defined, and engineering judgment and subjectiveness are inherent components of performance evaluation. This makes attractive the use of the mathematics of fuzzy sets to divide the performance evaluation into simpler questions and relate verbal statements and subjectiveness to quantitative statements. Techniques are presented to develop a "fuzzy pavement serviceability rating" that contains more information than the conventional pavement serviceability rating and incorporates each rating panel member's perceptiveness of pavements. The notion of a fuzzy binary relationship between roadmeter reading and pavement serviceability reading is introduced. Roadmeter readings can be composed with this relationship to give fuzzy pavement serviceability indices for different pavement sections.

Many of the properties that control the performance of highways are not precisely defined. This uncertainty requires that experience and engineering judgment supplement scientific knowledge in performance evaluation. The combination of objective information and subjective judgment can be performed methodically by the use of fuzzy sets mathematics (1).

Three kinds of uncertainty are encountered in engineering practice: random uncertainty, human-based uncertainty, and system uncertainty. Human and system uncertainty both derive from a lack of precision (or understanding) of an event. This results in the use of linguistic variables such as "economical" or "safe." The fact remains that these imprecisely defined or "fuzzy" classes play an important role in engineering decisions. The theory of fuzzy sets has proved to be an effective tool in handling these types of uncertainty.

A fuzzy set A in the space X is characterized by a membership function $\mu_A(x)$ that associates with each point in X a real number in the interval [0,1]. The value of $\mu_A(x)$ at x represents the "grade of membership" of x in A (i.e., the degree of support or belief that the element x belongs to the subset A). The closer the value of $\mu_A(x)$ is to unity, the higher is the grade of membership of x in A. The membership function is usually written as

$$A = \bigcup_j \mu_A(x_j)/x_j = \mu_A(x_1)/x_1 + \ldots + \mu_A(x_n)/x_n \qquad (1)$$

where the plus sign is used in place of "union" as in ordinary set theory, and $\mu_A(x_j)$ is the degree of support for any value x_j.

Many complex problems can be divided into a sequence of simpler questions, which can be answered by experienced engineers using descriptive phrases. The membership functions can be used to methodically quantify such linguistic variables; they can then be manipulated using the axioms of fuzzy set theory to obtain a meaningful answer to the original problem (2). In this paper, these techniques are applied to pavement serviceability.

PAVEMENT SERVICEABILITY

Roughness has the greatest impact on the serviceability of a pavement, and in many states it is used as the initial screening criterion of road sections in determining maintenance needs. The pavement serviceability rating (3) of a particular road section (PSR) is the mean of the ratings of a panel of road users (4,5) in the interval [1,5].

Judgments of the panel members are subjective and involve human instead of random uncertainty. To use fuzzy logic to develop a PSR that reflects the human uncertainty and the relative significance or perceptiveness of the various judgments, the panel is separated into groups of individuals with similar backgrounds, to account for the differences in perceptiveness. Furthermore, to avoid any differences within a group such as experience or age, each group is subdivided into a sufficient number of subgroups. Experienced engineers have a deeper insight into the road condition, so far as maintenance requirements are concerned, and their opinions are weighted more in arriving at the combined opinion of their group.

As an example, let us assume that the panel members have been divided in two groups, A of highway engineers and B of laymen (6). Group A has two subgroups: A_1 of experienced engineers, and A_2 of engineers with little experience. Similarly, the group of laymen in subdivided into B_1 and B_2, frequent and infrequent road users, respectively. Each subgroup's opinions of pavement quality are represented by the following fuzzy sets along with the relevant weights:

$A_1 = 0.6/2.7 + 0.8/2.8 + 1.0/2.9 + 0.8/3.0 \quad w_1 = 0.6$

$A_2 = 0.6/2.8 + 0.8/2.9 + 1.0/3.0 + 0.7/3.1 \quad w_2 = 0.4$

$B_1 = 0.8/2.8 + 1.0/2.9 + 0.7/3.0 + 0.5/3.1 \quad w_1 = 0.7$

$B_2 = 0.9/2.8 + 1.0/2.9 + 0.9/3.0 \quad w_2 = 0.3$

Group opinions are found by Dubois and Prade (7) to be

$$A = \bigcup_i w_i A_i \qquad (2)$$

where

$$\sum_i w_i = 1$$

with

$$\mu_A(x) = \max_i [w_i \times \mu_{A_i}(x)] \qquad (3)$$

Hence,

$A = 0.36/2.7 + 0.48/2.8 + 0.6/2.9 + 0.48/3.0 + 0.28/3.1$

$B = 0.56/2.8 + 0.7/2.9 + 0.49/3.0 + 0.35/3.1$

Groups A and B can now be assembled according to each group's relative significance or perceptiveness of the influence of roughness. In the previous example, assuming that the relative significance of Groups A and B are $\alpha = 2.0$ and $\beta = 0.5$, respectively, Group A is concentrated (8):

$$A^* = A^{\alpha} \tag{4}$$

$$= 0.13/2.7 + 0.23/2.8 + 0.36/2.9 + 0.23/3.0 + 0.08/3.1$$

and B is dilated (8):

$$B^* = B^{\beta} \tag{5}$$

$$= 0.75/2.8 + 0.84/2.9 + 0.70/3.0 + 0.59/3.1$$

The values of w_i, α, and β should be obtained by consulting highway experts. The authors prepared a questionnaire to obtain the factors denoting the relative significance of possible panel groups and also the relative weights assigned to the subgroups. If α and β factors are to represent experts' collective judgment, they themselves could turn out to be fuzzy sets (9).

Final aggregation of the information contained in A* and B* is possible using a number of operations (7); algebraic product is used herein to retain every independent judgment (rating) in the PSR:

$$\text{PSR} = A^*.B^* = A^{\alpha}.B^{\beta} \tag{6}$$

$$= 0.17/2.8 + 0.30/2.9 + 0.16/3.0 + 0.05/3.1$$

This is the fuzzy PSR for the pavement section under consideration. The PSR of a section originates from subjective judgments that support a region of values rather than a single value. The conventional PSR is a discrete number and thus does not clearly indicate this region of PSR, supported by the members of the panel. On the other hand fuzzy PSR shows this region of support as well as the degree of support for each value. Thus, the fuzzy PSR is an improvement over the conventional one. Further, it incorporates each individual's perceptiveness of pavements while carrying his judgment up to the final stage of the analysis.

MEASUREMENTS WITH THE ROADMETER

The roadmeter reading varies with the path traced by the vehicle, the driver characteristics, the vehicle speed, and the gas tank level. These introduce imprecision, and representing the roadmeter reading by a fuzzy set may be more appropriate (10). A typical representation of a roadmeter reading of 800 is shown in Figure 1. In this figure 800 is the reading obtained for a section and 840-760 is the range of values obtained by repeated measurements on the same pavement section. This curve may either be a straight line or a π curve (11) depending on the experts' subjective judgment.

FORMATION OF THE RELATIONSHIP

Rather than correlating by linear regression analysis, in the fuzzy sets theory the notion of a link between two elements belonging to the same universe or two different universes is expressed by a binary fuzzy relation (7). If A and B are fuzzy sets in two universes X and Y, respectively, the most common formulation of binary fuzzy relation R is done using the cartesian product:

$$R = A \times B \tag{7}$$

with

$$\mu_R(x_i,y_j) = \min[\mu_A(x_i), \mu_B(y_j)] \tag{8}$$

When a set of data is available for correlation, the global (binary) fuzzy relation is formed by the union of fuzzy relations for each pair of data. By making the highest membership 1.0 and increasing the other memberships proportionately, the fuzzy PSR in Equation 6 is normalized as

$$\text{PSR} = 0.57/2.8 + 1.0/2.9 + 0.53/3.0 + 0.17/3.1$$

and the binary fuzzy relationship between the PSR and the roadmeter reading (RR) of Figure 1 is formed according to Equation 8. As an example, μ_R (3.0, 790) is 0.53, the minimum of μ_{PSR} (3.0) = 0.53 and μ_{RR} (790) = 0.75. Repeating this operation for each set of values results in Table 1. Membership values of a fuzzy relation are analogous to the strength of the link between the corresponding RR and PSR values. For example, RR = 800 and PSR = 2.9 are strongly linked (membership values = 1.0) whereas RR = 830 and PSR = 3.1 are weakly related (membership values = 0.17). Such relationships can be formed for all the sample sections, covering wide ranges of PSR and RR. Aggregation of these data produces the global PSR-RR relationship for the highway network.

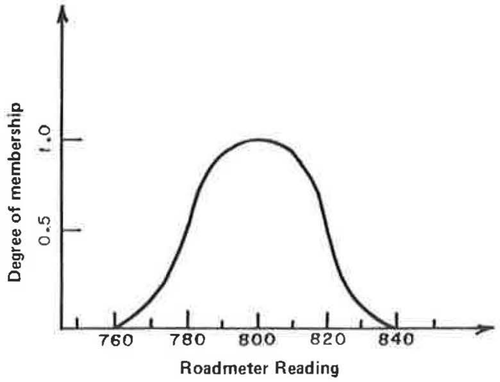

FIGURE 1 Typical fuzzified roadmeter reading.

TABLE 1 Fuzzy PSR-Roadmeter Reading Relationship

RR PSR	770	780	790	800	810	820	830
2.8	0.125	0.50	0.57	0.57	0.57	0.50	0.125
2.9	0.125	0.50	0.875	1.0	0.875	0.50	0.125
3.0	0.125	0.50	0.53	0.53	0.53	0.50	0.125
3.1	0.17	0.17	0.17	0.17	0.17	0.17	0.17

COMPOSITION OF THE FUZZY RELATIONSHIP

If A is a fuzzy set in the universe X and R is a fuzzy relation in the universe X x Y, the fuzzy set B (in the universe Y) induced from A through R is defined as

$$B = A.R \tag{9}$$

with

$$\mu_B(y) = \sup_x \min [\mu_A(x), \mu_R(x,y)] \tag{10}$$

Roadmeter-pavement serviceability rating data can be used to evaluate the pavement serviceability index (PSI) for a particular pavement section, if the roadmeter reading is known. As an example, suppose that the fuzzified form of the roadmeter reading for a different pavement section is given by

$$RR' = 0.6/810 + 1.0/820 + 0.6/830$$

The corresponding fuzzy PSI for this section is obtained according to Equation 10 by composing RR' with the fuzzy relation in Table 1, which is assumed to be the global relationship for simplicity:

$$PSI = 0.57/2.8 + 0.6/2.9 + 0.53/3.0 + 0.17/3.1$$

Decision theory techniques using fuzzy sets will be developed to compare the fuzzy pavement serviceability indices of pavement sections in the state and determine their maintenance priorities.

CONCLUSION

The initial stages of a procedure that enables the methodical manipulation of human-based and system uncertainties inherent in a pavement management system have been outlined. The concept of fuzzy PSR is described in detail with reference to the formation of membership functions and the incorporation of the perceptiveness of every member in the rating panel. This is accomplished by obtaining experts' opinions at different stages, in the form of relative significance factors and relative weights to be attached to the panel members' judgments.

Further, the need to fuzzify the roadmeter reading is emphasized. This facilitates gathering of pavement serviceability rating-roadmeter reading data for sample pavement sections, by means of a fuzzy binary relationship. Pavement serviceability indices for pavement sections can be extracted from this data base if the roadmeter readings are known.

The work discussed here is the preliminary stage of the development of fuzzy sets techniques to help pavement management.

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Development of Performance Prediction Models for Airfield Pavements

M.Y. SHAHIN and J.M. BECKER

ABSTRACT

Data for developing performance prediction models were obtained from 12 U.S. Air Force bases located throughout the United States. The data were used to develop performance prediction models for asphalt and concrete pavements. Data were also collected at a later date from 5 of the 12 bases originally surveyed to verify all developed models. It was found that the performance models do an adequate job of predicting pavement condition but that these models may not be precise enough for project level management. The concept of local modeling, which is the development of different models for each base, was investigated and the results appear promising. Local modeling has the advantage that factors such as construction methods, maintenance policies, and environmental factors do not need to be considered; in universal modeling, these factors are probably not accounted for fully. The performance of pavements as presented herein is measured by the pavement condition index that was developed for the U.S. Air Force and recently published by the FAA as an advisory circular.

The main objective of the prediction models is to forecast the condition of the pavement given different traffic, age, and environmental factors. Such models would help greatly in deciding what maintenance and repair (M&R) alternative to recommend for a specific pavement section (feature). The models should be capable of forecasting the performance of the pavement if current local routine maintenance policies are continued, if major maintenance is applied, if overall M&R (such as overlay, recycling, or reconstruction) is applied, or if a change in traffic occurs. The models should also provide insight into variables that cause deterioration of pavements and therefore could be used to predict the performance of new pavements for a variety of designs. To measure and predict the performance of a pavement, a repeatable condition rating system must be used.

MEASURING PAVEMENT PERFORMANCE

The performance of a pavement, as presented herein, is measured by the pavement condition index (PCI), which indicates the present condition of the pavement in terms of structural integrity and surface operational condition. The PCI was developed for the U.S. Air Force (1) for both asphalt and concrete surfaced pavements.

The condition survey for airfield pavements consists of the following:

1. The pavement must be divided into uniform sections or "features" (based on consistent structural thickness, design, and materials) that were constructed at the same time and that serve similar traffic types (aircraft) and volumes.
2. These uniform sections are divided into "sample units" consisting of approximately 20 slabs (concrete) or 2,500 ft² (asphalt). To save time and money, random sampling of units is used to obtain a 95 percent confidence of the true PCI of the entire uniform section or feature.
3. Each pavement feature is then inspected, and existing distress types, severity levels, and densities are recorded. See Shahin et al. (2) for a list of the guidelines required for performing this inspection.
4. A deduct value is determined from the appropriate curve for each distress type, density, and severity level.
5. The total deduct value (TDV) is determined by summing all deduct values from each distress condition observed.
6. The corrected deduct value (CDV) is determined based on the TDV and the number of distress conditions observed with individual deduct values greater than five points.
7. The pavement condition index (PCI) is calculated as PCI + 100 - CDV.

The PCI allows the engineer to objectively set priorities for maintenance and repair for a given feature and to rationally compare the condition of pavements from base to base. The PCI has been recently published by FAA as an advisory circular (3).

DATA COLLECTION

Airfield pavement data were obtained from 12 Air Force bases throughout the United States. A complete historical set of information about each pavement feature included feature identification; pavement layer information, including all overlays; joint design for concrete pavements; foundation soils; traffic for each mission (type, annual operations); past maintenance; current PCI and distress; and climatic variables (precipitation, temperature) and other geographic variables.

Air Force bases having both asphalt and concrete pavements were selected over a range of climates and traffic. An average of 27 features was obtained from each base, for a total of 327 features. These features are divided into pavement types and uses as follows:

Pavement Type	Feature (%)
PCC	60
PCC over PCC	1
PCC over AC	1
AC	10
AC over PCC	9
AC over AC	18
Other (e.g., AC sandwich construction)	1
Total	100

Use	Feature (%)
Runway	35
Taxiway	46
Apron	19
Total	100

The data for these features were obtained from (a) Air Force pavement evaluation reports, (b) construction records in the base engineering office and other historical records, and (c) current traffic records and the recollections of employees about past traffic missions. The traffic data were difficult to obtain, but even subjective estimates were considered better than no data at all.

All pavement features were surveyed using the PCI method, and existing distresses were recorded on the data collection sheets. Tables 1 and 2 give summaries of the means and ranges of some key variables. The predictive models are based on the collected data and are therefore limited by the ranges of the variables included in the data bank. The data represent a broad range of pavements constructed by the Air Force during the past 30 years.

TABLE 1 Means and Ranges of Key Rigid Pavement Variables

Variable	Mean Value	Range
Layer information variables		
Age (yr)	18.0	2-37
PCC thickness (in.)	15.3	2-24
Modulus of rupture (lb/in^2)	701	480-992
Base thickness[a] (in.)	12.7	2-55
Modulus of subgrade reaction (K)[b] lb/in^3	240	15-500
Environmental variables		
Average annual temperature (°F)	60.0	38.8-65.8
Average annual precipitation (in.)	29.7	3.8-52.1
Freezing index (degree days)	127.4	0-1,980
Freeze-thaw cycles (2-in. depth)	25.8	0-111
Water table (ft)	100	4-500
Mechanistic variables		
Fatigue	68,430	315-612,654
Damage	425.86	0-26,420

[a] Mean value does not include those features with no base course; 68 features had no base course.

[b] K-value on top of layer on which PCC surface rests.

DATA ANALYSIS

In addition to the collected field data, a number of mechanistic variables were also computed. Following is a description of these variables for both rigid [portland cement concrete (PCC) and asphalt concrete (AC)/PCC] and flexible (AC and AC/AC) pavements.

Rigid (PCC and AC/PCC) Pavements

The maximum free edge stress at the bottom of the concrete slab was selected as the main response parameter for rigid pavement analyses. Charts for 41 different aircraft were prepared to compute the edge stress as a function of slab thickness and of the modulus of subgrade reaction using the H51 program (4). The program models the PCC pavement structure as a rigid slab resting on an elastic (Winkler-type) foundation. A constant E-modulus of 4 million lb/in² and a Poisson's ratio of 0.15 were assumed for the PCC slab.

Figure 1 shows how the maximum free edge stress varies with slab thickness and subgrade support for the B-29 aircraft. The figure also shows the relative orientation of the main gear with respect to the free edge. In all computations, a circular tire imprint was assumed.

Two variables, computed using the edge stress, that were found to correlate with pavement perfor-

TABLE 2 Means and Ranges of Key Flexible Pavement Variables

Variable	Mean Value	Range
Layer information variables		
Age (yr)	10.58	0-27
Original AC thickness (in.)	3.80	2.0-7.0
Total AC thickness (in.)	5.85	2.0-14.0
Base CBR[a] (%)	85.13	20-100
Total select thickness (in.)	30.62	0.0-67.0
Subgrade CBR (%)	17.80	6-88
Environmental variables		
Average annual temperature (°F)	54.2	38.0-65.8
Average annual temperature range (°F)	45.2	31.6-54.2
Average daily temperature range (°F)	23.4	19.1-28.5
Average annual precipitation (in.)	26.2	3.8-52.1
Average annual solar radiation (langleys)	407	325-520
Freezing index (degree days)	491	0-1,980
Freeze-thaw cycles (2-in. depth)	26.5	0-99
Water table (ft)	100	4-500
Mechanistic variables		
Weighted average surface deflection—present period (in./ESWL)	0.001	0-0.005
Weighted average surface deflection[b]—first previous period (in./ESWL)	0.001	0-0.002
Weighted average vertical stress on base—present period (PS)	86.2	0-175
Weighted average vertical stress on base[a]—first previous period[b]	59.7	0-203
Cumulative vertical stress on base—present period (lb/in^2 x no. of passes)	1.039 x 10	0-1.414 x 10
Cumulative vertical stress on base—first previous period[b]	6.841 x 10	0-1.163 x 10
Cumulative vertical strain on subgrade—present period (0.001 in. x no. of passes)	6.067 x 10	0-8.881 x 10
Cumulative vertical stress on subgrade—first previous period[b] (0.0001 in. x no. of passes)	4.771 x 10	0-1.274 x 10

[a] Mean value does not include features with no base (four features have no base).

[b] A period is defined by the age of the surface or overlay. If no overlay exists and therefore there is no previous period, the value for this variable for that particular feature is recorded as 0. These features are included in the calculation of the mean value.

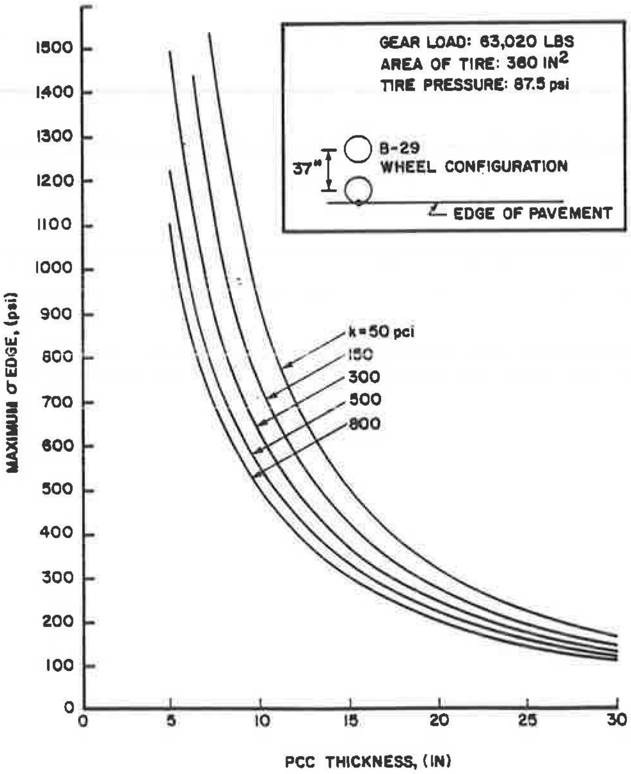

FIGURE 1 Edge stress at bottom of concrete slab as a function of slab thickness and modulus of subgrade reaction for a B-29 aircraft.

mance and pavement distress are FATAGE, a fatigue variable, and DAMAGE, which reflects a preestablished relationship between fatigue and cracking. The variables were computed as follows:

$$\text{FATAGE} = \sum_{i=1}^{a} [(0.75 \times \sigma_{e_i})/\text{MR}] \times n_i \times \text{AGE}$$

$$\text{DAMAGE} = \sum_{i=1}^{a} (n_i/N_i) \times \text{AGE}$$

where

a = number of different aircraft using the feature;
AGE = time (years since original construction or, if overlaid, time since overlay construction);
σ_{e_i} = edge stress caused by aircraft i as computed by H51 computer program (lb/in.^{2});
MR = modulus of rupture of concrete (lb/in.^{2});
n_i = total number of passes per year (not coverages) of aircraft i over pavement feature; and
N_i = number of repetitions of aircraft i to cause failure of concrete $= 10^{(17.61 - 0.01761 \times \sigma_{e_i})}$.

Note that if the edge stress < 500, n/N is assumed to be negligible. If $(17.61 - 0.01761 \times \sigma_e) < 0$, N is assumed to be equal to 1.

For asphalt overlaid concrete (AC/PCC) pavements, a transformed section analysis for stress determination was used to convert asphalt thickness to an equivalent concrete thickness (5). The FATAGE and DAMAGE variables were then computed as described earlier.

Flexible (AC and AC/AC) Pavements

The analysis of flexible pavements was based on linear elastic-layered theory using the BISAR computer program (6). The AC elastic modulus was estimated for each feature based on thickness of AC layer, mean annual temperature, and mean annual solar radiation. The elastic modulus for granular bases was estimated based on type of aircraft, thickness of AC layer, and elastic modulus of the AC layer. The developed procedures for estimating the AC and granular moduli are presented by Shahin et al. (7). Four response parameters were computed: (a) the maximum surface deflection, (b) the vertical stress at the top of the base layer, (c) the radial strain at the bottom of the AC layer, and (d) the vertical strain at the top of the subgrade. Response parameter computations were carried out using the BISAR computer program.

The data were also analyzed to compare the average life of asphalt pavements with and without overlay. It was found that, for those pavements that were overlaid with AC at least once, the average original asphalt surface had a life of 15.7 yr; an asphalt pavement that had been overlaid once had a life of 9.72 yr before being overlaid for the second time, and the life of an asphalt pavement that had been overlaid twice had an average of 7 yr. This general trend (Figure 2) suggests that, on the average, an asphalt surface layer will not last as long as the underlying layer. The reason may be that asphalt overlays were underdesigned or that the damage to a previous layer was not properly accounted for, causing the newer asphalt surface to fail earlier than expected.

MODEL DEVELOPMENT

The first step of model development was the establishment of correlation matrices between variables. Scattergrams were used to determine ranges and general trends of the variables. Various variable transformations and interactions were also investigated. The second step was to perform a stepwise regression analysis for the model development.

The stepwide regression analysis procedure starts with the simple correlation matrix between the dependent variable and each independent variable. It enters into regression the independent variables most highly correlated with the dependent variable. Using partial correlation coefficients, it then selects the next variable to enter regression (i.e., the variable whose partial correlation is highest with the dependent variable). At every step, the program reexamines the variables included in the equation in previous steps by testing each variable at each stage as if it were the last to enter and by checking its contribution by means of the partial F-test. Thus, some variables may be removed from the

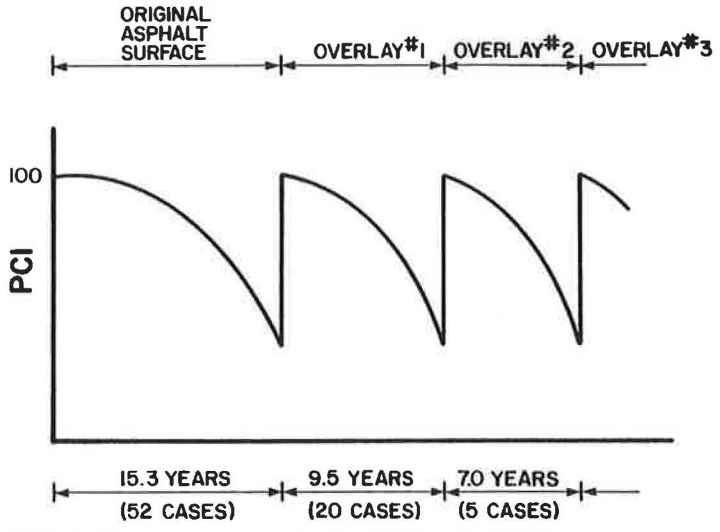

FIGURE 2 Average age of asphalt surface before overlay.

equation after they have been entered. After many attempts, the best linear regression model was selected on combined statistical and engineering criteria. A nonlinear regression analysis was then performed using the same variables that were used in the linear model in order to improve the prediction parameters. The SPSS statistical package (8) was used in all phases of model development. The two models presented herein are for PCI prediction of rigid and flexible pavement, respectively.

Rigid Pavement PCI Model

A model was developed for predicting the PCI for both PCC pavements and PCC pavements overlaid with asphalt. Initially, a separate model for AC/PCC pavements was considered, but the limited number of cases (only 25) for this pavement type made this impractical. Using a transformed section analysis for stress determination (5), the AC/PCC pavement features were combined with the PCC pavement features, and a PCC prediction model was developed to include both.

Data for developing the PCI prediction model were collected for 162 pavement features, 137 PCC pavements and 25 PCC pavements overlaid with asphalt. Table 3 gives some of the pertinent statistical data.

TABLE 3 Statistics for Pertinent Rigid Pavement Variables

Variable	Average Value	Standard Deviation	Low Value	High Value
No Overlays (19 cases)				
PCI	76.652	14.740	24	98
PCC THICK	15.625	3.858	6	24
AGE	17.978	7.353	2	37
MR	702.023	65.920	480	992
K-VALUE	239.606	116.162	15	500
PASSES/YR	17001.250	19804.793	0	75000
FATAGE	75716.871	120166.366	0	612654
DAMAGE	449.761	2773.442	0	26420
One AC Overlay (6 cases)				
PCI	66.520	16.187	17	87
PCC THICK	7.360	1.229	6	12
AC THICK	3.920	2.494	1.5	8
AGE	15.680	6.644	6	24
AGECOL	16.200	6.696	7	30
MR	554.167	237.860	450	900
K-VALUE	244.333	81.520	100	350
PASSES/YR	9780.000	12665.100	255	48150
FATAGE	151746.600	176564.628	3149	658325
DAMAGE	47880.252	77662.703	0	251360
DAMCOL	77998.633	160064.248	0	568460

The final model for PCI prediction was obtained as follows:

$$\begin{aligned}\mathrm{PCI} = {} & 99.503 - 2.4837 \times \mathrm{AGE}^{0.55857} \times \mathrm{LDAMAGE}^{0.6} \\ & - 0.00020334 \times \mathrm{AGE}^{0.5} \times \mathrm{FATAGE}^{0.74987} \\ & - 0.0028494 \times \mathrm{AGE}^{1.0} \times \mathrm{AAPREC}^{1.2188} \\ & - 0.028872 \times \mathrm{AGE}^{1.7366} \times \mathrm{FTC} \\ & - 0.076824\, [(\mathrm{AGE}^{5}\ \mathrm{AGECOL}^{0.76544}\ \mathrm{LDAMCOL}^{1.0}) \\ & \div \mathrm{THICK}^{1.6035}]\end{aligned}$$

$R^2 = 0.72155$

$\overline{\sigma} = 8.77083$ (standard error of estimate)

where

AAPREC = average annual precipitation (in.);
FTC = a freeze-thaw cycle discrete variable that is 1 if the number of freeze-thaw cycles in a PCC pavement at a 2-in. depth is greater than or equal to 10 and 0 if the number of freeze-thaw cycles in a PCC pavement at a 2-in. depth is less than 10 or if the existing surface is an asphalt overlay;
THICK = thickness of concrete pavement or, if overlaid, the most recent overlay thickness;
LDAMAGE = $\log_{10}$ (DAMAGE + 10);
LDAMCOL = $\log_{10}$ (DAMCOL + 10); and
DAMCOL = cumulative damage before last overlay.

The other variables in the PCI equation are defined as follows:

PCI = pavement condition index;
PCC THICK = thickness (in.) of the original PCC surface;
AC THICK = thickness (in.) of the most recent AC overlay;
AGECOL = age of the PCC slab, in years, at the time it is overlaid; if no overlay exists, AGECOL is zero;
MR = modulus of rupture (lb/in.^{2}) of the PCC slab;
K-VALUE = modulus of subgrade reaction (lb/in.^{3}); reading is taken on the surface immediately below the PCC surface;
PASSES/YR = reported annual traffic; this number represents the average number of passes per year the pavement services for the combined total of all aircraft types;
FATAGE = a mechanistic input variable used in the PCI prediction model; it represents the total critical stresses to which the pavement has been subjected;
DAMAGE = a mechanistic input variable used in the PCI prediction equation; using a given procedure, it determines the number of passes each aircraft can make over a given feature before structural damage occurs; the variable DAMAGE records how many times this number has been reached; and
DAMCOL = same as DAMAGE but records only the number before the pavement is overlaid (i.e., DAMAGE is damage since overlay or, if no overlay, since original construction and DAMCOL is damage before overlay).

Figure 3 is a scattergram of predicted versus actual PCI. The predicted values are plotted along the horizontal scale, and the actual values are plotted along the vertical scale. As the figure shows, the model is fairly good at predicting values above 65 but becomes less accurate at lower PCI values.

A sensitivity analysis was performed to evaluate the model response to changes in traffic, structure, foundation, material properties, and the environment.

Traffic and Pavement Structure

The variables DAMAGE, FATAGE, and DAMCOL are directly influenced by traffic and pavement structure. Figure 4 shows the effect of PCC thickness on the PCI. The figure shows that within the design range for each aircraft, the PCC thickness has a major impact. When a certain thickness is reached, the PCI value levels off. Because all three aircraft approach the same value for upper and lower bounds,

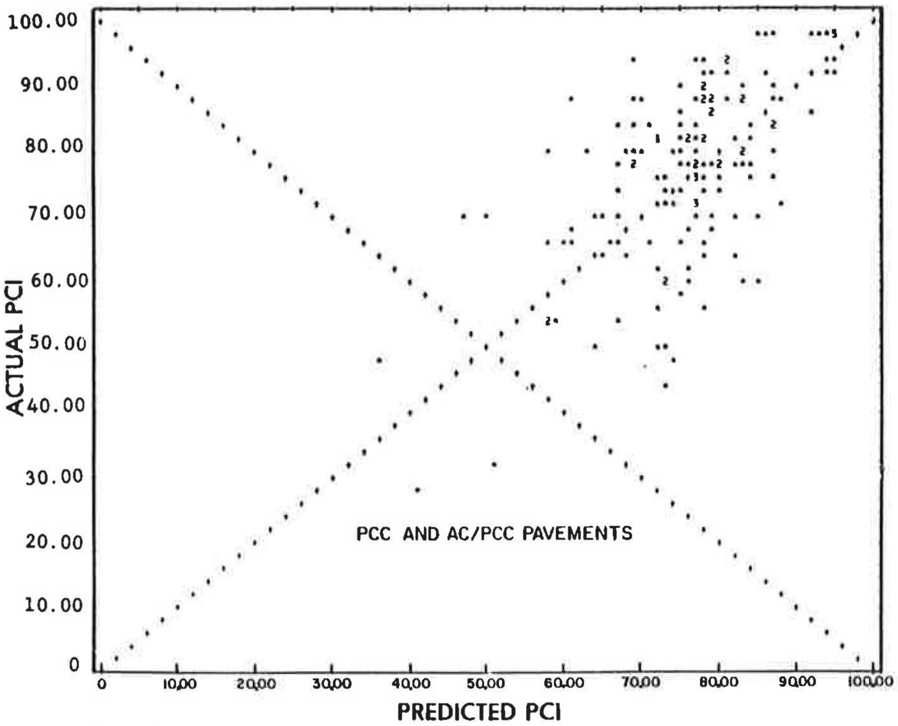

FIGURE 3 Actual PCI versus predicted PCI for PCC and AC/PCC pavements.

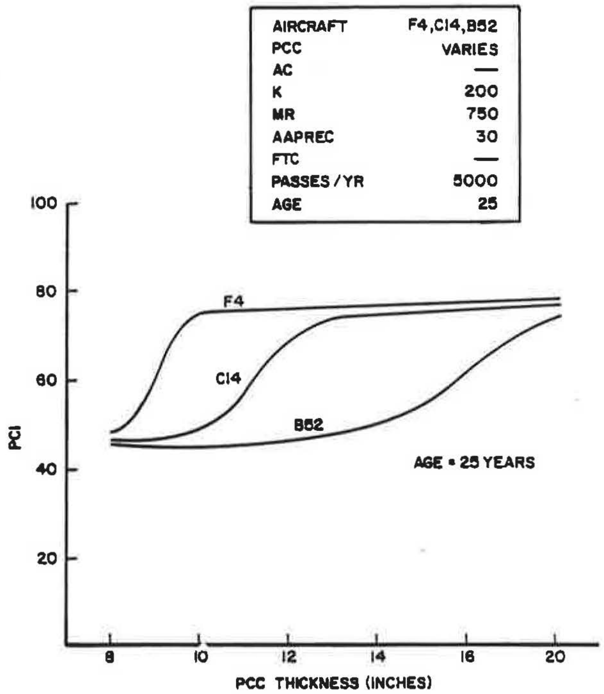

FIGURE 4 Effect of aircraft type on PCI as a function of PCC thickness.

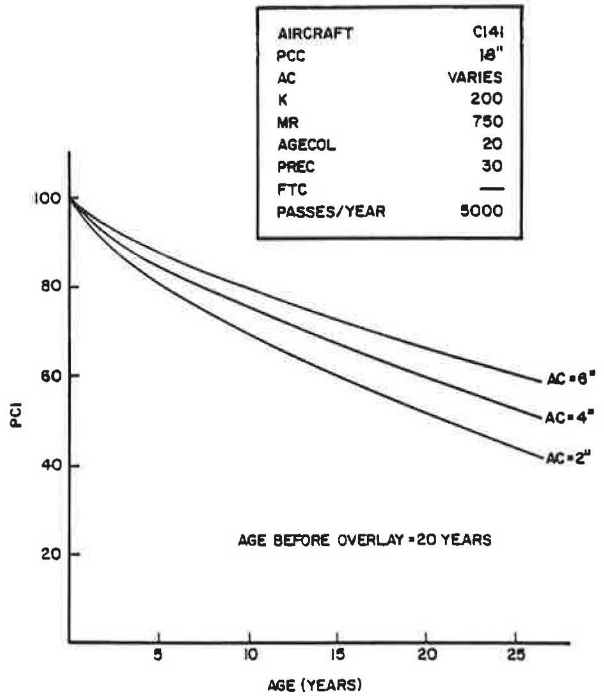

FIGURE 5 Effect of asphalt overlay thickness on PCI as a function of age.

the PCI loss at the upper level can most likely be attributed to the effects of age and environment. Figure 5 shows the effect of the AC overlay thickness for AC/PCC pavements. Figure 6 shows the possible effects of increases in the number of passes for a given pavement structure and aircraft, and Figure 7 shows the effects of different traffic types on a pavement.

Foundation

The only input that relates to the foundation is the K-value (modulus of subgrade reaction) of the layer directly beneath the concrete slab. The K-value is a measure of the layer's relative stiffness and plays an important role in determining the edge stress caused by a given pavement-aircraft combination. In

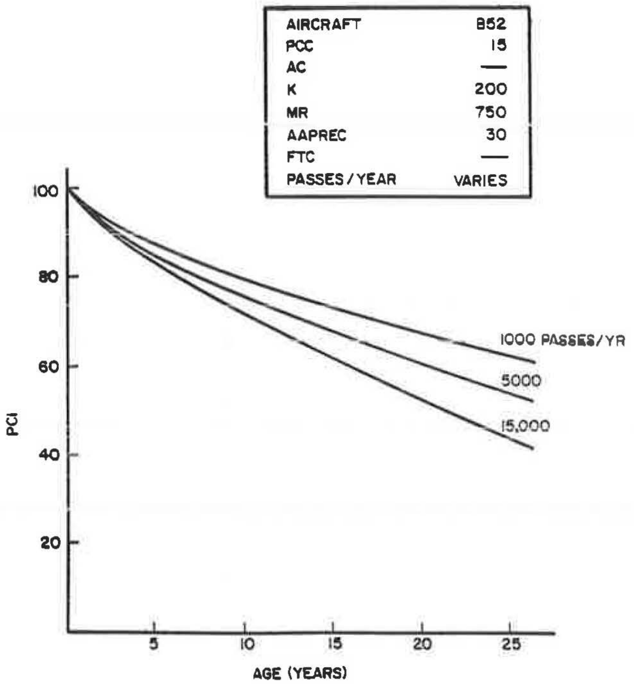

FIGURE 6 Effect of traffic volume (passes) on PCI as a function of age.

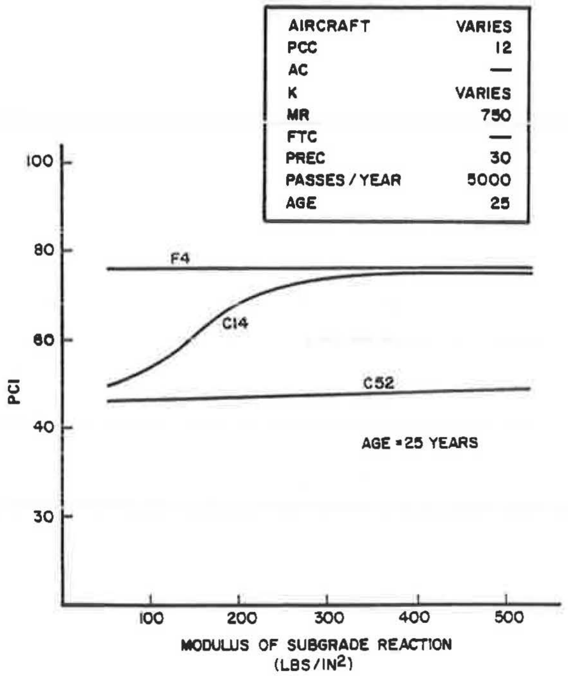

FIGURE 8 Effect of aircraft type on PCI as a function of modulus of subgrade reaction.

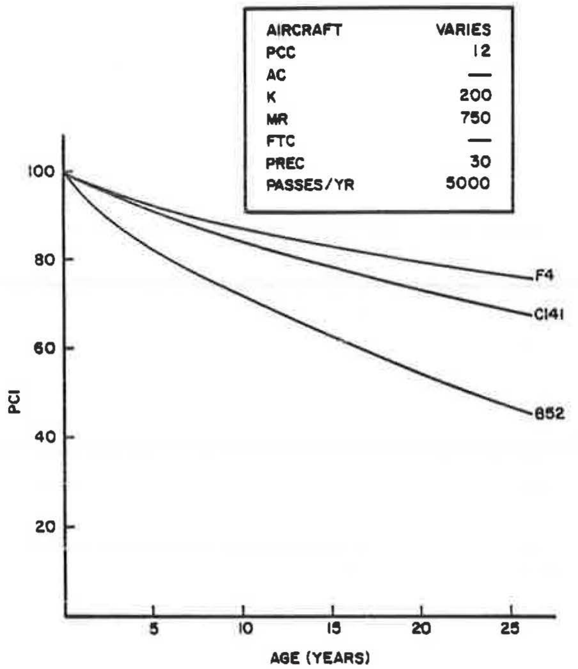

FIGURE 7 Effect of aircraft type on PCI as a function of age.

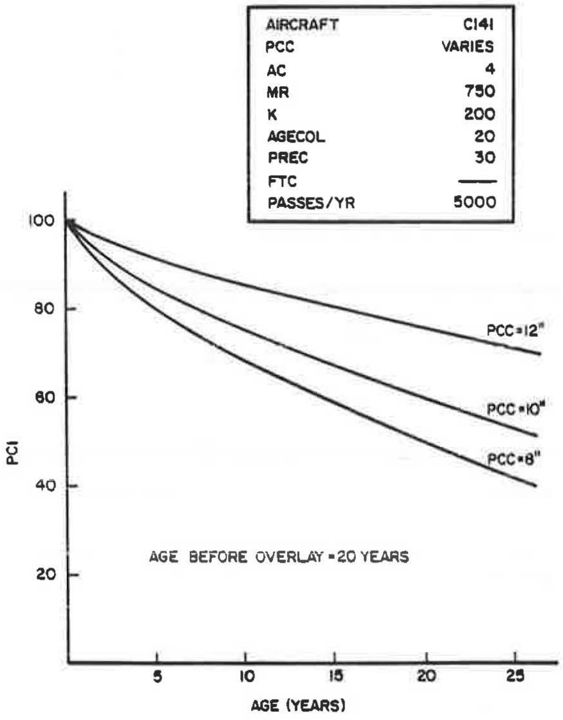

FIGURE 9 Effect of PCC thickness on PCI as a function of age.

the ranges of concrete thickness where the PCI would vary if the concrete thickness were altered slightly, the K-value has a major impact. Figure 8 shows this effect. The pavement structure used in Figure 9 is well above that needed for the F-4 aircraft, and the K-value has little influence on the PCI. Figure 9 shows that if values of PCC thickness were chosen that were not at the upper or lower limits for PCI values of the B-52 and F-4 aircraft, the K-value would also show a significant effect for these aircraft.

Material Properties

The material property that influences the model is the modulus of rupture (MR) of the concrete. A sensitivity analysis shows that for MRs ranging from 500 to 900 psi, the difference in PCI at an age of 25 years was only five points. This, plus the fact that there are no other variables relating to material properties and quality of construction, shows that the model is lacking in this area.

Environment

The environmental variables are precipitation and the freeze-thaw cycle. Figure 10 shows the varying effect of these variables. The top three lines of the graph show the effects of varying amounts of rainfall with no freeze-thaw cycles. The bottom line shows the effect of freeze-thaw cycles at a rainfall of 50 in. per year.

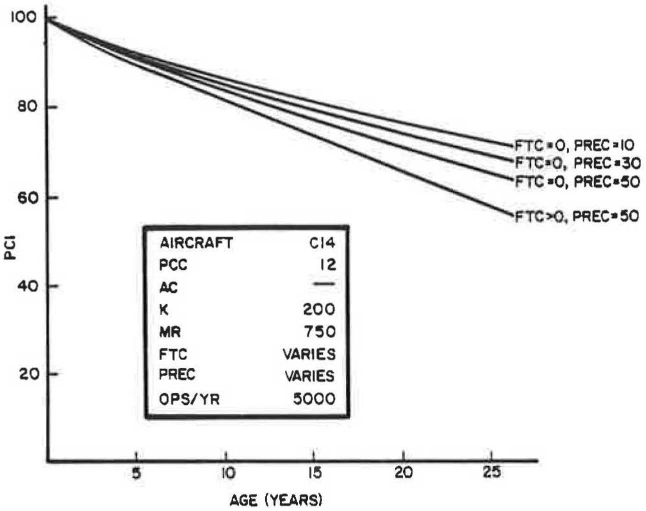

FIGURE 10 Effect of rainfall and freeze-thaw cycles on PCI as a function of age.

TABLE 4 Statistics for Pertinent Flexible Pavement Variables

Variable	Average Value	Standard Deviation	Low	High
No Overlays (26 cases)				
PCI	67.308	17.756	31	100
SURTHICK	3.808	0.708	2	5.5
PMAOPS	8371.808	14460.075	100	64200
AGE	17.077	8.727	0	27
SGCBR	13.269	8.151	6	35
BTHICK	7.135	3.719	6	24
1 Overlay (26 cases)				
PCI	72.615	12.989	39	100
SURTHICK	3.731	0.962	2	7
OL1THICK	1.942	1.061	1	6
AGE	7.115	4.625	0	26
AGECOL	17.038	5.524	6	27
2 Overlays (12 cases)				
PCI	77.667	12.886	46	99
SURTHICK	4.167	1.642	2	7
OL1THICK	2.517	1.329	1	5
OL2THICK	1.833	0.718	1.5	4
AGE	6.667	3.229	1	11
AGECOL	10.750	5.610	4	25
3 Overlays (5 cases)				
PCI	81.200	9.834	67	92
SURTHICK	3.200	1.643	2	5
OL1THICK	3.600	1.517	2	5
OL2THICK	1.660	0.144	1.3	2
OL3THICK	1.900	0.652	1.5	3
AGE	7.200	4.604	2	12
AGECOL	7.000	2.121	4	9

Flexible Pavement PCI Model Presentation

A model for predicting the PCI for AC and AC/AC pavements was developed. Data were collected from 69 asphalt pavement features, 26 nonoverlaid pavements and 43 features with one or more asphalt overlays. Table 4 gives statistical data on these features. In Table 4

PCI = pavement condition index;
SURTHICK = thickness of original asphalt pavement (in.);
PMAOPS = present mission annual operations in passes per year;
SGCBR = subgrade California bearing ratio percent;
BTHICK = base thickness (in.);
OL1THICK = thickness (in.) of the first asphalt overlay;
AGE = age, in years, since original construction or, if overlaid, since the most recent overlay construction (see Figure 11);
AGECOL = age, in years, from the second most previous overlay, or construction date, to the most recent overlay; if no overlay exists, AGECOL=0 (see Figure 11);
OL2THICK = thickness (in.) of the second asphalt overlay; and
OL3THICK = thickness (in.) of the third asphalt overlay.

The developed model was as follows:

$$\mathrm{PCI} = 99.824036 - 9.214053 \times \mathrm{AGE}^{0.38719987} \times \mathrm{ADSUR}^{0.1} \times \mathrm{AVSUR}^{0.19120227} - 1.0144967\mathrm{E}\text{-}05 \times \mathrm{AGE}^{1.7160520} \times \mathrm{VCOL}^{0.59024368}$$

$R^2 = 0.83389$

$\overline{\sigma} = 7.19736$ (standard error of estimate)

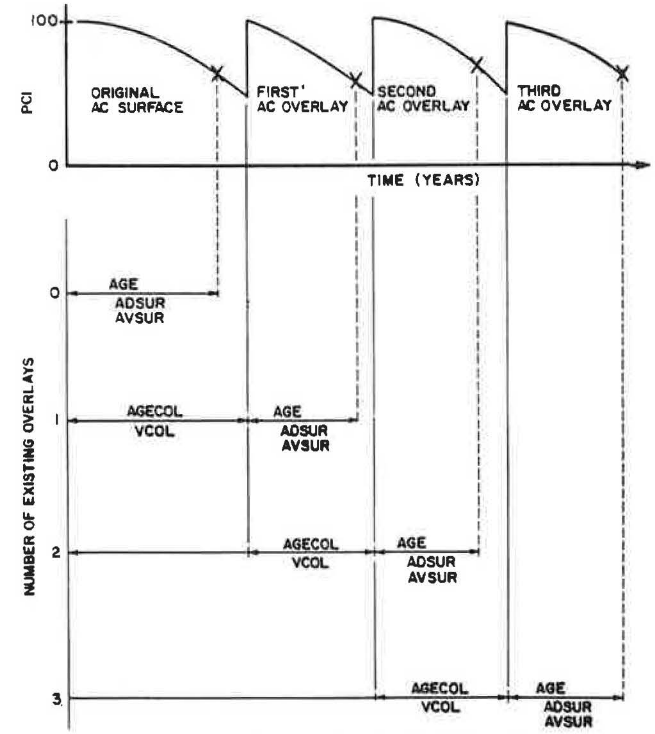

FIGURE 11 Time variables associated with PCI prediction variables.

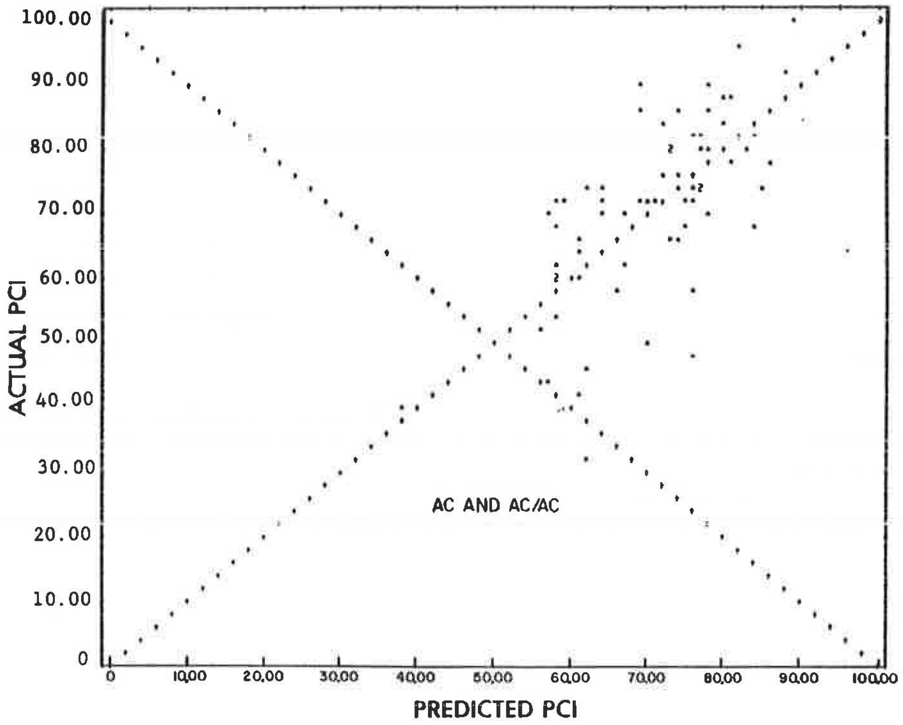

FIGURE 12 Actual PCI versus predicted PCI for AC and AC/AC pavements.

where

ADSUR = function of the weighted average surface deflection divided by the equivalent single-wheel load;
AVSUR = weighted average vertical stress on the base course (layer of material directly beneath the lowest asphalt layer); and
VCOL = cumulative amount of vertical stress on top of the base course before pavement was overlaid; if not overlaid, VCOL = 0; Figure 11 shows COL variables and the time periods they represent.

Figure 12 is a scattergram of the predicted PCI versus the actual PCI. Above the value of about 50, the model does remarkably well in predicting PCI. Below 50, the model tends to predict PCIs a little higher than they actually are, but overall the figure is very encouraging.

Sensitivity analyses were performed on the developed model to observe how pavement structure and foundation and environmental factors affect the PCI. Figure 13 shows the influence of asphalt thickness on the PCI. Figures 14 and 15 show the influence of age before overlay (AGECOL) and number of traffic passes, respectively.

The environmental effects are included in the model in terms of average daily temperature and solar radiation, both of which are inputs for determining the E-modulus for asphalt. The model contains no direct environmental variables.

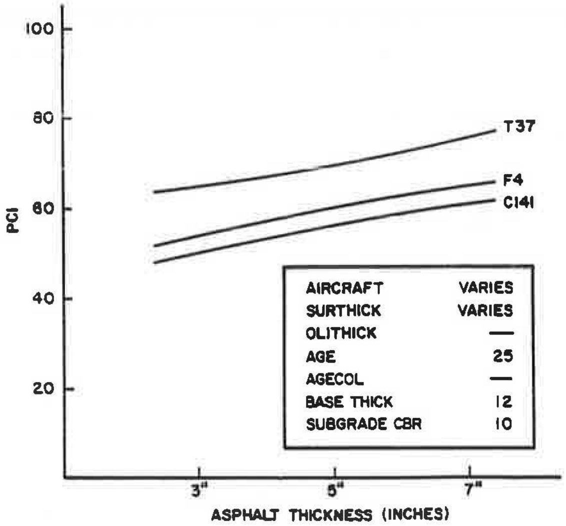

FIGURE 13 Effect of aircraft type on PCI as a function of asphalt thickness (age = 25 years).

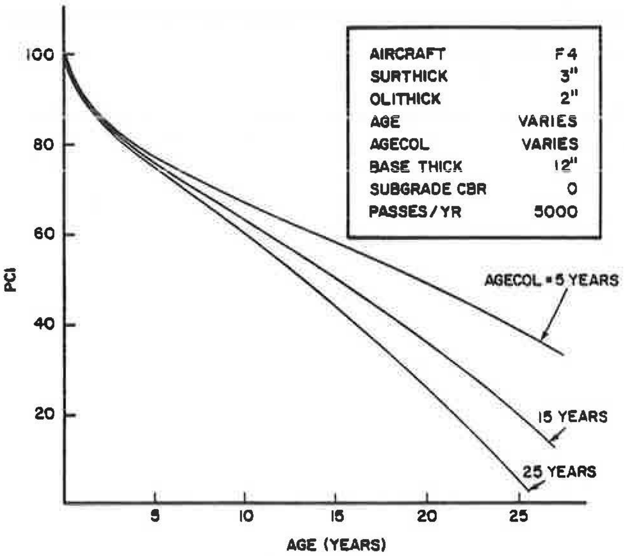

FIGURE 14 Effect of AGECOL on PCI as a function of age.

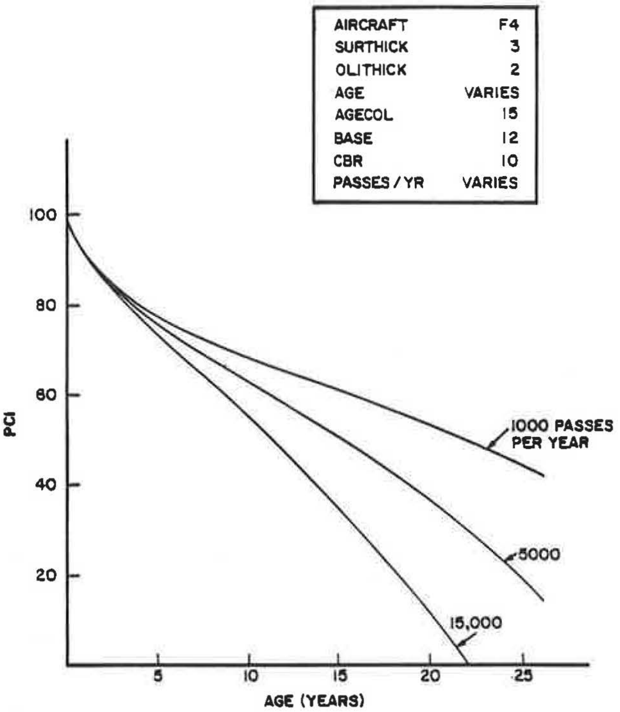

FIGURE 15 Effect of traffic volume on PCI as a function of age.

INTRODUCTION TO LOCAL MODELING

On the basis of the data analysis and model development, it became apparent that with a wide range of climatic, soil, traffic, and other variables the development of a precise universal prediction model (one model developed using data from numerous bases) is a difficult if not impossible task. A solution to this problem was found in developing prediction models for each base. The local models were developed using the same independent variables used in the universal (12-base) model with the exception of climatic variables. Table 5 gives a summary of the comparison of PCI prediction statistics for two of the Air Force bases using both the universal and localized models. The comparison shows that localized models give better predictions than universal models.

TABLE 5 Statistics for the Rigid and Flexible PCI Models Developed Using Localized Modeling

	Model Developed with Data from 12 Bases			Model Developed with Data from 1 Base		
	R^2	Standard Deviation	No. Cases	R^2	Standard Deviation	No. Cases
Universal model (12 bases)	0.721	8.73	322			
Dover AFB	0.638	8.58	32	0.749	7.67	32
Robins AFB	0.831	5.86	56	0.917	4.19	56

Traffic is suspected to be a large factor behind the improvement of localized models over universal models. In gathering traffic information from each Air Force base, percentages and approximate volumes of aircraft that use each pavement feature were gathered. The percentage breakdown of aircraft traffic is probably more accurate than the approximate volume of traffic, thus the traffic volume is not a good predictor when considering more than one base.

Another reason for favoring localized modeling is that, for a given base, construction methods, maintenance procedures and policies, environmental factors, and drainage conditions are relatively uniform. In the universal models developed, these differences were probably not accounted for fully.

The concept of local modeling appears to be promising and is currently being further developed.

CONCLUSIONS AND RECOMMENDATIONS

Extensive data were collected from 327 airfield pavement features at 12 U.S. Air Force bases. The data, which provided a wide range of information on designs, materials, traffic, and climate, were used to develop PCI and key distress prediction models for both rigid and flexible pavements. Only the PCI models are presented in this paper.

Evaluation of these models showed that predictions for some of the bases were much better than for others, possibly because climatic factors and traffic conditions in certain bases were not well represented in the overall model. Thus, it was concluded that localized modeling could provide much more accurate predictions. Furthermore, the concept of localized modeling offers the extra advantage of being able to update the models as more condition surveys are performed at a given base.

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County Maintenance of Unpaved Roads in Indiana

JOHN D.N. RIVERSON, KUMARES C. SINHA, and CHARLES F. SCHOLER

ABSTRACT

Unpaved roads still form a substantial proportion of the county road network in Indiana and most of the United States. A survey of maintenance practice on such roads by the Purdue University Highway Extension and Research Project for Indiana Counties and Cities shows the existing diversity in maintenance activities, standards, methods, and practices. Faced with the problem of inadequate funds, most highway departments have adopted methods of providing the barest maintenance, and little attempt is made to adopt available guidelines. Clearly, there is a need for uniform practices among counties. In addition, suitable guidelines should be adopted. Such guidelines will enable decisions to be made about project priorities, deferment of major maintenance, paving gravel roads, level and type of maintenance, appropriate abandonment criteria, and levels of expenditure. The suggestions are made that available research material provides a good basis for the development of such guidelines and that suitable maintenance management systems can be implemented successfully in various counties and local areas to provide for any special needs of unpaved roads.

Unpaved roads are an essential part of the existing road network in many states. Though they do not usually form a part of the state highway network, they represent a substantial percentage of the highway network of many counties, cities, and townships. In Indiana 41 percent of the county road mileage is unpaved (1). The Indiana Department of Highways is currently implementing a maintenance management system for state highways. However, maintenance practice in the counties is the responsibility of each county. The standard of maintenance differs among counties. The importance accorded to unpaved roads in the management of each county's system of roads, especially for maintenance, also varies among counties.

A number of counties in other states (2,3) either have implemented or are preparing maintenance management systems. However, the emphasis appears, at least for the moment, to be on paved road networks only. Extensive work on unpaved roads has been undertaken within the Forest Service in the United States and also in various other countries (4,5). In addition, the Transportation Research Board, the Organization for Economic Cooperation and Development (OECD), and the Overseas Unit of the Transport and Road Research Laboratory, United Kingdom, among others, have produced useful documents aimed at assisting in the maintenance of roads, paved or unpaved, in both developed and developing countries (6-8). The Action Series prepared by the National Association of County Engineers included a recommendation for a maintenance management system to be used in counties (9). However, it is not clear how readily such a system or the ideas from the other documents are being adopted and used by various counties in the United States.

The results of a survey of counties in Indiana by the Highway Extension and Research Project for Indiana Counties and Cities (HERPICC), School of Civil Engineering, Purdue University, to ascertain current maintenance practices especially for unpaved or gravel roads are presented. The knowledge gained from this survey will be used in designing a suitable maintenance management system inclusive of the special requirements of unpaved roads for Indiana counties.

SURVEY

A survey questionnaire was mailed to all 92 counties in Indiana. Completed questionnaires were received from 50 counties, representing a sample return of about 54 percent. The survey itself covered various aspects of unpaved road maintenance practice, including the following specific topics: data collection on road condition, traffic volumes, and accidents; equipment use, maintenance, and costs; maintenance personnel assigned to unpaved roads; planning and execution of routine maintenance activities; regraveling or addition of material and surface upgrading or paving; maintenance guidelines or management system used; problems and critical needs of unpaved roads in maintenance; and the pros and cons of abandoning or reducing the road network responsibility of counties faced with decreasing funds and increased network responsibility.

The term "unpaved roads," in this context, means roads that are normally not paved with asphaltic concrete or portland cement concrete or that are surface treated with an asphalt surface treatment. The general term "gravel road" is also used to describe such roads. The results of the analysis of the data obtained are presented in the following sections.

DISTRIBUTION OF UNPAVED ROADS IN THE COUNTIES

Of a total of about 68,297 miles (109 958 km) of roads maintained by the 92 counties in Indiana, about 2 percent are unimproved, 39 percent are gravel or stone, and the remainder are paved (1). The distribution of unpaved roads varies among counties. Fifty-three counties have more than 40 percent of their network unpaved. Fifty-nine counties have 200 miles or more to maintain and two counties list no unpaved roads in their network. In only four of those counties with fewer than 200 miles of unpaved roads do such roads represent more than 40 percent of the network. Table 1 gives the distribution of unpaved roads in counties.

In an attempt to understand the current pattern of unpaved road distribution, simple regressions were run between the percentage of the mileage unpaved in each county and the total unpaved road mileage and various population factors. The characteristics of the related variables are summarized in Table 2. The percentage of unpaved roads in any county appears to be significantly affected by the population (rural or total) as well as by the percentage of the population that is rural. The proportion of unpaved roads tends to decrease with an in-

TABLE 1 Distribution of Unpaved County Roads

Percent Unpaved	Number of Counties with Total Mileage Unpaved				Total
	Less than 100	100-200	200-500	More than 500	
Less than 40%	12	17	10	--	39
More than 40%	--	4	36	13	53
Total	12	21	46	13	92

TABLE 2 Factors Affecting Unpaved Roads—Some Regression Relationships

Dependent Variable	Independent Variable	Relationship (Significance F-test)
Total Unpaved Road Mileage	Total Rural Population	Not Significant at < 10%
	Total County Population	Significant at < 10%
	Percent Rural Population	Not Significant at < 10%
	Total Mileage of County Roads	Significant at < 1%
Percent Unpaved	Total Rural Population	Significant at 0.1%
	Total County Population	✓ ✓ 0.1%
	Percent Rural Population	✓ ✓ 0.5%

crease in the population (rural or total), and it increases as the percentage of total county population that is rural increases. Total mileage is also significantly affected by total population. The linear correlation coefficients were, however, all less than 40 percent signifying that relationships other than linear ones may exist between the variables. Further analysis will be required to determine the true form of the relationships but this is beyond the scope of this paper.

In the absence of specific traffic volume data from the counties, no regressions were run with traffic volume as a variable. However, as a proxy for vehicle ownership levels, population provides a close approximation of the levels of vehicle use. This further endorses the previous relationships showing an increase in total mileage with vehicle use and a decrease of the proportion of unpaved roads. It also appears from the results that counties with generally higher percentages of unpaved roads and rural populations would obtain greater benefits from guidelines aimed at improving the maintenance of unpaved roads.

CONDITION INVENTORY, TRAFFIC VOLUME, AND ACCIDENT DATA COLLECTION

The survey indicates that county highway departments seldom collect, on a continuous basis, data on road condition, traffic volume, and accidents for planning and determining priorities for road maintenance and upgrading. The Indiana Department of Highways prepares one major inventory report for all counties but the updating of this report is slow and inconsistent among counties. Thirty-eight percent of the counties responding indicated that they collect some form of traffic volume data. Nine of the 19 that do so collect the data only when needed--often for proposed improvement projects and sometimes only at the request of the commissioner. The frequency of counts varies from once a year or less to every 5 or more years. Counts are usually not made for gravel roads. The main reason given by counties that do not undertake traffic counts is the lack of equipment, staff, and funds. In two cases, traffic counts were not considered necessary because mere observation of patterns and a knowledge of the area were sufficient, in their experience, for making decisions.

Only 16 percent of the counties indicated that they maintained accident reports or kept abreast of accident records in the sheriff's department and used them as needed. Two-thirds of the counties were aware of the records at the sheriff's department but not all counties had used them.

About 36 percent of the sample indicated that they keep regular information on road condition. Seven counties mentioned that they use some form of rating system to differentiate among road conditions.

TYPICAL MAINTENANCE ACTIVITIES ON GRAVEL ROADS

Typical routine maintenance activities reported as undertaken on gravel roads are given in Table 3. In any year every activity would not necessarily be undertaken on every road; activities are undertaken as needed and as funds permit. In any case, maintenance requirements for gravel roads, usually less traveled, may sometimes be considered secondary to those for paved roads that usually carry higher traffic volumes. The smaller funds normally available to county highway departments often enable them to perform only the most basic maintenance activities required, especially on gravel roads. The extent to which this is done varies from county to county.

Inspection

Apart from one major inspection usually undertaken in the spring covering all roads in the county, opportunity is given to grader operators (assigned to certain gravel roads) and to a smaller extent to foremen and supervisors to provide reports, often verbal, on the changing condition of gravel roads throughout the year.

TABLE 3 Maintenance Activities on Unpaved Roads

Activity	Frequency
Inspection	Once in Spring or during the year.
Dragging or Grading Aggregate Roads.	Whenever required and after rains. Varies with road condition - e.g. Traffic Volume. Grader or Maintainer used.
Brushing/Spraying	As Needed (Not Necessarily Annually.)
Mowing	As Needed (Mostly by adjacent farmers.)
Culvert Maintenance and Replacement	As Needed (Over 4 or 6 ft. by Contract in some Counties.)
Side Ditching	As Needed using grader/gradall.
Bridge Inspection	Every 4 years as part of National Bridge Inspection.
Dust Control (Please specify the method used.)	As Needed. Payment by Residents.
Patching/Adding Gravel Material	Usually during Spring Thaw and as needed after thaw.
Sign Maintenance or Replacement.	As Needed
Snow Removal/Plowing	As Needed-priority to School Bus routes.

Grading and Dragging

Grading is the one basic maintenance activity on gravel roads that is undertaken throughout the year. One pass of the grader is usually considered sufficient though in some cases two or more passes may be undertaken depending on the road condition or the level of service determined for the road. However, the frequency in most counties is governed by that of rainfall. Most grading is done when roads are moist. In some cases grading may be combined with dragging using a truck- or tractor-mounted maintainer, especially when the road is in very poor condition. Otherwise, each may be undertaken independently of the other and as frequently as conditions determine. Pothole repairs usually form a part of grading or dragging.

Side-Ditching, Mowing, Brushing, or Spraying

Side-ditching is usually undertaken when roads are dry using the grader blade or in the winter in some counties using "Gradall" equipment. Mowing, brushing, and spraying may be undertaken if absolutely necessary, usually when conditions have deteriorated so much that bushes encroach on the narrow traveled way. In some counties mowing is undertaken only by the farmers on the roadside adjacent to their farms and not by the highway department.

Dust Control

Dust control, as a maintenance activity, is not undertaken by many county highway departments. In most counties this is the responsibility of the private resident. The highway department arranges for the chemical applicator who applies the calcium or magnesium chloride under highway department supervision. The citizen pays for the chemical. Used or dirty engine oil has been banned by the Environmental Protection Agency (EPA) because of lead contamination of adjacent soils, but the use of lighter emulsified asphalts is increasing.

A more permanent remedy is to use light emulsified asphalts frequently, which leads to an almost permanent hardening of the surface. Citizens sometimes request that a seal coat be used in the vicinity of their homes. Most counties indicate that in such cases the job is undertaken on a shared-cost basis. The county highway department pays half of the cost and the resident pays the other half. In this way, several short sections of gravel roads may be paved to provide effective dust control and a virtual paving of the entire road section.

County governments should ensure that the road base is sufficient to provide a reasonable support for the light surface treatment applied. Otherwise, the county may be creating a higher maintenance cost road, which can lead to dissatisfaction of landowners as well as to escalating highway maintenance costs. New road sections such as those for subdivisions should always meet adequate design requirements before they are accepted in the county or city road system.

Snowplowing and Other Activities

Snowplowing operations are only undertaken when roads are considered very dangerous. Priority is often assigned to school bus routes or high traffic volume roads where these are identifiable.

Culvert cleaning and sign maintenance and replacement are undertaken as needed, and bridge inspection is undertaken at least every 4 years as part of the National Bridge Inspection Program.

Assigning Priority in Maintenance

Thirty-eight percent of the counties stated that, in general, no priority is assigned for maintaining gravel roads. All roads are treated the same. A grader operator, for example, blades all the roads he is responsible for without differentiating between them. In 20 percent of the cases, however, it was stated that priority is assigned to school bus routes (e.g., for snow removal) or to roads carrying high traffic volumes.

Road and weather conditions, special needs, and citizen complaints are the other important considerations governing the assignment of priority for the maintenance of gravel roads.

EQUIPMENT USED TO MAINTAIN UNPAVED ROADS

Forty-four counties responded to questions about the number and types of equipment used in the maintenance of unpaved roads. The distribution of the types listed is given in Table 4. The returns showed a disparity among counties as to the number and type of equipment and vehicles owned or used. As expected, however, predominant among them are dump trucks, motor graders, and tractor- or truck-mounted maintainers. Some counties had no graders but used maintainers or vice versa; others had and used both types of equipment. These characteristics are a further indication of the varying standards of maintenance on gravel roads in the counties.

TABLE 4 Equipment Availability in Counties

Equipment Type	Number	Number of Counties
Dump trucks	243	18
Graders	157	39
Maintainer with tractors	53	18
Tractors	12	2
Trucks with Under Blades	53	6
Loaders	21	9
Gradall	14	9
Mowers/Brush Cutters	13	4
Back hoes	9	5
Excavator	3	3

Forty-seven of 50 counties indicated that they maintain their own equipment. The others either do not or gave no answer. Except for eleven counties, the others send some specialized maintenance jobs to outside firms when the counties do not have the expertise or other resources to do the jobs. Such jobs include major engine overhauls, particularly of diesel engines, and transmissions. The ability of counties to maintain their own equipment is usually an asset especially where preventive maintenance is concerned. Adequate control and supervision are usually required if potential cost savings are to be fully realized.

Maintenance Cost Accounting

Cost accounting of maintenance and sometimes of construction activities in some counties is not always up to the standard required by existing guidelines in Indiana. The quality of accounting tends to depend highly on the caliber and experience of the cost clerk in each county. Most current cost figures are grossed up according to the requirements of the annual reports submitted to the county and the state legislature. It is not always possible to isolate costs for specific items unless the particular county specially compiles them. In Indiana special accounting guidelines produced by HERPICC are used by counties to prepare reports. Provision exists in the guidelines to enable costing of individual items, but it appears that the implementation of this is on a voluntary basis. Budgetary and staff constraints seem to affect this tremendously. Some counties have, nevertheless, made considerable advancement and adopted computers for analysis or have plans to do so.

REGRAVELING OR ADDING NEW GRAVEL MATERIAL

Regraveling, usually involving a complete resurfacing with 15 cm (6 in.) thick stone or gravel base, which is classified as a periodic or major maintenance activity, is generally not undertaken separately by most counties. Instead, additional gravel or stone is usually applied to the gravel surface as part of recurrent annual or other more frequent activity depending on the rate of gravel loss or the weakness of subgrade support. This is usually done after the spring thaw to strengthen the weakened road surface that results from moisture saturation and freezing. Because the surface material usually contains little fines to act as binder, they are dispersed more quickly by traffic and are respread during the grading operation. When the traffic volume is heavy, more grading is required and the addition of material is required more than once a year.

Reasons for Adding Material

Forty-eight of the 50-county sample stated that the decision to add new material is based largely on inspection reports submitted by grader operators, foremen, or supervisors on routine or casual inspection. In 68 percent of the cases, citizen complaints were the second major deciding factor followed by traffic safety (32 percent) and traffic volume (26 percent). In a number of cases, material is added only after a need is created as a result of inclement weather conditions. Most decisions are based on personal judgment rather than on measured criteria.

Method of Execution

All maintenance activities are generally undertaken by the county highway departments themselves using their own resources. However, 16 percent of the counties undertake some major activities on a contract basis. These activities are mainly the construction or replacement of culverts larger than 6 ft in diameter and bridges. In several counties culverts 4 ft in diameter were considered the minimum size above which such projects were awarded on contract.

Sources of Materials

Eighty-eight percent of the counties obtain their gravel and stone material from private gravel pits or quarries. The rest obtain their material from county owned or leased pits. In half of these cases, pit run gravel is obtained from county pits and graded aggregates are obtained from private pits or quarries. Even in cases in which material is obtained from private sources, in some counties, county trucks load and haul material from the pits to their respective locations.

PAVING OF GRAVEL ROADS

During the period 1978-1982, only 19 counties in the sample undertook any program of paving gravel roads. The rest said they did not pave any gravel roads within the period. Paving in this case includes application of surface treatment or chip-and-seal to the gravel surface. In a few cases, some paved roads, mainly surface-treated roads, were scarified and returned to a gravel state. A total of about 670 miles of gravel roads was paved by chip-and-seal or hot or cold mix asphaltic concrete. This represented an annual paving rate of 7.1 miles per county, which also includes the application of a second or third seal coat to some paved road surfaces. Considering all counties in the sample, an estimated annual paving rate of 2.7 miles per county was achieved. Many counties would prefer to pave more roads if that were possible.

Reasons for Paving Gravel Roads

The major reasons for paving gravel roads in order of importance, according to number of responses, are given in Table 5. Higher traffic volume is the most important reason for paving gravel roads as indicated by 80 percent of the sample. However, 70 percent also indicated that local requests sometimes involving cost-sharing by the residents are also a major deciding factor. The latter appears to be a very important consideration especially if gravel roads can be paved at all with the limited funds usually available to the counties for such programs. In 48 percent and 28 percent of the cases, respectively, the roads that were paved were continuations of existing roads or were considered to be of administrative importance and were usually paved at the request of the county commissioner.

TABLE 5 Reasons for Paving Gravel Roads

Reason	Number of Responses
Higher traffic volumes	40
Local request/complaint	35
Continue existing paved road	22
Administrative Importance	14
Environmental (Dust)	9
Increase in Accidents	9
Other	5

MAINTENANCE MANAGEMENT AND PLANNING

Maintenance Guidelines

The National Association of County Engineers published, as part of its Action Series, guidelines for maintenance management of county roads (9). The survey of counties showed that 22 percent of the sample know of the guidelines but only three stated that they had previously used them or referred to them for any purpose. Asked what guidelines were used for maintenance, 30 percent indicated that common sense, experience, or the recommendations of the district supervisor or county engineer were the main sources of direction in their maintenance practice. A few others said the manuals of the Indiana Department of Highways or the Asphalt Institute were their main references for maintenance of their paved roads. The rest either use no guidelines or gave no answer.

Priority Rating System

Eleven of the 50 counties said they use some form of priority rating system for maintenance purposes. The main bases for assigning priority are traffic volume or population and to a large extent decisions by commissioners or the council. Forty percent of the sample follow an existing plan for carrying out major improvements including paving of gravel roads. The rest based their ad hoc decisions on needs as determined periodically or gave no definite answer.

Organization of Personnel and Equipment for Maintenance

About half of the counties in the sample make no distinction between gravel and paved roads in their assignment of personnel and equipment for road maintenance. A combined team carries out all maintenance activities and personnel and equipment are usually dispatched from a central workshop. Six counties said they have separate units responsible for paved and unpaved roads. In eight cases, personnel with assigned equipment (grader) operate from their homes, usually over specified zones or subdistricts, and receive supplies periodically from a central workshop.

It is anticipated from the foregoing that the importance accorded gravel roads in each county's organization will be largely dependent on the total mileage to be maintained and the proportion of the total network comprised of gravel surface.

Problems Connected with Gravel Road Maintenance

When asked to rank the top three problems they face with unpaved road maintenance, most counties (about 70 percent) indicated that clearly the inadequacy of funds is the number one problem. This problem seems to have affected the nature of maintenance activities and programs, especially the continuing paving of gravel roads in the counties.

Four factors shared the second ranking in problems listed based on the number of times they were mentioned. Some officials expressed concern about the number and total mileage of gravel roads in their networks. They would like to see a marked reduction in the mileage of gravel roads as more of them are paved. In addition, the problems caused by dust in neighborhoods, the lack of suitable equipment, and the effect of heavy traffic on the condition of their roads were mentioned by some counties as second-ranked problems. Heavy traffic on unpaved roads and the environmental problem created by dust stood out as the third-ranked problems of concern to county highway departments.

Critical Needs of Unpaved Roads

According to the number of responses, drainage maintenance is the most critical need of unpaved roads, followed by bridge rehabilitation and replacement and widening of unpaved roads. Routine maintenance needs followed fourth in rank. In general, the critical areas cited seem to be tied up with the inadequate right-of-way (ROW) on most unpaved roads in the counties. Widths of between 14 and 18 ft are common. This inhibits the provision of adequate side drainage and the possible widening of such roads. Most of the roads are adjacent to farmlands and highway departments cannot widen roads any further. Most unpaved roads drain directly onto the farms or, in some instances, the farms drain onto the road. For some of the unpaved roads, however, wider roadways would normally not be warranted owing to very low traffic volumes, but it should be possible to widen such roads when required for either drainage or safety. This could be negotiated and appropriate modifications made in each county to cater to road-widening needs.

PROBABLE IMPACT OF ROAD SECTION ABANDONMENT

The problem of the inadequacy of funds coupled with the shear size of the road networks in the counties and the cost of maintaining them, especially in the face of decreasing funds, has often raised the question of abandoning some sections or leaving them to be maintained by private landowners. Fruin (10) suggests that perhaps the number and mileage of rural roads in many areas are excessive and that consideration should be given to reducing them.

When asked their opinion of abandoning road sections to reduce total mileage of roads, 29 of the sample of 50 county highway departments agreed with the idea. They considered that roads likely to be chosen in such an exercise include roads providing access to a single property or to individual farms and also roads generally leading to a dead end. Both conditions were mentioned by 18 counties. About half that number indicated that very low-volume roads or roads for which alternative routes exist to perform the same function with a shorter connection from particular locations could be considered. However, it was not clear what traffic volume would represent a good cutoff point. Traffic volumes of even up to 20 vehicles per day were suggested but the level could be set much lower for practicality.

Pros and Cons of the Abandonment of Road Sections

In spite of the apparent acceptability of the idea of abandoning roads and the fact that 30 percent stated that the inclusion of some roads in their networks at present actually reduces their efficiency, some problems were raised about the idea. Most counties were apprehensive about discontinuing the precedent by which they maintain all roads irrespective of use. Most thought that everyone currently served by a county road is entitled as a taxpayer and should have access provided and maintained by the county. It was thought that considerable public reaction and complaints would accompany any attempt to abandon road sections under the jurisdiction of the county. It was pointed out that provisions within the Indiana State Statutes restrict abandonment and a change in state law would be required if counties were to be able to implement a scheme of abandoning or relinquishing responsibility for maintaining some road sections.

These considerations imply that sound arguments and adequate justification would be necessary if abandonment were ever to be accepted as an appropriate policy. At present, it appears that it will be necessary to spread the maintenance budget thin if no alternative is possible and no additional funds are forthcoming. There is already considerable private participation in the paving of gravel roads and in dust control as well as in the mowing of roadsides. A compromise is possible when further funds cannot be raised through the regular county sources. This could include relinquishing the county's responsibility for maintenance of some roads to private citizens.

CONCLUSIONS

The current maintenance practice for unpaved roads in Indiana counties could well represent that of similar counties elsewhere. Though reasonable amounts of maintenance already take place on unpaved roads, the need for uniform practices is evident. The diversity inherent in the different counties with regard to population, mileage (paved and unpaved), level of development, and availability of financial and other resources clearly affects the performance of individual counties. It may also present initial problems when attempting to implement uniform guidelines that can be adapted to individual county characteristics and needs for maintenance of unpaved roads.

In spite of the availability of several guidelines, including the series produced by the National Association of County Engineers, it appears, at least in Indiana and possibly in other states, that dissemination has not reached the potential users--the county highway staff. The establishment of Technology Transfer Centers throughout the United States is an initial step toward the dissemination of technical information useful to counties. This task, which has been begun by HERPICC, Purdue University, for Indiana, will continue with the new process.

For maintenance of roads, particularly unpaved roads, in a monetarily constrained situation, actions aimed at making the best use of the money available would be most expedient. In particular, among many other possible actions, suitable guidelines would be required for making decisions with regard to the following specific areas:

1. Priority setting among projects and on a network level;
2. Deferring major maintenance;
3. Requirements for and timing of the paving of gravel roads;
4. Methods for determining the appropriate level and type of maintenance; specific proposals for drainage maintenance and dust control would be of great benefit based on the ranking of problems; and
5. Suitable criteria for abandoning road sections or reducing the mileage responsibility of counties.

Considerable progress has been made in the development of methods through the research process initiated or assisted by the World Bank; the Transport and Road Research Laboratory, United Kingdom; and other agencies in Kenya, Brazil, and India. Some of the results are adequately reported in the Proceedings of the Third International Conference on Low-Volume Roads (11). Nevertheless, the maintenance practices identified for Indiana counties, especially for unpaved roads, confirm the needs identified here. The process of dissemination of research results should, however, ensure that methods to be applied are acceptable to local officials. Though most of them think that the application of common sense is sufficient for determining maintenance needs of unpaved roads, one cannot overemphasize the fact that a sound maintenance management system is still essential. Although they generally carry lower traffic volumes, unpaved roads still play an important role in the local economy and deserve proper maintenance planning.

Any system adopted should be simple and adaptable by even the less sophisticated counties or local authorities. Methods developed should also aid in making decisions about the appropriate levels of maintenance expenditures within the total road network. Methods should take into account the influence and role of various road surface types and enable optimum investment levels to be determined at any time. Using existing methods, a major step can be taken toward achieving these goals.

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