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Transportation Research Record 1102

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Choice of Surface Treatment: Dependency on Level of Road Improvement and Maintenance Budget

ROGER M. WEATHERELL AND AMIN A. N. EBRAHIM

The "best" option for road improvement in Jamaica is dependent on the "most economic" and "least-cost" solutions described in this paper. The financial situation of the country at any particular time dictates the choice of solution. Subjecting the whole road network to this type of analysis could be a valuable method of determining the desired level of the total road improvement and maintenance budget for a 10-year period.

Use of microcomputers at the Ministry of Construction (Works) of Jamaica has made it possible to process objective data for every road to specify the "best" method of improvement and then to revisit the priority sites to confirm or amend the automatic choice using engineering judgment.

Jamaica has some 3,000 mi of main roads and about 7,000 mi of feeder roads. The economic methods of evaluation used for these two types of roads are quite different. For main roads, traffic is considered the proxy for all economic and social travel, and all benefits due to road improvement are assumed to be savings in vehicle operating cost (VOC). For feeder roads the benefits due to road improvement are assumed to be increases in agricultural production.

The "least-cost" feeder road option is the one that costs the least and improves the road surface to an acceptable standard. Main roads are evaluated in terms of the "most economic" in addition to the least-cost solution. The most economic solution is the one that provides the highest economic return on investment. The least-cost option does not provide the highest return but still allows the project to be economically viable. The idea of most economic and least-cost solutions should be of interest to readers.

In an economic boom, a country would prefer the most economic solutions, but, under the current financial constraints, most governments lean toward the least-cost solution for improving and maintaining as much of the road network as possible, thereby spreading the benefits to a wider population.

LEAST-COST SOLUTION FOR FEEDER ROADS

Four road surfacing options were considered for feeder road improvement. The four options were double seal, single seal, prime MC2 and grit, and gravel surface. The MC2 and grit is a thin bitumen spray dressed with a fine grit, which is known locally as oiling the road. (Sometimes site teams choose a combination of actions as most appropriate.)

The results for a representative sample of the projects are given in Table 1, in which are compared the net present values (NPV) of the four options for a representative sample of a total of 58 projects. Except for prime MC2 and grit, the computation is straightforward. In general, the NPV was computed by adding the improvement cost to 5.3 times the maintenance cost, which is the sum of maintenance costs over years 2–10 discounted at the rate of 12 percent. For simplicity of calculation, the residual value is ignored. In the case of prime MC2 and grit, it was assumed that the surface would have only a 4-year life, that it would be resurfaced in years 5 and 9, and that 7.5 percent of the surface area would need scarification in addition to resurfacing with prime MC2 and grit. The renewal of the surface treatments was discounted and added to the initial costs, and again any residual value was ignored.

Using the road surfacing option proposed by the site teams, the 1984 cost of improvement of 195.9 mi given in Table 1 would be J$18 million. By adopting the least-cost solution, this was reduced to J$15.6 million, though in the long term there is only a reduction of J$1.2 million in the NPV after the cost of maintenance has been taken into account. Of the 58 projects considered in the first phase of study (*1*), the MC2 and grit treatment was the least-cost option in 37 cases. This is because the improvement cost of prime MC2 and grit is much lower than the cost of double seal or even single seal. The maintenance cost of prime MC2 and grit is lower than that of the gravel option. A careful monitoring of the performance of this type of surface will be needed to confirm the assumptions made in specifying this as the best option in many situations.

BEST SOLUTION FOR MAIN ROADS

The so-called best solution for improving a main road depends on the threshold levels of traffic needed to justify the selection of the various surface treatments (Figure 1).

To investigate the effect of inflation on the feasibility of road improvement, it was decided to compare improvement thresholds in 1982 and 1984. The threshold indicates the level of traffic above which a road improvement is economically justified (i.e., benefits > costs). All benefits are assumed to arise from the vehicle operating cost savings, which in total are directly proportional to the traffic level.

In the following subsections the logic of Figure 1 and the construction of the threshold curves are briefly explained and their usefulness, application, and limitations are given.

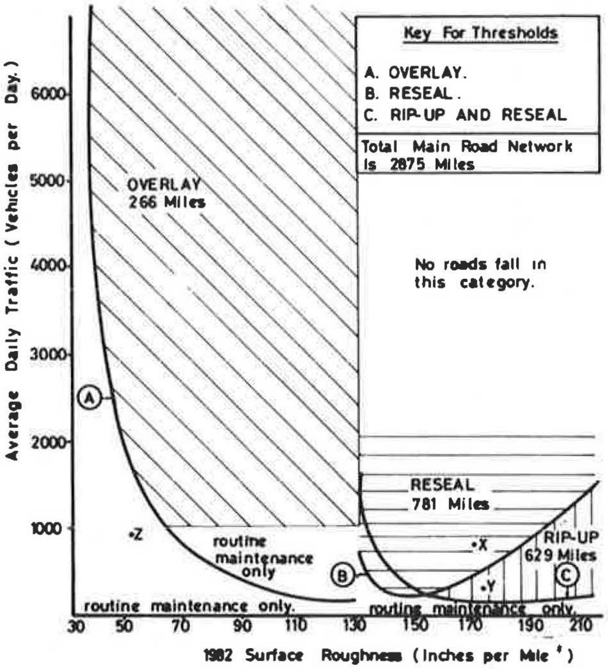
R. M. Weatherell, T. P. O'Sullivan & Partners, 56–58 Putney High Street, London SW15 15F, England. A. A. N. Ebrahim, Ministry of Construction (Works), 140 Maxfield Avenue, Kingston 10, Jamaica.

TABLE 1 COMPARATIVE ANALYSES OF VARIOUS SURFACE TREATMENT OPTIONS

Project Number	Length (Miles)	Current Asphalt Length		NPV of Improvement and Maintenance Costs(1)				On-Site Proposal			Least Cost Recommendation		
		Miles	%	Gravel	Double Seal	Single Seal	Prime MC2 & Grit	Surface Type	Improvement Cost	NPV	Surface Type	Improvement Cost	NPV
POR/016	2.75	0.00	0	598285	712599	654454	594078	DS+G	403871	601714	G	373255	598285
TRE/011	2.25	0.00	0	309387	406731	357870	335787	G	177519	309387	PS	177519	309387
AND/012	1.66	0.10	6	319551	363722	329106	305621	SS+MC2+G	212533	311753	MC2	223743	305621
JAM/010	5.83	0.37	6	943689	1193035	1090960	1008376	SS+DS+G	621158	962986	G	567836	943683
AND/005	1.52	0.10	7	270336	338074	305385	290603	G	184449	270336	PS	184449	270336
CLA/010	1.46	0.26	18	255774	321233	291570	276500	G	179211	255774	PS	179211	255774
THO/013	6.26	1.21	19	1289860	1071955	1014814	983735	SS+DS+G	750469	1176884	MC2	652981	983735
CAT/010	4.83	1.00	21	788825	818653	740128	705666	DS+G	590630	821090	MC2	487056	705666
ELI/002	1.14	0.24	21	166373	188725	171066	161921	SS+G	107712	168319	MC2	112569	161921
MAR/001	8.71	2.20	25	1496804	1594936	1516089	1452733	SS+DS	1219998	1529493	MC2	1081757	1452733
CLA/001	6.60	1.98	30	1234675	1350068	1247919	1144962	DS	1166092	1350068	MC2	839977	1144962
ELI/021	2.69	0.98	36	344116	375797	347677	326886	DS+G	171575	355521	MC2	217995	326886
THO/019	2.43	1.49	61	253588	240153	221261	194472	MC2	122171	194472	MC2	122171	194472
CAT/011	2.19	1.37	63	N/A	346873	315603	302547	DS	286667	346873	MC2	207171	302547
HAN/012	1.74	1.36	78	N/A	321755	302714	288456	SS	256560	302914	MC2	256560	288456
CAT/002	4.45	3.56	80	375236	280904	244590	257097	SS	116558	244590	PS	116558	244590
MAN/003	5.30	5.30	100	N/A	535461	497370	492428	SS	356178	497370	MC2	303555	492428
MAR/008	2.67	2.67	100	N/A	268924	241329	N/A	DS	185967	268924	SS	149725	241329
TRE/010	4.24	4.24	100	N/A	175493	165656	N/A	SS	42718	165656	PS	42718	165656
Summary Total of 58 Projects				18893058	28406969	26141356	24464688		18049097	25446114		15670383	24198790

(Representative sample of the projects showing at least one case for each category of surface treatment.)

Notes: (1) NPV of financial costs at July 1984, all discounted at 12% over 10 year period including renewals as applicable.
Legend: SS - single seal DS - double seal G - gravel MC2 - Prime MC2 and grit . PS - on-site proposal



* JAMAICA IN-VEHICLE BUMP INTEGRATOR, NOT F.W.B.I.

FIGURE 1 Average daily traffic threshold levels for selection of surface treatment.

Construction and Logic of the Threshold Curves

The threshold curves have been derived using

- Standard construction costs for overlay, double reseal, and "rip-up and seal," at 1984 prices, inclusive of all preparatory works;
- Vehicle operating costs according to the St. Lucia formulas (2) of the Transport and Road Research Laboratory (TRRL) at 1984 prices; and
- The deterioration model of roughness versus time generated from the data of the last complete road condition survey done in Jamaica during 1982.

The threshold average daily traffic (ADT) of a particular action depends mainly on the present roughness (R1) of the road, because it is the change in roughness due to the road improvement that gives the difference in the total vehicle operating costs (VOCs) with and without the project. This difference in VOCs determines the benefits. Table 2 gives the derivation of a threshold ADT of 1,030 vehicles per day. This ADT was arrived at to justify an overlay over an existing overlay that had an R1 of 60 in./mi. Figure 2 shows the VOCs that correspond with each new level of deteriorating surface roughness. A discount rate of 12 percent has been assumed and

TABLE 2 DERIVATION OF A PARTICULAR THRESHOLD TRAFFIC LEVEL

	Roughness (in./mi)[a]		Vehicle Operating Costs (J$/mi)[b]				
Year	With Treatment	Without Treatment	With Treatment	Without Treatment	Savings	Discount Factor[c]	Net Present Value
0	60	60	1.73	1.73	0	1	0
1	61.5	61.5	1.74	1.74	0	0.893	0
2	63.0	30.5	1.75	1.63	0.12	0.797	0.096
3	64.5	31.0	1.76	1.63	0.13	0.712	0.093
4	66.0	31.5	1.78	1.63	0.15	0.636	0.095
5	67.5	32.0	1.79	1.64	0.15	0.567	0.085
6	69.0	32.5	1.80	1.64	0.16	0.507	0.081
7	70.5	33.0	1.81	1.64	0.17	0.452	0.077
8	72.0	33.5	1.82	1.64	0.18	0.404	0.073
9	73.5	34.0	1.84	1.64	0.20	0.361	0.072
10	75.0	34.5	1.85	1.65	0.20	0.322	0.064

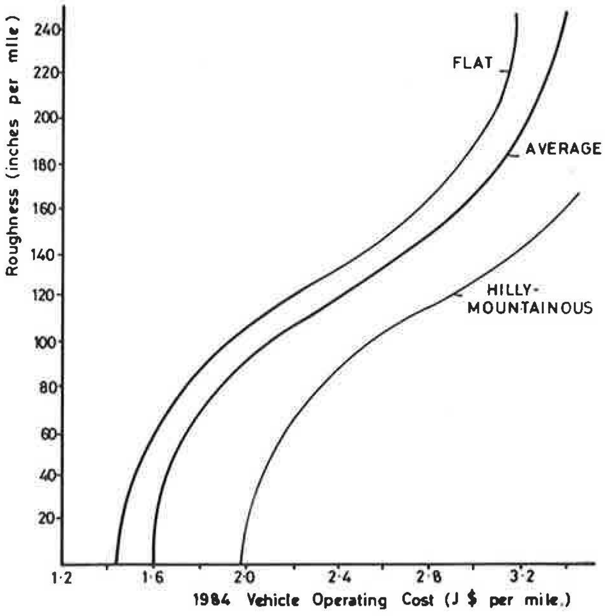
Note: Discounted benefits over a 10-year period per vehicle per mile = 0.736. Threshold ADT = Cost of 1 mi of overlay in Year 1/(365 × Benefits per vehicle) = 310,000/(365 × 0.736 × 1.12) = 1,030 vehicles per day.

[a] Roughnesses quoted are from Jamaica in-vehicle bump integrator (not the fifth-wheel bump integrator), and the 1982 condition survey indicated a range of linear deterioration for overlays of from 4.25 to 0.5 in./mi/year. This range was divided into five levels of deterioration. It is assumed that successive treatments will reduce the rate of deterioration by one level, in this case from 1.5 to 0.5 in./mi/year.

[b] In 1984 J$4.3 = U.S.$1.

[c] Includes 12 percent discount rate and 0 traffic growth.

the best estimate of overlay cost in 1984, including all preparatory works, was J$310,000 per mile. When 1982 construction and vehicle operating costs were used, the threshold was 853 vehicles per day, which indicates that between 1982 and 1984 construction costs rose faster than savings in vehicle operating costs.



NOTES : 1. Roughness as measured by Jamaica bump intregator.
2. At Aug. 1984 1 US $= J $ 4·30

FIGURE 2 Vehicle operating costs versus surface roughness.

The following nominal standard costs (1984) were adopted:

Asphalt overlay	J$310,000/mi
Double reseal	J$120,000/mi
Rip-up and reseal	J$140,000/mi

It is useful to note that the surface roughnesses quoted throughout this paper refer to in-vehicle bump integrator readings not those from the standard towed fifth-wheel bump integrator. The following ranges of roughness were associated with these surface specifications:

Overlaid road	30 to 140 in./mi
Double seal	120 to 240 in./mi

The 120- to 140-in. range has very few miles of road in it because it embraces the limiting bad roughness of an overlaid surface with the very best possible from a seal. In discounting the VOC savings over a 10-year period, a zero traffic growth rate has been assumed.

Usefulness and Application of Threshold Curves

The use of threshold curves can be readily appreciated when trying to choose the best option for surface treatment. Normally, the best option would be the most economical one, that is, the one that represents the best return on investment. However, in the current Jamaican financial climate, the best option is in many cases the least-cost solution.

Road X in Figure 1 has an ADT of 500 vehicles, which makes it feasible either to reseal it (J$130,000 per mile) or to rip it up and seal it again (J$150,000 per mile). At an R1 of 170 in./mi, the threshold ADT for resealing would be 400, and for rip-up and seal it would be 157, so with an actual ADT of 500 the benefit-to-cost ratios of the respective treatments are 500/400 = 1.25 and 500/157 = 3.18. The least-cost (feasible) option of reseal is being adopted in the present financial circumstances.

In the case of Road Y it would only be feasible to rip up and seal, and in the case of Road Z no periodic action should be recommended. The only situation in which there is a real choice of action therefore is the case of Road X, where to double seal the surface is still economically feasible and it would clearly cost less than ripping up and resealing. In the other two cases the less costly action of double sealing should not be considered as a solution because it would not be economically feasible.

The overall effect of choosing the least-cost option in preference to the most economic option depends on the types and grouping of roads chosen for improvement, but some indications are given as a rough guide in Table 3.

By comparing the actual ADT with the threshold ADT at R1, it is possible simply to deduce the benefit-to-cost ratio and from this derive the net present value (NPV) or the more useful indicator of NPV/cost. Furthermore, this can be aggregated for whole road sections to arrive at a new national list of priorities, by road control section, according to the least-cost strategy. This was done by computer because the records of length, roughness, and ADT are already filed, and it was an easy matter to divide Figure 1 into zones for the four options: overlay, reseal, rip up and seal, and do nothing except routine maintenance.

Limitations of the Method

The application of these threshold curves is a simple matter, but there are certain limitations to their use:

- Construction costs have been standardized, but in practice these costs vary from job to job because they are largely dependent on the amount of preparatory work needed.
- If poor road condition is due to foundation failure of the road structure, a surface treatment cannot remedy the situation and extra costs will be incurred in preparing the road to receive surface treatment.
- Accurate traffic data and roughness measurements are required.
- Types of terrain and deterioration regimes are also standardized, though sensitivity tests show that, in practice, these variables have little effect on the thresholds.

The first two of the preceding items represent costing inaccuracies. Investigation of recently completed reseals has shown some relationship between initial surface roughness and the variable cost of preparatory work, and this refinement has been incorporated in the threshold curves. In any event, the threshold value can easily be reproportioned by the ratio of the final detailed estimate to the standard cost assumed.

The sensitivity of the choice of treatment to the traffic and roughness measurements obviously varies throughout the curves, and, where points are close to the threshold, thought must be given to the consequences of an over- or underestimation of roughness or traffic. Though the former more detailed method took into account four types of terrain and five rates of deterioration, it was found that the resulting benefits were generally within 10 percent of the average situation that has been assumed for the threshold diagram.

In any case, the priority works program should include only those road improvements that are well above the thresholds, where a 10 percent error is not crucial to the selection of the surface treatment.

ROAD IMPROVEMENT AND MAINTENANCE BUDGET

Figure 1 can be used to generate a sound least-cost program of periodic maintenance work. Every subsection is represented by a point (a subsection is, by definition, a length of road of consistent width, surface type, traffic, and roughness). A complete road control section can include as many as 15 subsections though the variation of traffic is usually small. The same

TABLE 3 TYPICAL 10-YEAR RETURNS FROM SURFACE TREATMENTS IN 1984

Present Type	Surface Roughness (in./mi)[a]	Average Daily Traffic	Least-Cost Option			Most Economic Option		
			Treatment	Benefits[b] (J$ 000s)	Costs[b] (J$ 000s)	Treatment	Benefits[b] (J$ 000s)	Costs[b] (J$ 000s)
Overlay	75	3,000	—[c]			Overlay	1,603	310
			—[c]					
Overlay	110	750	—[c]			Overlay	894	310
			—[c]					
Overlay	120	300	—[c]			Overlay	531	310
Seal	150	500	Reseal	236	110	Reseal	236	110
Seal	190	1,500	Reseal	297	150	Rip up and seal	1,746	170
Seal	210	300	Rip up and seal	380	190	Rip up and seal	380	190

[a] Range of roughness of overlays is 25 to 140 in./mi and 120 to 260 in./mi for seals. At 240 in./mi the surface is fairly poor and is considered to have failed, though vehicle operating costs do not increase significantly with roughness beyond 240 in./mi (see Figure 2) unless the road becomes impassable and diversion costs arise.

[b] In August 1984 J$4.3 = U.S.$1.

[c] Normally, surface dressing an overlay will make it rougher. However, if cracking can be effectively treated by surface dressing this can be a worthwhile measure to extend the life of the existing overlay. A different assessment method is needed for checking the feasibility of this type of treatment.

diagram can be used for choosing the most economical option.

The most powerful implication of these curves is not so much at the subsection, or even the control section, level but at the level of national planning. The 1982 road condition survey provided ADT and roughness data for all 3,188 subsections of the Main Road Network (2,876 mi). By integrating the length of roads that exhibit a particular traffic roughness characteristic with the least-cost option (or alternatively the most economical), the amount of money that could be economically justified for overlays, double seals, and rip up and reseals can be seen immediately. Preliminary indications were that, for the least-cost option, 269 mi of overlay, 792 mi of reseal, and 396 mi of rip up and reseal could be justified. The most economical solution indicated 1,718 mi of overlay, 91 mi of reseal, and 27 mi to be ripped up and resealed, but at much greater cost.

Necessary periodic maintenance should be spread over a number of years so that the financial and physical work load can be sensibly evened out. Allowing for a design life of approximately 10 years for seals and 15 years for overlays, all necessary maintenance work should be completed in a 10-year period, by which time many other roads will have crossed the threshold and become eligible for treatment.

Figure 1 is provisional; however, order-of-magnitude budget requirements can be obtained. For periodic maintenance these are

Least-cost option	J$23.3 million per year (1984 prices)
Economical option	J$54.4 million per year (1984 prices)

to which have to be added the costs of necessary administration, training, and technical assistance. The allocation for periodic maintenance in 1985–1986 was J$40 million.

CONCLUSION

Traffic threshold curves provide a powerful and rapid method for determining options for surface treatments, and such curves can indicate to national authorities what should be spent on road maintenance. The curves can be quickly updated as either vehicle operating costs or construction costs change, and they can be used for whole road sections to try to bring a greater consistency to the way periodic maintenance contracts are arranged. In the parishes of Jamaica they can be applied without even a calculator, let alone a computer.

ACKNOWLEDGMENTS

This work forms part of an overall planning system that is being developed for road investments by the Ministry of Construction (Works), Jamaica, (Permanent Secretary, G. R. Kirkpatrick). The authors wish to acknowledge the assistance by the staff of the Road Planning Unit, and in particular E. Arthurton, for computer modeling. Views expressed in this paper are not necessarily those of the Ministry of Construction (Works).

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A Study of the Effects of Routine Pavement Maintenance

TIEN F. FWA AND KUMARES C. SINHA

Knowledge of the effects of routine maintenance on pavement performance is important to the management of highway pavements at both the network and the project level. In this paper is described a methodology for evaluating these effects on the basis of pavement performance data and aggregated pavement routine maintenance cost information. The proposed methodology was applied to assess the effects of routine pavement maintenance on 75 highway routes in Indiana. In addition, statistical analyses were performed to examine the influence of environmental and climatic conditions on the effects of routine maintenance on these routes.

In recent years the main emphasis of most state highway agencies has been shifted from building new facilities to maintaining and preserving the existing system. Pavement maintenance has now become a major area of expenditure in the budgets of many highway agencies. To make optimal use of the limited funds available, it is important for a highway agency to have knowledge of the effect that routine maintenance might have on the performance of a given pavement, or a network of pavements, under a known set of environmental conditions. Unfortunately, there is relatively little documentation and information on this in the literature.

In this paper is described a procedure for evaluating the effect of past routine pavement maintenance on pavement performance. This effect is expressed in terms of an index, known as the pavement routine maintenance effectiveness index, that provides a measure of the amount of improvement in pavement performance that is achievable with a unit increase in maintenance expenditure. The results of this analysis for each pavement may then be correlated with its characteristics and the associated environmental conditions to provide information that is useful in maintenance planning and programming.

The proposed procedure was used to evaluate the effects of routine pavement maintenance on 75 highway routes in Indiana. A description of this application is presented for purposes of illustration. In addition, statistical analyses were performed to examine the influence of environmental conditions on the effects of routine maintenance on rigid, flexible, and overlay pavements in Indiana.

CONCEPT

It is generally agreed that improved pavement performance can be achieved by having better routine pavement maintenance. This notion may be presented schematically as shown in Figure 1*a*, where the pavement condition at a given time is expressed in terms of its present serviceability index (PSI). The same notion can be expressed in mathematical terms:

$$(\text{PSI loss})_{1,t} < (\text{PSI loss})_{2,t} \quad (1)$$

where

$$(\text{PSI loss})_{1,t} = (\text{PSI})_0 - (\text{PSI})_{1,t} \quad (2)$$

$$(\text{PSI loss})_{2,t} = (\text{PSI})_0 - (\text{PSI})_{2,t} \quad (3)$$

Alternatively, as suggested by Fwa and Sinha (*1*), the relationship in Equation 1 may be expressed in terms of PSI-ESAL losses as defined in Figure 1*b*. Equation 1 may then be rewritten as follows:

$$(\text{PSI-ESAL loss})_{1,t} < (\text{PSI-ESAL loss})_{2,t} \quad (4)$$

where ESAL stands equivalent 18-kip single-axle loads.

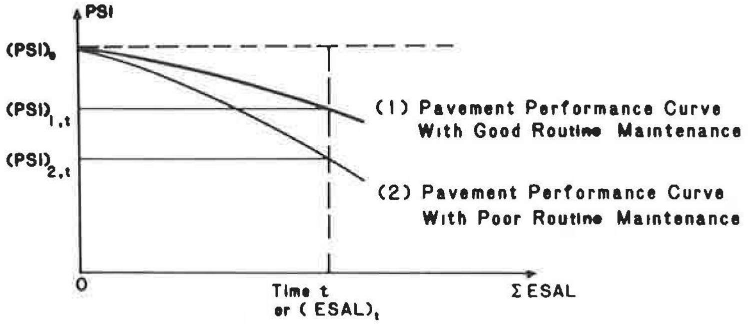
Although PSI loss represents the state of pavement at the time of analysis and makes no reference to its past history, PSI-ESAL loss is computed over the entire analysis period and therefore is also a function of the past conditions of the pavement. Because the effect of routine maintenance is a cumulative result of repetitive maintenance activities during the same analysis period for which PSI-ESAL loss is computed, it is reckoned that PSI-ESAL loss is a more suitable parameter for use in the analysis of routine maintenance effects.

The relationship depicted in Figure 1 is qualitative. To obtain a quantitative assessment of the effect of routine maintenance, it is necessary to replace the qualitative description of level of routine maintenance by some appropriate quantitative parameter. For a given maintenance policy and technology, the mean annual pavement routine maintenance expenditure per lane-mile appears to be a logical choice. An implicit assumption involved in adopting this parameter is that higher maintenance expenditure is associated with higher levels of routine maintenance and vice versa. This parameter has been used by Sharaf (*2*) in a study dealing with routine maintenance cost prediction and by Fwa (*3*) in investigating load- and non-load-related effects on pavement performance.

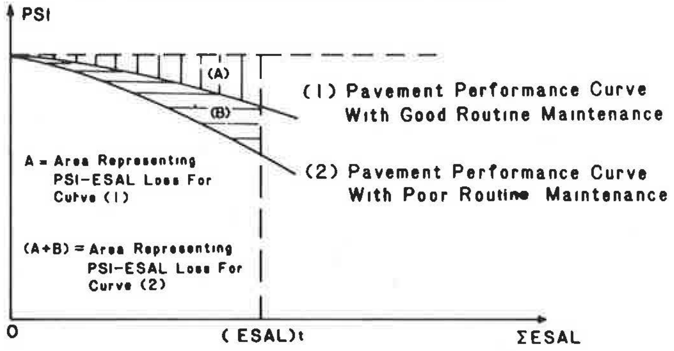
When the hypothesis of positive correlation between expenditure on routine pavement maintenance and level of routine maintenance is valid, a family of n possible pavement performance curves can be imagined for a given pavement. Expenditure on routine maintenance increases incrementally from Curve 1 to Curve n, as shown in Figure 2. The increment in maintenance expenditure from Curve i to Curve (i + 1) is given by δS_i. The corresponding difference in PSI-ESAL loss between the two curves is designated as δA_i.

Reduction in PSI-ESAL loss (δA_i) results when maintenance

T. F. Fwa, Department of Civil Engineering, National University of Singapore, Singapore. K. C. Sinha, School of Civil Engineering, Purdue University, West Lafayette, Ind. 47907.



(a) Pavement Deterioration Expressed In PSI Loss



(b) Pavement Deterioration Expressed In PSI-ESAL Loss

FIGURE 1 Relationship between pavement performance and routine maintenance.

expenditure is increased from S_i to $(S_i + \delta S_i)$ and represents the amount of improvement in pavement performance achieved. As the maintenance expenditure increment (δS_i) becomes infinitesimally small, the following index (defined as a routine pavement maintenance effectiveness index) provides a measure of improvement in pavement performance for a unit change in maintenance expenditure.

$$M_i = -\lim_{\delta S_i \to 0} (\delta A_i/\delta S_i) = -(dA/dS)_i \qquad (5)$$

where

M_i = routine pavement maintenance effectiveness index evaluated at the routine maintenance level represented by S_i in Figure 2,
A = PSI-ESAL loss,
S = routine maintenance expenditure, and
δA_i and δS_i are as defined in Figure 2.

When S is expressed in mean annual maintenance expenditure per lane-mile, the unit of an effectiveness index (M) has a

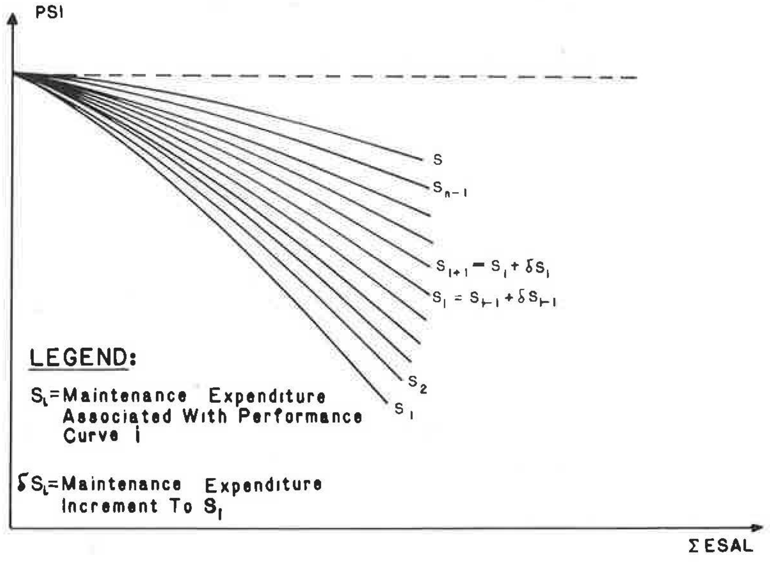


FIGURE 2 Family of possible performance curves for a given pavement.

unit given by PSI-ESAL loss per dollar per year per lane-mile. The expression in Equation 5 implies that, if A is plotted against S, the slopes of such a plot give the values of M at different levels of S. This offers a relatively convenient way to derive the values of M at desired levels of S. A negative sign is added to the expression in Equation 5 so that an M-value would be positive for the usual case in which a PSI-ESAL loss reduction would result from an increase in maintenance expenditure.

APPLICATION

A case study is presented in this paper as an example of the application of the concept described. The computations in this case study were based on data on the state highway system in Indiana. A total of 75 highway routes in Indiana were analyzed. These included 8 Interstate highways and 67 U.S. and state routes. These roads represent nearly 70 percent of the total state highway system mileage in Indiana.

The data requirements for pavement performance and routine maintenance analysis are discussed in this section. This discussion is followed by a description of the computational procedure involved in the analysis. The implications and significance of the results of this case study are also discussed.

Description of Data

Two main types of data were needed for the case study: data required for establishing the performance curve of a given highway route and routine pavement maintenance cost data.

Data on Pavement Performance

The PSI history of a given pavement section of a given highway route was determined from the annual Roadmeter roughness records maintained by the Indiana Department of Highways (IDOH). Three successive studies, covering a period of 8 years, were conducted by Purdue University and IDOH (*4–6*) in an effort to establish a comprehensive model of statistical correlation between Roadmeter roughness numbers and PSI for the state highway system of Indiana. The final results of this research effort are given in Equations 6 and 7.

For flexible and overlay pavements,

$$\mathrm{PSI} = 8.72 - 1.9633 * \log(\mathrm{RN}) \qquad R^2 = 0.71 \tag{6}$$

For rigid pavement,

$$\mathrm{PSI} = 11.73 - 2.83369 * \log(\mathrm{RN}) \qquad R^2 = 0.68 \tag{7}$$

where RN is roadmeter counts per mile and R^2 is the statistical coefficient of multiple determination.

The next requirement for establishing a performance curve is ESAL information. The data required for ESAL computation include traffic volume, traffic stream composition, vehicle axle configuration, and operating weights of vehicles. Traffic volume information was obtained from the annual traffic maps published by the IDOH. The remaining data were derived directly from the records of the 1984 Indiana Highway Cost Allocation Study (*7*). These records were the results of an extensive data collection effort made by the cost allocation study team. Fourteen vehicle classes were identified and subdivided into a total of 93 weight groups. Detailed information on axle weights and the traffic stream proportion of each weight group was available by highway functional class. These data enabled a sufficiently accurate computation of cumulative ESAL history to be made for the present case study.

Cost Data for Routine Pavement Maintenance

The IDOH maintains detailed records of routine highway maintenance activities. These records are compiled from information recorded on field crew-day cards. A field crew-day card is prepared each time a maintenance crew performs an activity. The information recorded on each field crew-day card includes type of routine maintenance activity, date, location, number of crew members, man-hours spent, types of equipment employed with corresponding usage in miles or hours, types and quantities of materials used, and work accomplishment measure such as lane-miles for seal coating and linear feet for cutting of relief joints. These data are recorded by activity and by fiscal year for each highway section. A highway section is defined as the portion of a highway that lies within the boundaries of a county.

The information from crew-day cards was summarized to aggregate yearly pavement maintenance costs that included the costs of the following routine pavement maintenance activities: shallow patching, deep patching, premix leveling, seal coating, sealing longitudinal cracks and joints, sealing cracks, cutting relief joints, joint and bump burning, and miscellaneous. A detailed description of the computational procedure for these aggregated pavement routine pavement maintenance costs is given elsewhere (*2*).

Analysis Procedure

The following steps were involved in the analysis of routine maintenance effects for each of the 75 highway routes considered in the case study:

1. Identify sections of the highway route that have the same pavement characteristics (material type, age, and thickness).
2. Compute routine pavement maintenance expenditure on each highway section for the analysis period.
3. Establish the performance curve for each highway section and calculate the corresponding PSI-ESAL loss for the analysis period.
4. Plot PSI-ESAL losses derived in Step 3 against the corresponding maintenance costs computed in Step 2, and calculate the routine pavement maintenance effectiveness index (M) as shown in Figure 3.

Because of the relatively small number of data points available in each of the 75 cases analyzed and because there was a

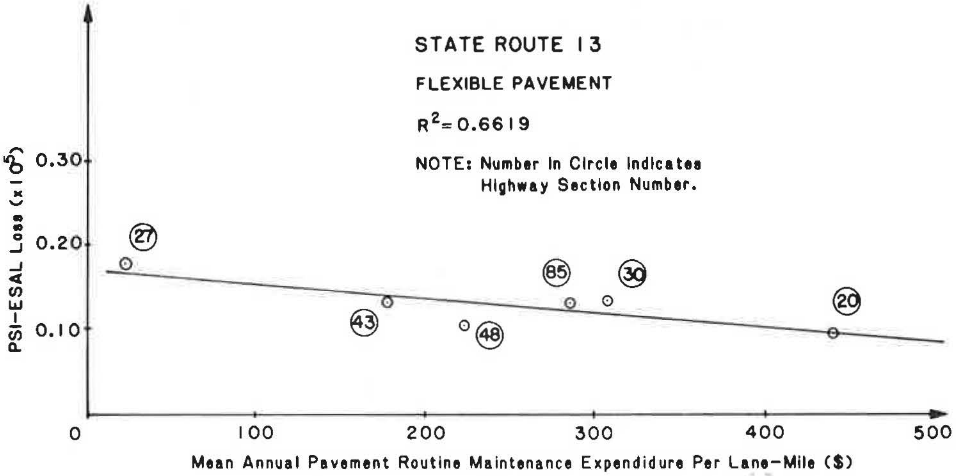


FIGURE 3 Example of PSI-ESAL loss versus maintenance expenditure.

lack of information on the true relationship between the parameters PSI-ESAL loss and routine pavement maintenance cost, the method of least squares was used to fit a straight line to the data points in each case.

Results of Analysis

The computed values of the routine pavement maintenance effectiveness index (M) for the 59 flexible, 10 overlay, and 6 rigid pavement cases are given in Tables 1 and 2. For flexible and overlay pavements, the M-values were evaluated at a cumulative ESAL level of 1.5×10^5. For rigid pavements, they were estimated at a cumulative ESAL-value of 1.5×10^7. These cumulative ESAL levels were selected by making reference to the median and mean values of the cumulative ESAL-values for the three pavement types. The six rigid pavements, because they are Interstate highways, carried greater traffic and were much older than most of the flexible and overlay pavement routes. This explains the large difference between the cumulative ESAL-values. A summary of the statistical characteristics of the distribution of the effectiveness indices (M) of Indiana highways is given in Table 3.

It is obvious from the definition of M and the results that a comparison of M-values is meaningful only if these values are evaluated at the same cumulative ESAL level and for the same pavement type. When these requirements are met, a higher M-value indicates a more effective routine maintenance program that produces more improvement in pavement performance for each maintenance dollar spent.

Regional Effects on Effectiveness of Maintenance

The effects of environmental and climatic factors on the effectiveness of routine maintenance work is an area on which relatively little research has been done. The routine pavement maintenance effectiveness index proposed in this study provides a convenient way of measuring such effects.

The results given in Tables 1 and 2 are also classified into N (northern) and S (southern) environmental-climatic regions. These two environmental-climatic regions of Indiana, as shown in Figure 4, have been commonly used in pavement-related studies conducted in Indiana (*2*, *3*, *7*).

The characteristics of these two regions are given in Table 4. Also given in this table are the ranges of values of various climatic and environmental variables for each of the two regions. In general, the northern region has a longer period of depressed temperature, as reflected by its higher freeze index, and heavier snowfall. On the other hand, the southern region receives more precipitation and is exposed to more changes of air temperature across the freezing point. It is interesting to study the impacts that the characteristics of these two regions have on routine maintenance.

Statistical regression analyses were performed for flexible, overlay, and rigid pavements to test the significance of regional effect in each case. The relevant regression model is

$$\begin{aligned} M_i &= c_0 + c_1 Z_i + c_2 X2_i + c_3 X3_i \\ &\quad + c_4 X4_i + c_5 X5_i + e_i \\ i &= 1, 2, \ldots, n \end{aligned} \tag{8}$$

where

M = pavement routine maintenance effectiveness index in PSI-ESAL loss/dollar/year/lane-mile;
Z = 0 for southern region and 1 for northern region;
X2 = pavement age in years;
X3 = pavement thickness in inches for rigid pavement and structural number for flexible pavement;
X4 = mean annual ESAL;
X5 = total cumulative ESAL;
e = random error term;
c_k = regression parameters, k = 1, 2, . . . , 6; and
n = total number of data points.

Only variables that do not represent any environmental or climatic conditions are included in the model. The environmental and climatic variables (Table 4) that describe the conditions in each of the two regions were qualitatively represented by the indicator variable Z.

Because the goal was to determine whether the effects of

TABLE 1 ROUTINE PAVEMENT MAINTENANCE EFFECTIVENESS INDICES FOR FLEXIBLE AND OVERLAY PAVEMENTS IN INDIANA

No.	Highway Route	Index M	Region	No.	Highway Route	Index M	Region
1	SR 1(n)	5.50	N	36	SR 39(n)	11.31	N
2	SR 1(s)	1.89	S	37	SR 39(s)	4.02	S
3	SR 2	26.22	N	38	US 40	7.18	S
4	SR 3(n)	20.18	N	39	US 41	3.20	S
5	SR 3(s)	12.49	S	40	SR 42	1.50	S
6	SR 4	23.71	N	41	SR 43(n)	10.41	N
7	SR 5	26.93	N	42	SR 43(s)	3.00	S
8	US 6	11.90	N	43	SR 44	10.61	S
9	SR 8	32.72	N	44	SR 46	10.22	S
10	SR 9(n)	11.11	N	45	SR 47	14.29	S
11	SR 9(s)	14.38	S	46	SR 48	16.48	S
12	SR 10	20.38	N	47	US 50	5.21	S
13	SR 13	16.41	N	48	US 52(n)	5.89	N
14	SR 14	2.80	N	49	US 52(s)	10.80	S
15	SR 16	24.32	N	50	SR 55	7.60	N
16	SR 17	29.78	N	51	SR 56	3.09	S
17	SR 18	6.70	N	52	SR 57	13.22	S
18	SR 19	13.32	N	53	SR 58	14.88	S
19	US 20	14.81	N	54	SR 60	15.68	S
20	SR 23	16.01	N	55	SR 62	4.50	S
21	US 24	8.79	N	56	SR 63	12.72	S
22	SR 25	22.78	N	57	SR 64	11.01	S
23	SR 26	22.91	N	58	I 64	11.48	S
24	SR 28	12.39	S	59	I 65(s)	6.50	S
25	SR 29	10.59	N	60	SR 67	11.47	S
26	US 30	17.61	N	61	SR 75	8.50	S
27	US 31(n)	20.23	N	62	SR 135	10.61	S
28	US 31(s)	4.19	S	63	US 150	5.40	S
29	SR 32	5.10	S	64	US 231(n)	8.51	N
30	SR 33	19.57	N	65	US 231(s)	6.62	S
31	US 35	12.79	N	66	SR 234	10.68	S
32	US 36	10.38	S	67	SR 236	6.60	S
33	SR 37(n)	8.31	N	68	US 421(n)	10.09	N
34	SR 37(s)	2.82	S	69	US 421(s)	7.70	S
35	SR 38	16.29	N				

Note : 1. M is pavement routine maintenance effectiveness in PSI-ESAL loss/dollar/year/lane-mile.
2. All M values are evaluated at cumulative Esal value of 150,000 .
3. Cases number 26, 27, 28, 39, 41, 42, 47, 54, 57, and 59 are overlay pavement routes.
4. N = northern environmental-climatic region
S = southern environmental-climatic region

TABLE 2 ROUTINE PAVEMENT MAINTENANCE EFFECTIVENESS INDICES FOR RIGID PAVEMENTS IN INDIANA

Case Number	Highway Route	Effectiveness Index M ($\times 10^4$)	Region
1	I-94	1.65	N
2	I-65	1.43	N
3	I-69	0.53	N
4	I-70	0.96	S
5	I-74	0.70	S
6	I-64	0.97	S

Note : 1. M is in PSI-ESAL loss/dollar/year/lane-mile
2. All M values are evaluated at cumulative ESAl value of 15,000,000 .
3. N = northern environmental-climatic region
S = southern environmental-climatic region

TABLE 3 CHARACTERISTICS OF ROUTINE PAVEMENT MAINTENANCE EFFECTIVENESS INDICES FOR INDIANA HIGHWAYS

	Rigid Pavement	Flexible Pavement	Overlay Pavement
No. of cases analyzed	6	59	10
Reference cumulative ESAL level	1.5×10^7	1.5×10^5	1.5×10^5
Range of M			
Minimum	0.53×10^4	1.50	3.00
Maximum	1.65×10^4	32.70	20.23
Mean	1.04×10^4	12.38	9.70
Standard deviation	0.43×10^4	7.13	6.31

routine maintenance on pavement performance were different in the two regions, no attempt was made to obtain the best regression model out of Equation 8. In drawing inferences about c_1, the appropriate statistical test was

$$H_0: \quad c_1 = 0$$

$$H_1: \quad c_1 \neq 0$$

Analysis of Regional Effect on Flexible Pavement

The results of the statistical analysis based on Equation 8 for the routine maintenance effectiveness index values of flexible pavements in Indiana are given in Table 5. The regional effect was found to be significant at both the 0.05 and the 0.01 level of significance, which means that the effects of routine maintenance on flexible pavements were significantly different statistically in the two regions of Indiana. The correlation matrix in Table 5 shows that there was little correlation between the indicator variable Z and the other independent variables included in the regression model.

These results led to the conclusion that the routine maintenance effectiveness index of flexible pavement was higher in the northern region than in the southern region. Physically, this means that the amount of pavement damage repaired (i.e., the amount of PSI-ESAL loss recovered) per dollar of maintenance work was greater in the northern region. In other words, it may be said that each dollar spent for maintenance per lane-mile in the northern region was more effective in improving pavement performance than it was in the southern region.

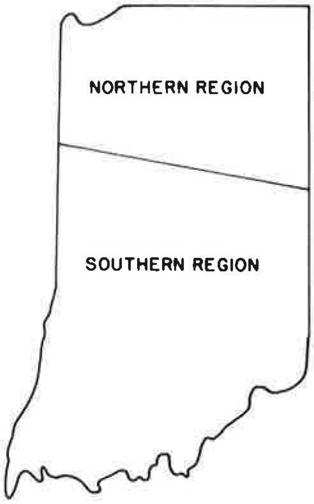


FIGURE 4 Northern and southern regions of Indiana.

Analysis of Regional Effect on Overlay Pavements

Because of the relatively small number of overlay pavement cases included in the case study, a reduced version of the general model in Equation 8 was used for the analysis presented in this section. Because the several reduced models selected all led to the same conclusion about the regional effect on maintenance effectiveness, only one of them is presented here for the purpose of discussion. The model with the best coefficient of multiple determination (R^2) was

$$M_i = c_0 + c_1 Z_i + c_2 X2_i + e_i \qquad (9)$$
$$i = 1, 2, \ldots, 10$$

TABLE 4 CHARACTERISTICS OF NORTHERN AND SOUTHERN REGIONS OF INDIANA

Climatic/Environmental Factors	Northern Region Minimum	Northern Region Maximum	Southern Region Minimum	Southern Region Maximum
Freezing Index (°F-Day)	100	350	0	170
Mean Annual Snowfall (in.)	22	60	11	24
Mean Annual Rainfall (in.)	34	38	37	46
Mean Daily Temperature (°F)	50	52	52	57
Thornthwaite Moisture Index	30	41	35	55
Freeze-Thaw Cycle Index(*)	105	111	105	160
Soil Support Value	4.0	6.8	4.0	6.8

(*) Freeze-thaw cycle index refers to the mean number of air temperature changes across the freezing point, 32°F.

TABLE 5 REGRESSION ANALYSIS FOR FLEXIBLE PAVEMENTS BASED ON MODEL IN EQUATION 8

Coefficient	Estimated Value	*t*-Statistic
c_0	54.933	3.898
c_1	6.531	4.143[a]
c_2	−1.868	−3.212
c_3	−5.387	−2.303
c_4	−266.608	−1.175
c_5	27.497	1.190

[a] Significant at levels 0.05 and 0.01.

Note: The correlation matrix is as follows:

	M	Z	X2	X3	X4	X5
M		0.428	−0.407	0.015	−0.041	−0.066
Z	0.428		−0.045	0.253	−0.083	−0.080
X2	−0.407	−0.045		−0.334	−0.001	0.083
X3	0.015	0.253	−0.334		0.118	0.092
X4	−0.041	−0.083	−0.001	0.118		0.995
X5	−0.066	−0.080	0.083	0.092	0.995	

where all terms are as defined for Equation 8.

The results given in Table 6 led to the conclusion that regional effect was significant at a level of significance equal to 0.05. That is, a unit of routine maintenance work performed in the northern region was more effective in improving overlay pavement performance than was a similar unit of work performed in the southern region.

TABLE 6 REGRESSION ANALYSIS FOR OVERLAY PAVEMENTS BASED ON MODEL IN EQUATION 9

Coefficient	Estimated Value	*t*-Statistic
c_0	9.851	1.890
c_1	9.504	2.693[a]
c_2	−0.329	−0.593

[a] Significant at level 0.05.

Note: The correlation matrix for all variables in Equation 8 is as follows:

	M	Z	X2	X3	X4	X5
M		0.696	−0.018	−0.078	−0.102	−0.022
Z	0.696		0.195	0.079	−0.138	−0.043
X2	−0.018	0.195		−0.583	−0.442	−0.388
X3	−0.078	0.079	−0.538		0.582	0.611
X4	−0.102	−0.138	−0.442	0.585		0.988
X5	−0.022	−0.043	−0.388	0.611	0.988	

Analysis of Regional Effect on Rigid Pavements

Because there were only six rigid pavement cases available for study, a reduced version of the general model in Equation 8 was again employed. Because all six pavements had the same slab thickness (10 in.) and because variables X4 and X5 were highly correlated, variables X3 and X5 were first eliminated from the model. All possible reduced models with different combinations of the remaining variables, Z, X2, and X4, gave similar conclusions to the statistical test for regional effect. Because X2 had the lowest correlation with Z, the following model is selected for illustration:

$$M_i = c_0 + c_1 Z + c_2 X2_i + e_i \qquad i = 1, 2, \ldots, 6 \tag{10}$$

where all terms are as defined in Equation 8.

The results of the statistical analysis for the model in Equation 10 are given in Table 7. It was found that regional effect was significant only at a level of significance of 0.431. It may therefore be concluded that there was no difference statistically between the effectiveness of routine maintenance in the two regions.

TABLE 7 REGRESSION ANALYSIS FOR RIGID PAVEMENTS BASED ON MODEL IN EQUATION 10

Coefficient	Estimated Value	*t*-Statistic
c_0	25942.82	2.982
c_1	2439.30	0.907[a]
c_2	−1034.76	−2.021

[a] Significant at level 0.431; not significant at level 0.05.

Note: The correlation matrix for all variables in Equation 8 is as follows:

	M	Z	X2	X4	X5
M		0.420	−0.745	0.801	0.670
Z	0.420		−0.153	0.558	0.547
X2	−0.745	−0.153		−0.368	−0.191
X4	0.801	0.558	−0.368		0.980
X5	0.670	0.547	−0.191	0.980	

Findings of the Case Study

Statistical analyses of the results of the case study indicated that there was a significant regional variation in the effects of routine maintenance on flexible pavements in Indiana. It was concluded, at the 99 percent confidence level, that a unit of routine maintenance work was more effective in improving pavement performance in the northern region. The same conclusion was obtained for overlay pavements but with a slightly lower confidence level of 95 percent. For rigid pavements, no significant regional variation in the effects of routine maintenance was found.

It should be noted that the qualitative variable (Z) in Equations 8–10 was used for testing the regional variation of routine maintenance effects. Each region covers a big area and a large number of highway routes. The regional variable (Z) represents the net combined effect of all environmental and climatic factors in a region. Further research is being undertaken to investigate the influence of individual environmental and climatic factors on the effects of routine maintenance by indentifying the specific conditions of each highway route.

CONCLUSIONS

Knowledge of the effects of routine maintenance on pavement performance is important to the management of highway pavement at both the network and the project level. A methodology for evaluating these effects, based on pavement performance data and aggregated routine pavement maintenance cost information, has been described.

An application of the concept has been illustrated with a case study in which 75 highway routes in Indiana were analyzed. The proposed methodology was employed to compute for each highway route a routine pavement maintenance effectiveness index that is a measure of the effect of routine maintenance work on pavement performance. The magnitude of the index provides a means of assessing the effectiveness of a given maintenance policy or program. Statistical analyses were performed to examine the regional variation in effects of routine maintenance in Indiana. Research is under way to derive further information about the effects of routine maintenance by taking into consideration the influence of individual environmental and climatic factors and the effectiveness of specific routine maintenance activities.

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Estimation of Service Life and Cost of Routine Maintenance Activities

KIERAN J. FEIGHAN, ESSAM A. SHARAF, THOMAS D. WHITE, AND KUMARES C. SINHA

Results of research on service life and cost of various routine maintenance activities in Indiana are presented. This research is a part of a larger project to develop an optimization program for the routine maintenance management system. The information on service life and cost is necessary to identify cost-effective solutions and to monitor whether or not changes in work practices or materials significantly influence the effectiveness of the activity. The routine maintenance activities considered were in the general areas of pavement, shoulder, and drainage. The unit cost information per production unit was obtained from an analysis of crew-day card reports. The service life data were developed through personal interviews with subdistrict foremen. The estimates of service life were related to pavement condition as well as to accomplishment per day. The resulting information provides a reasonable set of input data for the optimization of maintenance decisions.

Interest in pavement maintenance management has grown steadily during the last 10 years or so. This interest has been largely motivated by a desire to obtain a greater degree of control and standardization of approach in order to ultimately achieve a better return per dollar invested in the construction and maintenance of pavements. However, most of the research that has been undertaken to date has been in the area of major maintenance. Consequently, there is limited published information on techniques and data concerning routine maintenance activities and management. The awareness of routine maintenance as a major consumer of limited highway funds is the

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K. J. Feighan, T. D. White, and K. C. Sinha, School of Civil Engineering, Purdue University, West Lafayette, Ind. 47907. E. A. Sharaf, Department of Civil Engineering, Cairo University, Cairo, Egypt.

motivating factor for the research being conducted at Purdue University to develop a routine maintenance management program for the Indiana Department of Highways (IDOH). Research on service life and costs of some of the routine maintenance activities in Indiana are described. These values were deemed to be essential inputs for such a program.

BACKGROUND

There is currently a maintenance management system (*1*) operating successfully at the network level in Indiana. The major features of the current system that are relevant to this research are (*a*) the field operators manual (*2*) and (*b*) crew-day cards. The field operators manual provides a set of performance standards for each designated maintenance activity. Each activity is identified by a number. The performance standard gives a description of the activity in question and a recommended maintenance procedure as well as a standard crew size, equipment complement, and a range of expected average daily production.

The crew-day cards provide a means of authorizing work to be done and recording work completed. One crew-day card is given to each crew leader every morning with details of the nature and location of the work to be done as well as assignment of employees and equipment. At the end of the day, the crew leader fills in the number of accomplishment units achieved that day, the man-hours worked, and the equipment and materials used. Thus it is possible to subsequently determine average man-hours, material usage, and other information per production unit.

This management system has been in operation in Indiana since 1975 and a large amount of data has been accumulated. The system has produced a relatively high degree of uniformity in maintenance procedures.

NEED FOR DATA

A variety of treatment alternatives exists for different types and levels of pavement and shoulder distress. All of these treatments will be effective to one degree or another, but there is a need to evaluate which methods produce the best solution to a given problem. To determine such an optimal solution, regardless of the nature of the deficiency, it is essential that two parameters be known, the service life and the cost of each of the alternatives.

The following uses have been put forward as justification for research on the estimation of expected service life and costs (*3*, *4*):

1. To estimate and allocate available funds,
2. To identify the most cost-effective solutions,
3. To monitor whether changes in work practices or materials significantly increase service life and to evaluate whether such changes are cost-effective,
4. To identify locations where the expected life of a given treatment is consistently not attained,
5. To justify a change in emphasis at the network level; for example, advocating sealing (preventive maintenance) over patching (corrective maintenance),
6. To anticipate when necessary expenditures will recur, and
7. To coordinate with the pavement management system (PMS) and other management systems in working out the most cost-effective "holding" action until rehabilitation or reconstruction can take place.

DEFINITION OF PARAMETERS ESTIMATED

After the need for the data has been established, the next step is to determine how best to obtain the necessary information. A review of routine maintenance activities conducted by IDOH indicated that not all activities were of equal importance. Consequently, in the initial work a number of activities were selected from the general areas of pavement, shoulder, and highway drainage. The criteria applied in selecting the activities were (*a*) annual expenditure per activity and (*b*) annual volume of work performed per activity.

Service Life Estimates

The expected service life of any treatment may vary with the degree of deficiency of any particular distress type as well as from distress type to distress type. There are also unique influences peculiar to each general category of pavements, shoulders, and drainage.

A distinction between actual and effective service life must be made because it is crucial to understanding the uses to which the accumulated data can be put. The actual service life of a given treatment is regarded as the time elapsed between application of the treatment and when its condition falls below a prescribed, measurable value. In the present research, instead of using the actual service life of a treatment, an estimate of the effective service life was made to represent the time elapsed between the time the treatment is applied and that when, in the opinion of field personnel, it needs to be replaced.

In the establishment of a maintenance management program, what is of ultimate concern is the amount of money spent on any given activity and the way that available monies can be spent to produce the maximum good. Allocation of funds is basically carried out by field personnel. In the IDOH organization, geographic areas of responsibility for routine maintenance are broken down into districts, subdistricts, and units. A unit averages approximately 140 mi. Unit foremen are responsible for deciding in the first instance when and where work needs to be carried out. Hence, it is relevant and useful to obtain an estimate of how long a treatment lasts based on the opinion of the unit foreman.

This approach to service life estimation is not new or unique. Ontario has already carried out such a survey as part of its routine maintenance program (RMP) and has incorporated the results, both service life estimates and costs, into its overall RMP system (*5*).

There is no doubt that research needs to be done on actual service lives, however, so that, as such specific information becomes available in the future, the appropriate service life functions can be inserted in the proposed routine maintenance management program.

Cost Information

A large amount of research has been undertaken in recent years at Purdue on the overall and specific costs of routine maintenance activities in Indiana (*6, 7*). As a consequence of this prior research, it was possible to obtain a unit cost per production unit for each activity. Table 1 gives a summary of the unit cost data for each of the activities considered in the study. It was previously mentioned that crew-day cards were required to be filled in each day and that daily accomplishment was one of the values listed. Thus maintenance personnel are familiar with the concept of production units and with the variation in production caused by changing roadway or climatic conditions. It is also believed that using production units as an indirect measure of cost yields greater potential for transferability of results for comparison.

STRUCTURE OF QUESTIONNAIRE

A questionnaire was used to acquire service life estimates. The questionnaire is laid out in a tabular-matrix type of format. There are three categories of condition for each activity, which generally conform to the overall descriptors of poor, fair, and good, although there is some variation in definition depending on the particular activity in question.

The condition input is further subdivided into cells that consist of three components that roughly correspond to minimum, average, and maximum. All refer to service life estimates currently given by the unit foremen with available manpower, equipment, materials, and so on. A decision was made to look for minimum and maximum values as well as an average value because it was thought that, in terms of the overall range of performance, the average value alone could be misleading.

Minimum service life values are not intended to be the single worst case in the experience of the unit foreman but rather an indication of what is considered to be a realistic, poor service life value. Similarly, the maximum value is considered to reflect a generally high service life value as opposed to the longest service life history known to the unit foreman.

In a survey such as this, a decision must be made about the detail and accuracy of results that can be reasonably expected. A necessary trade-off must be made between the amount of data acquired and the consequent error induced in the respondents' estimates through boredom, desire to complete the survey rapidly, and so on. It is believed that the questionnaire used struck a reasonable compromise in this regard.

SURVEY METHODOLOGY

Implementation of the survey questionnaire involved consideration of where and how many interviews should be conducted. Indiana is divided into six administrative districts, each of which is comprised of a number of subdistricts. To interview personnel in all 37 of the subdistricts would have been extremely costly, time consuming, and difficult to arrange.

A decision was made to choose subdistricts to take part in

TABLE 1 PRODUCTION UNITS AND COSTS

ACTIVITY	PRODUCTION UNIT	TOTAL COST PER PROD. UNIT
Shallow Patching	Tons of Aggregate	$114.17
Premix Levelling	Tons of Premix	$41.46
Full Width Shoulder Seal	Foot Miles	$177.50
Seal Coating	Lane Miles	$1352.60
Long. Joint And Crack Sealing	Lineal Miles	$108.50
Crack Sealing	Lane Miles	$290.00
Spot Repair Of Unpaved Shoulders	Tons of Aggregate	$13.64
Blading Shoulders	Shoulder Miles	$13.73
Clipping Shoulders	Shoulder Miles	$205.50
Reconditioning Unpaved Shoulders	Shoulder Miles	$885.60
Clean and Reshape Ditches	Linear Feet of Ditch	$0.61
Motor Patrol Ditching	Ditch Miles	$377.80

the survey by a process of stratified random sampling. Two subdistricts were selected at random from each district. When the individual strata contain relatively homogeneous elements, the variability for a given stratified random sample will be less than in a simple random sample of the same size (i.e., the stratified sample is more efficient) (*8*).

Homogeneity for each stratum is considered reasonable in that each subdistrict within a district is subject to much the same climatic and topographic conditions and usually has the same source of maintenance materials and equipment. In addition, meetings of all subdistrict supervisors and general foremen occur on a regular basis, and consequently repair strategies and methods would be expected to be fairly consistent.

Discernible patterns in the service life estimates for a number of the activities were anticipated because of the large difference in climate and topography between northern and southern Indiana. The use of stratified sampling made it possible to examine and identify such patterns as well as to estimate the overall population characteristics. From the point of view of feasibility, the choice of two subdistricts from each district meant that it was generally possible to interview in two subdistricts each day, thus reducing time and travel costs. The entire survey was carried out in a 2-week period at the end of June 1985.

In general, at each subdistrict office a meeting was held with the general foreman and two unit foremen. A total of 33 maintenance personnel were interviewed. A personal interview approach was used instead of a mailed questionnaire to both reduce ambiguous responses and increase the response rate. It should be noted that the field personnel were extremely cooperative and knowledgeable in every instance. Care was taken to avoid asking leading questions and generally little prompting was required to get numerical estimates and justification for them.

ANALYSIS OF RESULTS

The results of the service life estimation survey are summarized in Tables 2–4 for pavement-related activities and in Tables 5 and 6 for shoulder- and drainage-related activities. A discussion of individual activities follows.

Shallow Patching

There are four subdivisions within this activity corresponding to the different possible materials used in patching. They are hot mix, cold mix, winter or fiber mix, and fiber mix heated in a Portapatcher. Each of these materials was treated as a separate subject of interest, and service life and accomplishments were recorded for all four types.

The effective service life of a patch was taken to be the time elapsed until more work was necessitated at the location where the patch was placed. This approach was taken because it was pointed out by maintenance personnel that although the material in the patch itself may remain in place for a considerable length of time, cracking and breakup at the edges of the patch

TABLE 2 SERVICE LIFE AND DAILY ACCOMPLISHMENTS FOR POOR ROADWAY CONDITION

ACTIVITY	Effective Service Life And Associated Accomplishments		
	MINIMUM	AVERAGE	MAXIMUM
Shallow Patching Hot Mix	S.L.=2.8 APD =7.7	S.L.=8.5 APD =7.2	S.L.=12.5 APD =6.7
Shallow Patching Cold Mix	S.L.=0.2 APD =8.9	S.L.=0.3 APD =7.1	S.L.=0.7 APD =5.5
Shallow Patching Winter Mix	S.L.=1.0 APD =8.0	S.L.=3.7 APD =6.7	S.L.=3.8 APD =5.4
Shallow Patching Portapatcher	S.L.=1.3 APD =6.5	S.L.=5.3 APD =5.4	S.L.=7.3 APD =4.3
Premix Levelling (Wedging)	S.L.=17.1 APD =151	S.L.=24.9 APD =120	S.L.=30.9 APD =88
Seal Coat Chip Seal	S.L.=24.6 APD =5.0	S.L.=26.4 APD =6.3	S.L.=32.4 APD =7.8
Seal Coat Sand Seal	S.L.=0 APD =0	S.L.=0 APD =0	S.L.=0 APD =0
Sealing Long. Cracks & Joints	S.L.=17.7 APD =5.9	S.L.=22.5 APD =6.3	S.L.=26.2 APD =6.7
Sealing Cracks	S.L.=8.2 APD =1.2	S.L.=13.1 APD =1.5	S.L.=17.4 APD =1.8

S.L. = Service Life (Months)

APD = Accomplishments Per Day (Units in Table 1)

TABLE 3 SERVICE LIFE AND DAILY ACCOMPLISHMENTS FOR FAIR ROADWAY CONDITION

ACTIVITY	Effective Service Life And Associated Accomplishments		
	MINIMUM	AVERAGE	MAXIMUM
Shallow Patching Hot Mix	S.L.=9.9 APD =4.4	S.L.=17.2 APD =4.2	S.L.=23.7 APD =4.2
Shallow Patching Cold Mix	S.L.=0.2 APD =4.7	S.L.=0.6 APD =3.9	S.L.=1.0 APD =3.3
Shallow Patching Winter Mix	S.L.=3.1 APD =4.6	S.L.=5.0 APD =4.0	S.L.=5.9 APD =3.3
Shallow Patching Portapatcher	S.L.=6.6 APD =4.8	S.L.=8.9 APD =3.8	S.L.=11.6 APD =2.8
Premix Levelling (Wedging)	S.L.=29.1 APD =105	S.L.=34.3 APD =89	S.L.=41.1 APD =69
Seal Coat Chip Seal	S.L.=31.8 APD =5.5	S.L.=37.4 APD =6.8	S.L.=45.6 APD =8.5
Seal Coat Sand Seal	S.L.=14.4 APD =6.2	S.L.=15.6 APD =8.2	S.L.=20.4 APD =10.8
Sealing Long. Cracks & Joints	S.L.=25.6 APD =8.0	S.L.=29.5 APD =8.4	S.L.=33.3 APD =9.1
Sealing Cracks	S.L.=13.6 APD =2.8	S.L.=19.9 APD =3.0	S.L.=24.5 APD =3.1

S.L. = Service Life (Months)

APD = Accomplishments Per Day (Units in Table 1)

TABLE 4 SERVICE LIFE AND DAILY ACCOMPLISHMENTS FOR GOOD ROADWAY CONDITION

ACTIVITY	Effective Service Life And Associated Accomplishments		
	MINIMUM	AVERAGE	MAXIMUM
Shallow Patching Hot Mix	S.L.=36.0 APD =3.0	S.L.=53.4 APD =2.8	S.L.=54.2 APD =2.5
Shallow Patching Cold Mix	S.L.=0.3 APD =3.2	S.L.=0.7 APD =2.6	S.L.=1.2 APD =2.2
Shallow Patching Winter Mix	S.L.=3.3 APD =3.3	S.L.=5.8 APD =2.7	S.L.=6.8 APD =2.4
Shallow Patching Portapatcher	S.L.=14.7 APD =3.1	S.L.=23.1 APD =2.7	S.L.=24.1 APD =2.3
Premix Levelling (Wedging)	S.L.=36.0 APD =65.7	S.L.=47.1 APD =55	S.L.=49.7 APD =48
Seal Coat Chip Seal	S.L.=37.8 APD =6.2	S.L.=48.0 APD =7.5	S.L.=55.2 APD =9.1
Seal Coat Sand Seal	S.L.=19.2 APD =6.2	S.L.=21.6 APD =8.2	S.L.=28.8 APD =10.8
Sealing Long. Cracks & Joints	S.L.=31.6 APD =9.8	S.L.=34.9 APD =10.2	S.L.=38.2 APD =10.9
Sealing Cracks	S.L.=20.7 APD =4.1	S.L.=26.5 APD =4.5	S.L.=31.6 APD =4.9

S.L. = Service Life (Months)

APD = Accomplishments Per Day (Units in Table 1)

TABLE 5 SERVICE LIFE AND DAILY ACCOMPLISHMENTS FOR POOR SHOULDER AND DITCH CONDITION

ACTIVITY	Effective Service Life And Associated Accomplishments		
	MINIMUM	AVERAGE	MAXIMUM
Full Width Shoulder Seal	S.L.=0 APD =0	S.L.=0 APD =0	S.L.=0 APD =0
Spot Repair Of Unpaved Shoulders	S.L.=3.0 APD =51.4	S.L.=4.7 APD =46.4	S.L.=6.2 APD =41.8
Blading Shoulders	S.L.=2.7 APD =10.2	S.L.=4.4 APD =10.6	S.L.=4.8 APD =11.3
Clipping Shoulders	S.L.=33.3 APD =1.5	S.L.=37.1 APD =1.9	S.L.=42.5 APD =2.3
Recondition Shoulders	S.L.=36.0 APD =3.3	S.L.=38.0 APD =3.4	S.L.=38.0 APD =3.4
Clean and Reshape Ditches	S.L.=28.6 APD =546	S.L.=30.8 APD =696	S.L.=34.4 APD =846
Motor Patrol Ditching	S.L.=28.9 APD =1.0	S.L.=29.8 APD =1.3	S.L.=30.5 APD =1.7

S.L. = Service Life (Months)

APD = Accomplishments Per Day (Units in Table 1)

may require early repair with additional patching. Patching accomplishments per day (APD) vary in an expected way, decreasing as roadway condition improves and decreasing as service life increases. This pattern is consistent for all four types of shallow patching.

Patching APD decreases with improving roadway condition simply because there is less severe distress at any one location and distressed locations are farther apart on a road in good condition than on a road in poor condition. There are two reasons why the service life and APD vary inversely for a given road condition. First, a location that yields a high APD generally exhibits a large amount of distress. Examples of sources of such distress are poor drainage and heavy traffic volumes. Undoubtedly the source will cause failure around the newly patched surface. Thus there is no cause-and-effect relationship between service life and APD per se in this case; both simply

TABLE 6 SERVICE LIFE AND DAILY ACCOMPLISHMENTS FOR FAIR SHOULDER AND DITCH CONDITION

ACTIVITY	Effective Service Life And Associated Accomplishments		
	MINIMUM	AVERAGE	MAXIMUM
Full Width Shoulder Seal	S.L.=24.0 APD =65.0	S.L.=30.6 APD =73.5	S.L.=37.2 APD =83.5
Spot Repair Of Unpaved Shoulders	S.L.=6.3 APD =32.7	S.L.=8.3 APD =30.5	S.L.=10.9 APD =27.7
Blading Shoulders	S.L.=5.7 APD =12.4	S.L.=7.2 APD =13.2	S.L.=7.8 APD =14.4
Clipping Shoulders	S.L.=39.3 APD =2.8	S.L.=43.1 APD =3.2	S.L.=47.5 APD =3.7
Recondition Shoulders	S.L.=46.0 APD =4.5	S.L.=46.0 APD =4.5	S.L.=46.0 APD =4.5
Clean and Reshape Ditches	S.L.=42.7 APD =1082	S.L.=45.3 APD =1255	S.L.=48.0 APD =1436
Motor Patrol Ditching	S.L.=36.0 APD =1.7	S.L.=38.3 APD =2.0	S.L.=42.8 APD =2.5

S.L. = Service Life (Months)

APD = Accomplishments Per Day (Units in Table 1)

reflect the effect of the source of distress. Second, if the patch mix is placed more carefully and thoroughly, daily accomplishment will go down, but such care and thoroughness will be reflected in an increased effective service life. These two factors combined explain the difference in APD between minimum, average, and maximum for any given roadway condition.

Hot-Mix Patch

Hot-mix patching consistently has the highest estimate of effective service life. There are a number of reasons for this. First, the material is usually of superior quality and therefore is easier to place and compact than are the other three types of patching material. Also, hot mix is generally available only between April and October because plant production is limited to these months. Consequently, the climatic and road-base conditions are usually favorable for placement of the patch, which naturally leads to greater longevity.

It was generally considered that a hot-mix patch placed on a good road should last for the life of the road. Road life, represented by the resurfacing cycle, was taken to be 60 months for the purposes of calculation.

Cold-Mix Patch

Cold-mix patching material was considered by all personnel surveyed to be the poorest performer of the four types of patch material. The results given in Table 2 indicates that most service life estimates were given in days rather than months. The primary reason for this low service life is that the conditions under which the cold mix is placed make it difficult for the patch to hold. Cold mix is generally used in winter when no hot mix is available and consequently is placed in poor weather conditions that may cause the road base to be wet.

The combination of water and traffic loads can lead to early patch failure and, if snow ploughs are being used, the patches can be removed overnight. In addition, cold patch material as used is not adequate; it is prone to shoving.

Winter-Mix Patch

Winter-mix patching material is essentially a cold mix with fibers added to produce greater stability and resistance to shoving and is used under the same conditions as cold mix. Almost all personnel interviewed believed that the winter patch material was significantly better than cold mix in its ability to stay in position, and this opinion is reflected in the service life estimates obtained.

Winter-Mix Patch Using Portapatcher

A Portapatcher provides the facility to heat patching material. Heating patching material improves its workability for placement and compaction. Patches made with material heated in a Portapatcher were estimated to have a longer service life than patches made with cold mix. Personnel in two of the four northern subdistricts of IDOH expressed the opinion that the performance of winter mix heated in a Portapatcher was as good as that of patches made with hot mix.

In locations where flexibility and elasticity are important (e.g., on bridge decks) the heated fiber-mix patch appeared to perform better than a hot-mix patch. One drawback to using the Portapatcher is that a larger crew size is required.

Premix Leveling

Premix leveling or wedging involves placement of bituminous mixtures to correct depressions and rutting. Personnel in several subdistricts indicated that this activity is now primarily carried out by contract rather than by IDOH personnel. However, most subdistricts had sufficient experience to estimate service life and daily accomplishments.

The estimates follow an expected pattern for reasons similar to those mentioned in the discussion on patching. The primary reason given for early failure of wedging was that the roadway surface was not being tacked properly before application of the bituminous mixture.

In the case of premix leveling, a distinction was frequently made between service life when the material was placed using a grader and when it was placed using a paving machine. The prevailing opinion was that the paver produces a more uniform, better riding, and longer lasting surface.

Full-Width Shoulder Seal

Shoulder sealing involves seal coating of an existing paved shoulder. When the condition of the paved shoulder is poor, the general consensus of opinion was that a shoulder seal was not an appropriate treatment because no additional structural support is provided. The appropriate treatment of a paved shoulder in poor condition was deemed to be rebuilding.

Survey results indicate that service life and APD vary directly in shoulder sealing. The explanation for this relation is that the unit of accomplishment is foot miles. Thus a shoulder at the lower end of the fair range will require more work (and hence fewer miles covered) and yet will break up faster than a shoulder at the upper end of the range. Consequently, as in previous relations, the source of the deficiency establishes the relationship between accomplishment and service life. The major factor that influences the APD obtained is the width of the shoulder to be sealed because the unit of accomplishment is foot miles. Obviously a much higher APD will be obtainable on a 10-ft shoulder than on a 3-ft one.

Seal Coating

There are two subdivisions under the general heading of seal coating. These are chip seal treatments and sand seal treatments. As the names imply, they differ primarily in the aggregate coating used in the seal coating operation

Chip Seal

Chip sealing consists of coating full-width roadway sections with hot bituminous material and covering with No. 11 or No. 12 stone. One factor that can influence the service life obtained is the type of stone used in the surfacing operation; limestone chips were believed to be preferable to pea gravel.

The service life and APD pattern of seal coating is similar to that seen in the discussion of full-width shoulder seal. The major factor governing the APD was the haulage distance for bituminous material and aggregate rather than the roadway surface itself.

Sand Seal

The cover aggregate in sand seal is, as implied, sand rather than stone. Personnel in only five subdistricts believed they had sufficient experience to estimate sand seal values, although a number of the other subdistricts have begun to use this technique in the last two to three years. In general, it was thought that the sand seal was not effective on roadways in poor condition. On such surfaces, the sand seal does not prevent further deterioration or correct cracking for any appreciable length of time. The consensus of opinion was that on roads in fair or good condition, a sand seal is effective in sealing cracks and will contribute substantially to the longevity of road life. Personnel in one subdistrict reported that the sand seal was effective when placed over a "fatted" surface (i.e., a pavement surface with flushed asphalt) whereas the chip seal was better suited to dried-out pavements. The same trends in service life and APD observed in the shoulder seal activity are again evident here; there is a direct relationship between daily accomplishment and service life.

Sealing Longitudinal Cracks and Joints

Sealing longitudinal cracks and joints is accomplished by cleaning the cracks and joints and then filling them with liquid bituminous sealant. The usual method of crack and joint cleaning is to use a stream of compressed air to blow out the accumulated debris. An alternative method of cleaning the cracks and joints is to use a crack router attached to a tractor, but this operation is not considered here.

An examination of Tables 2–4 shows that there is not a large difference between maximum and minimum service life estimates of crack and joint sealing for any given roadway condition. However, the APD estimates for sealing do vary substantially as the condition of the roadway changes. This is to be expected because the accomplishment unit is linear miles and less sealing is required on a road in good condition than on a road in poor condition.

Sealing Cracks

The purpose of this activity is to clean and seal cracks in both bituminous and concrete roadways. Unlike the values for sealing longitudinal cracks and joints, the values obtained for sealing cracks show a marked difference between maximum and minimum service life for each roadway condition.

A definite relation exists between APD and roadway condition. This is to be expected because a workman will cover fewer lane miles as the amount of cracking increases.

Spot Repair of Unpaved Shoulders

Spot repair involves the repair of small areas of unpaved shoulders by adding aggregate and reshaping. Little significant difference exists overall in service life estimates given by personnel of the various subdistricts except for the minimum values of service life in the southern region of the state. A reason for this lower value may be the hilly topography of southern Indiana.

A strong influence on the service life of unpaved shoulder spot repair was believed to be rainfall in combination with high gradients. These factors, reinforced by traffic encroachment onto the shoulder at curves, provided the lowest estimate of service life. Service life and APD vary inversely for this activity because the accomplishment unit is tons of aggregate and the worst locations require more aggregate.

Blading Shoulders

Blading shoulders involves redistributing material and reshaping unpaved shoulders. Because the daily accomplishment unit is in shoulder miles, there is a direct relationship between service life and APD: the poorest locations yield the lowest service life and the lowest APD. The preferred equipment for this activity was a dump truck with scraper or underblade attached.

Clipping Shoulders

In shoulder clipping excess growth is removed from unpaved shoulders to restore adequate shoulder drainage. For a given shoulder condition, personnel in the southern subdistricts gave estimates of service life that were significantly under the overall average, and personnel in the northern subdistricts gave estimates of service life that were significantly above the overall average. The milder climate in southern Indiana, which encourages vegetable growth, may explain the difference.

A number of subdistricts distinguished between the APD using a front-end loader and what was variously described as a dirt loader, belt loader, or travel loader. The latter type of loader significantly increased the APD. Factors that influence the APD include the amount of sand to be cut and loaded and the haulage distance to a disposal site.

Reconditioning Unpaved Shoulders

Unpaved shoulder reconditioning involves adding aggregate and reshaping continuous sections of unpaved shoulder as opposed to spot repair, which is carried out at isolated locations. Personnel in none of the four southern subdistricts sampled had sufficient experience to estimate service life or APD for this activity. However, a comparison of service life and APD indicates that values for the central region were substantially lower than for the nothern region. A possible explanation of this difference is that the northern subdistricts tend to seal or oil the rebuilt shoulder in the same year that it is rebuilt, which should lead to a longer service life.

An examination of the results shows that in general there was little variation in the service life or the APD for a given shoulder condition. The main variable that influences accomplishment was generally thought to be the aggregate haulage distance.

Cleaning and Reshaping Ditches

Cleaning and reshaping ditches involves the excavation of dirt and debris from roadside ditches using a gradall that restores adequate drainage. Geography plays a major role in the estimates of both service life and APD. Personnel in the central and northern subdistricts did not vary excessively in their estimates; estimates of both service life and APD were much lower in the southern subdistricts, and within the southern region the subdistricts farthest south were significantly lower in their estimation.

These results indicate that topography and soil conditions play an important role in the rapidity and extent of ditch blockage; in areas with steep hills, heavy rainfall, and poor soil conditions, the effective service life is low. For the same reason, the APD, measured in lineal feet of ditch, is also low in such areas. Another factor that influences the APD obtained is the distance that material must be hauled from the ditch for disposal. An interesting point that was often repeated in discussion with maintenance personnel was that daily production can be very misleading. In a ditch that is badly clogged with debris, it may be necessary to make two or three passes with the excavator to restore an adequate cross section. However, this extra work does not show up in the daily record. This is the basic reason why an examination of Tables 4 and 5 shows such a large variation in APD with ditch condition.

Motor Patrol Ditching

Motor patrol ditching, as the name implies, involves cleaning of ditches using a motor patrol rather than a gradall. There was much discussion of the advantages and disadvantages of the two methods. In one southern subdistrict, motor patrol ditching is not carried out at all because of the difficulty of operating such equipment on hilly terrain with heavily blocked ditches. Other limitations on using motor patrols for cleaning ditches include difficulty of operation in wet weather and in areas of clayey soils with steep ditches. Conditions favorable to motor patrol ditching include operation in dry weather and in areas with sandy soil and on flat, wide ditches. The consensus of opinion was that the gradall produces a better, more rounded, and longer lasting ditch cross section than does the motor patrol. A comparison of the values of APD shows that motor patrol ditching, measured in ditch miles, has a higher production rate than does gradall ditching, which is measured in feet. The principal explanation of this is that motor patrol ditching is limited to wide areas where few obstructions are present. The main factor that governs the APD attained is the distance the debris must be hauled from the ditch to a designated dump site.

CONCLUSIONS

The overall goal of this research is to further evolve a functioning system for routine maintenance management in Indiana. Results reported in this paper provide a first, meaningful estimate of service life for a major portion of the routine maintenance activities engaged in by the IDOH. Records and prior research were used to determine both APD and costs for the various activities, and these values were tabulated. Now that service life, APD, and cost are known, basic information is available for establishing the framework of a maintenance management system that will address optimal allocation of maintenance resources. Specifically, the data reported here will give initial estimates for parameters that are necessary to make a management system possible. Further research is being conducted that will, over a period of time, provide more definitive functional relations for maintenance activity service life. In the meantime, the information generated in the survey can furnish a reasonable set of input data for use in the optimization of maintenance decisions.

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Abridgment

Analysis of Fuel Consumption in Routine Maintenance of State Highways in Indiana

MITSURU SAITO, KUMARES C. SINHA, AND ESSAM A. SHARAF

In this paper is presented an analysis of trends in fuel consumption in highway routine maintenance based on data from the Indiana Department of Highways for FY 1982, 1983, and 1984. The purpose of the analysis was to identify routine maintenance activities and associated types of equipment with which a high volume of fuel consumption is associated so that energy conservation efforts could be directed to these elements. It was found that pavement- and drainage-related activities and hauling equipment were the major elements that should be considered first. A set of possible conservation strategies involving these elements is also presented.

Routine maintenance of highways is highly fuel-intensive work. Approximately 4.0 million to 5.5 million gallons of fuel are required each year for routine maintenance of state highways in Indiana. In the first phase of a study to identify potential cost and energy savings in routine maintenance of state highways in Indiana (*1*), a detailed field investigation was conducted to estimate fuel consumption rates by type of activity and by activity-equipment combination. It was found that a single type of equipment had different fuel consumption rates for different maintenance activities. Also, some types of equipment were more frequently used than others. Several maintenance activities dominate the use of fuel. The same was true for maintenance equipment. Although there were various types of equipment used in performing different maintenance activities, it was found that only a few types of equipment use the majority of fuel consumed for maintenance. In planning for energy conservation in maintenance, it is necessary to concentrate on those activities and types of equipment that consume most of the fuel. The objectives of this part of the study were to determine if there existed definite trends in the consumption of fuel by type of activity and by type of equipment, to identify the elements of routine maintenance that should be the prime targets for fuel conservation efforts, and to develop energy conservation guidelines and strategies.

DATA BASE

The unit equipment usage factors and fuel consumption rates developed in the first phase of the study (*1*) were used as input to the present analysis. Also used were annual maintenance accomplishment records (*2*) kept by the Indiana Department of Highways (IDOH). The IDOH develops maintenance accomplishment plans based on actual accomplishments of the past 3 consecutive years. The data from 3 consecutive fiscal years, 1982, 1983, and 1984, were used in this trend analysis.

DATA ANALYSIS

Three fuel use–related variables were computed for each activity: equipment usage factor (F_{ij}), fuel consumption rate by type of equipment (R_{ij}), and fuel consumption by type of activity (T_i). Subscript i denotes the ith type of activity and subscript j denotes the jth type of equipment. Fuel consumption by an activity is therefore

$$T_i = \sum_j R_{ij} * F_{ij}.$$

Using these three variables, three types of fuel share values were computed. These fuel share values are (*a*) fuel share by type of equipment within an individual activity (S_{ij}), (*b*) fuel share by type of activity in total fuel consumption (A_i), and (*c*) fuel share by type of equipment in total fuel consumption (E_j).

$$S_{ij} = F_{ij} * (R_{ij}/T_i) * 100 \quad (1)$$

$$A_i = 100 * P_i * T_i \Big/ \sum_{i=1}^{n} P_i * T_i \quad (2)$$

$$E_j = \sum_{i=1}^{n} S_{ij} * A_i/100 \quad (3)$$

where

S_{ij} = share of equipment type j in the total fuel consumption of activity i (percent),
A_i = share of activity type i in total fuel consumption for all activities (percent),
E_j = share of equipment type j in the total fuel consumption for all activities (percent),
F_{ij} = usage factor of equipment type j when used in activity i,
R_{ij} = consumption rate (gallons per production unit) of equipment type j when used in activity i,
T_i = consumption rate (gallons per production unit) of activity i,
P_i = total units of production of activity i, and
n = total number of activity types.

M. Saito and K. C. Sinha, School of Civil Engineering, Purdue University, West Lafayette, Ind. 47907. E. A. Sharaf, Department of Civil Engineering, Cairo University, Cairo, Egypt.

RESULTS OF TREND ANALYSIS

Despite the differences in the amounts of accomplishment of individual activities each year, a similar fuel consumption trend was found among equipment during fiscal years 1982, 1983, and 1984. Approximately 4.0 million to 5.5 million gallons of fuel were consumed annually by maintenance equipment units used for field activities only. This value does not account for the fuel used by field maintenance supervision. Currently, maintenance supervision is not recorded on daily report cards called crew-day cards. About 3.5 million gallons of the total annual fuel consumption are used for regular maintenance activities, and the rest is spent for snow and ice removal. A reduction of a mere 1 percent of the fuel used for regular activities, therefore, would save about 35,000 gal of fuel each year. The results presented in this section refer to fuel consumption in regular activities and do not include snow and ice removal.

Fuel Consumption by Maintenance Activity

The trends in fuel consumption by activity group and by activity type were analyzed to find what specific activities or groups must be targeted to achieve the highest return on energy conservation efforts. The three activity groups used for maintenance management purposes in Indiana are (*a*) highway class (Interstates and other state highways), (*b*) maintenance work category, and (*c*) major activity area.

Highway Class

The split of fuel consumption between the two highway classes remained stable during the 3 years studied. On average, Interstate highways required 340 to 350 gal/mi/year of fuel for maintenance, and other state highways required 250 to 260 gal/mi/year. Approximately 15 percent of the estimated total fuel consumed was for maintenance activities on Interstate highways, and the remaining 85 percent was used on other state highways. Efforts for energy conservation, therefore, should focus particularly on maintenance work on other state highways.

Work Category

Routine maintenance work consists of four categories (*3*): (*a*) limited, (*b*) unlimited, (*c*) overhead, and (*d*) variable. These categories represent the importance and ranking of routine maintenance activities. Limited activities include activities for which quantites can be established. Unlimited activities include activities that are to be performed when needed and in the amount required to correct the deficiency. Overhead activities include work items such as rest area attendant, standby time, and maintenance field supervision. Variable activities include activities for which a given amount of work is not urgently needed each year. The planned work for variable activities is desirable, but it is not critical if all of the planned work is not completed during any one year.

Of the 63 activities considered in the study, 14 are in the limited category, 22 are in the unlimited category, 14 are in the variable category, and the remaining 13 are in the overhead category. Approximately two-thirds of estimated total annual fuel consumption is attributable to activities in the limited and unlimited categories. Because the amount of work done in these two categories greatly affects fuel consumption, an improvement in the procedures used to assess the needs of specific maintenance activities within these categories is desirable if energy conservation programs are directed to these activities. Activities in the overhead category mostly fall into public service and "other" maintenance areas. These activities are not directly related to the performance of the highway. Activities in the variable category are minor maintenance work that is left out of the limited or unlimited categories. Therefore fuel consumption by this category can be reduced if the activities in the limited and unlimited categories are better managed.

Major Activity Area

Types of maintenance activities were grouped into the eight major maintenance areas given in Table 1. A substantial portion of total maintenance cost can be attributed to the roadway and shoulder area (Area 1), followed by the others area (Area 8) as shown in Figure 1*a*. Total cost was broken down into fuel, material, and labor costs. All costs were computed using 1982 unit cost data. Areas 1, 3, and 8 consumed most of the fuel used in maintenance work (Figure 1*b*). Indeed, Area 8 uses more fuel than is shown here because the fuel used for field maintenance supervision is not currently recorded on crew-day cards.

TABLE 1 ROUTINE MAINTENANCE AREAS INCLUDED IN THE STUDY

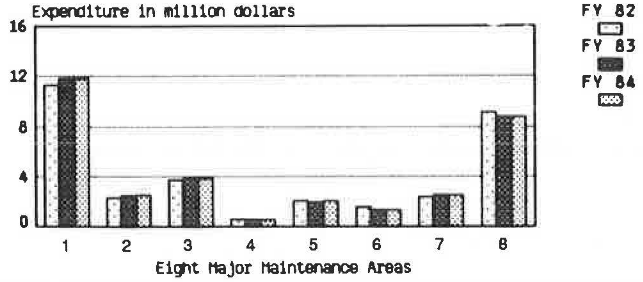
Area No.	Activity Area
1	Road and shoulder
2	Roadside
3	Drainage
4	Bridges
5	Traffic control
6	Winter and emergency
7	Public service[a]
8	Others[b]

[a] Includes activities such as rest area maintenance and litter pickup.

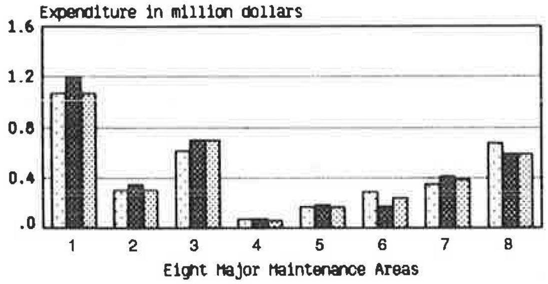
[b] Includes activities such as material handling and storage and other support activities.

The roadway and shoulder area accounts for most of the materials cost (Figure 1*c*). Although this paper deals only with direct energy use, petroleum products are a substantial part of the materials used in highway routine maintenance. Therefore improvement in the quality of materials and maintenance work should provide opportunities to reduce overall energy use including indirect energy. Good management of the first three areas—roadway and shoulder, roadside, and drainage—can contribute greatly to energy conservation.

(a) Total Costs



(b) Fuel Cost



(c) material Cost

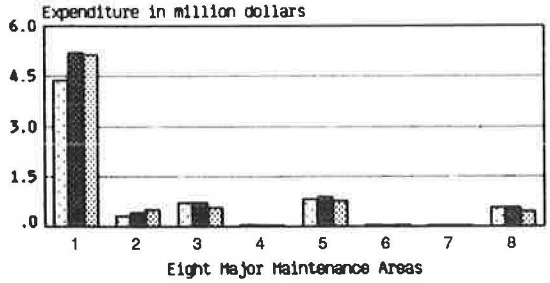


FIGURE 1 Maintenance cost splits among eight major activity groups.

Fuel Consumption by Activity

Fuel consumption by activity tends to be concentrated in a few activities each year. Most of the activities considered in the study used less than 2 percent of the total fuel consumed. Activities that used more than 3 percent of the total fuel consumed were identified as dominant activities, and they are given in Table 2. These activities, excluding snow and ice removal and supervision, account for approximately 65 percent of total fuel consumed.

As the data in Table 2 indicate, the major fuel-consuming activities are included in a small number of maintenance areas. Roadway and shoulder maintenance area (Area 1) and cleaning and reshaping of ditches (Area 3) alone accounted for approximately 39 percent of the total fuel consumed in FY 1984. Similar trends were found in fiscal years 1982 and 1983. Energy-saving efforts therefore should be first directed to these areas. According to an optimization procedure developed in this study (see paper by Sinha et al. in this Record), it was found that the rest area work would contribute most substantially to fuel savings if assignment of equipment to this task were properly done.

Fuel Consumption by Equipment Type

A variety of types of equipment is used for routine maintenance activities. First, the demand level for a particular type of equipment by various activities was identified. Then, dominant equipment types were singled out and their fuel consumption was examined.

A majority of the types of equipment are used for fewer than 10 different types of activity. Some types of equipment, such as water truck or catch basin cleaner, can be used only in specific activities and their low shares of fuel consumption reflect their limited use. Only five types of equipment were used by more than 20 activities: pickup truck, pickup crew cab, dump truck, do-all truck, and loader. Equipment used mostly for hauling consumed most of the fuel used in maintenance in each of the 3 years considered in the study.

Table 3 gives the dominant types of equipment that use more than 1 percent of the total fuel consumed annually. Altogether

TABLE 2 MAJOR FUEL-CONSUMING ACTIVITIES (FY 1984 state-level total)

Maintenance Area	Activity Code	Description	Fuel Consumed (1,000 gal)	Share (%)
1	201	Shallow patching	233.1	7.00
	205	Seal coating	119.3	3.58
	207	Sealing cracks	170.4	5.11
	210	Spot repair of unpaved shoulders	102.2	3.07
	212	Clipping unpaved shoulders	117.9	3.54
2	221	Machine mowing	126.9	3.81
3	231	Clean and reshape ditches	451.7	13.56
	235	Cleaning minor drainage structures	90.2	2.71
5	251	Subdistrict sign maintenance	103.9	3.12
7	271	Rest area and lift bridge attendant	161.8	4.86
8	283	Buildings and grounds maintenance	200.3	6.01
	284	Materials handling and storage	134.0	4.02
	289	Other support activities	160.7	4.82
Total			2,172.4	65.21

Note: Activity 263, snow and ice removal, was excluded from the share computation.

TABLE 3 MAJOR TYPES OF FUEL-CONSUMING EQUIPMENT (FY 1984 state-level total)

Equipment Code	Equipment Type	Fuel Consumed (1,000 gallons)	Share in Percent	Demand Level
1	Pickup truck	326.5	9.8%	A
2	Pickup crewcab	370.4	11.1%	A
4	Flatbed truck	33.8	1.0%	E
7	Distributer	80.7	2.4%	E
8	Utility truck	127.7	3.8%	E
9	Dump truck	1,480.8	44.4%	A
10	Do-all truck	164.9	5.0%	D
24	Excavator	139.7	4.2%	F
25	Grader	68.8	2.1%	E
26	Loader	135.1	4.1%	D
42	Tractor truck	145.5	4.4%	E
44	Compressor	35.0	1.1%	E
64	Gradall	47.9	1.4%	F
	Total	3,156.8	94.9%	

* Demand level:
A = Used by equal to or more than 50 activity types
B = Used by equal to or more than 40 but less than 50 activity types
C = Used by equal to or more than 30 but less than 40 activity types
D = Used by equal to or more than 20 but less than 30 activity types
E = Used by equal to or more than 10 but less than 20 activity types
F = Used by less than 10 activity types

Note: Activity 263, snow and ice removal, was excluded from share computation.

they accounted for about 95 percent of the total fuel consumed. Dump trucks alone accounted for approximately 45 percent of the total fuel used every year for all routine maintenance activities. Their fuel use shares remained stable during the 3 years despite the variation in annual accomplishment of activities. Therefore, if better management of the equipment fleet is considered as a means of conserving energy, these 13 types are the ones that should be included first. Some equipment, such as dump trucks and pickup trucks, can be interchanged for some activities.

ENERGY CONSERVATION STRATEGIES

The analysis indicated that there exist definite trends in fuel consumption by type of activity and equipment. The findings of the trend analysis made it possible to identify a set of strategies for conserving fuel and reducing the cost of routine highway maintenance.

Fuel Savings by Managing Activities

About one-third of the routine maintenance activities considered in the study consumed most of the fuel. The following two broad approaches can be considered for these major fuel-consuming activities.

The first approach is to improve the current procedure for assessing routine maintenance needs of major fuel-consuming activities so that actual accomplishments can be close to planned accomplishments and the fuel consumption of a particular year can be reasonably estimated. If a substantial amount of fuel reduction becomes necessary for that year, low-priority works, such as those in the variable category, can be postponed to the following year, provided that the limited and unlimited activities are well controlled.

The second approach is to evaluate the effectiveness of maintenance activities. This approach is particularly applicable to those activities that have a cause-and-effect relation. A good example of this approach is discussed in the paper by Sharaf and Sinha in this Record. They report that after pavement maintenance costs were analyzed, it was found that highway segments that received more crack sealing in the fall require smaller amounts of shallow patching the following spring. Crack sealing is a preventive maintenance activity, whereas shallow patching is remedial work. It was estimated that Indiana could save nearly 10,000 gal of fuel every year simply by completing crack sealing as scheduled. One-third of the 37 subdistricts in Indiana fall sort of their planned production units of crack sealing by more than 10 percent every year.

Fuel Savings by Managing Equipment Use

Of the 79 types of equipment used in routine maintenance, only 13 consumed more than 1 percent of the total fuel. Altogether they used about 95 percent of the total fuel. Four kinds of hauling equipment (pickup truck, pickup crew cab, dump truck, and do-all truck) consumed most of it (about 70 percent). For some activities, these types of equipment are interchangeable. Other types of equipment, such as grader, excavator, and tractor truck, are intended for specific tasks and usually cannot be interchanged.

Because different equipment types can be used interchangeably to perform some of the same tasks, careful equipment assignment can save a considerable amount of fuel because of the wide variation in fuel usage rates of different types of equipment. A mathematical optimization model has been developed in the study for the purpose of determining the optimal mix of types of equipment for performing various activities (see paper by Sinha et al. in this Record). Furthermore, an effort is needed to control the amount of time equipment idles. Reduction of hauling distance of excavated materials can also contribute to reduction of fuel consumption.

Dieselization of Equipment

Maintenance equipment is either gasoline or diesel powered. Diesel is now widely viewed as the desirable power source for many types of maintenance equipment. Dieselization of maintenance equipment units has just recently been started at IDOH and diesel fuel consumed is still a small portion of the total fuel consumed. The percentage of diesel fuel consumed was well below 10 percent of total fuel consumption in the past 3 years. Dieselization of dominant fuel-consuming equipment, such as dump trucks and tractor trucks, would eventually contribute to overall energy savings.

CONCLUSIONS

The trend analysis conducted in this study formed a basis for identifying components of routine highway maintenance to which energy conservation efforts should be directed. Thirteen dominant activities, which were mostly in the road and shoulder, roadside, and drainage maintenance groups, were identified.

The analysis also identified critical types of equipment. Thirteen of the 79 types of equipment included in the study were found to be critical with respect to energy conservation. These types account for about 95 percent of total fuel consumed. Furthermore, the four major fuel-consuming types of equipment—pickup truck, pickup crew cab, dump truck, and do-all truck—use about 70 percent of total fuel consumed every year.

By carefully managing the dominant activities and critical types of equipment, highway agencies should be able to better control fuel consumption in routine highway maintenance. To implement such a program, however, it is desirable that equipment use and fuel consumption data be regularly recorded and monitored.

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Energy Savings from Increased Preventive Maintenance on Indiana Highways

ESSAM A. SHARAF AND KUMARES C. SINHA

In this paper are described the development of trade-off relationships between routine pavement maintenance activities and the application of these relationships in estimating the savings in fuel used in pavement maintenance in Indiana. Two major routine pavement maintenance activities were considered: patching (corrective maintenance) and sealing (preventive maintenance). The results showed that when more sealing was done before winter less patching was required after winter. Different highway classes, pavement types, and geographic locations are taken into consideration. The application example assesses possible cost savings in terms of savings in direct fuel consumption by the maintenance equipment fleet.

The trade-off concept is a central issue in highway system analysis including pavement management systems (PMSs), maintenance management systems (MMSs), and other related areas (*1*). A trade-off relation is a way of determining how much of one alternative has to be sacrificed in order to gain something of another alternative.

In highway programming, trade-off relations can be used to split the available funds among different options at several levels. At the first level, trade-offs may be used to determine the split of total available funds between state roads and other local roads. At the second level, trade-off relations can determine portions of available funds to be allocated to specific highway classes (e.g., Interstates and other state highways). At the third level, trade-offs may be used to distribute available funds between major maintenance activities (federally funded activities) and routine maintenance activities (state-funded activities). Finally, at the fourth level, trade-offs may be used to split available funds among specific maintenance actions. Resurfacing, rehabilitation, and reconstruction are examples of major maintenance actions; and crack sealing, pothole patching, and so on are examples of routine maintenance activities. The last of the four levels is the most significant for a PMS as well as for an MMS because this level deals with the allocation of funds to specific maintenance activities.

The trade-off relations between two routine pavement maintenance activities in Indiana, namely, patching (corrective maintenance) and sealing (preventive maintenance), are discussed in this paper. Total routine pavement maintenance needs are first identified through a set of prediction models; then trade-off relations are developed to indicate the split of total need between patching and sealing activities. Finally, an example is presented to show the use of the trade-off models in assessing possible cost savings in direct fuel consumption.

DATA BASE

The state highway system of Indiana is divided into two categories: Interstate and other state highways (OSHs). In this study, the two highway systems were further subdivided by geographic location (climatic zones) and pavement type. Two geographic locations, north and south, were included to reflect the major climatic differences in Indiana. The pavement types considered were flexible pavement, rigid pavement, and resurfaced pavement. The units used for data collection and analysis were 820 sections (a section is defined as the portion of a highway within county limits).

For each of the 820 sections, four major groups of information were summarized: traffic, pavement characteristics, climatic zone, and pavement maintenance records. Traffic information included average annual daily traffic (AADT), percentage of trucks, and equivalent axle load (EAL). Pavement characteristics included pavement type, layer thickness, and age. Climatic zones included geographic areas with climates that are similar in terms of snowfall, rainfall, temperature difference, and so on. Finally, pavement maintenance records included total production units, total man-hours, and types and quantities of materials. Pavement maintenance information was summarized for each highway section by activity and by fiscal year. The details of the development of this data base are given elsewhere (*2*, *3*). An important feature of the study was that it used only those data that are routinely collected by the Indiana Department of Highways (IDOH).

DESCRIPTION OF MODEL

In Indiana rigid pavement is the major type of pavement on the Interstate system (about 70 percent of total Interstate lane-miles), and flexible pavement and resurfaced pavement are the major pavement types on the OSH system (about 90 percent of total OSH lane-miles). The three categories constitute about 85 percent of the total lane-miles of state highway system in Indiana. Consequently, there are enough homogeneous sections of pavement type and characteristics to give 26 sections of Interstate rigid, 213 sections of OSH flexible, and 84 sections of OSH resurfaced. There were only a limited number of homogeneous sections in other pavement categories (five sections for Interstate flexible, eight sections for Interstate resurfaced, and five sections for OSH rigid), and most of these sections were located in the southern part of the state. These limitations were considered in the statistical analysis (*4–6*).

The general form of the total routine pavement maintenance cost prediction model is given in Equation 1. The model parameters are given in Table 1.

E. A. Sharaf, Department of Civil Engineering, Cairo University, Cairo, Egypt. K. C. Sinha, School of Civil Engineering, Purdue University, West Lafayette, Ind. 47907.

$$\text{Log}_{10}(\text{TC}) = m * \text{Log}_{10}(\Sigma\ \text{EAL}) + n * \text{Log}_{10}(\Sigma\ \text{EAL}) * (Z) \quad (1)$$

where

TC = total pavement maintenance cost in dollars per lane-mile per year;
Σ EAL = accumulated equivalent axle load applications during the entire age of the pavement section (in thousands); and
Z = dummy variable representing the location of the section (north or south).

The term Σ EAL * Z was introduced to measure the effect of the interaction between traffic level and climatic zone.

TABLE 1 PARAMETERS FOR THE ROUTINE PAVEMENT MAINTENANCE COST ESTIMATION MODELS OF EQUATION 1

	Pavement Category					
	Interstate			OSH		
Parameter	Flexible	Rigid	Resurfaced	Flexible	Rigid	Resurfaced
m	0.610	0.530	0.590	0.974	0.681	0.850
n	0.000	0.032	0.000	0.240	0.000	0.040
R^2	0.870	0.890	0.810	0.850	0.870	0.800

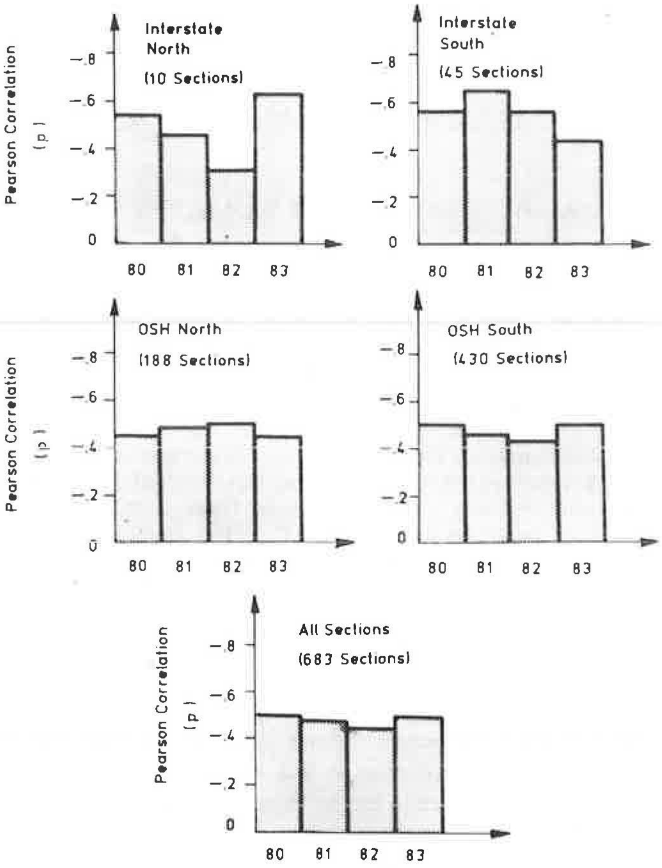

FIGURE 1 Correlation analysis of sealing and patching activities based on percentage of cost allocated to each.

TRADE-OFF RELATIONS BETWEEN PATCHING AND SEALING ACTIVITIES

Cost models were developed for individual maintenance activity groups, namely patching and sealing. The patching group included shallow patching and deep patching. The sealing group included sealing longitudinal cracks and joints and sealing cracks. Patching and sealing activities account for about 85 percent of the total pavement maintenance cost in Indiana (*3*), and there is a high correlation between patching and sealing performed in the same fiscal year. The results of a detailed correlation analysis performed on the portions of total cost allocated to patching versus those allocated to sealing for different highway categories and fiscal years resulted in a correlation value as high as −0.65, as shown in Figure 1. The scheduling of different maintenance activities in a fiscal year (July-June) adds a particular characteristic to the correlation between patching and sealing. This is because sealing activities usually precede patching activities in a fiscal year. Sealing activities take place in the late summer and fall, and patching usually takes place in the spring. Although there may be some variation in the scheduling of these activities, most sealing and patching jobs are done during the periods mentioned.

The high correlation between patching and sealing in a fiscal year is a one-way correlation that indicates that the amount of patching done in a year is generally dependent on the extent of sealing performed before the winter. However, the sealing activity does not depend on the patching activity.

The general regression models for patching and sealing follow the form presented in Equations 2 and 3.

$$\text{PS} = a * \text{Log}_{10}(\Sigma\ \text{EAL}) + b * \text{Log}_{10}(\Sigma\ \text{EAL}) * Z \quad (2)$$

$$\text{PP} = c * \text{Log}_{10}(\Sigma\ \text{EAL}) + d * \text{Log}_{10}(\Sigma\ \text{EAL}) * Z + e * \text{PS} \quad (3)$$

where PS is the percentage of total pavement maintenance cost allocated to the sealing group and PP is the percentage of total pavement maintenance cost allocated to the patching group.

The model parameters for the six pavement categories are given in Table 2. The models indicate that, although an increased traffic level requires an increased level of pavement maintenance (patching and sealing), the rate of increase in the share of patching cost as traffic level increases is higher than that in the share of sealing cost. Furthermore, it can be concluded that patching level (amount of patching activity taking place after winter) is negatively affected by the level of sealing (amount of sealing activity taking place before winter). That is, if more cracks are sealed before winter, less patching is required after winter, primarily because of fewer potholes.

TABLE 2 PARAMETERS FOR ESTIMATING PERCENTAGE OF TOTAL COST FOR PATCHING AND SEALING ACTIVITIES (Equations 2 and 3)

		Pavement Category					
		Interstate			OSH		
Activity	Parameter	Flexible	Rigid	Resurfaced	Flexible	Rigid	Resurfaced
Sealing	a	0.185	0.098	0.115	0.220	0.108	0.196
	b	0.000	–0.015	0.000	–0.074	0.000	–0.062
	R^2	0.870	0.810	0.91	0.780	0.820	0.810
Patching	c	0.182	0.206	0.186	0.346	0.150	0.228
	d	0.000	–0.023	0.000	0.025	0.000	0.011
	e	–0.670	–0.998	–0.621	–0.786	–0.135	–0.550
	R^2	0.830	0.950	0.850	0.890	0.920	0.840

EXAMPLE OF USE OF TRADE-OFF MODELS

One of the applications of the trade-off models involves an assessment of cost savings in routine pavement maintenance in terms of direct fuel consumption. In the example given here, the energy cost savings associated with the trade-off between preventive maintenance (sealing) and corrective maintenance (patching) are considered.

Equation 3 established that the extent of patching under a given traffic level is a function of the extent of sealing performed in the same fiscal year. The implication is that a higher level of prewinter preventive maintenance (sealing) can reduce the extent of postwinter corrective or repair maintenance (patching). It was also found that direct fuel consumption (gallons per dollar spent) for sealing group activities is less than for patching group activities (*7*, *8*). Consequently, an increased level of sealing activity would not only reduce the need for subsequent patching activities and thus improve overall pavement serviceability, it would also cause savings in direct fuel consumption for routine pavement maintenance.

In this example five scenarios were considered: increasing sealing level by 5, 10, 15, 20, and 25 percent. For each of these scenarios total fuel consumption (gallons per lane-mile per year) was calculated and then compared with the current level of energy consumption in order to estimate the amount of energy saved. With an increase in sealing activity, fuel consumption for sealing would increase. However, the increase in sealing activity would reduce the level of patching, and the corresponding decrease in fuel consumption would more than offset the increase in fuel consumption for the increased level of sealing. The result would be a net savings in fuel consumed by the maintenance equipment fleet. In the following paragraphs a detailed explanation of the procedure for estimating energy savings at different traffic levels is presented.

First, fuel consumption rates in terms of gallons per dollar spent for both patching and sealing groups were developed to avoid the difference in production units of the two groups. A summary of the resulting rates is given in Table 3. It can be seen that energy consumption levels of the patching group are consistently higher than those of the sealing group.

Energy savings were then calculated for all highway categories under different traffic levels. For example, the case of Interstate rigid pavement in the southern zone can be considered. Assuming a traffic level (accumulated EAL) of 20 million, the computations are

TABLE 3 ENERGY CONSUMPTION RATES FOR SEALING AND PATCHING GROUPS

	Energy Consumption Rates (gallons/dollar)			
	South		North	
Highway Category	Patching	Sealing	Patching	Sealing
Interstate, flexible	0.091	0.070	NA	NA
Interstate, rigid	0.094	0.065	0.091	0.063
Interstate, resurfaced	0.096	0.066	NA	NA
OSH, flexible	0.088	0.056	0.096	0.059
OSH, rigid	0.092	0.065	NA	NA
OSH, resurfaced	0.088	0.065	0.089	0.066

Note: NA = not applicable.

1. From Equation 1 with appropriate parameters for Interstate rigid pavement, total pavement maintenance cost = \$190.35 per lane-mile per year.
2. From Equation 2 with appropriate parameters for Interstate rigid pavement, percentage allocated to sealing = 42.15 percent.
3. From Equation 3 with appropriate parameters for Interstate rigid pavement, percentage allocated to patching = 46.54 percent.
4. Sealing cost = 0.4215 * \$190.35 = \$80.23 per lane-mile per year.
5. Patching cost = 0.4654 * \$190.35 = \$88.58 per lane-mile per year.
6. From Table 3, fuel consumption rates are 0.094 gal per dollar of patching and 0.065 gal per dollar of sealing.

Energy consumed in sealing = 80.23 * 0.065 = 5.22 gal per lane-mile per year. Energy consumed in patching = 88.58 * 0.094 = 8.33 gal per lane-mile per year. Total energy consumption = 13.55 gal per lane-mile per year.

7. For a 15 percent increase in sealing activity, the percentage of total pavement maintenance cost allocated to sealing is 48.47 percent.
8. From Equation 3 with appropriate parameters for Inter-

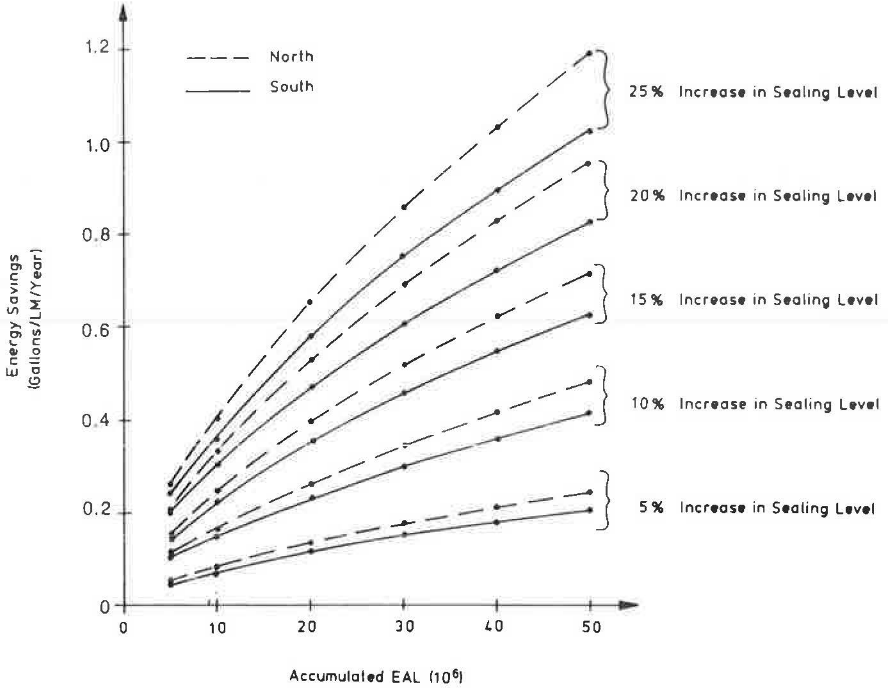

FIGURE 2 Energy savings due to increase in sealing level for Interstate rigid pavement.

state rigid pavement, the corresponding patching percentage is 40.23 percent.

9. Repeating Steps 4 through 6 gives the new total energy consumption as 13.19 gal per lane-mile per year, which results in a savings of 0.35 gal per lane-mile per year due to a 15 percent increase in the current level of sealing.

These computations were repeated for all highway categories for each of the five levels of sealing activity. The resulting savings in fuel consumption for the three major highway categories, Interstate rigid pavement, OSH flexible pavement, and OSH resurfaced pavement, are shown in Figures 2–4, respectively.

The information summarized in Figures 2–4 was then used to estimate expected total energy savings for the IDOH under the five options of increasing sealing level. For example, for Interstate rigid pavement in the north, with an average traffic level of 25 million accumulated EAL, a savings of 0.15 gal per lane-mile per year can be expected with a 5 percent increase in sealing level. This is equivalent to about an 0.85 percent reduction from the current level. Similar computations were done for all other highway categories under the average traffic level and

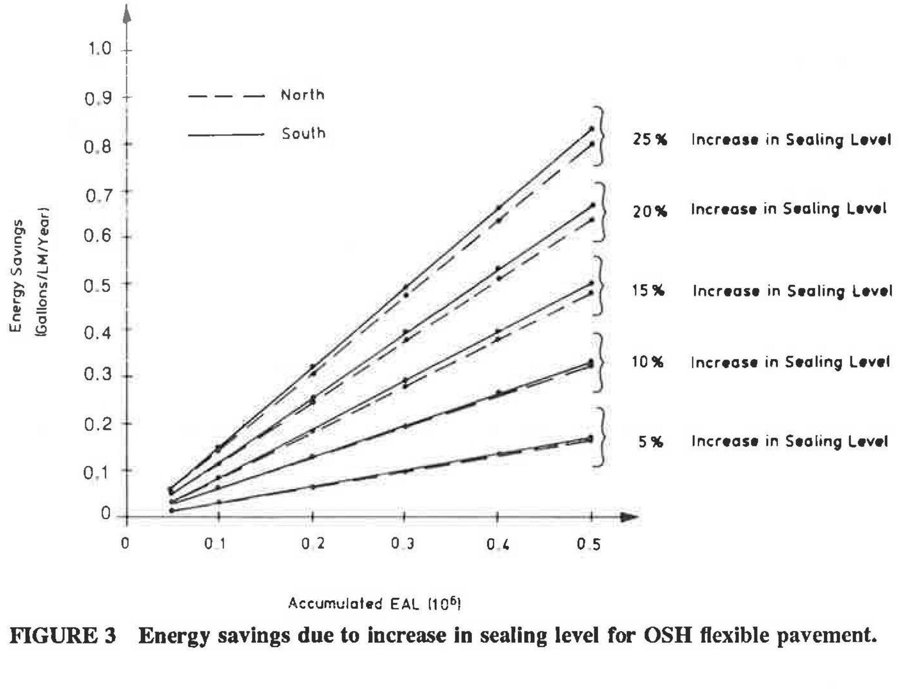

FIGURE 3 Energy savings due to increase in sealing level for OSH flexible pavement.

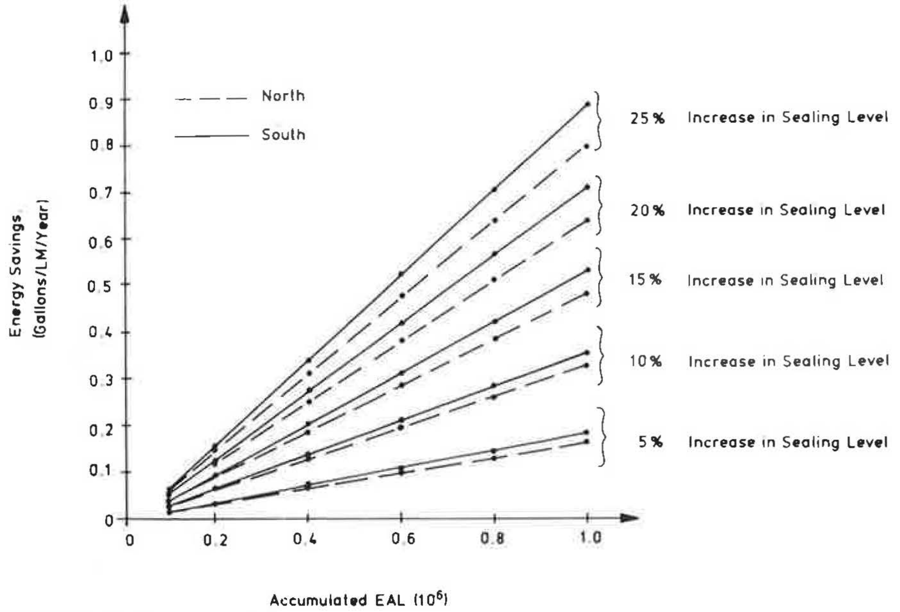

FIGURE 4 Energy savings due to increase in sealing level for OSH resurfaced pavement.

the corresponding percentage reductions in energy consumption. These reduction rates were then weighted by the percentage of total lane-miles of each highway category. The resulting weighted value was taken as the average percentage reduction in energy consumption for the entire state highway system. Under a 5 percent increase in sealing level, it was estimated that the average reduction in energy consumption would be about 0.82 percent. The corresponding reduction rates were 1.64, 2.5, 3.3, and 4.1 percent with an increase in sealing level of 10, 15, 20, and 25 percent, respectively. With an estimated 0.7 million gallons of fuel directly consumed by the equipment fleet in pavement maintenance activities (*8*), the expected savings in motor fuel consumption can be 5,700, 11,500, 17,200, 23,000 and 28,700 gal, respectively, under the five levels of increase in sealing activity.

It should be mentioned here that the energy savings are only the direct benefits of increasing the sealing level. There are also several indirect benefits associated with an increased sealing program. With an increased level of sealing, the amount of patching required is reduced, which indicates a lower level of pavement damage (e.g., potholes). A lower level of pavement damage would improve traffic safety and provide a higher level of service to highway users at less vehicle operating cost.

CONCLUSIONS

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

1. There is a definite trade-off relation between the amount of sealing (preventive routine maintenance) and that of patching (corrective maintenance). This trade-off relation is negative, which indicates that if more sealing is done before winter, less pavement repair (patching) is required after winter.
2. A direct cost savings, attributable to reduction in fuel consumption by the routine maintenance equipment fleet, could be achieved by increasing the level of sealing activity.
3. The developed trade-off relations indicated that the level of service and effectiveness of routine maintenance dollars could be increased through increasing the sealing level, which in turn results in a reduction in required pavement repair (less patching).

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Pothole Repair: You Can't Afford Not To Do It Right

H. RANDOLPH THOMAS AND DAVID A. ANDERSON

Pothole repair has traditionally been done using a "throw-and-go" or a "run-and-dump" procedure. Many transportation agency administrators are of the opinion that correct procedures are too expensive and time consuming and not cost-effective. Correct procedures include paying proper attention to cutting, compaction, and the use of quality materials. The results of a comprehensive study of pothole repairs, their longevity, and their cost-effectiveness are reported in this paper. The results are directly applicable to northern snow-belt states. Life-cycle cost analysis was used to compare the cost-effectiveness of several different procedures for pothole repair. The conditions and practices analyzed in the paper are based on actual observations of repair operations and performance during a 2-year period. Mathematical models were used to calculate the annualized cost per ton for each repair method. Rigorous repair procedures that involve cutting, cleaning, and compacting are the most cost-effective ways to repair potholes. Throw-and-go procedures cost approximately three times more than do the more rigorous procedures. Material costs are a small percentage of the total cost for pothole repair, which implies that newer, more expensive materials that can provide greater repair longevity will be cost-effective.

The choice of an appropriate procedure for the manual repair of potholes in flexible- and rigid-base pavements has generated considerable discussion. The options range from rapid, inexpensive procedures that require no cutting or compactive effort to time-consuming procedures that call for cutting to sound pavement, cleaning the distressed area of loose debris and dirt, and compacting the new repair with a mechanical compaction device (*1*). The controversy is whether the more rigorous procedure results in a repair that lasts longer and thus provides a more cost-effective solution to the problem of pothole repair.

The results of a comprehensive study of pothole repair procedures and longevity are described in this paper, which represents the culmination of a much broader study of the overall repair practices of the Pennsylvania Department of Transportation (PaDOT) (*2*). A life-cycle analysis of several procedures was performed. The conditions and practices analyzed here are based on actual field observations of numerous repair operations during a 2-year period. Repair performance was monitored for 2 years thereafter, and the longevity of the repair is factored into the mathematical model to show the annualized cost per ton of material for each method. The four methods and results described are directly applicable to northern snow-belt states. The methodology for evaluating various repair strategies is applicable to all states.

METHODS OF REPAIR USED IN ANALYSIS

Establishing a Unit Cost for Repair

Before different methods can be evaluated, some basis of comparison must be established. The unit cost for placing patch material, based on dollars per ton, was chosen.

The unit cost approach requires that the number of hours charged per day be defined. As a general rule, those cost components charged on the basis of 7.5 hr per day (the full day) are total crew hours, including traffic control, and the hours for support equipment (e.g., crew cab and dump trucks).

Production equipment is charged for the entire day because it is not available for use elsewhere. Accordingly, the following equation is used to calculate the unit cost of repairing potholes in flexible- and rigid-base pavements:

$$\begin{aligned}\text{Cost/Ton} = {} & [(\text{Hourly crew cost} \\ & + \text{Hourly support equipment cost} \\ & + \text{Hourly production equipment cost}) \\ & \times (\text{Hours/Day})] \div \text{Tons/Day} \\ & + \text{Material cost}\end{aligned} \qquad (1)$$

Method 1—Performance Standard and Roads with a High Frequency of Potholes

The following data are for Method 1, the method described in PaDOT performance standard 711–121–01.

Application
  Repair of numerous holes that are close together
Workday
  7.5 hr (450 min)
Production time
  5.58 hr (335 min)
Procedure
  PaDOT 711–121–01
Manpower
  1 foreman @ $14.97/hr = $14.97
  2 operators @ $13.74/hr = 27.48
  4 HMWs (includes 2 flagmen) @ $10.93/hr = 43.72
  Hourly crew cost (base wages plus fringe benefits) = $86.17/hr
Support equipment
  Crew cab @ $6.04/hr = $6.04
  Two 33,000-lb GVW dump trucks @ $14.80/hr = 29.60
  Total cost of support equipment = $35.64/hr

The Pennsylvania Transportation Institute, Pennsylvania State University, University Park, Pa. 16802.

Production equipment
Air compressor @ $12.88/hr = $12.88
Poinjar cutting tool @ $6.35/hr = $6.35
Essick roller @ $3.54/hr = 3.54 3.54
Total cost of production equipment = $16.42/hr $9.89/hr
Material
Plant mix @ $31.00/ton
Production
6.0 tons/day

A seven-man crew, which includes two highway maintenance workers (HMWs) for traffic control, is used. If this crew is properly deployed, the production rate in the performance standard can be achieved (*3*). Therefore it is assumed that a standard size crew can place 6.0 tons per day regardless of the makeup of the equipment fleet. This assumption is believed to be realistic because daily production is more likely to be controlled by the amount of material in the truck than by the cutting tool used.

A summary of the results of applying Equation 1 and the preceding data is given in Table 1. Obviously, if the crew can place more than 6 tons per day, the cost per ton will be reduced.

Method 2—Repair Practices During Initial Study (1979–1980)

Data on Method 2 are as follows:

Application
Repair of numerous holes that are close together
Workday
7.5 hr (450 min)
Production time
4.75 hr (285 min)
Procedure
PaDOT 711–121–01 except for crew size
Manpower
1 foreman @ $14.97/hr = $14.97
2 operators @ $13.74/hr = 27.48
6 HMWs (includes 2 flagmen) @ $10.93/hr = 65.58
Hourly crew cost = $108.03/hr
(base wages plus fringe benefits)
Support equipment
Crew cab @ $6.04/hr = $6.04
Two 33,000-lb GVW dump trucks @ $14.80/hr = 29.60
Total cost of support equipment = $35.64/hr
Production equipment
Air compressor @ $12.88/hr = $12.88
Poinjar cutting tool @ $6.35/hr = $6.35
4- to 6-ton roller @ $9.40/hr = 9.40 9.40
Total cost of production equipment = $22.28/hr $15.75/hr
Material
Plant mix @ $31.00/ton
Production
Repair density
120 lb/ft^3
Daily production
4 tons/day

Method 2 is identical to Method 1 except that (*a*) the crew size is increased by two additional HMWs, (*b*) the daily production rate is reduced to 4 tons per day, (*c*) the crews do not spend as much actual production time in the field, and (*d*) the equipment fleet is not the same. These adjustments to Method 1 are consistent with the observations made during the 1979–1980 repair season (initial study). This was the first year that the vigorous do-it-right procedure was instituted, but departmental training efforts had not yet been fully effective. Also, the equipment fleet had not been standardized. Using Equation 1 yields the results shown in Table 1.

The cost per ton in place observed in the initial study is considerably higher than that required to achieve the goals in the performance standard. The chief reasons are increased crew size, more costly compaction equipment, and reduced daily output.

Method 3—Performance Standard and Roads with a Low Frequency of Potholes

The third repair method is unlike the first two in that the potholes are widely spaced, which makes it impossible to work in an "assembly-line" fashion. Nevertheless, repairs are made in accordance with standard procedure. Determining daily pro-

TABLE 1 SUMMARY OF COST PER TON FOR EACH METHOD

Method No. and Cutting Tool	Crew Size (total)	Daily Production (tons/day)	Hourly Crew Cost ($/hr)	Support Equipment ($/hr)	Production Equipment ($/hr)	Material Cost ($/ton)	Cost per Ton ($/ton)
1, AC	7	6.00	86.17	35.64	16.42	31.00	203.79
1, P	7	6.00	86.17	35.64	9.89	31.00	195.63
2, AC	9	4.00	108.03	35.64	22.28	31.00	342.16
2, P	9	4.00	108.03	35.64	15.75	31.00	329.91
3, P	5	2.51	61.50	20.84	9.89	31.00	329.16
4	5	7.28	61.50	20.84		31.00	115.83
5	5	3.40	61.50	20.84		31.00	212.64

Note: AC = air compressor and P = Poinjar gasoline-powered cutting tool.

duction must be approached differently because the manpower and production data in the performance standard do not apply. Data on Method 3 follow:

Application
  Widely spaced holes
Workday
  7.5 hr (450 min)
Production time
  5.58 hr (335 min)
Procedure
  PaDOT 711–121–01
Manpower
  1 foreman @ $14.97/hr = $14.97
  1 operator @ $13.74/hr = 13.74
  3 HMWs (includes 2 flagmen) @ $10.93/hr = 32.79
  Hourly crew cost = $61.50/hr
  (base wages plus fringe benefits)
Support equipment
  Crew cab @ $6.04/hr = $6.04
  One 33,000-lb GVW dump truck @ $14.80/hr = 14.80
  Total cost of support equipment = $20.84/hr
Production equipment
  Poinjar cutting tool @ $6.35/hr = $6.35
  Essick roller @ $3.54/hr = 3.54
  Total cost of production equipment = $9.89/hr
Material
  Plant mix @ $31.00/ton
Production
  Assume 23 min for actual repair
    7 min for setting up and removing traffic control devices
    5 min travel to next hole
    35 min/repair
  Repair density
    135 lb/ft^3
  Hole volume
    3.60 ft^3
  Daily production
    [(5.58*60)/35][(3.60*135)/2000] = 2.32 tons/day

A five-person crew, including the foreman, one operator, one HMW, and two flagmen, is used. The assumptions relative to repair time are consistent with field observations. The density of repair is assumed to be 135 lb/ft^3, and the volume of the hole is assumed as 3.60 ft^3. Thus, on average, the crew will place 0.24 ton of material every 35 min or 2.32 tons per day. The production rate is based on the crew spending 5.58 hr (335 min) engaged in actual work.

Method 3 is used when conditions do not allow the work to be done in an assembly-line fashion. Accordingly, crew size is reduced. Considerable travel time is involved in going from hole to hole. Therefore a mobile crew can use a Pionjar, which is a gas-operated cutting tool, much more effectively than an air compressor. Table 1 gives a summary of the cost per ton using Equation 1.

Methods 4 and 5—Nonstandard Throw-and-Go Method

The final method to be examined is the nonstandard throw-and-go method that was widely practiced in Pennsylvania before 1979. The particular characteristics of this method are as follows:

Application
  Initial repair in a given year
Workday
  7.5 hr (450 min)
Production time
  4.75 hr (285 min)
Procedure
  Nonstandard (throw and go)
Manpower
  1 foreman @ $14.97/hr = $14.97
  1 operator @ $13.74/hr = 13.74
  3 HMWs (includes 1 flagman) @ $10.93/hr = 32.79
  Hourly crew cost = $61.50/hr
  (base wages plus fringe benefits)
Support equipment
  Crew cab @ $6.04/hr = $6.04
  One 33,000-lb GVW dump truck @ $14.80/hr = 14.80
  Total cost of support equipment = $20.84/hr
Production equipment
  None
Material
  Plant mix @ $31.00/ton
Production
  Assume 3 min for actual repair
    3 min for setting up and removing traffic control devices
    1 min travel to next hole
    7 min/repair
  Repair density
    110 lb/ft^3
  Hole volume
    3.25 ft^3
  Daily production
    [(4.75*60)/7][(3.25*110)/2000] = 7.28 tons/day

A five-person crew that includes one flagman is used. Because foreman and crew training has not been initiated, an assumed production day of 4.75 hr is used. Because the crew is comparatively small, a crew cab and one dump truck are considered sufficient. The holes are not squared, so no cutting equipment is needed. Compaction is performed with a truck tire, a shovel, or not at all.

Actual repair time is assumed to be 3 min per hole. This is considerably less than with the first three methods because there is no cutting or cleaning operation, and compaction time is minimal. There was an acute pothole problem at the time the throw-and-go method was being used; crews spent little time traveling from one pothole to the next. The time to set up and remove traffic control devices could also be distributed over a large number of holes.

Finally, repair density is assumed to be 110 lb/ft^3, which is about 10 percent less than was observed in field observations in 1979–1980 when compaction equipment was used. The hole volumes are also smaller because there is no cutting. The net result is that each hole repaired using this method contains about ¼ less material than do holes repaired using Methods 1 and 3.

It is a matter of record that the same pothole was often repaired several times in the same year when the throw-and-go method was used. It is also realistic to assume that, on average, such repairs took longer because there was more travel time involved. The time requirements for traffic control are also distributed over a smaller number of holes. Subsequent repairs using the nonstandard method are denoted as Method 5 and are summarized as follows:

Application
  Subsequent repairs in a single year using the same procedures as in Method 4
Workday
  7.5 hr (450 min)
Production time
  4.75 hr (285 min)
Procedure
  Nonstandard (throw and go)
Manpower
  1 foreman @ \$14.97/hr = \$14.97
  1 operator @ \$13.74/hr = 13.74
  3 HMWs (includes 1 flagman) @ \$10.93/hr = 32.79
  Hourly crew cost (base wages plus fringe benefits) = \$61.50/hr
Support equipment
  Crew cab @ \$6.04/hr = \$6.04
  One 33,000-lb GVW dump truck @ \$14.80/hr = 14.80
  Total cost of support equipment = \$20.84/hr
Production equipment
  None
Material
  Plant mix @ \$31.00/ton
Production
  Assume 3 min for actual repair
    7 min for setting up and removing traffic control devices
    5 min travel to next hole
    15 min/repair
Repair density
  110 lb/ft^3
Hole volume
  3.25 ft^3
Daily production
  [(4.75*60)/15][(3.25*110)/2000] = 3.40 tons/day

Method 5 is essentially the same as Method 4 except that the daily production rate is substantially reduced because the holes are more widely dispersed.

Table 1 gives a summary of the cost per ton for each repair method. On the basis of placement costs alone, the nonstandard method has the least cost per ton. It should also be noted that the percentage contribution to the total cost per ton of each of the various resources is as follows:

	Manpower	*Equipment*	*Material*
Method 1	54	30	16
Method 2	60	31	9
Method 3	60	31	9
Method 4	55	18	27

When standard procedures are used, material costs represent only a small portion of the total cost per ton.

COMPARISON OF METHODS USING ANNUAL COST

Any comparison of pothole repair methods would be incomplete if it did not take into account the longevity of the repair. Generalized cash flow diagrams were developed to show an initial expenditure (P_0) at the end of year zero. The uniform annual cost that is equivalent to an expenditure P_0 is designated A. Comparisons of the various repair methods are made on the basis of a 10 percent interest rate. The analysis period is 3 years.

Method 1—Using an Air Compressor

Equivalent annual costs are calculated by assuming that a repair will be performed annually, every 2 years, and every 3 years. Subsequent calculations will also be made for repairs performed two and four times in the same year. It is assumed that, in each instance, the repair will be made according to Method 1.

For a repair that lasts 1 year or longer, the following generalized equation can be developed:

$$A_{i,j} = P_0(A/P,\ 10\%,\ n) \tag{2}$$

where i represents the method used for the initial repair, j represents the longevity of the repair in years, and n represents the period of analysis. The capital recovery factor (A/P, 10%, n) converts the present worth value to uniform series payments lasting n years based on 10 percent interest. The various factors are tabulated in numerous engineering economy texts. Substituting the appropriate factors and the cost per ton figures determined earlier into Equation 2 yields the following annual costs for Method 1:

$$\begin{aligned} A_{1,1} &= 203.79\ (A/P,\ 10\%,\ 1) \\ &= 203.79\ (1.1000) \\ &= \$224.16/\text{ton} \end{aligned} \tag{3}$$

$$\begin{aligned} A_{1,2} &= P_0\ (A/P,\ 10\%,\ 2) \\ &= 203.16\ (0.5762) \\ &= \$117.06/\text{ton} \end{aligned} \tag{4}$$

$$\begin{aligned} A_{1,3} &= P_0\,(A/P,\ 10\%,\ 3) \\ &= 203.16\ (0.4021) \\ &= \$81.69/\text{ton} \end{aligned} \qquad (5)$$

If the repair is made more than once annually, the calculations take on a slightly different form. Two assumptions are made. The first is that the repair season lasts only 4 months. When a repair is made four times a year, it will be made at the end of months 0, 1, 2, and 3. The effective interest rate per month is $^{10}/_{12}$ or 0.83 percent. Repairs made twice a year will be made at the end of months 0 and 3. The second assumption is that when more than one repair is made in a given year, all subsequent repairs are performed using a more streamlined method. In this case, subsequent repairs are made with Method 3. Thus the initial and subsequent repairs are made according to the performance standard.

The present worth equation for repairs made four times a year is as follows:

$$\begin{aligned} P'_{i,1/12} = P_0 &+ F_1(P/F,\ 0.83\%,\ 1) \\ &+ F_2(P/F,\ 0.83\%,\ 2) \\ &+ F_3(P/F,\ 0.83\%,\ 3) \end{aligned} \qquad (6)$$

where F represents the cost of the subsequent repairs.

For repairs made twice a year, the following expression applies:

$$P'_{i,3/12} = P_0 + F_2(P/F,\ 0.83\%,\ 3) \qquad (7)$$

Notice that when the two present worth values have been calculated, they become present worth payments that can be substituted in Equation 2. Substituting the appropriate values for Method 1 into Equations 6 and 7 yields:

$$\begin{aligned} P'_{i,1/12} = 203.79 &+ 329.16\ (0.9234) \\ &+ 329.16\ (0.8526) \\ &+ 329.16\ (0.7873) \\ P'_{i,1/12} = \$1{,}047.53&/\text{ton} \end{aligned} \qquad (8)$$

and

$$\begin{aligned} P'_{i,3/12} &= 203.79 + 329.16\ (0.7873) \\ P'_{i,3/12} &= \$462.94/\text{ton} \end{aligned} \qquad (9)$$

The costs calculated for Equations 8 and 9 can now be substituted into Equation 2. For repairs that are made four times a year,

$$\begin{aligned} A_{1,1/12} &= 1047.53\ (1.100) \\ &= \$1{,}152.28/\text{ton} \end{aligned} \qquad (10)$$

For repairs that are made twice a year,

$$\begin{aligned} A_{1,3/12} &= 462.94\ (1.100) \\ &= \$509.23/\text{ton} \end{aligned} \qquad (11)$$

Summary of the Various Methods

Similar calculations were performed using Equations 2, 6, and 7 for the remaining methods. For Methods 1 and 2, separate calculations were made for an air compressor and the gas-operated cutting tool (Pionjar). The results are shown in Figure 1 and summarized in Table 2. Notice the dramatic decline in annual cost per ton as the longevity of the repair increases. As can be seen, if longevity of repair is not a function of the method, Method 2 is always the most expensive and Method 4 is the least expensive.

LONGEVITY OF REPAIR

Obviously it is not possible to compare repair strategies without considering the longevity of the repair. Field evaluations were used to calculate this information. Because no discernible

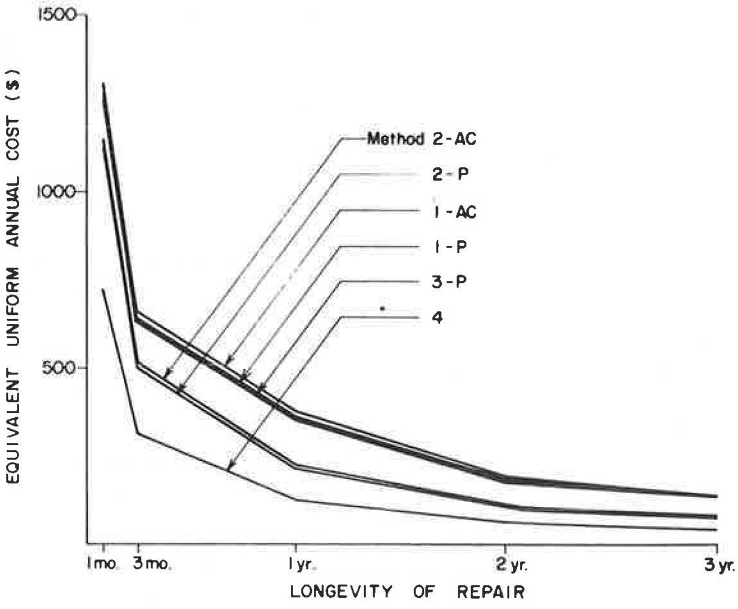

FIGURE 1 Equivalent uniform annual cost for different repair procedures.

TABLE 2 EQUIVALENT UNIFORM ANNUAL COST ($)

Method No. and Cutting Tool	Longevity of Repair 1 Month (4 times annually)	3 Months (2 times annually)	1 Year	2 Years	3 Years
1, AC	1,152.28	509.23	224.16	117.06	81.69
1, P	1,143.40	500.26	215.19	112.72	78.66
2, AC	1,304.49	661.44	376.38	197.15	137.58
2,P	1,291.01	647.96	362.90	190.09	132.66
3, P	1,290.19	647.14	362.08	189.66	132.36
4	726.95	311.56	127.41	66.74	46.58

Note: AC = air compressor and P = Poinjar gasoline-powered cutting tool.

differences were noted in longevity between repairs made with the air compressor and the hand-held gas-operated cutting tool (Pionjar), the two data sets were grouped together. Thus two sets of longevity calculations were performed, one with the initial study data and the other with data collected the following year (denoted as the foremen study data).

The initial study data were collected the first year the do-it-right philosophy was adapted. This data set corresponds to Method 2. The foremen study data were collected the following year when an effective training program had been implemented, material problems corrected, and new equipment purchased. The foremen study data are used in conjunction with Methods 1 and 3.

3-Year Forecast

Field evaluation data were collected for 650 days after the repair was made, whereas the life-cycle analysis in this paper is based on a 3-year analysis period. Therefore it was necessary to smooth the data and forecast the results for a 3-year period. Four statistical forecasting routines were tried. Based on the average error and the mean squared error, an exponential function was identified as the best. Table 3 gives a summary of the results. Note that after 22 time periods or 1,100 days it is predicted that 47 percent of the initial study repairs will remain in service compared with 62 percent of the foremen study repairs.

Average Longevity

The data in Table 3 provide the information needed for calculating the average longevity for each data set. Let $(PR)_i$ be the predicted percentage of repairs in service at the end of time period i. Then $(PR_{i-1} - PR_i)$ represents the predicted percentage of repairs that failed during that time period. This percentage is denoted as $(PF)_i$. The average longevity for repairs that fail in that period is $[(D_i - D_{i-1})/2]$ where D_i is the number of cumulative days at the end of the time period i. Thus the average longevity for each data set can be calculated using the following equation:

$$\text{Average longevity} = \sum_{i=1}^{n+1} [(PF)_i L_i/100]$$

where

n = number of time periods;
$(PF)_i$ = percentage of repairs failing during time period i [e.g., $(PF)_i = (PR_{i-1} - PR_i)$; and
L_i = average longevity for repairs failing during time period i [e.g., $L_i = (D_i - D_{i-1})/2$].

As can be seen from the data in Tables 4 and 5, the average longevity of repairs in the initial data set was 820 days and 899 days for the repairs included in the foremen study. No longevity data were available for repairs performed using the throw-and-go technique; however, an earlier study (*4*) indicated that repairs using this method lasted from 1 to 2 months. For comparative purposes, it will be assumed that repairs will be required twice a year, which means that the average longevity is 2 months.

Cost per Ton as a Function of Repair Method

The longevity values calculated previously were used in conjunction with Figure 1 to determine the cost per ton for making a repair using a particular procedure and crew makeup. The results are summarized in Table 6.

SYNOPSIS OF RESULTS

A review of Table 6 indicates that there are several observations worth noting. First, it should be quite clear that the nonstandard throw-and-go method is not cost-effective compared with the standard method using proper procedures and equipment in a well-organized manner. Although administrators of state highway agencies may claim that they cannot afford to use such a demanding procedure, the data show that they cannot afford not to use the do-it-right procedure.

The return on investment is long term, but it can be achieved. This is made clear by the data in Table 7, which gives the number of tons of material used in manual pothole repair in Pennsylvania Engineering District 3-0 for the period

TABLE 3 PERCENTAGE OF REPAIRS IN SERVICE AS A FUNCTION OF TIME

		Percentage of Holes Remaining in Service			
		Initial Studies		Foremen Studies	
Time Period i	Days, D_i	Actual %	Predicted PR_I %	Actual %	Predicted PR_F %
1	50	100	100	100	99
2	100	98	100	79	97
3	150	94	97	96	95
4	200	94	94	96	93
5	250	96	90	96	91
6	300	91	87	96	89
7	350	91	84	96	87
8	400	86	80	88	85
9	450	77	77	88	83
10	500	68	75	87	81
11	550	68	72	72	80
12	600	68	69	72	78
13	650	68	67	73	76
14	700	--	64	--	74
15	750	--	62	--	73
16	800	--	59	--	71
17	850	--	57	--	70
18	900	--	55	--	68
19	950	--	53	--	67
20	1000	--	51	--	65
21	1050	--	49	--	64
22	1100	--	47	--	62
Average Error			0.0908		0.2857
Mean Squared Error			18.7114		51.0202
Mean Absolute Error			3.6961		5.6489

Initial Study Equation $(PR_I)_i = e^{(4.6917-0.0379i)}$

Foreman Study Equation $(PR_F)_i = e^{(4.6223 - 0.0223i)}$

1978–1983. The 1978–1979 data represent tonnage placed using the nonstandard approach. The first year in which the standard procedure was enforced was 1979–1980, and, as expected, the tonnage dropped to 75.1 percent or 24,135 tons. However, the procedure was effective, as is made evident by the further reductions in annual tonnage. The downward trend in tons per year is a strong indicator that pothole repairs that were previously made several times a year now have much greater longevity. By applying the dollar figures for Methods 1 and 4 in Table 5 to the tonnage figures for 1978–1979 and 1982–1983, an annual dollar savings of approximately $8,797,800 for this one district can be calculated. Statewide, the savings are perhaps 10 times greater.

Training and management emphasis is an important part of any effective organization, yet the economic benefits of training are often difficult to quantify. In Table 6, the data for Methods 1 and 2 primarily reflect differences in training and a management emphasis that resulted in better material and equipment. It can be seen that the return on investment is about $80 per ton.

CONCLUSIONS

The following conclusions can be drawn:

1. Rigorous procedures that involve cutting, cleaning, and compacting are the most cost-effective way to repair potholes. Nonstandard throw-and-go procedures cost about three times more than rigorous standard PaDOT procedures.
2. Training programs and the proper selection and standardization of equipment can significantly reduce overall costs.
3. The factors that have the greatest influence on total repair costs are repair longevity (procedures), daily production, and crew deployment practices. Material costs account for less than 20 percent of the total cost when standard procedures are used. The implication is that if newer, more expensive materials can

TABLE 4 AVERAGE LONGEVITY CALCULATIONS FOR INITIAL STUDY

Time Period i	Days (D_i)	Percent Remaining $(PR_I)_i$	Percent Failed $(PF_I)_i$	Average Longevity $(L_I)_i$	$\frac{(PF_I)_i \times (L_I)_i}{100}$
1	50	100	0	--	0
2	100	100	0	--	0
3	150	97	3	125	3.75
4	200	94	3	175	5.25
5	250	90	4	225	9.00
6	300	87	3	275	8.25
7	350	84	3	325	9.75
8	400	80	4	375	15.00
9	450	77	3	425	12.75
10	500	75	2	475	9.50
11	550	72	3	525	15.75
12	600	69	3	575	17.25
13	650	67	2	625	12.50
14	700	64	3	675	20.25
15	750	62	2	725	14.50
16	800	59	3	775	23.25
17	850	57	2	825	16.50
18	900	55	2	875	17.50
19	950	53	2	925	18.50
20	1000	51	2	975	19.50
21	1050	49	2	1025	20.50
22	1100	47	2	1075	21.50
23	1150	0	47	1125	528.75
			$\sum = 100$		$\sum = 819.50$

TABLE 5 AVERAGE LONGEVITY CALCULATIONS FOR FOREMEN STUDY

Time Period i	Days (D_i)	Percent Remaining $(PR_F)_i$	Percent Failed $(PF_F)_i$	Average Longevity $(L_F)_i$	$\frac{(PF_F)_i \times (L_F)_i}{100}$
0	0	100	0	--	0
1	50	99	1	25	0.25
2	100	97	2	75	1.50
3	150	95	2	125	2.50
4	200	93	2	175	3.50
5	250	91	2	225	4.50
6	300	89	2	275	5.50
7	350	87	2	325	6.50
8	400	85	2	375	7.50
9	450	83	2	425	8.50
10	500	81	2	475	9.50
11	550	80	1	525	5.25
12	600	78	2	575	11.50
13	650	76	2	625	12.50
14	700	74	2	675	13.50
15	750	73	1	725	7.25
16	800	71	2	775	15.50
17	850	70	1	825	8.25
18	900	68	2	875	17.50
19	950	67	1	925	9.25
20	1000	65	2	975	19.50
21	1050	64	1	1025	10.25
22	1100	62	2	1075	21.50
23	1150	0	62	1125	697.50
			$\sum = 100$		$\sum = 899.00$

TABLE 6 COST PER TON AS A FUNCTION OF REPAIR METHOD

Method	Description	Longevity in Days	Cost Per Ton ($/Ton)
1	Standard procedure using air compressor, after training emphasis	899	100.68
	Standard procedure using Pionjar, after training emphasis	899	96.95
2	Standard procedure using air compressor, before training emphasis (1979-80)	820	182.46
	Standard procedure using Pionjar before training emphasis (1979-80)	820	175.93
3	Standard procedure for complaint crew or widely scattered holes, after training emphasis	899	163.13
4	Nonstandard "throw and go" procedure	60	311.56

TABLE 7 TONNAGE OF MATERIAL PLACED IN MANUAL POTHOLE REPAIR, DISTRICT 3-0.

Fiscal Year	Tons	Fiscal Year	Tons
1978–1979	32,146	1981–1982	13,635
1979–1980	24,135	1982–1983	12,322
1980–1981	18,403		

provide longer repair longevity, then they potentially can be less costly overall.

4. State DOTs should consider all cost components in deciding on a strategy for pothole repair. The methodology described in this paper is a valid way to evaluate total repair costs and can be used in selecting an equipment fleet and in developing new repair materials. The methodology can also be extended to other types of maintenance activities.

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Optimization of Equipment Use in Routine Highway Maintenance

KUMARES C. SINHA, MITSURU SAITO, AND JALAL NAFAKH

An optimization procedure was developed for assigning equipment to routine highway maintenance activities so that total fuel consumption would be minimized. The procedure is based on a linear programming technique and determines the optimal assignment of equipment in terms of the number of equipment days of a particular type of equipment to be assigned to a specific maintenance activity. The program is capable of handling a large number of activity-equipment combinations and performs optimization of fuel use as long as some of the types of equipment considered are interchangeable. An application of the procedure using the actual equipment use data from a typical subdistrict in Indiana is presented to demonstrate an equipment assignment problem. The technique was found to be efficient, and it provided feasible results to use in establishing equipment assignment guidelines for fuel conservation.

Highway maintenance consists of a variety of activities that require many different types of equipment. These activities are both labor and fuel intensive. Fuel consumed by maintenance equipment may account for as much as one-third of the total material cost and about one-tenth of the total actual maintenance cost *(1)*. A previous study of fuel use in routine highway maintenance found that some types of equipment were interchangeably used to do the same task and that fuel consumption rates were substantially different for the different types of equipment *(1)*. Consequently, equipment management tools that make possible better control of fuel consumption are important elements of maintenance management. Optimization techniques can be applied to the problem of assigning different equipment to various maintenance activities so that the total fuel consumption can be minimized.

Mathematical modeling techniques have been successfully applied to the problems related to pavement management *(2–4)*. However, the application of mathematical optimization techniques to routine highway maintenance has long been considered infeasible because of the wide variation in the characteristics of routine maintenance activities, because of the many uncertain elements such as the weather, and because of the difficulty of accurately assessing maintenance needs.

Simulation is another operations research technique that can be applied to routine maintenance activities. A project-level simulation model of roadside mowing was developed in the early 1970s *(5)*. Later, a highway maintenance simulation model was developed for the Louisiana Department of Highways *(6)*. Except for these two simulation models, there have not been serious efforts in this area. One reason for this is that simulation models often require a great many assumptions, such as a probability distribution of activity occurrences, that may inversely affect the validity of the models.

Because the specific objective of the present study was to maximize energy conservation, an approach that was focused on the equipment assignment component of the overall maintenance scheduling process was needed. A linear programming technique was applied to develop a mathematical model for determining optimal equipment assignment to minimize total fuel consumption. A sample application is discussed to demonstrate the feasibility of incorporating this equipment assignment technique into the current activity scheduling process.

OPTIMIZATION METHODOLOGY

The concept of the optimization model developed in this study is based on the interchangeability of types of equipment for performing particular tasks of each activity. Equipment that uses less fuel should be assigned as much as possible to minimize total fuel consumption. The field survey data collected in a previous study *(1)* and field observations conducted in the present study showed that different types of equipment are used to perform the same tasks. For example, pickup crew cabs and dump trucks are interchangeably used in rest area maintenance. Similarly, for hauling purposes, pickup trucks, pickup crew cabs, dump trucks, and do-all trucks have been found to be interchangeably used. However, the fuel usage rates of these types of equipment vary considerably. Furthermore, the same type of equipment, when used in different activities, has different fuel usage rates. It is possible, therefore, to optimize the equipment assignment so that the total fuel consumed in performing various activities is minimized.

A trend analysis of fuel use conducted during the study indicated that pickup trucks, pickup crew cabs, dump trucks, and do-all trucks used about 70 percent of the total fuel consumed for all routine maintenance activities excluding snow and ice removal work. Therefore consideration of only these types of equipment can result in a substantial amount of fuel savings.

The optimization model approaches the problem of fuel savings on an aggregated basis. The decision variable used in the model is the number of equipment days of a particular type to be used for an activity. This optimal value can then be taken as the target value of equipment days to be assigned to the activities. The variable of equipment days was used as an aggregate measure because there are daily fluctuations in equipment scheduling due to such factors as the amount of accomplishment, equipment availability, labor availability, and weather conditions. Specific scheduling can be best dealt with by experienced schedulers. Scheduling equipment units while making efforts to conform to targeted values resembles the activity scheduling procedure currently used by subdistricts of the Indiana Department of Highways for preparing the biweekly activity plan *(7)*.

School of Civil Engineering, Purdue University, West Lafayette, Ind. 47907.

Development of the Model

The optimization model developed in the present study has two types of constraints: *(a)* planned accomplishments of activities included in the model and *(b)* equipment availability. Both constraints are expressed in equipment days. A flow chart showing the process of model development is shown in Figure 1. A data base that contains equipment usage, fuel usage, productivity, and equipment breakdown data is frequently used during model development.

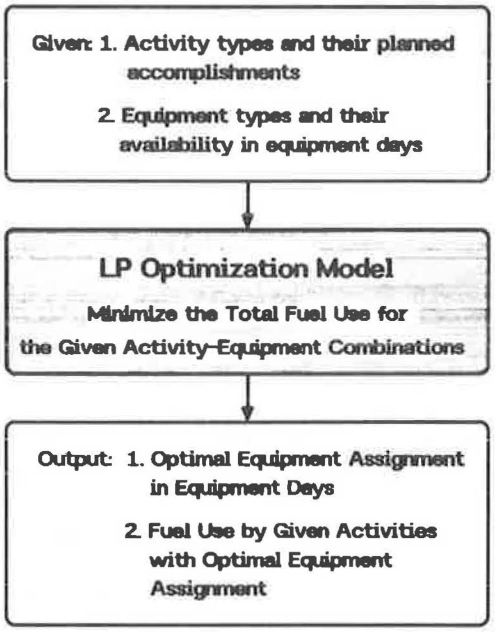


FIGURE 1 Maintenance equipment assignment technique.

First, planned accomplishments of all maintenance activities are set and activities that are considered in the model are selected from the activity list. A set of types of equipment of interest is then selected. The availability of selected types of equipment is expressed in equipment days. Total available equipment days of a particular type of equipment are computed by simply multiplying the number of units of the type of equipment by the number of working days available during the analysis period. From the total available equipment days, the number of equipment days lost due to mechanical breakdowns and the number of equipment days necessary to perform other activities that are not considered in the model must be subtracted. The remaining equipment days for each selected type of equipment form equipment availability constraints.

After the equipment-activity combinations are identified, interchangeable types of equipment are grouped within each activity. Only types of equipment that are interchanageable for a specific task are grouped. If only a particular type of equipment must be used to perform a task, then constraints are appropriately formulated to indicate this requirement. The equipment usage factor of each type of equipment within an interchangeable equipment group is provided as input and the resulting sum of equipment usage rates is considered a combined equipment usage factor. The equipment usage factor is defined as the average number of equipment units of a particular type used to complete a scheduled amount of an activity within 1 working day. The combined equipment usage factor reflects the actual need of equipment for an activity. For example, if a pickup truck and a pickup crew cab are used interchangeably in shallow patching, and if the pickup truck's usage factor is 0.5 and the pickup crew cab's usage factor is 0.7, the combined usage factor of this interchangeable equipment group will be 1.2. This means that for every 100 working days of shallow patching, 120 units of either pickup trucks or pickup crew cabs, or a combination of these two types, will be needed. Combined equipment usage factors are used to compute conversion factors called K-values, which translate the amount of accomplishment for an activity to the number of equipment days necessary to complete the activity using particular equipment within an analysis period. The resulting equipment days form equipment requirement constraints.

After these constraints are determined, the objective function can be formulated. Each coefficient of the decision variable in the model is computed by multiplying a combined usage factor, the fuel usage rate of equipment used for an activity, and a conversion factor (K-value).

Model Formulation

The formulation of the maintenance equipment assignment technique using linear programming is discussed next. The objective function is to minimize the total number of gallons of fuel consumed in performing all scheduled maintenance activities considered.

$$\text{Minimize} \sum_{i} \sum_{j} R_{i,j} \times U_{i,j(l)} \times K_{i,j(l)} \times Y_{i,j}$$

subject to the following constraints:

- Demand constraints—The demand for all scheduled activities must be met:

$$\sum_{j} Y_{i,j} \geq D_{i(l)} \quad \text{for all } i$$

- Capacity constraints—The total number of equipment days assigned to any type of equipment must not exceed the number of equipment days available:

$$\sum_{i} Y_{i,j} \leq C_j \quad \text{for all } j$$

- Nonnegativity constraints—All variables must be greater than or equal to zero:

$$Y_{i,j} \geq 0 \quad \text{for all } i,j$$

where

$Y_{i,j}$ = number of equipment days of equipment j assigned to activity i,

$R_{i,j}$ = fuel consumed by one unit of equipment j in accomplishing one production unit of activity i,

$U_{i,j(l)}$ = combined usage factor of equipment j in interchangeable equipment group l when used in activity i,

N_i = scheduled level of accomplishment of activity i,

$D_{i(l)}$ = number of equipment days required to perform the scheduled accomplishment (N_i) of an activity i by equipment j that belongs to an interchangeable equipment group l,

C_j = number of available equipment days of equipment j,

$K_{i,j(l)}$ = units of accomplishment of activity i by equipment j of equipment group l.

$D_{i(l)}$ is computed as follows:

$$D_{i(l)} = N_i/K_{i,j(l)}$$

It should be noted that the types of equipment that are interchangeable must have the same K-value.

Procedure for Estimating K-Values

The K-value can be interpreted as the capacity of one unit of equipment of a particular type to perform a particular task in 1 workday called a crew day. This value is stated in terms of the production unit of the activity in which the equipment is used. Thus K-value is expressed in units of accomplishment per equipment per crew day.

For example, a K-value of 1.1 for dump trucks used in crack sealing indicates that 1.1 lane miles of sealing can be accomplished on the average by one dump truck per crew day. The use of K-values allows different units of measurement to be converted to a common measure—equipment days—for the decision variables employed. K-values are used for translating the information on scheduled production units of different activities into the equipment days necessary to complete the scheduled levels. The resulting equipment days are then used as work demand constraints in the optimization model. K-values are also used to transform the optimal solutions given in equipment days back into original units of production of each activity so that fuel consumption can be computed by using available fuel usage rates given in gallons per production unit. K-values are computed by the following formula:

$$K_{ij(l)} = P_i \Big/ \sum_{j \varepsilon l} F_{ij}$$

where

$K_{ij(l)}$ = K-value for equipment type j in an interchangeable equipment group l for activity i,

P_i = production per crew day for activity i,

F_{ij} = usage factor of equipment j when used in activity i,

$\sum_{j \varepsilon l} F_{ij}$ = combined usage factor for equipment type j in an interchangeable equipment group l when used in activity i.

The combined usage factor indicates how many equipment units would be required to perform a certain amount of accomplishments per crew day if only one type of equipment were used.

Model Output

The unit of decision variables is given in equipment days. For example, $Y_{207,1}$ is the number of equipment days allowed for equipment number 1, a pickup truck, to be used for activity 207, crack sealing. The model tries to minimize the total amount of fuel consumed by the activity-equipment combinations considered. Therefore the optimization model may indicate that some activities would receive more than or less than the amount of equipment days for certain types of equipment than normally are used for those activities. As long as the equipment can be interchanged, such recommendations should be followed because the overall fuel use would eventually be minimized by letting other activities use equipment that is less fuel consuming. If the results appear to be grossly misrepresented or far from reality, equipment grouping needs to be reconsidered and constraints adjusted to reflect any corresponding changes.

In actual scheduling, when an equipment unit has been assigned to an activity, it is not available for other activities for the entire day. The average number of equipment units to be assigned to do one activity during one crew day can be computed by dividing the values for decision variables by proper crew days scheduled. Therefore, if one decision variable has 200 equipment days for a particular type of equipment and 100 crew days are scheduled, the new usage factor will be 2.0.

APPLICATION OF THE MODEL

A sample problem applied to the subdistrict level was used to compare the fuel use expected on the basis of the current equipment assignment practice observed in the field survey with that of the optimal equipment assignment determined by the model. The problem was developed by using routine maintenance accomplishment data *(8)*, equipment use data *(1)*, and equipment availability data compiled during the study. The purpose of the application problem was to demonstrate the possible use of the methodology.

Description of the Sample Subdistrict

The Fowler subdistrict chosen for the analysis is a typical subdistrict in Indiana, where most of the highways are non-Interstate routes. This sample subdistrict was one of the six subdistricts in which a field survey of equipment and fuel use was previously conducted *(1)*.

TABLE 1 ACTUAL ACCOMPLISHMENTS OF 12 MAJOR ACTIVITIES AND ESTIMATED FUEL CONSUMPTION DURING FY 1984 FOR THE FOWLER SUBDISTRICT

				Interstates		OSH		All	
Activity Code	Activity Name	Unit of Measurement	Fuel Use (gal/unit) *(1)*	Actual Accomplishment (units) *(8)*	Estimated Fuel Use (gal)	Actual Accomplishment (units) *(8)*	Estimated Fuel Use (gal)	Actual Accomplishment (units) *(8)*	Estimated Fuel Use (gal)
201	Shallow patching	Tons of mix	8.78	113	990	814	7,150	928	8,150
205	Seal coating	Lane miles	85.14	–	–	95	8,090	95	8,090
207	Sealing cracks	Lane miles	23.27	–	–	186	4,330	186	4,330
210	Spot repair of unpaved shoulders	Tons of aggregate	2.15	36	80	655	1,410	691	1,490
212	Clipping unpaved shoulders	Shoulder miles	52.86	–	–	75	3,960	75	3,960
221	Machine mowing	Swath miles	1.35	–	–	2,177	2,940	2,177	2,940
231	Clean and reshape drainage structures	Linear feet	0.22	140	30	41,426	9,110	41,566	9,140
235	Clean minor drainage structures	No. of structures	3.81	32	120	361	1,380	393	1,500
251	Subdistrict sign maintenance	Man-hours	1.02	638	650	2,306	2,350	2,944	3,000
283	Buildings and grounds maintenance	Man-hours	1.52	–	–	4,170	6,340	4,170	6,340
284	Material handling and storage	Man-hours	3.52	–	–	2,153	7,580	2,153	7,580
289	Other support activities	Man-hours	2.69	–	–	3,742	10,070	3,743	10,070

Note: Dashes = activity not carried out or information unavailable.

Description of Maintenance Demand

Table 1 gives the 1984 maintenance accomplishments of the subdistrict for the 12 major fuel-consuming activities. It provides the overall maintenance need for this subdistrict including the work done both on Interstate and on other state highways (OSH). It can be seen that activity 271 on the Interstate system is a major fuel-consuming activity and that other activities on the Interstate system require much less fuel. On the other hand, most of the activities on the OSH consume a considerable amount of fuel. Therefore the sample problem considered only the 12 activities on the OSH for modeling purposes.

Availability of Equipment

The data in Table 2 indicate how equipment availability constraints were derived. In this sample problem, five types of hauling equipment were considered. First, four major types of equipment were selected: pickup truck, pickup crew cab, dump truck, and do-all truck. Utility trucks were then added because pickup trucks and pickup crew cabs can often be used for the same sign maintenance work as utility trucks. During FY 1984 the sample subdistrict had 11 pickup trucks, 6 pickup crew cabs, 1 utility truck, 20 dump trucks, and 7 do-all trucks. To compute the number of available equipment days of each type of equipment, 250 working days or crew days per year were used. The value for annual available equipment days was adjusted for possible mechanical breakdowns. The statewide average breakdown rates were used here because the existing equipment management system does not provide equipment breakdown rates for each type of equipment by subdistrict.

The equipment days used for activities not included in the optimization model were subtracted from the adjusted equipment days. It was also necessary to subtract equipment days used for supervision of field activities by the superintendent and three unit foremen because this activity (Activity 112) is no recorded on crew-day cards. It was assumed that personnel in supervisory positions use one pickup each working day. The remaining equipment days then become constraints to the optimization model.

Computation of K-Values

The computation of K-values is a key element of the maintenance equipment assignment technique. In a previous report *(1)* equipment usage factors were computed for all equipment and activity combinations. The usage factor indicates how often a particular type of equipment is used for an activity. For example, a usage factor of 1.10 indicates that 110 units of this type of equipment are used in 100 crew days of this activity, or 110 equipment days are assigned for 100 crew days of this activity. This means that more than one unit is used on some of the crew days.

A comparison of computed usage factors, field survey data (crew-day cards), and the field operations handbook *(7)* shows which types of equipment can be interchanged. For example, for Activity 207, crack sealing, the equipment usage factors for dump trucks and do-all trucks are 1.77 and 0.57, respectively, as the data given in Table 3 indicate. Dump trucks are used in

TABLE 2 ESTIMATED AVAILABLE EQUIPMENT DAYS OF FIVE TYPES OF EQUIPMENT FOR THE 12 ACTIVITIES INCLUDED IN THE MODEL: FY 1984, FOWLER SUBDISTRICT DATA

	Pickup Truck	Pickup Crew Cab	Utility Truck	Dump Truck	Do-All Truck
Availability					
No. of pieces of equipment	11	6	1	20	7
Total No. of equipment days available[a]	2,750	1,500	250	5,000	1,750
Breakdown rate[b] (%)	12	4	2	18	12
Remaining equipment days available	2,420	1,440	245	4,100	1,540
Equipment days used for activities other than the 12 included in the model					
Interstate (INT)	76	637	37	1,021	10
Other state highways (OSH)	404	224	69	2,014	57
INT + OSH	480	861	106	3,035	67
Supervision[c]	1,000	–	–	–	–
Total excluded	1,480	861	106	3,035	67
Equipment days available for 12 activities included in the model	940	579	139	1,165	1,473

[a] 250 working days per year.
[b] Statewide average equipment breakdown rates were used.
[c] One superintendent and three unit foremen are assumed to each use one pickup truck each day to supervise field maintenance activities.

crack sealing to spread cover aggregate (usually sand) over the bituminous material applied to cracks. Do-all trucks can be used to do the same work. Because these two types are used for the same purpose, they form an interchangeable group for this particular activity (207), and the usage factor of this group is the summation of the usage factors of dump trucks and do-all trucks. For the sample analysis, the combined usage factor then becomes 2.34. This value is reasonable; the handbook for foremen *(7)* estimates two dump trucks for each crack-sealing activity.

The basic idea of a trade-off between types of equipment was used to estimate other combined usage factors. Table 3 gives the 12 activities and equipment usage factors for the five major types of hauling equipment. Pickup trucks and pickup crew cabs were treated as interchangeable, and dump trucks and do-all trucks were assumed to be interchangeable. When equipment types were not interchangeable, constraints were constructed accordingly. In the case of sign maintenance, pickup trucks, pickup crew cabs, and utility trucks can be interchanged.

After the combined usage factors for the types of equipment needed for different activities were determined, K-values were computed. Table 4 gives the annual average accomplishments per crew day for the 12 activities in the Fowler subdistrict

TABLE 3 INDIVIDUAL EQUIPMENT USAGE FACTORS AND COMBINED USAGE FACTORS

	Usage Factors *(1)* for Equipment Type					Combined Usage Factors for Interchangeable Equipment Types				
Activity Code	1	2	8	9	10	1 + 2	9 + 10	1 + 2 + 9 + 10	1 + 2 + 8	9
201	0.10	1.10	–	0.91	0.12	1.20	1.03	–	–	–
205	1.00	1.00	–	9.00	–	2.00	–	–	–	9.00
207	0.53	1.13	–	1.77	0.57	1.66	2.34	–	–	–
210	0.75	0.36	–	0.50	1.33	1.11	1.83	–	–	–
212	0.85	0.60	–	3.35	–	1.45	–	–	–	3.35
221	0.12	0.81	–	0.07	0.01	–	–	1.01	–	–
231	0.51	0.86	–	2.56	–	1.37	–	–	–	2.56
235	0.74	0.35	–	0.17	0.04	–	–	1.30	–	–
251	0.18	0.03	0.79	–	–	–	–	–	1.00	–
283	0.37	0.37	–	1.05	–	0.74	–	–	–	1.05
284	0.09	0.02	–	1.23	0.14	0.11	1.37	–	–	–
289	0.19	0.14	–	0.70	0.14	0.33	0.84	–	–	–

Note: 1 = pickup truck, 2 = pickup crew cab, 8 = utility truck, 9 = dump truck, and 10 = do-all truck. Dashes = this equipment not used for this activity.

TABLE 4 ESTIMATED CAPACITY OF TYPES OF EQUIPMENT, K-VALUE

			Combined Usage Factors (equipment/crew day)					K-Values (production/equipment/crew day)				
Activity Code	Accomplishment per Day[a]	Unit of Measure	Pickup Truck	Pickup Crew Cab	Utility Truck	Dump Truck	Do-All Truck	Pickup Truck	Pickup Crew Cab	Utility Truck	Dump Truck	Do-All Truck
201	3.79	Tons of aggregate	1.20	1.20	–	1.03	1.03	3.16	3.16	–	3.68	3.68
205	8.64	Lane miles	2.00	2.00	–	9.00	–	4.32	4.32	–	0.96	–
207	2.51	Lane miles	1.66	1.66	–	2.34	2.34	1.51	1.51	–	1.07	1.07
210	26.20	Tons of aggregate	1.11	1.11	–	1.83	1.83	23.60	23.60	–	14.32	14.32
212	3.13	Shoulder miles	1.45	1.45	–	3.35	–	2.16	2.16	–	0.93	–
221	22.21	Swath miles	1.01	1.01	–	1.01	1.01	21.99	21.99	–	21.99	21.99
231	881.40	Linear feet	1.37	1.37	–	2.56	–	643.36	643.36	–	344.3	–
235	20.06	Structures	1.30	1.30	–	1.30	1.30	15.43	15.43	–	15.43	15.43
251	15.07	Man-hours	1.00	1.00	1.00	–	–	15.07	15.07	15.07	–	–
283	32.00	Man-hours	0.74	0.74	–	1.05	–	43.24	43.24	–	30.48	–
284	16.19	Man-hours	–	–	–	1.37	1.37	–	–	–	11.81	11.81
289	12.23	Man-hours	0.33	0.33	–	0.84	0.84	37.06	37.06	–	14.56	14.56

Note: Dashes = this equipment not used for this activity.

[a] Estimated from crew-day cards and IDOH's accomplishment records (MM–113) *(8)*.

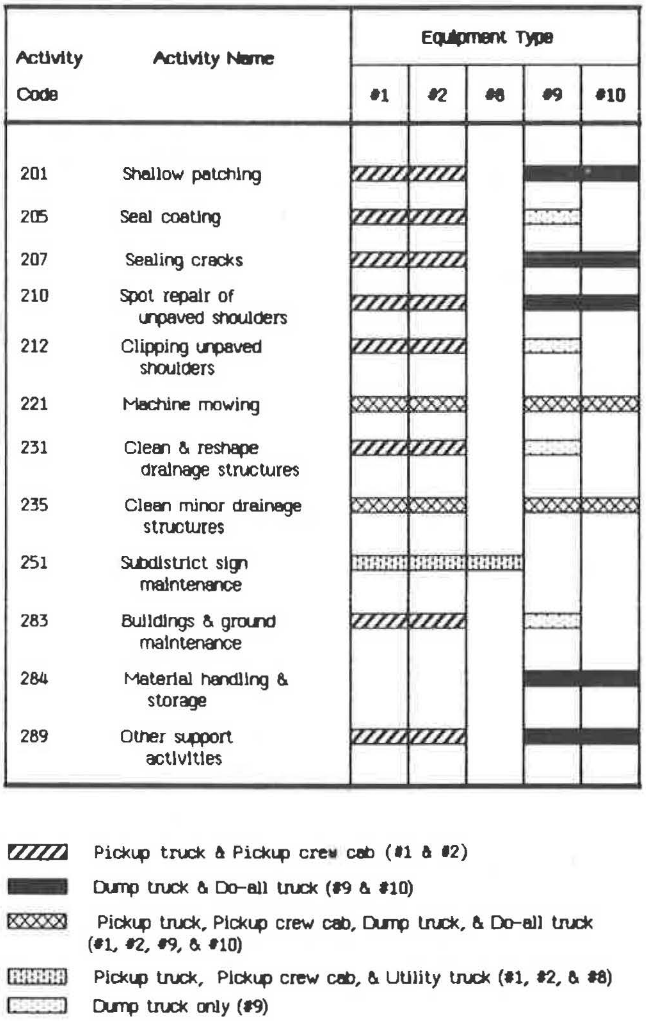
during FY 1984. The K-value is obtained by dividing the average accomplishment per day by the combined usage factor as is done in Table 4. The measurement unit of the K-value is therefore the accomplished production units per equipment unit per crew day. Figure 2 shows which types of equipment were considered interchangeable for various activities.

Estimated Fuel Consumption

The objective function of the optimization model is to minimize total fuel consumed by types of equipment in accomplishing needed maintenance work. The model is run for cases of unconstrained and constrained equipment availability. The unconstrained case refers to the situation in which optimal equipment assignment was derived without considering availability of the equipment at the subdistrict level, and the constrained case considers actual availability of equipment. The fuel consumption calculated under both cases was compared with actual fuel consumption, as estimated. Table 5 gives fuel consumption rates of types of equipment for different activities included as input to the optimization model. The values for estimated fuel consumed by various types of equipment under current assignment practices were computed using these rates. Table 6 gives fuel consumption for the activities included in the model for the sample subdistrict in FY 1984.

Summary of Results

The Linear, Interactive and Discrete Optimization (LINDO) computer program developed at the University of Chicago *(9)* was used to solve the problem. Results of the optimization efforts are summarized in tables and are discussed next.



Activity Code	Activity Name	Equipment Type #1	#2	#8	#9	#10
201	Shallow patching	▨	▨		■	■
205	Seal coating	▨	▨		░	
207	Sealing cracks	▨	▨		■	■
210	Spot repair of unpaved shoulders	▨	▨		■	■
212	Clipping unpaved shoulders	▨	▨		░	
221	Machine mowing	⊠	⊠		⊠	⊠
231	Clean & reshape drainage structures	▨	▨		░	
235	Clean minor drainage structures	⊠	⊠		⊠	⊠
251	Subdistrict sign maintenance	▦	▦	▦		
283	Buildings & ground maintenance	▨	▨		░	
284	Material handling & storage				■	■
289	Other support activities	▨	▨		■	■

▨ Pickup truck & Pickup crew cab (#1 & #2)

■ Dump truck & Do-all truck (#9 & #10)

⊠ Pickup truck, Pickup crew cab, Dump truck, & Do-all truck (#1, #2, #9, & #10)

▦ Pickup truck, Pickup crew cab, & Utility truck (#1, #2, & #8)

░ Dump truck only (#9)

FIGURE 2 Combinations of types of equipment considered interchangeable for the example subdistrict.

TABLE 5 FUEL CONSUMPTION RATES FOR FIVE TYPES OF EQUIPMENT FOR DIFFERENT ACTIVITIES INCLUDED IN THE OPTIMIZATION MODEL (gal per production unit/mpg) *(1)*

Activity Code	Activity Name	Unit of Measurement	Pickup Truck	Pickup Crew Cab	Utility Truck	Dump Truck	Do-All Truck
201	Shallow patching	Tons of mix	3.66/7.35	2.69/6.67	–	4.78/3.17	3.71/3.08
205	Seal coating	Lane miles	1.10/9.00	2.42/4.40	–	8.03/4.14	–
207	Sealing cracks	Lane miles	2.89/4.33	3.07/5.75	–	6.15/2.17	6.55/2.36
210	Spot repair of unpaved shoulders	Tons of aggregate	0.21/8.24	0.54/5.27	–	0.93/2.74	0.76/6.20
212	Clipping unpaved shoulders	Shoulder miles	4.32/7.31	4.11/8.05	–	10.25/2.95	–
221	Machine mowing	Swath miles	0.36/7.10	0.48/7.92	–	1.60/4.30	0.80/2.88
231	Clean and reshape drainage structures	Linear feet	0.01/6.68	0.02/6.82	–	0.05/2.84	–
235	Cleaning minor drainage structures	No. of structures	1.28/7.88	0.92/7.50	–	7.20/3.39	1.92/6.83
251	Subdistrict sign maintenance	Man-hours	1.04/10.69	0.69/9.03	1.03/7.62	–	–
283	Buildings and ground maintenance	Man-hours	0.27/10.45	0.16/7.45	–	0.43/3.35	–
284	Material handling and storage	Man-hours	–	–	–	1.35/3.84	1.54/3.80
289	Other support activities	Man-hours	0.68/11.53	0.62/8.69	–	1.37/4.68	2.00/3.52

Note: Dashes = this equipment not used for this activity.

Constrained Problem

Table 7 gives a comparison of optimal equipment assignment resulting from the model and the actual equipment use derived from the field survey data *(1)*. For the constrained case the disposable equipment days given in Table 2 formed the equipment availability constraints. It can be seen that there is a difference between estimated field equipment use and optimal equipment use. For example, in the case of crack-sealing activity, the optimal assignment was to use only pickup trucks and dump trucks instead of pickup trucks, pickup crew cabs, dump trucks, and do-all trucks as was done in the estimated field assignment.

Estimated fuel consumption by the equipment-activity combinations included in the model under the field assignment practice was 44,442 gal (Table 6), whereas fuel consumption for the optimal equipment assignment was 40,612 gal (Table 8), an 8.6 percent reduction from estimated equipment use. This

TABLE 6 FUEL CONSUMED BY FIVE MAJOR TYPES OF HAULING EQUIPMENT FOR THE 12 MAJOR ACTIVITIES IN THE FOWLER SUBDISTRICT

Activity Code	Fuel Use by Type of Equipment per Activity[a] (%)						Total Fuel Used by All Types of Equipment[b] (gal) on OSH	Fuel Used by the Five Types of Equipment (gal) on OSH
	1	2	8	9	10	Total		
201	4.17	33.70	–	49.54	5.07	92.5	7,150	6,614
205	1.29	2.84	–	84.88	–	89.0	8,090	7,200
207	6.58	14.91	–	46.78	16.04	84.3	4,330	3,650
210	7.33	9.04	–	21.63	47.01	85.0	1,410	1,199
212	6.95	4.67	–	64.96	–	76.6	3,960	3,033
221	3.20	28.80	–	8.30	0.59	40.9	2,940	1,202
231	2.32	7.82	–	58.18	–	68.3	9,110	6,225
235	24.86	8.45	–	32.13	2.02	67.5	1,380	932
251	18.35	2.03	79.77	–	–	100.0	2,350	2,350
283	6.57	3.89	–	29.70	–	40.2	6,340	2,549
284	–	–	–	47.17	6.13	53.3	7,580	4,040
289	4.80	3.23	–	35.65	10.41	54.1	10,070	5,448
Total								44,442

Note: 1 = pickup truck, 2 = pickup crew cab, 8 = utility truck, 9 = dump truck, and 10 = do-all truck. Dashes = this equipment not used for this activity.

[a] Computed using data found in Sharaf et al. *(1)*.

[b] From Table 1.

TABLE 7 ESTIMATED FIELD EQUIPMENT ASSIGNMENT VERSUS OPTIMAL EQUIPMENT ASSIGNMENT (in equipment days)

	Estimated Field Assignment[a] for Equipment Type					Optimal—Constrained—for Equipment Types					Optimal—Unconstrained—for Equipment Types				
Activity	1	2	8	9	10	1	2	8	9	10	1	2	8	9	10
201	22	237	–	196	26	0	258	–	0	221	0	258	–	0	221
205	11	11	–	99	–	22	0	–	99	–	22	0	–	99	–
207	39	84	–	131	42	123	0	–	174	0	123	0	–	174	0
210	19	9	–	13	33	28	0	–	0	46	28	0	–	0	46
212	20	14	–	80	–	35	0	–	81	–	0	35	–	81	–
221	12	79	–	7	1	99	0	–	0	0	99	0	–	0	0
231	24	40	–	120	–	64	0	–	120	–	64	0	–	120	–
235	13	6	–	3	1	0	23	–	0	0	0	23	–	0	0
251	28	5	121	–	–	0	154	0	–	–	0	154	0	–	–
283	48	48	–	137	–	0	96	–	137	–	0	96	–	137	–
284	12	3	–	164	19	–	–	–	182	0	–	–	–	182	0
289	58	43	–	214	43	53	48	–	257	0	0	101	–	257	0
Total	306	579	121	1,165	165	424	579	0	1,050	267	336	667	0	1,050	266

Note: 1 = pickup truck, 2 = pickup crew cab, 8 = utility truck, 9 = dump truck, and 10 = do-all truck. Dashes = this equipment not used for this activity.

[a] Estimated using data found in Sharaf et al. *(1)* and Report MM–113 *(8)*.

reduction is substantial because the fuel consumed by the activities considered in the model accounts for only about 60 percent of the total fuel consumed in routine maintenance at the state level. Therefore, if other activities were included in the model, the estimation of the amount of fuel saved would increase even if the percentage reduction remained the same. A simple multiplication of the number of subdistricts (37 subdistricts in Indiana) by the reduction of this example can mean a savings of approximately 141,710 gal of fuel every year. This could amount to about $106,283 in cost savings every year if fuel cost is assumed to be $0.75/gal. Table 8 also gives the activities that would use less or more fuel in the optimal case than in field assignment.

Table 9 gives the available equipment days and the consumed equipment days for each type of equipment for both the estimated field equipment assignment and the optimal equipment assignment. It is evident that the model can determine critical types of equipment as well as redundant types of equipment. This information can help determine which types of equipment need to be added to or removed from the current fleet. For example, the most critical type of equipment for this subdistrict is pickup crew cab. The other four types considered in the model are sufficient to meet the needs of this subdistrict for carrying out regular maintenance activities. Equipment days available for do-all trucks greatly exceed actual demand. The reason for this is that most do-all trucks are kept for snow and ice removal work in winter, and the model did not include this emergency activity.

Unconstrained Problem

To check how much fuel could be saved if all needed equipment were available, an unconstrained case was analyzed.

TABLE 8 FUEL CONSUMED BY EACH ACTIVITY UNDER THREE EQUIPMENT ASSIGNMENT SCENARIOS

Activity Code	Estimated Field Assignment (gal)	Optimal Assignment for Constrained Case (gal)	Optimal Assignment for Unconstrained Case (gal)
201	6,614	5,738 (–876)	5,738 (–876)
205	7,200	7,078 (–122)	7,078 (–122)
207	3,650	3,568 (–82)	3,568 (–82)
210	1,199	1,063 (–136)	1,063 (–136)
212	3,033	3,043 (+10)	3,020 (–13)
221	1,020	792 (–410)	792 (–410)
231	6,225	5,827 (–398)	5,827 (–398)
235	932	432 (–500)	432 (–500)
251	2,350	1,602 (–748)	1,602 (–748)
283	2,549	2,376 (–173)	2,376 (–173)
284	4,040	3,981 (–59)	3,981 (–59)
289	5,448	5,112 (–336)	5,073 (–375)
Total	44,442	40,612 (–3,830)	40,550 (–3,892)

Note: Values in parentheses are the difference between estimated fuel consumption and fuel consumption under optimal equipment assignment.

TABLE 9 EQUIPMENT DAYS USED BY EACH TYPE OF EQUIPMENT UNDER THREE EQUIPMENT ASSIGNMENT SCENARIOS

			Equipment Days Used		
			Estimated		
Equipment	Type of	Available Equipment	Field	Optimal Assignment	
No.	Equipment	Days	Assignment	Constrained	Unconstrained
1	Pickup truck	940	306	424	336
2	Pickup crew cab	579	579	579	667
3	Utility truck	139	121	0	0
9	Dump truck	1,165	1,165	1,050	1,050
10	Do-all truck	1,473	165	267	267

Table 7 gives the equipment assignment obtained by the unconstrained version of the optimization model. The unconstrained equipment assignment is somewhat different from both the field assignment and the constrained assignment. Fuel consumption for the unconstrained optimal assignment resulted in 40,550 gal, as given in Table 8. There could be as much as an 8.8 percent reduction from estimated current fuel consumption. However, because there was only one critical type of equipment, pickup crew cab, the difference in total fuel consumption between the constrained and the unconstrained assignments was only about 0.2 percent for this subdistrict.

Sensitivity Analysis

A sensitivity analysis is recommended when any type of equipment is found to be critical for equipment assignment. Critical types of equipment can be identified by examining the results of the constrained and unconstrained versions of the optimization program. The objective of the sensitivity analysis is to determine explicitly the impact of each type of equipment on overall fuel consumption. In the sample problem, only the pickup crew cab was found to be critical. Adding an extra pickup crew cab to the current fleet of the subdistrict would help conserve fuel; however, the marginal fuel savings is only 0.2 percent. In other subdistricts, the marginal fuel savings might be substantial if one or two types of equipment were available. In such situations, it may be beneficial to borrow the necessary units from other subdistricts as needed.

Importance of Input Data

The validity of the results of the optimization technique developed in this study is largely dependent on the accuracy of the input data. Three types of information are critical: *(a)* equipment usage factors, *(b)* fuel consumption rates, and *(c)* interchangeability of types of equipment.

Currently, usage factors obtained from the field survey *(1)* are average usage factors of six subdistricts selected for the survey. Therefore they may not necessarily reflect exactly the equipment usage pattern of a particular subdistrict. There is also a problem of time lapse between the period (FY 1982) when the field data were taken for computing equipment usage factors and the study period (FY 1984).

Fuel consumption rates are probably the input that most affect the accuracy of the results. Fuel consumption rates for all equipment types are given in gallons per production unit. These rates are greatly affected by the condition of job sites, even within each activity. Hauling distance and the manner in which equipment units are used can also substantially affect the fuel requirement for one unit of production. Fuel consumption rates now available are average values for the six subdistricts used for the field survey *(1)*. To increase the accuracy of the results for a particular subdistrict, it is recommended that each subdistrict monitor fuel consumption rates for its own fleet.

Interchangeability of equipment can be found by observing crew-day cards and by field observation. In the example, it was assumed that the interchangeability observed in the period when the field survey was done had remained the same for the study period. However, equipment interchangeability may alter over the years. Such alterations need to be taken into account before the optimization program is run.

The problems of usage factors, fuel consumption rates, and interchangeability of equipment types can be resolved by regularly updating the equipment use and fuel consumption data. Any changes in equipment interchangeability can be evaluated by examining updated equipment usage factors. The only data that are not currently recorded on crew-day cards are fuel consumption data. If the fuel consumption data were kept current, IDOH would be in a better position to maintain close control of its fuel conservation programs.

CONCLUSIONS

The example discussed in this paper demonstrated the usefulness and efficiency of the maintenance equipment assignment technique developed in the study. The technique allocates equipment to various maintenance activities within given constraints on resources and maintenance requirements.

Because this technique treats the equipment assignment problem from a macroscopic view, it will not be affected by fluctuations in equipment use due to various conditions pertinent to equipment scheduling, such as weather and equipment breakdowns. The technique is capable of dealing with a large number of activities and a variety of types of equipment. Fuel reduction will not, of course, be attained unless interchangeable equipment types or units exist, because minimized fuel consumption is basically the result of substituting one type of equipment for another. Use of such an optimization technique in highway maintenance equipment management is considered potentially feasible.

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