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Contents

OPTIMUM AXLE-LOAD LIMITS IN OMAN
Yuichiro Motomura 1

EVALUATION OF PATCHING IN CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS
Darrell J. Maxey, Michael I. Darter, and Scott A. Smiley 9

EVALUATION OF HIGHWAY MAINTENANCE COST AND ORGANIZATION IN PENNSYLVANIA
David J. Sallack and Stephen M. Greecher, Jr. 17

HIGHWAY QUALITY AND MAINTENANCE: CONCEPTS AND QUANTIFICATION
John G. Schoon 25

A SYSTEMS APPROACH TO MAINTENANCE STATION LOCATION
G. L. Russell, D. E. Mosier, and J. M. Carr 32

SYSTEMATIC DEVELOPMENT OF A HIGHWAY MAINTENANCE SIMULATION MODEL
James M. Pruett and Ertan Ozerdem 38

COUNTYWIDE TRAFFIC SIGNAL MAINTENANCE PROGRAM
Dennis A. Randolph and Tapan K. Datta 44

PRIORITY ASSIGNMENT FOR BRIDGE DECK REPAIRS
Robert G. Tracy 50

SOLAR ENERGY: HEDGE AGAINST THE FUTURE (Abridgment)
Joanne S. Orr 55

Optimum Axle-Load Limits in Oman

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The cost of highway maintenance and construction increases as the axle loading increases, whereas the cost of cargo transport decreases as axle loading increases because fewer trips are needed to transport a given amount of cargo. Each country has its own specific optimum axle-load limit that produces the lowest total cost in highway maintenance and construction and in cargo transport. An analysis was performed, for a developing country, wherein existing axle-load distribution patterns were modified in a specific manner to devise estimated distribution patterns under various axle-load limit alternatives. Subsequent changes in traffic volumes were also estimated. Pavement maintenance and construction requirements were estimated on the basis of total equivalent number of standard axles, for which costs of combined total and relative levels were examined. Some conclusions are (a) that for a given highway the optimum limit exists only for a range of intermediate traffic levels (for the low and high traffic levels, no-limit case always yields the least total cost), (b) that although the total cost may not vary significantly by axle-load limits, public and private sectors share the total cost in considerably different proportion under different axle-load limits, and (c) that an axle-load limit may have significantly different effects on different types of vehicles.

Paved highways are being constructed at a quickening pace in many developing countries, which has made maintenance needs and expenditures increase accordingly.

A phenomenon frequently observed in developing countries is overloading of trucks. The necessity for controlling such axle-loading practices is clear. However, given prevailing economic considerations, the problem is more complex than it may at first seem. On the one hand, if heavier loads are permitted, fewer trucks will be needed and less trips will be required to transport a given amount of cargo. The cost of cargo transport borne by the trucking industry will thus decrease, and, theoretically, if a competitive market exists, the resulting benefit will spread from truckers to shippers and eventually to consumers. On the other hand, heavier loading increases the cost of maintenance or shortens the life of pavement. A subordinate issue here is the allocation of the total cost. Generally, the cost of road maintenance and construction is borne by the public sector, while most direct transportation costs are paid by the private sector. Therefore, the axle-load limit can be a way of allocating expenses between the public and the private sectors.

Each country, with its existing and planned highways, transport and other industries, agricultural and mineral production, and predicted freight volume, has its own specific optimum axle-load limit that results in the lowest total cost in highway maintenance and construction and in cargo transport.

In a study conducted for the government of the Sultanate of Oman, various elements relating to axle-load limitations were considered and recommendations were made. This paper presents an analysis of such limits based on this study. A practical method for analyzing the quantifiable aspect of the problem is presented.

METHOD

Effects of axle-load limit alternatives were identified as changes in the predicted vehicle fleet composition and the axle-load distribution pattern extrapolated from the existing situation. It was assumed that the same amount of total cargo would have to be transported in any case. These estimated axle-load distribution patterns and vehicle fleet compositions were then converted into two separate sets of data: The number of passes of 80-kN (18 000-lbf) standard axles whose effect was equivalent to the effect of actual axle loads on the pavement and traffic volumes for each vehicle type with its average loadings. The maintenance and construction costs were derived from the former; the vehicle operating costs were derived from the latter.

A study period of 20 years was chosen. All highways were assumed to be maintained, on the average, in fair condition throughout the study period. Since automobile and pickup traffic was found to have practically no effect on pavement life, only heavy-vehicle traffic was considered.

Characteristics of Heavy-Vehicle Traffic

Axle-load distribution patterns in Oman were obtained for single and tandem axles for each of three vehicle types. Figures 1 and 2 show these and comparable data for the United States (1) and the United Kingdom (2). It should be noted that axle loadings are substantially higher in Oman than in the other countries, particularly the United States, and that in the United Kingdom tandem axles are regarded as two single axles for commercial vehicles. Table 1 summarizes the characteristics of heavy-vehicle traffic.

Pavement Strength and Maintenance Requirements

The analysis of pavement strength and maintenance requirements was carried out solely on the basis of design parameters by using the method recommended for design purposes in the AASHO Interim Guide for Design of Pavement Structures (3).

The damaging power of axle loads is often expressed in terms of equivalent standard axles of 80 kN (18 000 lbf). The AASHO method calls for applying separate sets of factors to single and tandem axles in order to convert axle loads to equivalent standard axles. Two single axles, each carrying a load W, are treated as causing 40 percent more damage than a tandem axle carrying a load of 2W.

It should be noted that there is some uncertainty concerning the tandem-axle conversion factors. The Transport and Road Research Laboratory has recommended that all axles be considered as single axles on the grounds that empirical results are not conclusive and that the loads of each axle of a tandem axle might differ greatly.

In this study, however, the AASHO method was applied without modification.

Pavement life can be expressed as a function of the structural number (SN) of the pavement; the initial traffic number (ITN), which varies depending on the legal axle load limit; and the traffic growth rate. The difference between the SN that corresponds to the pavement life 10 years beyond the existing pavement life and the SN of existing pavement at the end of its life indicates the required SN for an overlay meant to extend the life of the pavement an additional 10 years. The SN of a pavement at the end of its life is assumed

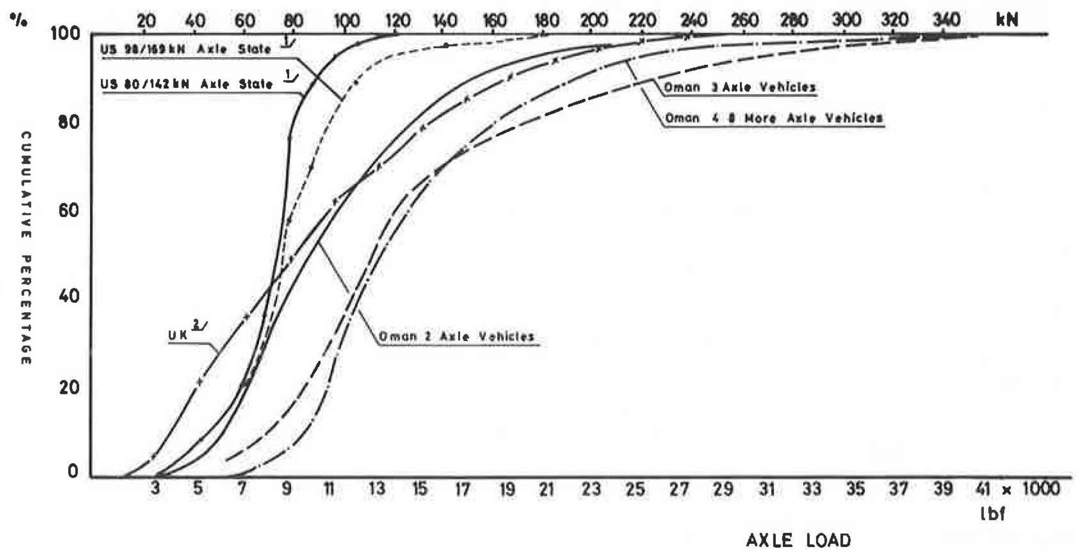


Figure 1. Axle-load distribution for single axles.

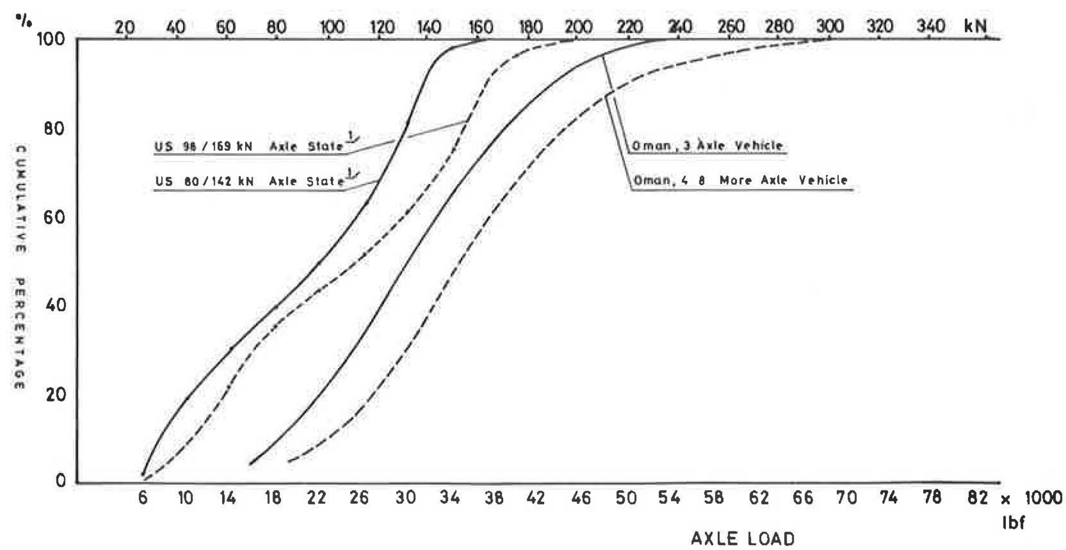


Figure 2. Axle-load distribution for tandem axles.

Table 1. Characteristics of heavy-vehicle traffic in Oman.

Characteristic	Vehicle Type by No. of Axles		
	Two Axles	Three Axles	Four Axles and More
Heavy-vehicle traffic, % of total	68	11	21
Average no. of axles per vehicle			
Single	2	2.13	1.53
Tandem	-	0.43	1.51
Average axle load			
Single, kN	48.0	64.7	66.6
Tandem, kN	-	130.3	158.7
97 percentile axle load			
Single, kN	100.9	146.0	115.6
Tandem, kN	-	216.5	266.5
Average curb weight, t	7.7	12.5	19.6
Average gross weight, t	9.9	19.8	34.8
Average payload, t	3.2	7.3	15.2

Note: 1 kN = 225 lbf; 1 t = 1.1 ton.

to be 80 percent of the SN at the beginning of its life.

The lengths of pavement lives were computed for various parameters. Examples of results were illustrated in Figure 3. Such figures were used to determine overlay thickness as well.

It should be noted that this procedure describes pavement life only from the viewpoint of structural strength. This structural life can be considerably shortened by a factor such as the intrusion of water through neglected cracks. Thus surface treatment, such as seal coating before overlaying, is necessary in order to attain the full structural life. It was assumed in this study that on the average these seal coats would be required two-thirds of the way through a pavement's life.

After an investigation of experiences in other countries that have similar conditions, it was assumed that 40 m^2/km (77 yd^2/mile) of surface would be patched just before the overlay or the seal-coat operation.

It was further assumed that the area needing to be patched annually in the intervening years would be proportional to the cumulative traffic level up to that year. It was assumed that a seal coating would bring the pavement back to such a condition that the area needing patching would increase during the subsequent years until it reaches 40 m^2/km again at the year of overlay. It was assumed that base repair was required in 50 percent of the patch work.

Unit Costs of Pavement Maintenance and Vehicle Operation

The cost of pavement maintenance depends on various

Figure 3. Pavement design life for an interior road.

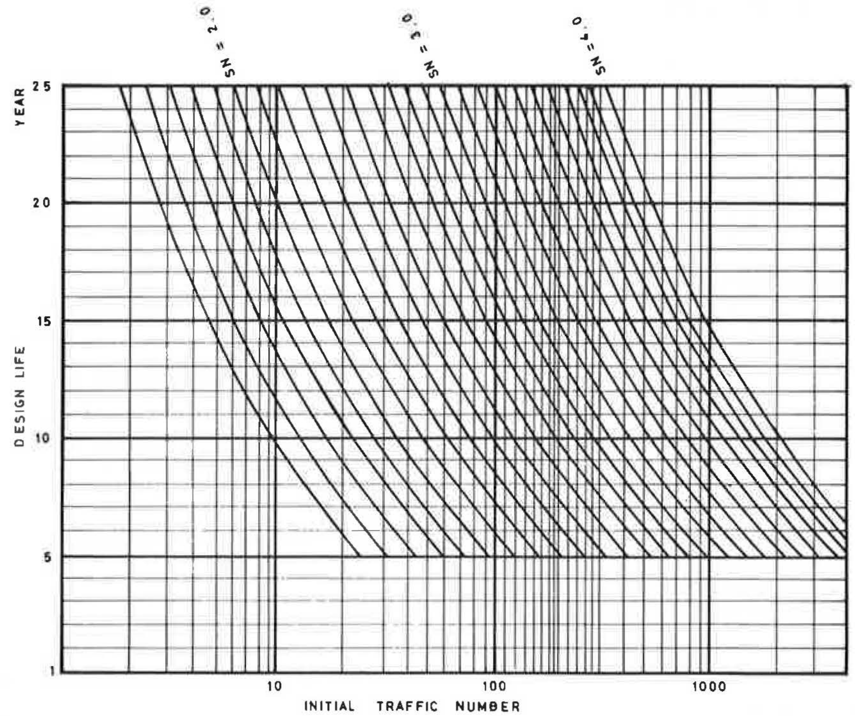


Table 2. Average vehicle characteristics and operating costs.

Vehicle Type	Operating Speed (km/h)	Costs per Vehicle Kilometer ($): Fully Loaded	Costs per Vehicle Kilometer ($): Empty	Load Limit Single/Tandem (kN)	Average Load Condition: Load Factor	Average Load Condition: Vehicle Kilometer Costs ($)	Average Load Condition: Ton-Kilometer Costs ($)
Two axles, capacity 7.2 t	60	0.376	-	78/147	0.327	0.338	0.144
				98/181	0.409	0.342	0.116
				118/216	0.447	0.345	0.107
				137/255	0.447	0.345	0.107
				157/294	0.447	0.345	0.107
				No limit	0.447	0.345	0.107
	70	-	0.319	-	-	0.319	-
Three axles, capacity 12 t	60	0.487	-	78/147	0.189	0.423	0.186
				98/181	0.327	0.433	0.110
				118/216	0.468	0.445	0.079
				137/255	0.577	0.453	0.066
				157/294	0.608	0.456	0.062
				No limit	0.608	0.456	0.062
	70	-	0.407	-	-	0.407	-
Four axles and more, capacity 19 t	50	0.574	-	78/147	0.215	0.501	0.123
				98/181	0.442	0.522	0.062
				118/216	0.640	0.541	0.044
				137/255	0.771	0.553	0.038
				157/294	0.800	0.556	0.037
				No limit	0.800	0.556	0.037
	60	-	0.481	-	-	0.481	-

Note: 1 km/h = 0.6 mph; 1 kN = 225 lbf; 1 km = 0.62 mile; 1 t = 1.1 ton.

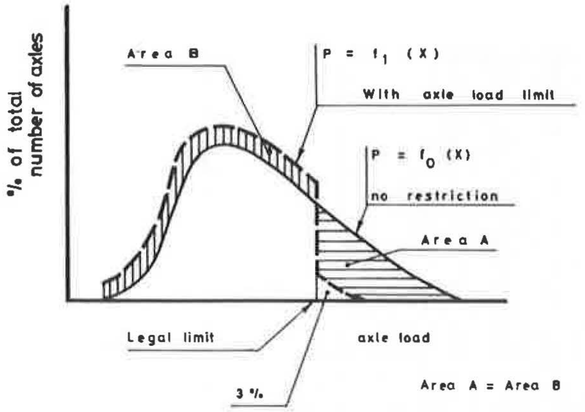
factors. The unit cost of overlay is roughly proportional to its thickness. Average unit costs (1 m^2 = 1.2 yd^2; 1 mm = 0.039 in) of pavement maintenance are shown below.

Maintenance Activity	Cost ($\$/m^2$)
Overlay: Supply and lay 40-mm wearing course	7.25
Seal coats: Clean existing surface dressing and add one coat spray and chipping	2.12
Pothole patch and base repair: Cut out existing wearing course and base course and supply and lay base and wearing course (base-course repair is applied to only 50 percent of the total area)	31.9

In the study, the difference in construction costs by axle loading is interpreted as the difference in construction costs of different thicknesses of wearing course on top of the base course and the subbase course with fixed thicknesses. This simplification was possible because available construction methods were very limited in Oman. Thus the procedure for arriving at cost differences by axle-load limit is the same as that applied for overlays except that the life of each new highway is assumed to be 20 years.

Vehicle operating cost items considered were fuel, motor oil, tires and tubes, maintenance, depreciation, interest, insurance, driver's salary, vehicle taxes, and license fee. The latter two are included here as a substitute for the unknown economic cost of administration. Table 2 summarizes the results.

Figure 4. Assumed change in distribution pattern.



EFFECT OF AXLE-LOAD LIMIT ON TRAFFIC

Imposing axle-load limits on vehicle traffic can have many effects, two of which can readily be identified. First (case A), the weight of the individual payload of each truck is reduced, which shifts the axle-load distribution pattern of each vehicle type downward. This shift naturally forces truckers to make more trips in order to haul the same amount of cargo, which in turn increases total traffic volumes of each vehicle type. Second (case B), the use of certain types of vehicles that have more economical advantages is encouraged, while the use of other vehicles is discouraged. This results in a change in traffic composition. The degree of change is very difficult to predict, however, because it cannot be determined by historical records. For the purpose of quantitative analysis in this study, two sets of assumptions were adopted.

Case A

In case A, it was assumed that only the first type of change would occur and that amounts of cargo that could no longer be transported in one trip would be transported by an additional trip by a vehicle of the same type. This is a realistic assumption, considering the strong linkage between commodity types and the kinds of vehicles that transport them.

In the absence of shippers and truckers who possess weighing scales, the most likely change in the axle-load distribution pattern would be the redistribution of excess percentages throughout the range under the limit: Each trucker would try to load the vehicle without exceeding the limit and would sometimes break up a consignment into two vehicle loads. It was assumed that this change in distribution pattern would result in the even redistribution of excess percentages over the entire range under the limit.

It is unrealistic to assume that no operator will violate the limit. A study conducted in the United States reported that 2.9 percent of vehicles sampled had axle loads in excess of the legal limits. In the present study it was assumed that 3 percent of the total number of axles of each type were exceeding the limit.

Figure 4 illustrates the foregoing discussion. If it can be assumed, in addition, that tare weights of each vehicle type will not significantly change, a change in axle load should correspond directly to a change in average payload in each vehicle category. If

$$\bar{x}_{k1} = (1/a)x_{k0} \qquad (1)$$

then

$$\bar{w}_1 = (1/a)\bar{w}_0 - w[1 - (1/a)] \qquad (2)$$

where

$\bar{x}_{k1}$ and $\bar{x}_{k0}$ = average axle loads of number k axle with and without limit, respectively;
$\bar{w}_1$ and $\bar{w}_0$ = average paylods with and without limit, respectively; and
w = the average vehicle tare weight.

By assumption, the total amount of cargo transported by each type of vehicle remains the same regardless of the limit, so

$$\bar{w}_1 N_1 = \bar{w}_0 N_0 \qquad (3)$$

where N_1 and N_0 are the total number of vehicles in this category with and without the limit.

Therefore

$$N_1 = (\bar{w}_0/\bar{w}_1)N_0 \qquad (4)$$

Case B

The excess cargo that can no longer be transported by the same number of vehicles in a vehicle category due to an axle-load limit is to be borne by the next larger category. Overloading is probably caused by large consignment sizes, so these excess cargos are likely to be transported by larger vehicles.

Let $\bar{w}_{j0}$ and N_{j0} stand for the average payload and the total number of vehicles, respectively, for the vehicle category j for the case without the axle-load limit. Let $\bar{w}_{j1}$ and N_{j1} be the average payload and the number of vehicles, respectively, for the case with the axle-load limit. The subscript j is in the ascending order of vehicle size.

The $\bar{w}_{j1}$ can be derived from $\bar{w}_{j0}$ and axle-load distribution patterns as shown in the discussion of case A. The N_{j1} can be expressed as follows

Vehicle Category	Total Cargo	Total No. of Vehicles	Excess Cargo
1	$N_{10}\bar{w}_{11}$	N_{10}	$N_{10}(\bar{w}_{10} - \bar{w}_{11})$
2	$N_{20}\bar{w}_{21} + N_{10}(\bar{w}_{10} - \bar{w}_{11})$	$N_{20} + N_{10} \times [(\bar{w}_{10} - \bar{w}_{11}) \div \bar{w}_{21}]$	$N_{20}(\bar{w}_{20} - \bar{w}_{21})$
3	$N_{30}\bar{w}_{30} + N_{20}(\bar{w}_{20} - \bar{w}_{21})$	$[N_{30}\bar{w}_{30} + N_{20} \times (\bar{w}_{20} - \bar{w}_{21})] \div \bar{w}_{31}$	0

The ratio of total numbers of vehicles with a limit to those without a limit can be expressed as follows: For vehicle category 1 the ratio is 1.0; for category 2 it is $1 + (N_{10}/N_{20})[(\bar{w}_{10} - \bar{w}_{11})/\bar{w}_{21}]$; and for category 3 it is $(\bar{w}_{30}/\bar{w}_{31}) + (N_{20}/N_{30})[(\bar{w}_{20} - \bar{w}_{21})/\bar{w}_{31}]$.

Five combinations of maximum axle-load limits for single axle and for tandem axle were stipulated: 78/147 kN (17 600/33 000 lbf), 98/181 kN (22 000/41 000 lbf), 117/215 kN (26 000/48 500 lbf), 140/255 kN (31 000/57 000 lbf), and 157/294 kN (35 000/66 000 lbf) (the first number in each pair is for single axles and the second number for tandem axles). Axle loads of single and tandem axles for the same combination give roughly the same AASHO load-equivalency factors.

Axle-load distribution patterns were established for each of the stipulated axle-load limits by modifying the existing patterns in accordance with the method described above. If a limit fell within a range exceeding

Table 3. Traffic increase factors.

Legal Axle-Load Limit Single/Tandem (kN)	Traffic Increase Factor					
	Two Axles		Three Axles		Four Axles and More	
	Case A	Case B	Case A	Case B	Case A	Case B
78/147	1.37	1.0	3.22	3.21	3.72	4.34
98/181	1.09	1.0	1.86	1.40	1.81	2.01
118/216	1.0	1.0	1.30	1.0	1.25	1.32
137/255	1.0	1.0	1.05	1.0	1.04	1.05
157/294	1.0	1.0	1.0	1.0	1.0	1.0
No limit	1.0	1.0	1.0	1.0	1.0	1.0

Note: 1 kN = 225 lbf.

Table 4. Average vehicle operating costs by load limit.

Legal Axle-Load Limit Single/Tandem (kN)	Costs per Vehicle Kilometer ($)		
	Two Axles	Three Axles	Four Axles and More
78/147	0.338	0.423	0.501
98/181	0.342	0.433	0.522
118/216	0.345	0.445	0.541
137/255	0.345	0.453	0.553
157/294	0.345	0.456	0.556
No limit	0.345	0.456	0.556
Empty	0.319	0.407	0.481

Note: 1 kN = 225 lbf; 1 km = 0.62 mile.

Table 5. Average vehicle load-equivalency factors.

Legal Axle-Load Limit Single/Tandem (kN)	Vehicle Load-Equivalency Factor		
	Two Axles	Three Axles	Four Axles and More
78/147	0.518	0.665	0.882
98/181	0.830	1.149	1.686
118/216	1.004	1.927	2.907
137/255	1.004	2.990	4.349
157/294	1.004	3.623	4.841
No limit	1.004	3.623	4.841
Empty	0.118	0.270	0.447

Note: 1 kN = 225 lbf.

the 97 percentile value of the existing distribution, no modification was made, since the limit would not significantly affect the loading pattern.

Theoretically, the loading of a vehicle having both single and tandem axles can be limited by either a single or a tandem axle-load limit. If the load on one of the axles reaches the limit, this is the maximum loading condition regardless of the loads on the other axles. In other words, reducing the payload does not necessarily reduce each axle load to desired limits. To see the degree of discrepancies between reduction factors of single and tandem axles, a comparison was drawn by applying the properties of reference vehicles and average loads. The discrepancies were found to be small. Because of the variety among vehicle dimensions and weights included in each vehicle type, it was decided that axle-load distribution patterns for single and tandem axles developed independently were sufficient for the purposes of this study.

Average load-equivalency factors for each vehicle and axle type for loaded vehicles and for empty vehicles were computed as weighted averages of load-equivalency factors for each load range by percentage distribution of axle loads under each axle-load limit combination.

Load factors were then computed as ratios of average payloads to the capacities of reference vehicles. As noted previously, reduction in average payload causes a corresponding increase in traffic volume needed to transport the same amount of cargo. And, as described before with the equations for the assumed cases A and B, heavy-vehicle traffic increase factors were computed for the traffic of loaded trucks. However, it is unlikely that truckers would find cargo to carry on their return from additional trips necessitated by the load limit in Oman. It has therefore been assumed that empty-vehicle trips would increase by the same proportion.

Operating speeds of fully loaded vehicles adopted in this study were 60 km/h (38 mph) for two- and three-axle vehicles and 50 km/h (31 mph) for vehicles with four and more axles. It was assumed that empty vehicles were operated at speeds 10 km/h (6.3 mph) faster than these speeds. Average vehicle-kilometer costs corresponding to each axle-load limit for each vehicle type were developed by interpolating between fully loaded costs and empty costs by means of load factors already developed (see Table 2).

Tables 3, 4, and 5 show the computational results along with other parameters that characterize operating conditions of each vehicle type under different legal axle-load limits. These parameters were then combined by means of weighting by traffic composition percentages and empty-loaded percentages in order to reach overall averages. To see clearly the effect of axle-load limits, the base of the average load-equivalency factor was set at the level of traffic without the limit.

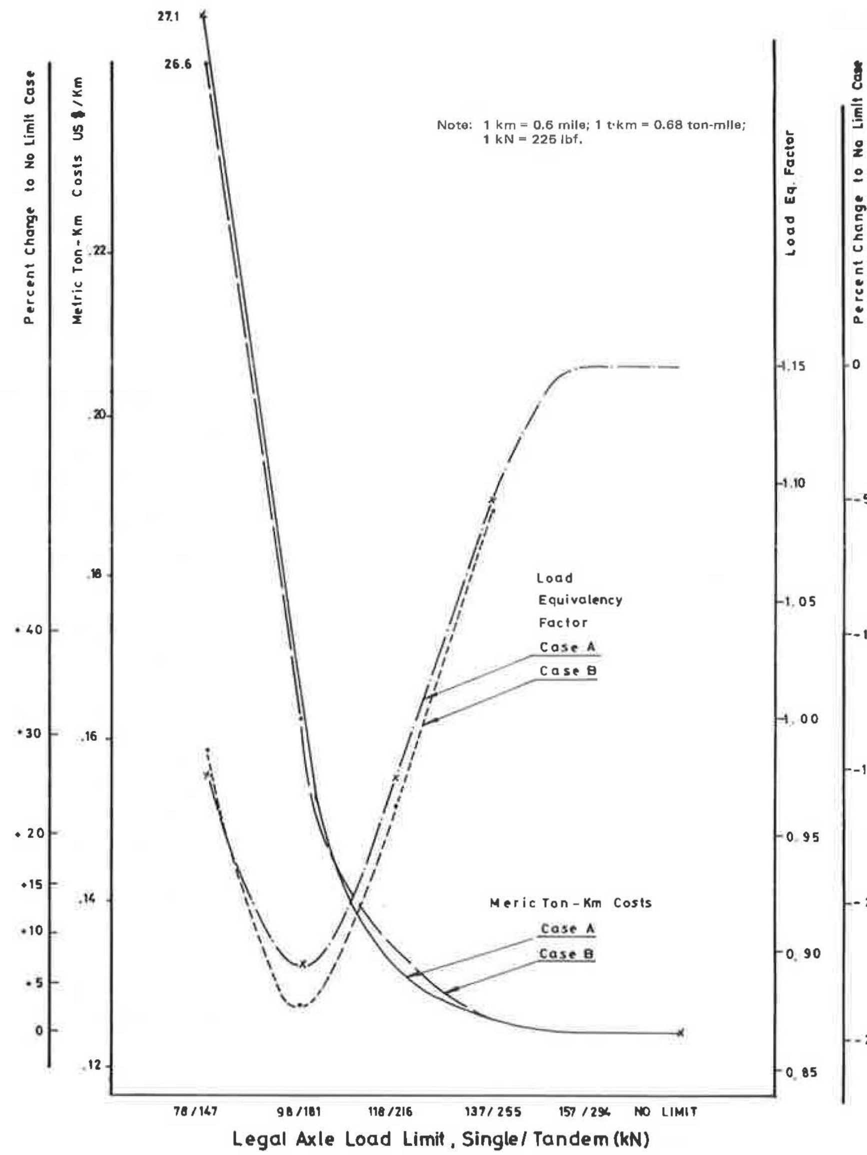
Vehicle Type	Two Axles	Three Axles	Four Axles and More
Percentage of total heavy-vehicle traffic (no limit)	68	11	21
Percentage of loaded vehicles (two-way)	47	50	52

Therefore, the difference in this average load-equivalency factor directly indicates the difference in the aggregate level of the effect that various axle-load limits have on the pavement. Figure 5 illustrates the results for the case of the average empty-loaded percentages.

Overall average metric ton-kilometer costs and average load-equivalency factors for two different assumptions regarding changes in traffic caused by axle-load limit (cases A and B) turned out to be very close. The percentage contribution to the overall value of each vehicle type differs somewhat according to the case in question, but the effects of changes in percentages for each type compensate for each other to yield similar overall values. What actually occurs is somewhere between cases A and B. It was decided, therefore, that average values of the two cases were to be used in further analysis.

It should be noted that the average load-equivalency factors actually applied in estimating the maintenance requirements of each highway link were different from

Figure 5. Overall average costs and load-equivalency factor per vehicle of no-limit case.



the values shown in Figure 5 because of concentration of loaded vehicles in one direction.

Figure 5 suggests that the limits of 78 kN (17 600 lbf) for single axles and 147 kN (33 000 lbf) for tandem axles would result in disproportionately high vehicle operating costs accompanied by an average load-equivalency factor higher than the 98/181-kN (22 000/41 000-lbf) case. This guarantees that the 78/147-kN limit cannot give the minimum total operating and maintenance cost. This phenomenon results primarily from the fact that larger vehicles have heavy axle loads when empty and that their payload must therefore be drastically reduced to meet the very low axle-load limit.

If consignment sizes of excess cargo are such that they are evenly distributed over the range under the load limit, as was assumed in this study, the relative advantage of larger vehicles decreases as the load limit is lowered.

CHARACTERISTICS OF TOTAL SYSTEM PER-KILOMETER COSTS

The costs under consideration are to be incurred over a 20-year period. Because the value of consumption at a future date is lower than the value of consumption of the same amount today, the total costs must be compared in present values, which are the sum of discounted future costs.

General characteristics of system costs were investigated on selected highways. Table 6 shows pavement data pertaining to these highways as well as others in Oman. By definition, total highway user costs are in direct proportion to the traffic level for a given traffic composition. Highway maintenance costs, however, show more complex characteristics. Figure 6 illustrates these relationships.

At very low traffic levels, fewer than 30 heavy vehicles a day, no major improvement work such as overlaying is needed within the 20-year period, resulting in low maintenance costs. As traffic levels grow, however, overlay and seal-coat operations are increasingly needed, but the percentage increase in maintenance costs is lower than the percentage increase in traffic, except at low traffic levels. The major reason for this characteristic is that the percentage increase in the strength of the pavement is more than the percentage increase in the pavement thickness, to

Table 6. Pavement data for existing highways and highways under construction.

Highway	Year Open to Traffic	Total Length (km)	Pavement Width (m)	Pavement Thickness[a] Surface (cm)	Base (cm)	Subbase (cm)	Structural Number	California Bearing Ratio	Assumed Soil Support Value
Muscat-Mutrah (new)	1978	3	14.0	AC 3	AC 16	GR 15	3.75	>30	6.5
Mutrah-Al Bustan	1976	8	7.5	AC3 3.5[b]	AC6 6.5[b]	BS 10[c]	2.17 2.34[b]		6.5
Mutrah-Seeb	1977	50	14.0-14.6	AC 4	AC 11	GR 15	3.13	min. 10	5.0
Seeb-Khatmat Al Malaha	1973-1974	263	7.0	AC 4	AC 8	GR 15	2.66	min. 10	5.0
Spur Shinas	1974	12	7.0	AC 4	AC 8	GR 15	2.66	min. 10	5.0
Mujis-Buraimi	1977	103	7.0	AC 2.5	AC 6	GR 10.5	1.87	min. 20	6.5
Buraimi-Ibri-Tana'am	1976	137	7.5	AC 6	AC 15	-	3.40	-	6.5
Seeb-Nizwa	1976	137	7.0	AC 4	AC11 7[d]	GR15 0.0[d]	3.13 2.27[d]	>30	6.5
Sumail Link	1976	4	7.0	AC 4	AC 11	GR 10	2.27	-	6.5
Bid Bid-Sur	1977	263	7.5	AC 4	AC 12	GR 7.5[e]	1.80	-	6.5
Al Musana'a-Ar Rustaq	1977	35	7.0	AC 5	CR 15	-	1.57	>30	6.5
Nizwa-Ibri	1978-1980	132	7.5	AC 4	AC 11	GR 15	3.13	>30	6.5
Mutrah-Qurayat	1979-1980	85	7.6	AC 3	AC 5	GR 15	1.87	>30	6.5
Al Bustan-Sidab	1979	5	7.6	AC 4	AC 8	GR 15	2.66	>30	6.5

Note: 1 km = 0.62 mile; 1 m = 3.3 ft; 1 cm = 0.39 in.
[a] AC = asphalt concrete, GR = CR = crushed rock, BS = bituminous subbase.
[b] Thickness in mountainous section.
[c] Bituminous subbase course equivalent to gravel 15 cm thick.
[d] Thickness in the last 29-km section.
[e] Subbase was laid for 20 percent of the total length only.

Figure 6. Costs versus traffic level for an interior road.

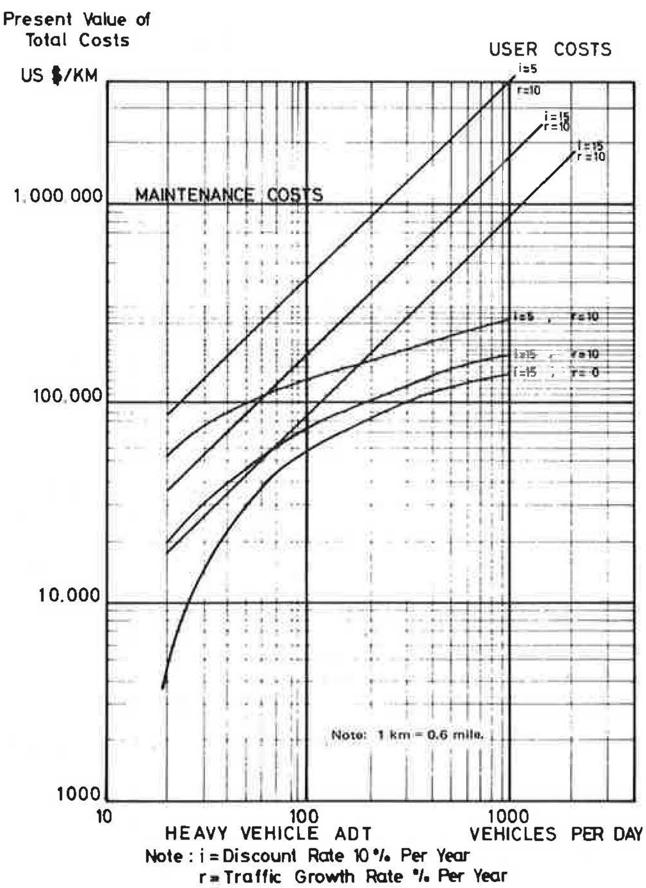
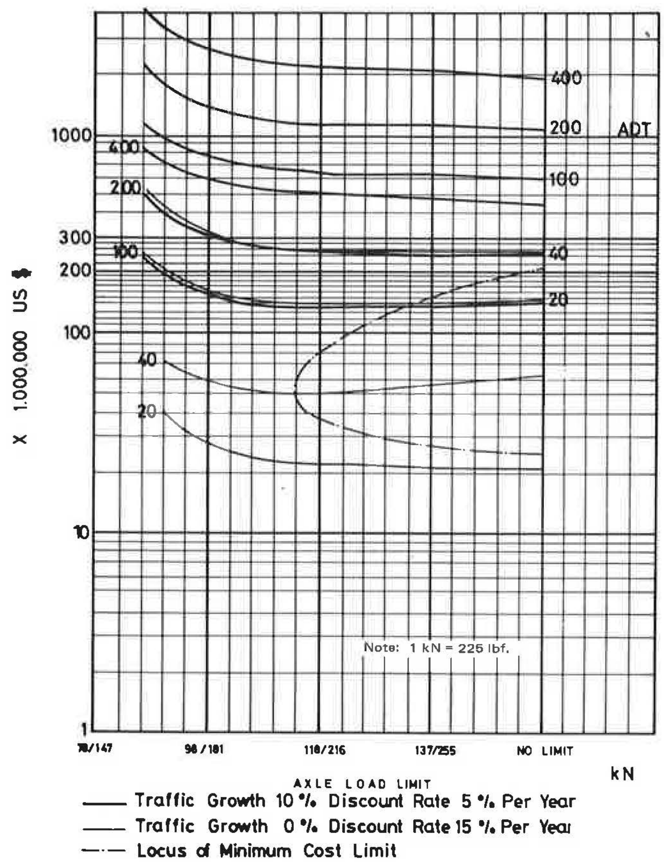


Figure 7. Present value of total system cost and minimum cost limit for an interior road.



which the overlay cost is closely related. In the range of heavy traffic, more than 200 heavy vehicles a day, the percentage of highway maintenance cost to total cost decreases rapidly as the traffic level increases.

Figure 7 illustrates costs under the presence of axle-load limit for the interior highway. Differences in total cost under different axle-load limits are generally not large. In particular, differences between the 117/215-kN (26 000/48 500-lbf) limit case, the 140/255-kN (31 000/57 000-lbf) limit case, and the no-limit case are so slight (no greater than 6 percent except in the case of 40 initial daily heavy traffic) that they are almost indistinguishable in a graphic presentation such as this one.

It was found for the interior and coastal highways in Oman that, for initial traffic levels higher than 200 heavy vehicles a day, the no-limit case always yields the least present value of total costs. Below the level of 200 heavy vehicles a day, the least-cost limit tends to be at the 117/215-kN limit to the 140/255-kN limit in the

Figure 8. User and maintenance costs changes by axle-load limit for an interior road.

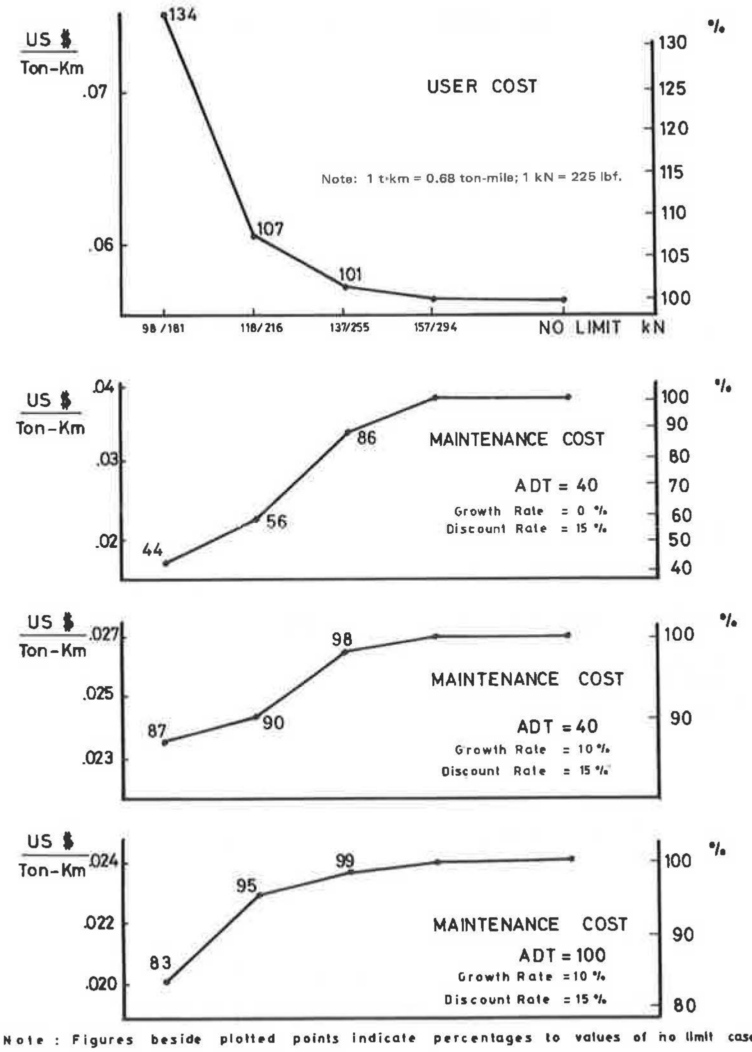


Table 7. Percentage shares of operator and user costs and percentage changes by axle load.

Share Breakdown	Legal Axle-Load Limit, Single/Tandem (kN) No Limit	137/255	118/216
Traffic growth 0 percent			
Discount rate 15 percent			
Operator cost			
Percent of total	24.3	22.8	19.6
Percent change	0	-6.5	-18.4
User cost			
Percent of total	75.7	77.2	80.4
Percent change	0	+1.5	+7.4
Total Cost			
Percent change	0	-0.5	+1.2
Traffic growth 10 percent			
Discount rate 5 percent			
Operator cost			
Percent of total	13.9	13.1	12.0
Percent change	0	-4.8	-9.4
User cost			
Percent of total	86.1	86.9	88.0
Percent change	0	+1.4	+7.4
Total cost			
Percent change	0	+0.6	+5.1

Note: 1 kN = 225 lbf.

middle range and to show an upward shift in the very low traffic range with little differences, depending on the case.

The total cost for the 98/181-kN (22 000/41 000-lbf) limit was found not to be the minimum in any case and not to be even near the minimum relative to the difference between the least-cost limit and the second-best limit. The line comprising the minimum cost points at various initial traffic levels, or the locus of the minimum cost point, appears to be on the curves shown in Figure 7.

The position of the minimum cost point depends on the relative level of the user cost, which is a decreasing function of the axle-load limit and the maintenance cost, which in turn is an increasing function of the axle-load limit. A comparison was made between differential user and maintenance costs with respect to the axle-load limit. The ratios of differential costs indicated stable minimum point characteristics against unit cost changes of up to 20 percent.

Changes in Shares of Public and Private Sectors

When the 117/215-kN limit is imposed, the share of the maintenance cost incurred mostly by the public sector is reduced by 10 percent in the medium traffic range and 20 percent in the lower traffic range. This reduction is the result of the decrease in the maintenance cost augmented by increases in user costs. Figure 8 shows changes in each total cost component.

Where the 117/215-kN limit is imposed, the user cost would increase by 7 percent, whereas the maintenance cost would decrease by about 35 percent.

System Evaluation

The total system costs were computed for two sets of parameters. Three axle-load limit alternatives were tested: the no-limit case, the 140/255-kN-limit case, and the 117/215-kN-limit case, since a limit less than the latter one would yield a considerably higher total system cost. The highway network of 1493 km (933 miles), including existing highways, highways under construction, and highways to be constructed, was divided into 32 sections. Maintenance and construction costs and user costs were estimated for each section, then added together to obtain total system costs. Table 7 summarizes the results in terms of percentage changes.

CONCLUSIONS

General conclusions drawn from the study are as follows.

1. The axle-load limit that gives the minimum total combined costs of highway maintenance and user costs depends on pavement strength and traffic level. For a given highway, the optimum axle-load limit is no limit for the very low traffic level, a certain value for the intermediate traffic level, and again no limit for the high traffic level.
2. Although the total cost may not vary significantly by axle-load limits, public and private sectors share the total cost in considerably different proportions under different axle-load limits.
3. An axle-load limit may have significantly different effects on different types of vehicles depending on their weight and current loading characteristics. Thus, it may change the relative competitiveness of vehicles and consequently that of vehicle operators.
4. The actual level of the optimum axle-load limit depends a great deal on local conditions of existing pavement strength, present and anticipated traffic, traffic composition, loading practices, and unit costs of pavement maintenance and vehicle operation. The procedure presented in this paper, however, can be applied to any country that has a sufficiently simple highway network and vehicle fleet.

ACKNOWLEDGMENT

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Evaluation of Patching in Continuously Reinforced Concrete Pavements

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An evaluation of concrete patching in continuously reinforced concrete pavements (CRCP) located in Illinois was made. Problems in designing and constructing permanent concrete patches were identified; the costs of patching were estimated; and the performance of typical patches was evaluated. Illinois has constructed over 4827 two-lane km (3000 miles) of CRCP, major portions of which are displaying increasing occurrence of distress that requires patching. Patches placed in recent years are performing inadequately. A survey of over 800 CRCP patches showed one-fourth requiring replacement and one-fifth requiring an adjoining patch. Constructing a typical 3x3.7-m (10x12-ft) patch is labor intensive, time consuming, and expensive. Between six and eight people can only place a patch a day at a cost of $1000-1600. The poor performance of many patches can be attributed to inadequate design specifications and poor construction techniques. The information in this paper can be used to improve the design specifications and construction techniques for CRCP patching. Many experimental patches have been placed and are being evaluated.

In this paper, current problems in designing and constructing permanent concrete patches in continuously reinforced concrete pavement (CRCP) are identified. In addition, the costs of patching are estimated, and the performances of typical patches are evaluated. This information can be used to improve future CRCP patches.

Illinois has now constructed nearly 4827 equivalent two-lane km (3000 miles) of CRCP, having begun constructing CRCP as a result of the excellent performance of several experimental sections in both Illinois (e.g., the Vandalia test section in 1947-1948) and other states. The excellent performance was specifically revealed in the low maintenance requirements of the pavement, that is, no joint sealing, corner breaks, blowups, or joint deterioration and very little patching.

However, in recent years CRCP in Illinois and

Figure 1. Typical edge punchout.

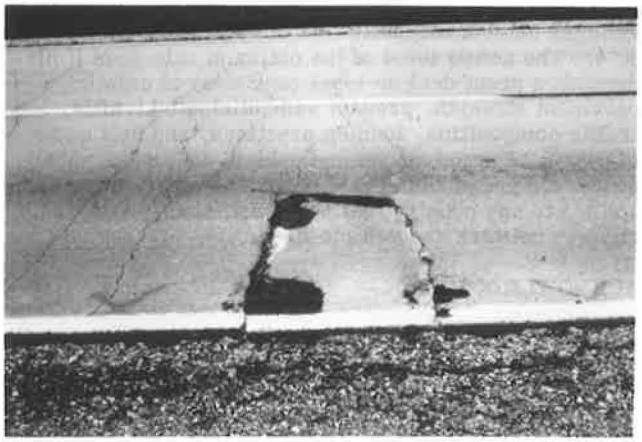


Figure 2. Effect of traffic loadings on mean edge punchouts per kilometer.

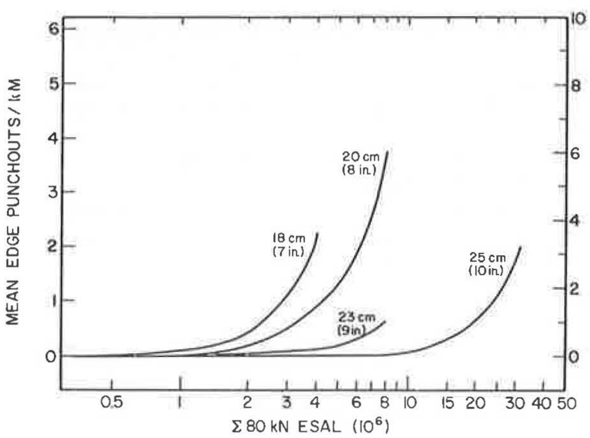
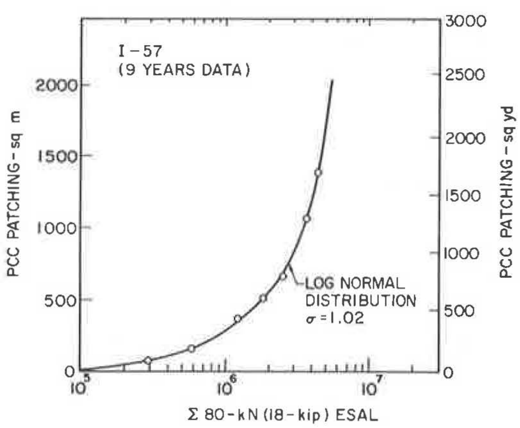


Figure 3. Cumulative patching requirements versus cumulative traffic loading.



other states has displayed increasing distress that requires permanent patches. It has also become clear that CRCP is perhaps the most difficult pavement type to repair because of its unique characteristics such as large amounts of steel and closely spaced transverse cracks. For these reasons, a research project was initiated by the Illinois Department of Transportation (IDOT) to (a) develop guidelines to assist maintenance personnel in identifying the types and causes of CRCP distress, (b) evaluate current practice and develop improved maintenance procedures and materials for repair of localized failures, (c) develop preventive maintenance procedures to reduce the rate of distress occurrence, and (d) formulate recommendations for design and construction that will reduce CRCP maintenance requirements.

This paper deals primarily with point b, evaluating current practice and developing improved maintenance procedures and materials.

CRCP DISTRESS REQUIRING PATCHING

In the initial phase of the project the types and mechanisms of distress in Illinois CRCP were studied (1). An extensive field survey was conducted of 1979 km (1230 miles) of Interstate (132 construction projects) ranging in age from 5 to 14 years. Many distress types that required pavement patching were identified.

1. Edge punchout: A block of pavement that has been depressed or punched down relative to the surrounding pavement is an edge punchout. It almost always develops at the pavement edge between two closely spaced transverse cracks (Figure 1).
2. Wide cracks: Originally tight transverse cracks widen, fault, and spall into wide cracks. Loss of aggregate interlock, corrosion, and rupture of the steel often follows.
3. Lane settlement: This entails faulting of the outside lane or separation of the two lanes at the centerline joint for a distance of 3.05-15.24 m (10-50 ft) and usually occurs along with punchouts and wide cracks.
4. Construction joint failures: The appearance near a CRCP construction joint of any of the distress types previously mentioned is such a failure. The underlying cause is poor construction techniques.
5. Blowups: A blowup is a crushing or buckling of the slab caused by thermal and moisture expansive forces. Once believed to be a nonexistent distress in CRCP, the occurrence of blowups has been increasing in recent years, especially where wide cracks exist.
6. D-cracking or reactive aggregate distress: This is a distress that originates in the concrete aggregate from undesirable chemical and physical reactions. Depending on the aggregate properties and local environment, D-cracking can eventually result in the complete disintegration of the pavement in 10-15 years.

The mechanism of development of these distress types is described in detail elsewhere (1). The importance of recognizing the various distress types and having a basic knowledge of their nature and extent cannot be understated. If properly applied, this knowledge can be used to improve the design and construction of patches. In addition, one or several of the factors causing premature patch failure may be identified and eliminated to improve patch performance.

An estimate of CRCP patching requirements, in terms of the effects of time and traffic, was determined from distress data collected from the 132 projects surveyed. A summary graph is shown in Figure 2 for 18-, 20-, 23-, and 25-cm (7-, 8-, 9-, and 10-in) CRCP. The rate of occurrence of edge punchouts for 18- and 20-cm slabs is very high. These pavements constitute a majority of the Interstate length in Illinois. It is important to note that many of the pavements have been subjected to large amounts of traffic that in many cases have exceeded the 20-year design life of the 18- and 20-cm (7- and 8-in.) slabs.

The cumulative patching requirements versus the

Figure 4. Overall performance of 831 CRCP patches in Illinois.

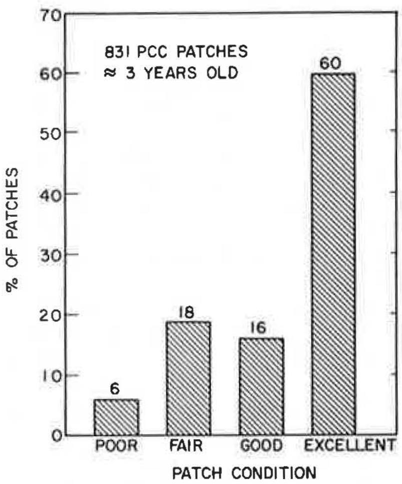
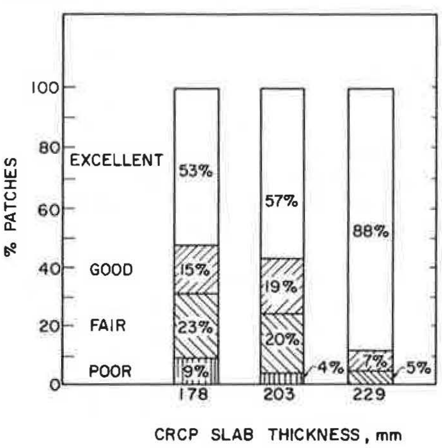


Figure 5. Performance of patches according to thickness.



cumulative traffic loadings for a given Interstate CRCP project are shown in Figure 3. The increase in patching over several years has been fitted to a log-normal distribution curve. The data indicate that distress requiring patching is greatly influenced by the fatigue damage created by large traffic loadings. Other factors, such as the environment, local pavement characteristics, and maintenance crew performance can greatly influence the amount of patching needed.

In addition to the increase in structural distress, CRCP is plagued by D-cracking in about one-sixth of the projects surveyed. Once the deterioration of the concrete pavement has progressed beyond a certain point, an extensive amount of patching is required. Many projects containing this D-cracked concrete will require major rehabilitation long before the ends of their design lives.

PERFORMANCE OF TYPICAL PATCHES IN CRCP

A field performance study of the existing patches on Interstate CRCP in Illinois was conducted. The procedures and techniques used in placing these patches will be discussed in what follows.

Nearly all of the patches surveyed were placed by either an IDOT district maintenance crew or a roving IDOT crew known as "day labor". The day labor crew travels from district to district placing patches. A few of the patches surveyed were placed by contractors repairing construction defects that appeared very early in the pavement's life. All patches placed by IDOT crews were reinforced portland cement concrete (PCC) patches.

A rating system was developed for evaluating patches on a structural basis. Each patch was evaluated and then placed in a category based on the presence of cracking, spalling, faulting, etc. In addition, records were kept of the number of patches that had severely distressed concrete adjacent to the patch. When two or more adjoining patches were found (which indicated that an adjacent distressed area had already been patched), it was counted as adjacent slab distress. Most patches surveyed were between one and seven years old, with an average of about three. As would be expected, new patches displayed fewer of the distress features. Also, some patches had been replaced one or more times. More than 800 patches located in all parts of the state were surveyed. The rating categories for PCC patches are as follows.

1. Excellent: No visible cracks are evident within the boundaries of the patch, which is smooth and flush with the adjacent pavement, and all joints are tight, although a very slight amount of joint spalling may be present in older patches.
2. Good: One or more tight transverse cracks exist within the boundaries of the patch, but no longitudinal or diagonal cracks are present and the patch is smooth and flush with the adjacent pavement. Moderate joint spalling or raveling may exist.
3. Fair: Transverse cracks within patch boundaries and joints at the patch ends display considerable spalling or faulting or both. Longitudinal or diagonal cracks that will eventually cause the patch to break up into blocks may exist. The patch may appear to rock and pump as truck loads pass over it. Replacement will probably be required within the year.
4. Poor: The patch is severely damaged and requires the removal and repatching of a major portion in the near future.

Figures 4, 5, and 6 summarize the overall results for the patch performance survey. It is interesting to note that a major proportion of the patches did not contain any cracks and were rated excellent. About one-quarter of the patches were rated fair to poor and will soon require replacement (Figure 4).

The effect of CRCP slab thickness on the patch and adjacent slab performance can be seen in Figures 5 and 6. The thinner CRCP slabs and patches exhibit more frequent occurrence of distress than the thicker slabs and patches. This seems reasonable, considering that nearly all patches were placed at the same thickness as the slab and that stresses and deflections decrease with increased slab thickness.

In summary, the data show that at least one out of every four concrete patches must be replaced with another patch and that about one out of every five patches will have adjacent slab distress that requires the construction of an adjoining patch. This high rate of patch replacement will result in excessive and unnecessary maintenance expenditures on CRCP. As will be explained, patching CRCP presents many problems not found in other pavement types.

Figure 6. Distress adjacent to CRCP patches.

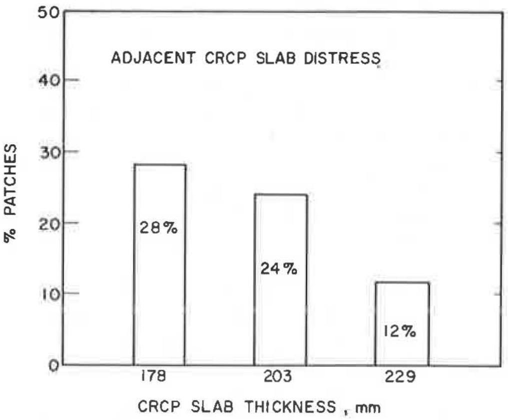
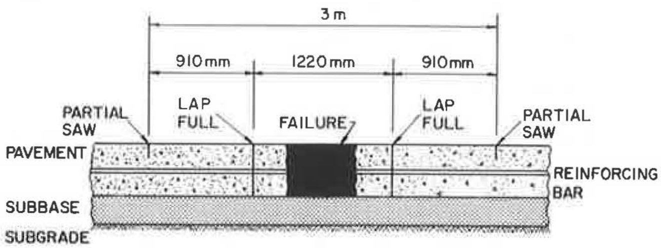


Figure 7. Section of a standard Illinois CRCP patch.



PATCHING TECHNIQUES AND COSTS

Typical Illinois Patching Procedures

Most of the IDOT maintenance crews attempt to follow a standard procedure for CRCP patching, although some have developed variations adapting to their own particular equipment, time, or crew requirements. The maintenance engineer or technician is guided by the specifications set forth in the IDOT standard specifications (2), many of which are illustrated in Figure 7. A brief list of the more important specifications dealing with CRCP patching is given below.

1. All CRCP patches must be of PCC (620.01).
2. The edges of all patches shall be sawed to a depth just above the reinforcing bar (620.05 b.1.).
3. The saw cuts shall be no closer than 45.7 cm (18 in) from an existing crack and shall not cross an existing crack (620.06 b.1.).
4. Reinforcing steel shall not be removed for patches less than 3 m (10 ft) long (620.05 b.1.).
5. For patches longer than 3 m (10 ft) (Figure 7), the steel may be cut and removed, provided that a 91-cm (36-in) length of steel is left for lap at both ends of the patch (620.05 b.2.).
6. The concrete in the area of the 91-cm (36-in) lap may only be removed by hand, so as not to damage the steel (620.05 b.2.).
7. Not more than 10 percent of the existing 91-cm (36-in) lap steel may be damaged; otherwise the patch must be lengthened (620.05 b.2.).
8. Before opening a patch to traffic, a minimum modulus of rupture of 4200 kPa (600 lb/in^2) or a compressive strength of 22 000 kPa (3200 lb/in^2) at age two days will be required (630.06 b.).

A typical patching job is performed by a district maintenance crew of from six to eight people using equipment such as a dump truck, front-end loader, air compressor, and jackhammers. Permanent patches are generally placed between April and September.

Steps in CRCP Patch Construction

From one day to several weeks before CRCP distress is to be patched, a maintenance engineer or technician surveys the project and marks off the boundaries of the distressed area. Consideration is given to the shape and size of the distressed area and to pertinent IDOT specifications (e.g., minimum distance from a crack). Regardless of the width of the distressed area, all patches are one full lane wide and 3 m (10 ft) long.

Sawing the premarked boundaries of a patch may be performed from one to several days before the actual breakout and removal of the pavement. However, some crews are able to saw the first thing in the morning and then perform the other patching operations later the same day.

The next patching operation is the removal of the distressed pavement. Removal is done in two steps: (a) the breakout and removal of the center section and (b) the breakout and removal of the end lap areas. The center section is usually broken into small pieces with jackhammers and then removed with hand tools. However, the day labor crew and some contractors have available specialized pavement-breaking equipment (drop hammers or hydrahammers) that is used on the center section (Figure 8). At least one maintenance crew completely cuts the steel around the center section and removes the pavement in one large block. A chain is then wrapped around the piece of concrete, and it is carefully lifted up and placed in a nearby dump truck.

The two end sections of the patch are supposed to be carefully broken out using only jackhammers, prying bars, picks, shovels, and other hand tools. Breaking around the reinforcing steel is a difficult, time-consuming process, especially when the required lap length is 91 cm (36 in). Because this is such a hard job, there is an irresistible urge on the part of most crews to use the drop hammers or hydrahammers to speed up their work.

After all of the distressed concrete has been removed, an attempt is made to dress and level up the subbase. Deteriorated subbases are usually not replaced with new material or compacted before placement of the concrete. If the patch was longer than 3 m (10 ft) and the old steel was removed, new reinforcing steel is installed and tied lapped to the 91 cm (36 in) of old steel to make a continuous steel connection into the adjacent slab. The new steel is matched with the existing steel in number (percentage of steel), quality, and grade. To keep the bars at the right depth in the patch, they are supported by chairs.

By this time, the patch is ready to be filled with PCC. A nearby ready-mixed concrete producer is contacted and a low-slump, seven-bag, rich mix is ordered. When the ready-mix truck arrives, the sides of the patch are wetted down in preparation for the concrete. The plastic concrete is spread from one end of the patch to the other in one lift. If a vibrator is available, it is used to consolidate the concrete around the patch ends and edges and in between the bars. The patch is then struck off, floated, and surfaced. About half the crews apply a liquid membrane-forming compound, while the rest use no curing method. Curing times range from 3 to 72 h before the patch is opened to traffic. Strength tests to determine whether the patch concrete will sustain traffic loadings are rarely conducted.

A simplified flowchart of a typical PCC patching operation is shown in Figure 9. Information concerning the durations and procedures were obtained by field checks and a questionnaire was sent to maintenance personnel in each district. The usual production rate for an IDOT maintenance crew is one large 3-m (10-ft) full-lane-width patch per day. Most crews place patches on the first three or four days of the week. The last one or two days are reserved for patch curing so that all traffic lanes can be open over the weekend. Often the maintenance crews will use this time to saw the next week's patches.

Cost of a Typical Patch

The average costs for constructing a 3x3.7-m (10x12-ft) PCC patch in CRCP are shown in Table 1. The 1977 cost data were obtained from a survey of the IDOT district maintenance engineers and from observations at several patching sites. The average cost for a patch, including traffic control, labor, equipment, and materials, was found to be \$102/m^2 (\$85/yd^2). An estimate of the range of cost (1977 prices) would be \$102-\$143/m^2 (\$85-\$120/yd^2). This results in total costs of from \$1067 to \$1600 for a single CRCP standard patch.

In summary, patching CRCP is time consuming and expensive. That current design specifications and construction techniques are inadequate is reflected by the poor performance of many patches. Much confusion exists regarding when, where, and how to properly place a CRCP patch.

Figure 8. Hydrahammer breakout and mechanized pavement removal operation.

Figure 9. Flowchart of a typical PCC patching operation.

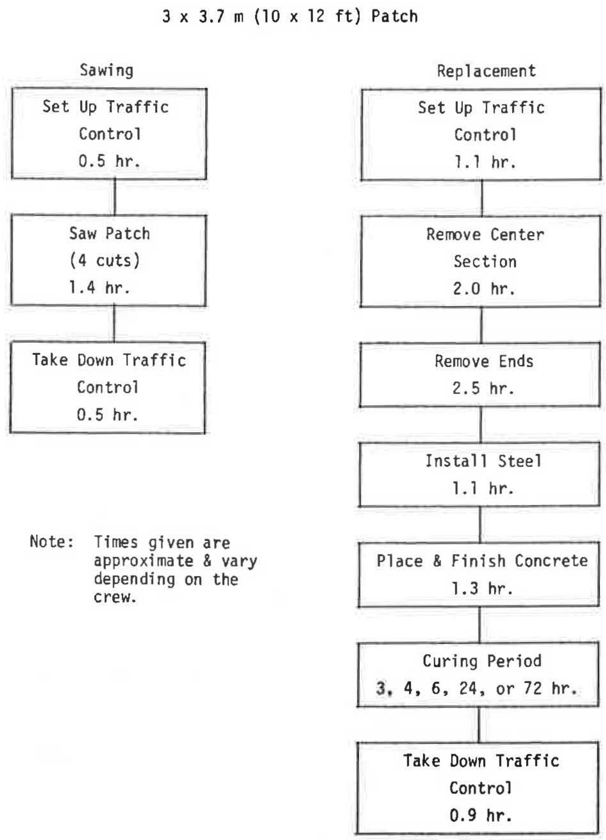


Table 1. Average costs for a typical 3.0x3.7-m (10x12-ft) CRCP patch.

Category	Costs (\$) Unit	For 3.0x3.7-m Patch	Reported Range	Percentage of Total
Traffic control				
Sawing	50/patch	50		
Set up or take down	25/time	50		
Equipment: barricades and light arrow	25/day	100		
Flagperson	60/day	60		
Subtotal		260	150-380	23
Materials				
Steel rebars	0.67/N	40		
Concrete	52.3/m^2	120		
Concrete hauling	35/truck	35		
Miscellaneous		5		
Subtotal		200	180-205	17
Equipment				
Concrete saw, dump trucks, pickup trucks, front-end loader or backhoe, compressor, jackhammers, vibrator, others		275	95-456	24
Labor				
Sawing (3 people, 2 h)				
Replacement (6 people, 8 h)	7/h	375	222-675	36
Total		1110		
Average	102/m^2			

Note: 1 m = 3.3 ft; 1 N = 0.225 lbf; 1 m^2 = 1.2 yd^2.

Figure 10. Extent of damage surrounding an edge punchout.

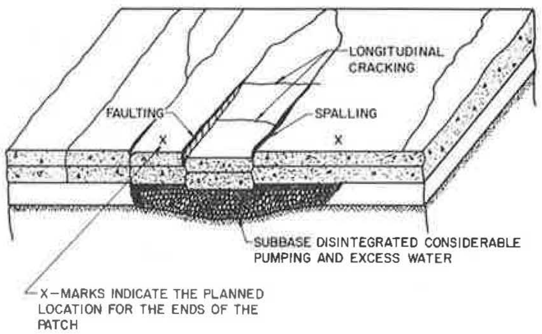
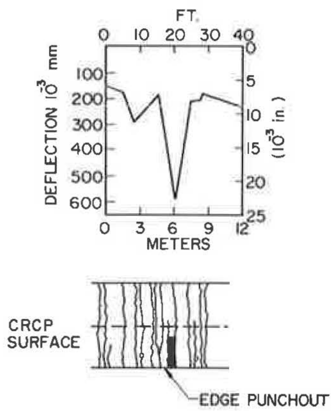


Figure 11. Deflection profile near edge punchout.



PROBLEMS ENCOUNTERED IN PATCHING CRCP

The initial step for improving the performance of CRCP patches is to identify those design features and construction techniques that contribute to patch distress. These problem areas are identified and discussed under the following patching operations.

Diagnosing Distress and Delineating Patch Boundaries

The first problem encountered in patching CRCP occurs when the engineer or technician must diagnose the distress. During this important operation, the nature and extent of the distress should be determined so that the boundaries of the patch may be delineated. Because patching CRCP is so expensive, the patched area should be kept at a minimum. At the same time, the length and width of the patch should not be so small as to adversely affect the performance of the patch or adjacent slab.

Rational guidelines for determining patch boundaries do not now exist. In most cases, maintenance personnel follow rigid specifications that tend to predetermine the boundaries of the patch, regardless of distress type. If maintenance personnel are made aware of the various CRCP distress types and causes, they can better estimate the correct patch size.

As an example, consider the definition of wide-crack distress given above. From experience, it is known that this distress is confined to a small width. Instead of constructing a standard 3-m (10-ft) long patch, a smaller more economical 0.9-m (3-ft) patch may be used.

In most instances, the engineer will have to depend on a visual observation of the pavement surface to determine the nature and extent of the distress. Since one can only see the surface, sometimes the assumption that the distress is confined to a smaller region than it actually is will be made.

For example, consider the common edge punchout shown in Figure 1 and illustrated in Figure 10. Note carefully the Xs in the picture and in the illustration. These are the actual marks made by an engineer to designate the ends of the patch. From the surface appearance of the distress in the picture, the ends of the patch appear to be sufficiently far from the edge punchout. However, it has been learned through experience, core samples, and deflection studies that a region of disintegrated subbase often extends a couple of meters beyond the edge punchout. An example of this is shown in Figure 11, where the extent of the distressed area is greater than might be observed on the surface.

Inspection of core 1 showed that the crack had spalled and faulted 3 mm (0.12 in). If the condition shown in Figures 10 and 11 exists, the patch will be too short. Either the patch or the adjacent slab will soon break up from lack of sound support.

When marking the two ends of the patch, the engineer must also consider the effect that any nearby transverse cracks may have on the patch. From research studies, it is known that a debonded region of steel and concrete exists for 15-31 cm (6-12 in) on each side of a CRCP transverse crack (3). It is expected that the length of this debonded region will increase from the jarring and shaking the reinforcing bars experienced during breakout.

Currently, the effect of locating the patch joint near a transverse crack is unknown. There have definitely been instances of fractured concrete in the region between a transverse crack and a nearby patch joint. As an example, consider the left X in Figure 1. Adjacent slab distress (e.g., spalling) might occur because of the close proximity of the transverse crack and patch joint.

Some guidelines have been issued with this problem in mind. Illinois specifies that there be 46 cm (18 in) between the nearest transverse crack and the patch joint. A Texas report recommends the patch ends be located halfway between adjacent cracks where possible (4).

To make matters worse, problems arise when engineers and technicians try to follow Illinois specifications in regions of close crack spacing. If these specifications are rigidly followed and the crack spacing is very close, it can result in an unnecessarily long and expensive patch. The minimum distance from the saw cut to the nearest crack is under study but is believed to be at least 20 cm (8 in).

Sawing, Breaking Out, and Removing the Pavement

After the patch boundaries have been sawed, the distressed pavement inside must be removed. The method of removal will depend on the specifications, the available equipment, and the preferences of the maintenance crew. Through experience, it has been learned that rectangular patches are easy to construct and give better performance than any other shape. Diagonal patches inevitably cross transverse cracks and result in spalling and corner breaks. There is some doubt as to whether the boundaries of the patch need to be saw cut.

Several states and one or two districts in Illinois break out patches with jackhammers and use transverse cracks as boundaries where possible. The rest of the

Figure 12. Equipment damage to subbase and subgrade.

districts saw cut the boundaries as shown in Figure 7. While sawing can raise the cost of patching by 4-10 percent, it reduces spalling along the joint. A sawed joint provides a clean vertical face that gives a good bond between the patch concrete and the existing slab, and a tight joint will be formed. Field surveys of sawed joints show significant resistance to spalling, while nonsawed boundaries show considerable spalling.

Another important reason for sawing patches is to reduce the transmission of damaging shock waves into the adjacent pavement during break out. The hydrahammer and drop are particularly damaging. The gap made by both the partial- and full-depth saw cuts protects the adjacent pavement from fracturing and the steel from debonding.

Before the distressed segment of concrete can be removed, it is usually broken into small pieces that are easy to remove. The pavement-breaking job can be done with jackhammers or with specialized pavement-breaking equipment such as drop hammers or hydrahammers (Figure 8). If not operated carefully, however, this heavy equipment is capable of damaging the subbase, reinforcing steel, and the adjacent slab. In particular, the heavy equipment should never be used in the lap area because it generally fractures the adjacent slab and debonds the steel from the concrete. Undercutting of the adjacent slab also occurs. Poor breakout techniques are suspected of being a major cause of adjacent slab distress.

Evaluating the Condition of the Subbase and Subgrade

After the distressed concrete has been removed, the maintenance crew can examine the subbase and determine its condition. In many instances, the subbase will be saturated and badly disintegrated (Figure 12). The generally poor condition of the subbase can be expected whenever a patch is planned for an edge punchout or wide crack or when lane settlement suggested by faulting along the centerline between lanes exists. This is because the initiating factor in these two distresses and several others may be a localized loss of support. This loss of support can be caused by (a) a weak subgrade underneath the subbase, (b) accumulation of water in the subbase and subgrade, and (c) disintegration of the stabilized subbase and localized pumping of the stabilized granular subbase. Much foundation support is lost by allowing the distressed area to deteriorate and spread to a large area.

There are no known guidelines for inspecting and evaluating the condition of the subbases. These are needed so that the maintenance crews can apply corrective measures to improve the subbase and subgrade when necessary. The type of subbase (granular or stabilized), thickness of the slab, amount of free water present, subgrade condition, and planned patch thickness are important factors in evaluating the subbase and applying corrective measures.

Over the years, several corrective measures have been used to improve the subbase and subgrade for a patch. Examples would include (a) removing the entire thickness of subbase and replacing with concrete, (b) recompacting the existing subbase, or (c) installing a lateral drain beneath the patch for a path located in a low, wet area. These activities can usually be performed at moderate cost and time increases.

Installing and Splicing the Reinforcing Steel

There are four major unresolved problems associated with installing and splicing the reinforcing steel. First, the minimum length of lap splice required to provide a continuous connection between the patch and the adjacent slab is not known. The lap between the existing bars and the newly installed steel should be long enough to prevent a pullout when the adjacent slab contracts. If slippage does occur, the patch joint will either open up or a series of wide cracks will develop near the ends of the patch.

The current Illinois specification requiring a 91-cm (36-in) tied lap splice appears to be excessive and is not based on any data. Theoretical and experimental work (3) indicates that a 51-cm (20-in) tied lap would be reasonable for number 5 bars. In addition, shorter lap requirements result in much less damage to the steel during breakout.

The second problem encountered by maintenance crews is the occurrence of corroded, nicked, or bent rebars in the lap area. The cross-sectional area of the rebar is often reduced by corrosion or by careless removal operations. This might cause the steel rebar to yield excessively and result in a wide crack, usually at the patch joint. Also, some crews bend the lap bars up so they can easily remove pavement debris. The bars are then bent back to an S-curve. This has been identified as causing distress in some patches.

The third problem occurs when maintenance crews are patching in CRCP reinforced with welded wire fabric. It is difficult to match the new steel with this old steel because of differences in the size and number of bars.

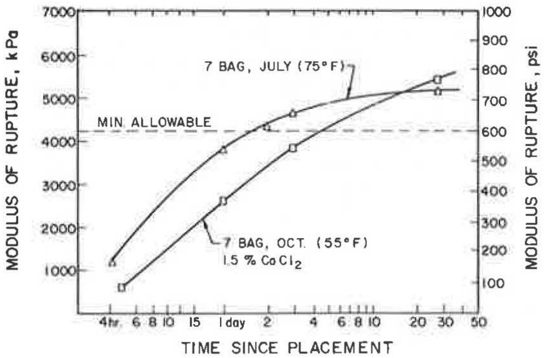
Finally, as an alternative to using the relatively long lap splice, some patching crews have attempted to use a short, 15-cm (6-in), single lap weld to make a continuous connection. Lap welding shows some promise for reducing the time of patching. However, welding equipment must be available at the patch site. Also, it is difficult to get high-quality welds on rebar.

Curing Time of Patch

The standard specified curing procedure is to allow the concrete to reach a modulus of rupture (center point loading) of 4100 kPa (600 lbf/in^2) or a compressive strength of 22 000 kPa (3200 lbf/in^2). Because of varying district policies, the curing time for patches before they are opened to traffic ranges from 3 to 72 h. If possible, most maintenance crews would prefer to open the patch the same day it is placed to avoid costly nighttime traffic control.

A question arises about what the minimum curing

Figure 13. Patch concrete strength gain.



time for a patch concrete is, in order that it not incur significant damage from traffic loading. Subjective evidence indicates that patches placed and opened the same day (about 4-5 h of curing) are replaced more often than those that cure from 24 to 72 h.

Data were collected from several patching sites to determine the typical strength-time relation for the concrete used in actual patching. A plot of some typical results is shown in Figure 13. The patches were placed during warm weather in July and during cool weather in October. The mean modulus of rupture over time is plotted from beam breaks. To achieve the 4100-kPa strength, the July patch should have been closed to traffic for 40 h and the October patch for 110 h. If the patches had been opened to traffic before these times, would any damage have resulted? Even if the patch had cracked, would not the crack have acted like a typical transverse crack in CRCP and have remained tight because of the amount of reinforcement present? The answer to the second question can be obtained from lab and field observations and the answer to the first from analytical analysis.

Tests are being conducted to determine the early strength of ready-mixed concrete used for patching. The effects of concrete mix design and curing procedures on the early strength of patch concrete are also being considered in these tests.

EXPERIMENTAL PATCHES

An experimental patching program is under way to field test various alternate patch design features and construction techniques. Discussions with IDOT maintenance personnel, analytical analyses, field observations, and information gained from other states were all considered in developing a comprehensive list of potential patching improvements.

Those design and construction alternatives that have the greatest potential were selected for field testing. Examples of these alternatives include (a) varying the length, width, and thickness of the patch, (b) undercutting the adjoining slab next to a patch, (c) shortening the length of tied lap splices, (d) welding splices, (e) varying the patch concrete mix design, (f) slab jacking patch ends, (g) placing subdrainage, and (h) constructing asphalt concrete patches. Many experimental patches were placed in 1977 and 1978 and are currently being field tested.

CONCLUSIONS

Constructing high-quality, economical CRCP patches is not an easy task. It is vitally important that the design and the construction methods for CRCP patching be improved so that the service life of CRCP pavements can be extended.

1. Considerable CRCP patching will be required on many projects in the future. This is because the load- and environment-associated distress is increasing on many CRCP projects.
2. Several of the more common distress types that require patching were identified. These include edge punchouts, wide cracks, centerline lane settlement and faulting, construction joint failure, blowups, and D-cracking. Patches should be designed by considering distress type and cause. Placing a standard patch for all distress types is not the solution.
3. CRCP patches suffer from an unacceptable rate of failure, and corrective measures to improve patch performance should be taken. At least one out of every four patches must be replaced with another patch, and one out of every five patches shows distress in the adjacent slab. This requires additional patching.
4. The standard Illinois patching procedure needs significant revision to better represent the conditions encountered by private contractors and state maintenance crews. The standard patch procedure was initially developed for contractor use in repairing defects in new construction.
5. CRCP patching is very expensive. Average costs for a typical 3x3.7-m (10x12-ft) patch are \$102/m^2 (\$85/yd^2) or more than \$1000/patch.
6. Current patching procedures are labor intensive and time consuming. A six- to eight-person crew can only repair one single isolated patch per day. Traffic lanes are often kept closed for three days to allow the patch to cure.
7. There are many unresolved problems associated with CRCP patching. Major problems have been encountered in the following areas: diagnosing the distress and delineating the patch area; sawing, breaking out, and removing the pavement; evaluating and improving the condition of the subbase and subgrade; installing and splicing the reinforcement; and curing the patch concrete.
8. An experimental patching program is under way to evaluate costs, lane closure time, and patch performance. The object of this program is to develop maintenance guidelines so that long-lasting, economical CRCP patches can be easily constructed.

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DISCLAIMER

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Evaluation of Highway Maintenance Cost and Organization in Pennsylvania

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The analysis focuses on Pennsylvania's highway maintenance organization in its 67 counties and the cost of five maintenance activities common to all counties: manual patching, mechanical patching, shoulder repair, surface treatment, and snowplowing. In this analysis those counties and groups of counties that produce these activities at either very high or very low total costs relative to one another will be identified. Operational and environmental factors that cause maintenance costs to vary from county to county will be used in multiple regression techniques. Based on the comprehensive nature of the variables used to explain variation in maintenance costs, inferences are made about the relative efficiency of county maintenance organizations according to actual total costs compared to those predicted by the regression equations. These equations were based on data from 1976. The primary source of operational data was the highway maintenance management system developed for the Pennsylvania Department of Transportation. The study compares counties that produce unusually high- or low-cost maintenance and gives possible reasons for unexplained cost variations by examining operational characteristics. On-site management studies are recommended in order to identify areas for efficiency and cost savings.

In the last 30 years Pennsylvania has constructed a vast highway network. In 1977, the total state-maintained system amounted to 72 000 km (45 000 miles). Recently, because of the mounting cost of construction and debt service, the push for construction has diminished and increased emphasis has been placed on maintaining and improving the existing system. This trend is anticipated to continue.

This study was directed toward dealing with the problems of the efficient and effective use of resources in one area of the total highway maintenance operation, specifically, the operations of the 67 highway maintenance organizations located in the 67 counties of Pennsylvania.

The questions that prompted the study concern the comparability of maintenance work done in the county maintenance organizations in terms of cost, quality, quantity, efficiency, and effectiveness. Critical questions addressed concern which factors influence the total cost of various maintenance activities, which counties vary significantly from the statewide norm for costs of producing a particular maintenance activity, and why some counties do vary. It was hoped that identifying these counties would provide the impetus for an in-depth review of maintenance activities in them in order to determine the operational reasons for the variations.

Highway maintenance functions consist of a large number of individual activities. In order to make the study manageable in terms of length, only five maintenance activities were examined: surface treatment, manual patching, mechanical patching, shoulder operations, and snowplowing. They were selected because they represent a major share of the cost and time of highway maintenance and because they represent summer as well as winter maintenance activities.

Hypothesized cost functions, developed for each of the activities listed above, were estimated through the use of multiple regression analysis. The results were then used to determine which counties vary considerably from expected behavior. These counties were then singled out for a special analysis of the possible causes of their deviation.

This study was thus intended to be a first step in an effort to analyze highway maintenance in Pennsylvania and thus to increase efficiency and reduce costs. It did not provide definitive results in itself but did identify counties that may need on-site management studies. It should also be noted that the method employed was intended to be flexible enough to be applied to the management of highway maintenance on a yearly basis. The Pennsylvania Department of Transportation (PennDOT) is now using the study method and two recent years of management data to validate the models and results. This new study could serve to further refine the method and to provide conclusive evidence of the value of initiating management studies in the identified counties.

THEORETICAL CONSIDERATIONS

Economic theory states that the level of output is the major influence on the cost of production. Costs may rise at an increasing, constant, or decreasing rate as output increases. However, when one is examining behavior across many plants or counties it is necessary to consider other influences on costs that become important because of variations in conditions and practices across the counties. Werner Hirsch in his study of urban refuse collection provided a framework for this type of analysis (1).

Hirsch used 1960 cross-sectional data for 24 municipalities in the St. Louis metropolitan area to build an ideal model of the average cost of refuse collection. This model served as a guide in selecting the variables to explain the cost of maintenance activities. The factors that Hirsch used to explain average cost were the amount or quantity of service, the service quality, the service conditions affecting input requirements, the factor price level, and the state of technology and productivity.

The amount- or quantity-of-service variable represents the output of refuse collection. The theory states that average cost should first decrease over a range and then increase as output increases.

The quality-of-service variable refers to factors such as the reliability of service, cleanliness, quietness, and courtesy of the pickup crew. Higher-quality service would be expected to result in higher average costs at any level of output.

The third variable, service conditions, refers to the peculiarities of each community that result in higher or lower collection costs. These factors include the pickup density, average distance to the disposal site, and the method of financing the operation.

The fourth variable, factor price level, is useful for explaining the variation in average costs that result from the different prices municipalities pay for their inputs. Of primary concern to Hirsch were differences in wages.

Finally, if technology and productivity vary across the municipalities this could also push average costs higher or lower. The municipalities with more advanced technologies should be capable of lower average costs.

The theory of cost and Hirsch's work guided the selection of potential variables and the form of equations used to analyze the cost of highway maintenance. Quantity of maintenance was the major explanatory factor. The equations also included variables representing the quality of output, the service conditions, the factor prices, and the state of technology and productivity. In addition, linear, quadratic, and cubic forms of the cost-output relation were examined. The general forms of the models are presented below. The X term represents the non-output influences on costs. These are assumed to be linearly related to costs.

$$\text{Total cost} = a + B_1 \text{ output} + CX \qquad (1)$$

$$\text{Total cost} = a + B_1 \text{ output} + B_2 \text{ output}^2 + CX \qquad (2)$$

$$\text{Total cost} = a + B_1 \text{ output} + B_2 \text{ output}^2 + B_3 \text{ output}^3 + CX \qquad (3)$$

THE MODELS

The hypothesized influences on the cost of producing each of the selected maintenance activities vary across the activities. However, they do correspond to the general categorization proposed by Hirsch, and the discussion below follows his format. The proposed models were not created in a vacuum; they were developed after consultations with PennDOT maintenance engineers whose operational insights were invaluable.

Dependent Variables

For each maintenance activity studied, the dependent variable was the total cost of producing the output associated with the activity during fiscal year 1975/76. The cost data were those reported for each county through PennDOT's highway maintenance management system (HMMS), which was developed by PennDOT to aid the bureau of maintenance in planning, budgeting, and evaluating the maintenance activities of the county maintenance organizations.

The cost data were from the HMMS expenditure analysis report (2), which presents the costs directly associated with the production of the various maintenance activities. The major items reported are wages and salaries paid to workers involved in an activity, payments to outside contractors for performing an activity (which represent at most 4 percent of the statewide cost of any of the examined activities), the cost of materials used in production valued at the price of their most recent purchase, and costs for equipment used on an activity, valued at an hourly rental rate determined by PennDOT.

Independent Variables

Quantity of Output

Of course, each of the maintenance activities was represented by a different output measure. However, there was commonality across these output measures. It was assumed, as was indicated by the theory, that, after controlling for the other influences on costs across the counties, an increase in output would yield an increase in total costs.

The outputs of surface treatment, shoulder operations, and snowplowing were stated in terms of lane kilometers treated, kilometers of shoulders repaired, and lane kilometers plowed. Because output was measured in lane kilometers for these activities, it was necessary to include variables to account for the degree of highway or shoulder deterioration and snow condition severity. This is because greater deterioration or more severe snow conditions should result in higher costs for each kilometer of production. The service-conditions variables include hypothesized variables for highway and shoulder deterioration and snow condition severity.

The outputs of manual and mechanical patching are the kilograms of material applied. Measuring the output of these activities in terms of kilograms of material applied rather than lane kilometers tends to compensate for differences in the conditions of the roads that are patched. However, road-conditions variables were included in the hypothesized service-conditions variables for these activities.

Quality of Output

It cannot be assumed that each county performs each activity in the same way or with the same attention to the quality of their work, so some measure was needed to account for the differences. This measure was provided by the results of a survey of PennDOT's district engineers, each of whom has responsibility for several counties. For each activity, except snowplowing, they were asked to rate, according to stated objective criteria, the performances of maintenance crews in each of the counties under their jurisdictions. It was assumed that the factors affecting higher-quality work would be associated with higher costs. This assumption was made because higher-quality work would consume more time and attention to detail than lower-quality work.

Service Conditions

This group of variables was the largest of the variable categories. The factors measured by the variables are generally beyond the control of the highway maintenance manager. In general, the variables deal with the geography, the weather, the population, and the highway systems in the counties.

Three variables were proposed as potential representations of the physical size of the county and its highway system. The first of these was the land area of a county. It was assumed that larger counties would have higher costs because travel expenses would be greater in physically larger counties than in smaller counties. A second indicator of size was the number of state-maintained lane kilometers. It was assumed that this variable would be positively associated with costs because it is an indication of physically larger counties that have higher travel expenses. The third size variable was road density. For each county this measure was represented by the total linear kilometers of road per land area. For this variable higher values should result in lower costs because there are more roads to less land area and probably lower travel costs.

However, for snowplowing, increased road density should indicate more lane kilometers of production over the existing land area of the county, particularly since each lane kilometer is plowed. Higher road density may indicate more intense production and higher costs. Because of the relations that exist among these three variables, it was assumed that they would probably not enter the equations together. A selection from among the variables was made based on which variable best explained costs.

A variable was also developed that represented the topography of each county. This variable was calculated as the number of 15-m contours per 16 km (50 ft/10 miles) of federally aided primary highway in each county. For each activity, it was assumed that more mountainous areas, other things being equal, would experience higher costs because of difficulties encountered in working there and the greater deterioration of the roads in the mountainous areas. Also, for snowplowing, it was assumed that the mountainous areas have more severe winters, which may add to the cost of snowplowing.

The interaction of an area's population and travel patterns can also affect costs. This was recognized by hypothesizing that average daily traffic or population density might influence the cost of the maintenance activities. It was reasoned that in more densely populated and traveled areas certain support costs such as traffic control should be higher than in other areas and therefore yield higher overall costs. For snowplowing, however, while congestion may hinder plowing, heavy traffic may inhibit accumulation, thereby making plowing easier and resulting in lower costs.

For certain activities, the type of highway repaired may also influence costs. It was hypothesized that this was the case for surface treatment and manual and mechanical patching. This hypothesis was confirmed by an examination of the cost per unit of output for performing these activities on rigid base, flexible base, and rigid pavement roads. Therefore, it was necessary to include a variable to account for variations across the counties in the type of road that was repaired. This variable was calculated as the weighted average of the statewide average cost per unit of output by road type where the weights were the units of output on each type of road by county. Therefore, the more production on an expensive road type, the higher the cost.

For several of the activities—manual patching, mechanical patching, surface treatment, shoulder repairs, and snowplowing—an effort was made to include a variable that would represent the severity of maintenance problems across the state. For manual patching, mechanical patching, and surface treatment a variable for freeze-thaw cycle was included, as was a variable that measures the number of days during which at least 25 mm (1 in) of snow was on the ground. For each of these variables it was assumed that more severe winters and frequent thawing and freezing caused added deterioration. It was assumed that this deterioration, if severe enough, could result in costs that would not be picked up even with production measured in terms of kilograms of patching material.

For shoulder operations, three variables were included as surrogates for severe deterioration. Maximum daily rainfall was included to represent erosion. Severely eroded shoulders should be more difficult and therefore more costly to repair. Also PennDOT's bureau of maintenance calculated by county the percentage of substandard-width roads that have high average daily traffic. It was reasoned that, as this increased, vehicles were more likely to slip off the road and damage the shoulder. Another effort to develop a proxy for shoulder condition was a variable to measure the frequency of shoulder operations. A higher frequency should indicate less deterioration between shoulder repairs and therefore, everything else equal, lower costs. As was the case above, these variables were likely to be interrelated; therefore, the statistically superior explainer of cost was included in a final equation.

In snowplowing, three weather variables were proposed as potential indicators of severe snowplowing conditions. These were number of days with 25 mm of snow on the ground, mean temperature November-March, and total amount of snow during the year. It was hypothesized that more severe weather would increase plowing costs by making difficult conditions such as greater accumulation of snow and packing and freezing of the snow.

Two additional variables were proposed as explainers of the cost of snowplowing. These were the production units of spreading chemicals and abrasives and total meters of snow fence erected. Higher levels of these activities were assumed to be associated with more severe winters and therefore higher costs or could be used as substitutes for plowing and therefore be associated with lower costs. In either case their link to the level of snowplowing may result in the production of a snowplowing variable that adequately explains their influence on costs.

Factor Prices

The production factors of major importance in maintenance are labor, materials, and equipment. Because all the labor is employed by PennDOT and covered by the same pay scales, it was assumed that the price paid for labor would not vary significantly across the counties. Also, because the same equipment rates are charged across the counties, it was assumed that equipment-factor price should not be important except in snowplowing and shoulder operations. In snowplowing, renting equipment was hypothesized to be a significant factor. In shoulder operations, two different types of equipment are used.

Rented equipment is more expensive than department-owned equipment. To account for this, in snowplowing, the ratio of rented equipment cost to total equipment cost was included as an explanatory factor. Higher values of this ratio should be associated with higher costs.

For shoulder operations counties may use a belt loader or a front-end loader. The belt loader was the more expensive piece of equipment. If a county uses a belt loader their costs should be higher. A dummy variable was created where counties with a belt loader were assigned a value of one and counties without a belt loader were assigned a zero.

For the other activities, the factor for price variables attempts to take account of the variation across counties in the price paid for materials used in the activities. For surface treatment, manual patching, and mechanical patching, the material-costs variable was calculated as the absolute difference between the per unit material cost by county and the statewide average unit material cost. It was hypothesized that the larger this difference, the higher would be the cost of the maintenance activity.

An additional material-cost variable was included in the surface treatment function. This was plant mix surface treatment as a percentage of total surface treatment. This was included because the plant mix materials are more expensive than the liquid bituminous materials. As was indicated above, both types of materials are used in surface treatment.

State of Technology and Productivity

To the extent that productivity and technology vary across the counties, they will influence the cost of production. Other factors being equal, counties that use a more advanced technology or have higher output per unit of input should have lower cost than other counties.

For the most part, it was assumed that the level of technology would not vary across the counties, because each county is part of the same larger organization and because they were producing their outputs within the same limited time period. Productivity, which broadly defined is output per unit of an input, may vary significantly across the counties.

For each of the activities, two productivity variables were proposed as possible explanatory variables. These were production hours per production unit and crew specialization. Production hours per production unit is a direct productivity measure. It was calculated by dividing activity hours (working hours spent in production of each activity) by the total output for each activity. Costs should increase when the value of this variable increases.

Crew specialization is a less direct measure of productivity. This variable was calculated by determining how many different foremen were involved in the production of 75 percent of the output of a given activity in a county. The smaller this percentage for an activity in a county, the more specialized was the county in the activity.

Specialization should result in lower costs for the production of a given level of output. Therefore, the higher the value of the variable for an activity, the higher the cost of producing the outputs. Specialized crews should be more proficient at their tasks, should be more familiar with the equipment involved in the production, and should have developed a greater understanding of the skills involved in the production than the unspecialized crews. These crews should be more productive.

For snowplowing, a technology variable was also included that sought to indicate the amount of capital available for snowplowing across the counties. This was measured by the maximum allowance of snowplowing vehicles by county. It was assumed that the larger the number of vehicles available the lower the cost. Counties with more vehicles have more capital available for use by their work force. This, of course, assumes that increasing the amount of capital used for a given level of output reduces the cost of producing the output. This means that there is excess manpower in relation to the available equipment, after controlling for other factors.

RESULTS OF THE ANALYSIS

The discussion above attempted to categorize and outline the hypothesized influences on the cost of producing the outputs of each of the five maintenance activities. This section presents the results of statistically analyzing the relationship between the proposed explanatory variables and the cost of producing the products of the activities. This is done through the use of single-equation ordinary least-squares regression. Also reported are the results of using the regression equations to identify counties that vary significantly from expected behavior.

Regression Results

Table 1 presents the regression coefficients and related statistics for the preferred model for each of the five maintenance activities. These equations were selected from among the several alternate models examined for each activity. For each activity the models consisted of different forms of the cost-output relation, either a linear, a quadratic, or a cubic cost-output relation, and various combinations of the proposed quality, service conditions, factor price, and technology and productivity variables.

The models presented were selected on the basis of their ability to explain the costs of production across the counties, the significance of the regression coefficients, the reasonableness of the signs, and the magnitudes of the regression coefficients. Unless indicated otherwise, all of the regression coefficients and F-statistics listed in the table were significant at the 0.05 level. For each of the explanatory variables both the regression coefficient (B) and the beta coefficient are presented. The regression coefficient indicates the effect on the dependent variable, all else constant, of a one-unit change in the explanatory variable. The absolute size of the beta coefficient indicates the relative strength of each explanatory variable.

Quantity of Output

For each of the five activities, output was the most powerful explainer of the cost of production, as was expected. For manual patching and snowplowing, the linear cost-output relation proved superior, while for surface treatment, mechanical patching, and shoulder operations, the quadratic cost-output relation was superior. In no instance was the cubic cost-output relation a significant explainer of total cost.

Quality of Output

The quality-of-output variable was not a significant explainer of cost for any activity. It could be that the evaluation of quality by the district engineers was not a valid measurement. On the other hand, it is possible that the quality of output does not vary enough across the counties to be a significant explainer of the cost of production. This variable will be examined below in the discussion of those counties that vary significantly from expected behavior. It may be that, although quality of production does not vary to a large extent across the state, it could be an explanatory factor for those counties that deviate sharply from expected behavior.

Service Conditions

As was pointed out above, several variables were proposed as possible representations of special conditions existing in the counties that may influence the cost of production. However, the bulk of the service-conditions variables proposed for each activity proved to be insignificant explainers of the cost of production.

State-maintained lane kilometers appeared as a significant explainer of total cost for manual patching, mechanical patching, and shoulder operations. It was hypothesized that this variable would be positively associated with the cost of production. This prediction proved true. The positive relation indicates that counties that are larger in terms of the size of their highway network tend to have higher costs, other influences being equal. Apparently the travel costs and other factors peculiar to larger counties push up costs.

Road density, which also represents the size of a county's maintenance area, was a significant explainer of the cost of snowplowing. It was found to be positively associated with the cost of snowplowing. For the other activities it was hypothesized that higher road densities would be associated with lower costs. However, for snowplowing, as was discussed above, a positive relation was expected between road density and costs. This was observed.

Also, for snowplowing, total snowfall was found to be significantly related to the cost of plowing. Greater amounts of snow were associated with higher costs. As was argued above, greater amounts of snow result in difficulties with removal and cause higher costs.

The final service-condition variable that entered an equation was population density. This variable entered the equation for surface treatment. However, it showed a negative relation to the cost of production. It was assumed that this variable would be positively related to costs because of the additional support costs involved with working in more densely populated areas. However, it appears that certain economies are associated with production in more densely populated areas and yield lower costs for surface treatment in these areas.

For the service-conditions variables that did not enter the equations, such as average daily traffic, topography, and production by road type, it appears that they were not associated with the cost of production as anticipated. Of course, in any particular county these factors may be important influences on costs, but across the state their effects were not evident. For the freeze-thaw variable and the snow-accumulation variable, both of which were assumed to influence the cost of manual patching, it would seem that the quantity of production, measured in kilograms, explains whatever effect they may have on cost. It also seems to be the case that the quantity of snowplowing explains whatever influence the erection of snow fence or the spreading of chemicals and abrasives would have on cost.

Factor Prices

The material-cost-deviation variable was significant in only the manual patching and mechanical patching equations. Material cost was a major component of the cost of producing these activities. Therefore, it was expected that higher values of the material-cost variable would be associated with higher costs of these activities, and this was observed.

For surface treatment it was surprising that neither the material-cost-deviation variable nor the variable plant mix as a percentage of total production entered the equation. Although these factors were not found to be significant across the state, they were examined as potential explanatory factors for the counties that stray from expected behavior.

A similar situation existed in snowplowing, with the variable that measured the ratio of rented to total snowplowing equipment costs. This variable was also examined as a potential explainer for those counties that vary from their predicted total cost of snowplowing.

State of Technology and Productivity

Only the mechanical-patching equation did not include a productivity variable. This was not unexpected, because mechanical patching is a highly mechanized activity and involves a similar process across the state. Also, the activity is such that it encourages crew specialization across the counties. Production hours per production unit were significant for manual patching, shoulder operations, and snowplowing. In each case, as predicted,

Table 1. Coefficients and statistics for five maintenance activities.

	Coefficients and Statistics for Maintenance Activities				
Explanatory Variable (adjusted R^2)	Surface Treatment (0.77)	Manual Patching (0.90)	Mechanical Patching (0.86)	Shoulder Repair (0.74)	Snowplowing (0.82)
Output					
B	7 436.00	31.46	16.01	285.00	1.52
Beta	2.02	0.788	1.51	1.95	0.540
$Output^2$					
B	-33.21		0.000 2	-0.133	
Beta	-1.34		0.783	-1.46	
Population density					
B	-46.68				
Beta	0.176				
Crew specialization					
B	2 978.00	1 845.00			
Beta	0.202	0.122			
State-maintained lane miles[a]					
B		92.77	21.41	27.28	
Beta		0.243	0.12	0.229	
Material cost					
B		999.14	41 948.00		
Beta		0.061	0.085		
Production hours per unit					
B		15 733.00		2 270.00	126 411.00
Beta		0.227		0.444	0.213
Road density					
B					20 532.00
Beta					0.141
Total snowfall					
B					1 069.00
Beta					0.395
Maximum allowed snowplows					
B					711.00
Beta					0.213
Constant	-45 467.00	-253 295.00	-50 995.00	-64 607.00	-72 703.00

[a]The models were run in lane miles rather than in lane kilometers.

higher costs followed higher production hours per production unit.

Crew specialization entered as a significant explainer of costs for surface treatment and manual patching. More highly specialized counties experienced lower costs. The benefits of specialization, a greater familiarity on the part of the crew with the equipment and skills involved in the activity, apparently include lower costs for these activities.

For snowplowing, the maximum allowed snowplows was also a significant explainer of total costs. However, it was positively related to the cost of production, which is contrary to previous assumptions. It was felt that a given work force with more equipment would produce the output at a lower cost. But the equipment-allowance variable was highly related to total lane kilometers with a simple correlation coefficient of 0.95. Therefore, the equipment allowance actually served as a surrogate variable for county size, and larger counties were assumed to experience higher costs, other factors being equal.

Residual Analysis

The five regression equations discussed above were used to generate predicted costs of production for each activity for each county, given the actual values for each of the explanatory variables. For each activity for each county a residual was calculated, which is the difference between the actual total cost and the predicted total cost. The value of the residual was then used to select the counties that varied considerably from expected behavior.

Regression equations are quite appropriate for this process, because the strategy of regression is to select coefficients for the independent variables so that the difference between the actual and predicted values of the dependent variable is minimized.

For each activity, the residuals were standardized by dividing them by the standard error of the regression equations. The results were examined, and those counties that had standardized residuals with an absolute value greater than 0.5 were selected for further analysis. This figure was used as a cutoff because preliminary analysis indicated that the vast bulk of the counties had standardized residuals for each activity that were less than 0.5. Yet enough counties exceeded this value for each activity to provide adequate observations for analysis.

The purpose of the examination of the operations of the counties that deviate more than ±0.5 standard residuals was to attempt to identify general areas of operational difference to which costs higher or lower than predicted could be attributed. It was assumed that those counties that were singled out as spending less than predicted for an activity have achieved some operational efficiencies that permit the county to produce the maintenance activity at lower than predicted costs. On the other hand, it was assumed that those counties that spend more than predicted for an activity have operational inefficiencies.

For the counties that were above or below their predicted costs, three major elements of maintenance operation were examined: labor costs per unit of output, material costs per unit of output, and equipment costs per unit of output. In addition, independent variables that did not enter the total cost equations were examined for the deviating counties. These independent variables were analyzed based on the assumption that they were not significant explainers of total cost for the state as a whole because of a lack of variability in them across the counties. However, the outlying counties may be different from the rest of the state, and thus the variables could provide some insight into why a county had costs substantially higher or lower than predicted. Included in this group of independent variables were the productivity variable, the crew-specialization variable, the quality variable, and the material-cost-deviation variable.

The final area of operation that was examined for the deviating counties was the cost of rented equipment and the cost of contracts and services used in maintenance activities. Significant differences in rented equipment and contracts between the counties that spend more or less than predicted could indicate a need for further study of renting and contracting practices of individual counties.

Surface Treatment

As with all the maintenance activities, there was a great deal of variation among individual counties in the two groups in terms of personnel, material, and equipment costs per unit output. However, when the two groups were examined as a whole, several patterns emerged. The average personnel and equipment costs per unit of output were relatively close for the two groups of counties. Those counties that had higher-than-predicted total costs had average personnel and equipment costs of $1292 and $918, respectively, while the same average costs for the counties with lower-than-predicted total costs were $782 and $560.

The material cost per unit of output appears to be the major area of difference between the two groups. On the average the material cost per unit of output was nearly two times as high for the counties that spent more than expected as for counties that spent less than expected.

A possible explanation for the sharp divergence of material costs per unit of output for the two groups is the distribution of surface treatment between the two possible surface-treatment procedures: plant mix and liquid bituminous. In terms of materials, plant mix surface treatment is more expensive than liquid bituminous surface treatment. The counties that had higher-than-expected costs did, on the average, twice as many lane kilometers of surface treatment with the more expensive plant mix procedure than did the counties with lower-than-expected costs.

Several factors beyond the unit cost of the input factors appear to distinguish the two groups of counties. For instance, those counties that spent more than predicted for surface treatment reported higher expenditures for contracts and services than those counties that spent less than predicted. In terms of the number of counties with contract costs, 5 of the 11 higher-cost counties had contracted costs, while 2 of 9 of the lower-cost counties reported contracted costs. Of the counties with higher-than-predicted total costs, one county stood out with contract and service costs of $255 331. Because of the relatively small number of counties with expenditures on rented equipment, no conclusions could be drawn as to basic differences between the two groups of counties.

There appeared to be no substantial difference between the two groups of counties in terms of the quality of the work. However, there does appear to be a difference in the productivity of the two groups. Those counties that had higher-than-predicted total cost required 181 production hours per production unit of surface treatment, while those counties that spent less than predicted required 161.

Manual Patching

For manual patching it was found that, on the average, those counties that spent more on manual patching than predicted had higher personnel, material, and equipment costs per production unit than those counties whose costs were lower than predicted. In the three general areas of operation, the material costs per production unit were substantially higher for counties with higher-than-predicted costs. Material costs per production unit for the higher-cost counties averaged three times higher than those for the lower-cost counties.

Personnel and equipment costs per production unit were both higher in the higher-cost counties than in the lower-cost counties. The average difference in personnel costs per production unit between the two groups of counties was roughly $9, while the average difference in equipment cost was only $6. Because the charges for personnel and specific pieces of equipment were relatively uniform throughout the state, one can speculate that those counties with high personnel or equipment costs per unit of output were using different combinations and amounts of personnel and equipment.

The final operational factor that appeared to be significantly different for the two groups of counties was the quality of the manual patching operation. Those counties with manual patching costs significantly more than predicted had an average quality score of 4.8 out of 10, and those with costs lower than predicted had an average score of 6.2. This difference indicates generally higher-quality work in those counties that spend less than predicted. Higher quality may be related to better management in the lower-cost counties. The better management in the lower-cost counties is indicated by the lower input costs per unit of output observed above.

Mechanical Patching

For mechanical patching, only eight counties had expected costs that varied from actual costs by more than ±0.5 standardized residual units. The two groups of counties varied substantially in terms of per unit expenditures on personnel and materials. Those counties with higher costs than expected spent a little less than twice as much per unit of output on personnel than did those counties with negative residuals. In materials, the difference was much more dramatic. Those counties that had mechanical patching costs higher than predicted on the average spent four times as much per unit of output as those counties spending less than predicted. This difference occurred after the deviation of each county's raw material cost from the state average had been accounted for in the regression equation.

The material costs must be examined with a jaundiced eye, particularly since there is a high probability that reporting errors exist in the material-cost data. The possibility of reporting errors became evident after comparing the $3.65 mean material cost per unit of output for the counties with lower costs than expected with the $15/900 kg average cost for the material used in mechanical patching. Units of production for mechanical patching were measured in kilograms of material. According to PennDOT's bureau of maintenance personnel, certain economies were possible in the area of material costs, but the costs reported were unrealistically low.

The cost per unit of output of department equipment was virtually identical for both groups of counties. However, there were major differences in the amount of rented equipment used in the two groups of counties. Those counties that spent more than predicted had an average rented equipment cost of $1216, while the counties that spent less than predicted had no rented equipment expenditures.

Along the same lines, the use of contracts and services was much more prevalent among the counties that had costs higher than predicted. The county that had the highest positive residual spent $57 000 on contracts and services for mechanical patching, while no county with a negative residual reported any expenditure for contracted mechanical patching.

Since the productivity variable was not a significant explainer of mechanical patching costs for the state as a whole, it was useful to examine the productivity variable in terms of those counties that deviated the most from the predicted cost of mechanical patching. This examination revealed a significant difference between the two groups of counties. Those counties with costs higher than predicted required an average of 0.84 production hours to produce a production unit. On the other hand, those counties that spent less than predicted for mechanical patching required only 0.31 production hours. This would tend to indicate higher levels of productivity in the latter group of counties.

Shoulder Repair

Fourteen counties had expected costs for shoulder operations that varied by more than ±0.5 standardized residual units from their actual costs. Among the counties there was a great deal of variation in the cost of personnel and equipment per production unit of shoulder operations. The averages revealed, however, that those counties with total costs higher than predicted spent $91 more per unit of output on personnel and $68 more per unit of output on equipment than those counties that spent less than predicted.

The use of rental equipment was somewhat different for the two groups. Those counties with higher costs tended to spend more on rental equipment than did those with lower costs. In particular, one county reported an expenditure of $15 772 on rented equipment, while the highest rented-equipment expenditure for a lower-cost county was $7300.

The difference in the quality of the shoulder repair between the two groups of counties appears to shed more light on possible causes of cost variation. The counties that spent more money than predicted on shoulder operations ranked lower in terms of the quality of their work than the counties that spent less. The score for the higher-cost counties averaged 6.00 out of 10, while the score for the lower-cost counties averaged 6.25. The county that had the highest positive residual received a score of 1 on the quality variable, which was the lowest possible score.

Finally, there were minor differences between the groups of counties in terms of the specializations of crews in shoulder repair. The higher-cost counties averaged 24 percent of crew foremen to do 75 percent of the production, while the lower cost counties averaged 18 percent. It was difficult to draw conclusions on this basis because shoulder operations appear to be equally specialized across the state. However, in one county where 40 percent of the crews were involved in shoulder activities, a lack of specialization could be singled out as a possible cause of high costs. This fact is reinforced by the relatively high cost of personnel per production unit for this county.

Snowplowing

In snowplowing, the 17 counties whose expected costs varied by more than ±0.5 standardized residual units from their actual costs showed considerable differences among their per unit personnel and equipment expenditures.

Because of the nature of some of the variables that entered the total cost equation for snowplowing, such as productivity and maximum equipment allowance, the opportunities for operational analysis were rather limited. Two criteria on which the counties could be analyzed, however, were the personnel costs per unit of output and the equipment costs per unit of output. The positive residual group of counties had a $1.27/km ($2.05/mile) of snowplowing for personnel and a $1.97/km ($3.18/mile) for equipment, while for the same categories of unit costs, the lower-than-predicted-cost counties had costs of $0.70 and $1.36 ($1.13 and $1.35).

The difference in unit costs for equipment between the two groups would appear to be the more significant of the two. To further trace equipment cost, the costs of rented snowplowing equipment were examined. For the counties whose costs were higher than predicted, the average total rented snowplowing equipment cost was $31 676, while for the other group of counties, the same figure was only $9853, a difference of nearly $22 000.

The expenditures for contracted snowplowing were another area of snowplowing operations that indicated basic differences between the two groups of counties. It was difficult to draw any firm conclusions because of the limited number of counties that contracted for snowplowing. However, it was significant to note that no county with a lower-than-predicted cost for snowplowing had any expenditure for contracted plowing. On the other hand, two of the nine counties with higher-than-predicted total costs had significant expenditures for contracts. One of these counties reported an expenditure of $16 000 on snowplowing contracts, while another of these counties reported a $17 000 expenditure.

SUMMARY AND CONCLUSIONS

As was expected, the quantity of output produced was the most important explainer of total cost for each activity. However, the quality of output, as measured in this study, failed to appear as a significant explainer of cost.

The size of the county, as represented by total state-maintained lane kilometers was significant for manual patching, mechanical patching, and shoulder repair. Road density was a significant factor for snowplowing. Except for population density, the variables that were intended to measure traffic congestion did not enter the equations. Population density entered the surface-treatment equation, but with a negative sign, which was not expected.

In general, independent variables that represented the climate of a county did not enter the total cost equations as significant explanatory variables. The one exception was in snowplowing, where the total number of millimeters of snowfall was a significant explainer of the total cost of snowplowing.

Productivity variables were not a factor in explaining the cost of mechanical patching. However, each of the equations contained either or both productivity hours per production unit or crew specialization. This illustrates the importance of productivity in cost containment.

Material costs entered the mechanical and manual patching equations. This was not surprising because materials represent a large part of the costs of these activities.

For those counties that varied considerably from expected behavior, it can be said that the counties with higher-than-expected costs had higher costs of personnel, equipment, and materials per unit output than did the counties with lower-than-expected costs. This indicated a more efficient use of inputs in those counties with lower-than-expected costs than was observed in the counties with higher-than-expected costs.

In addition, further study should be directed toward the practice of contracting for maintenance services and renting equipment. For each of the activities, except manual patching, where the vast bulk of production is done by the state work force, the higher-cost counties spent more for contracts and equipment rental than did the lower-cost counties. It is possible that the discrepancies are justifiable, but they do deserve further study.

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Highway Quality and Maintenance: Concepts and Quantification

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This paper presents concepts and considerations associated with defining highway quality and its implications, particularly for highway maintenance. Factors that affect highway quality are reviewed, and the roles and needs of various organizational elements are discussed. These elements, which range from national and statewide policy decisions to maintenance activities in the field, emphasize the need for a consistent scale of quality assessment and presentation techniques relevant to highway user impacts, financial and economic policy decisions, program scheduling and management, and maintenance activity monitoring. Definitions of micro- and macro-quality and their impacts are addressed, and quantitative relationships between new, threshold, and critical quality levels are illustrated and related to maintenance impacts in order to provide a context and framework for establishing maintenance workload, performance, budget, and cost models. Key issues in highway quality related to maintenance impacts are explored, and initial descriptions of maintenance impacts are related to threshold and critical quality levels to assist in developing an integrated approach to user cost and impact analysis.

Deterioration of the national highway system has generated technical and general (1, 2) concern for some time. A recent review (3) of highway maintenance expenditures describes rapid deterioration of facilities caused by inadequate maintenance funding. This indicates a need for better quantifying and presenting factual and readily understandable indicators of cost, travel comfort, and related impacts to policymakers and the public.

Highway quality, how it is measured, who interprets and acts on the information, and how the implications for users and nonusers can be expressed and presented most effectively are subjects for which guidelines are at present being developed. Two examples of current efforts are a project concerning maintenance level-of-service guidelines (4) and a project developing relationships between highway damage components and maintenance costs (5).

The concepts presented here describe potential methods of quantifying highway quality relationships to assist those concerned with maintenance in better responding to emerging needs. They also describe some key relations between user impacts and highway quality as a basis for further analysis.

Concepts of micro- and macro-quality described in this paper are extensions of work done in development of the Massachusetts maintenance management system. The user impact concepts described here that relate to micro- and macro-quality were developed separately.

POLICY AND FUNCTIONAL DETERMINANTS OF HIGHWAY QUALITY

A brief overview of the context in which highway quality exists and its relation to factors affecting it—quality determinants—are summarized in Table 1.

The standard management response to deterioration of highway quality is to attempt to satisfy the need for maintenance through a logical process of actions determined by specific decisions. A series of steps leading from an objective, quantitative estimate of existing highway quality through the budgeting and resource-allocation process is shown in Figure 1. This process and its components provide a guide for isolating and considering highway quality, maintenance, and resulting impacts.

The state of the art in highway maintenance needs a generally acceptable definition of highway quality to provide a basis for improved decision making. An approach to defining needs, agency roles, and quantification of quality and maintenance programs is described in the following sections.

ORGANIZATIONAL ROLES AND ASSOCIATED QUALITY DEFINITIONS

The term "highway quality" undoubtedly has different meanings for different individuals. For example, a pavement maintenance foreman will view a certain segment of highway as needing specific repairs based on his or her evaluation of how severe the cracking, rutting, or other deterioration may be. Policymakers at national, state, or municipal levels, however, must take a wider view and balance the quality of a segment of a system (and a user's reaction to it) against that of other segments and, ultimately, the need for funds in competing sectors of the economy such as housing and education.

Because the budget and policy issues affecting legislative decisions are basically influenced by the actual level of maintenance, and vice versa, it is desirable that methods of measuring and quantifying highway quality be consistent. Each organizational element, however, will be faced with decisions, variables, and data-presentation needs unique to its role, as summarized in Table 2.

Furthermore, maintenance of a highway network must be responsive to user opinions about how well the system satisfies perceived needs. An information flow process for a typical state highway system is shown in Figure 2. To enable an adequate response by legislative officials to user perceptions of quality, a generally understood and recognized method of quality measurement and its maintenance implications is essential. Policymakers must be informed of the effects of their maintenance funding decisions in a readily understood manner.

With the foregoing considerations in mind, one finds that an adequate and consistent definition of highway quality should

1. Be based on measurements needed to describe the condition of highway components from a detailed engineering and technical viewpoint to assist engineers and maintenance and management personnel;
2. Have a structure that assists in formulating direct relations with construction and maintenance performance standards;
3. Be consistent with potential national and international standards to assist in establishing uniform measurement and quality-assessment procedures and methods of comparison; and
4. Be readily adaptable to displaying broad areas of impacts resulting from specific budgeting strategies to policymakers.

Table 1. Highway quality organization, maintenance roles, decision variables, and information needs.

Highway Quality Determinants	Effects on Highway Quality and Maintenance Needs
Policy and financing	
Capital- or non-capital-intensive investment strategy based on available program funding, sector apportionments, and economic assistance policies	Determination of maintenance extent and frequency
Facility characteristics	
Geometrics such as grade, cross slope, curvature, and placement of appurtenances	Effects of surface drainage and vehicle climbing, braking, and accident characteristics on facility condition
Pavement, structural, and dimensional specifications	Service capability and rate of deterioration
Appurtenance design and specifications such as drainage structures, light standards, and energy attenuators	Efficiency in ensuring protection of facility from environmental conditions and users
Materials specifications such as those for aggregate, concrete, paint, and bitumen	Service capability and rates of deterioration
Environmental conditions	
Subsurface condition such as ground water, soil, and geological conditions	Subsurface and bearing capability of pavement and rate of facility deterioration
Climatic conditions such as rainfall, snowfall, temperature (levels and variations), and freeze-thaw cycles	Amount of moisture and number of freezing cycles and related deteriorating agents
Regional conditions such as potential floods, rock falls, wind-borne deposits, storms, and other natural hazards	Frequent need for emergency maintenance work often the cause of general deterioration
Human environment	Debris
Traffic and use conditions	
Traffic volumes such as annual daily traffic and seasonal and daily variations	General traffic use indicator
Vehicle mix such as percentage of trucks and buses	Characteristics of loading, particularly heavy trucks and other special conditions, affecting pavement deterioration
Vehicle loading (axle loads)	
User characteristics (trip purposes)	Special highway needs such as provision of rest areas and special seasonal or weekend traffic activities
Accidents	Need for clearing traveled way of accident debris
Prior maintenance	
Expenditure levels	Limts on the extent of resources expended on maintenance resources
Field operational efficiency	Productivity and efficiency of resource use
Maintenance management effectiveness	Setting priorities, responding to defined needs, monitoring performance, assisting field operations, and informing public and policy-making bodies

HIGHWAY QUALITY CONCEPTS

If one ignores the effects or impacts of the quality on the users or environment, physical highway quality can be defined as the state of a particular highway element or group of elements existing within the facility itself at any point in time. However, to define more precisely what is meant by highway quality and how it can be measured, it is useful to explore in greater detail the concepts of micro- and macro-quality and how they can assist in providing meaningful functional relationships.

Essentially, micro-quality can be described as the condition of a specific small segment of the highway, such as a limited area of pavement or the amount of loss of cross-sectional area of a structural member in a bridge. Macro-quality, on the other hand, would pertain to the extent that the micro-quality exists throughout the system. It could be stated, for instance, that 40 percent of the pavement in the system had significant cracking damage and that 5 percent of the bridges had one or more structural members with a significant loss of cross section.

Table 3 lists some examples of micro- and macro-quality descriptions for typical maintenance items. Further characteristics of this approach are described in the sections that follow.

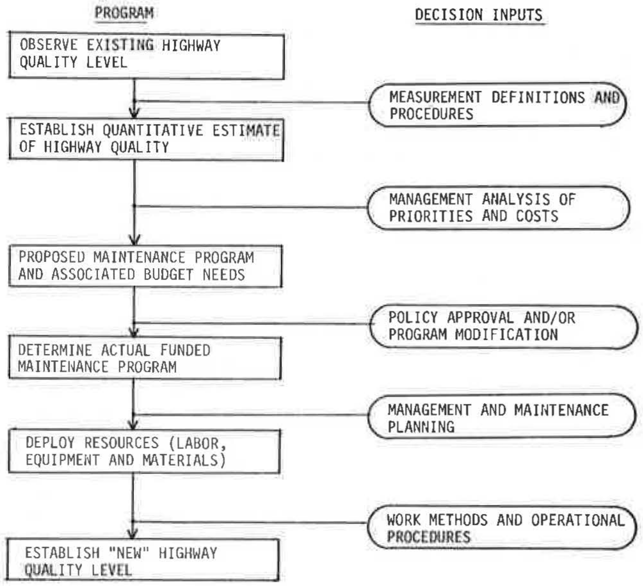
Micro-Quality

Micro-quality of each element of a new facility is initially set by the design specifications for each element. For example, surface roughness can be specified in terms of present serviceability index (PSI), and drainage flow is determined by the capacity of the drainage pipe or culvert. Over time, the micro-quality of each element will deteriorate to a different extent according to variations in use and environmental conditions.

Micro-quality is directly related to the functional and operational effectiveness of an element. It is the micro-quality that directly affects user safety, comfort, and convenience and indicates whether remedial steps should be taken to preserve the initial investment.

Uniform micro-quality will normally exist at any

Figure 1. Maintenance program and decision impacts.



point in time over those portions of an element where design, construction, specification, traffic, environmental factors, and age are also uniform. Other portions of the same element that are subjected to different use and environmental conditions will deteriorate at different rates. Hence, at any time following original implementation, the total inventory of any element will consist of a number of portions at different micro-quality levels—a distribution of micro-quality levels.

Deterioration of the micro-quality of a highway element over time can be illustrated graphically: Figure 3 shows the micro-quality deterioration curve of an element with respect to three important levels.

The first level is the new, or as-built quality q_N, which is generally the quality level at which an element should ideally be maintained, although in practice this is often not fully achieved. Second is a threshold quality, q_T, at which point it is desirable (as established by policy) to commence maintenance operations. This quality level can be established (a) by means of engineering judgment concerning the extent to which an element of the highway system should be allowed to deteriorate (usually considerations of preservation of investment and user safety are key determinants in this decision); (b) by means of mathematical techniques that consider

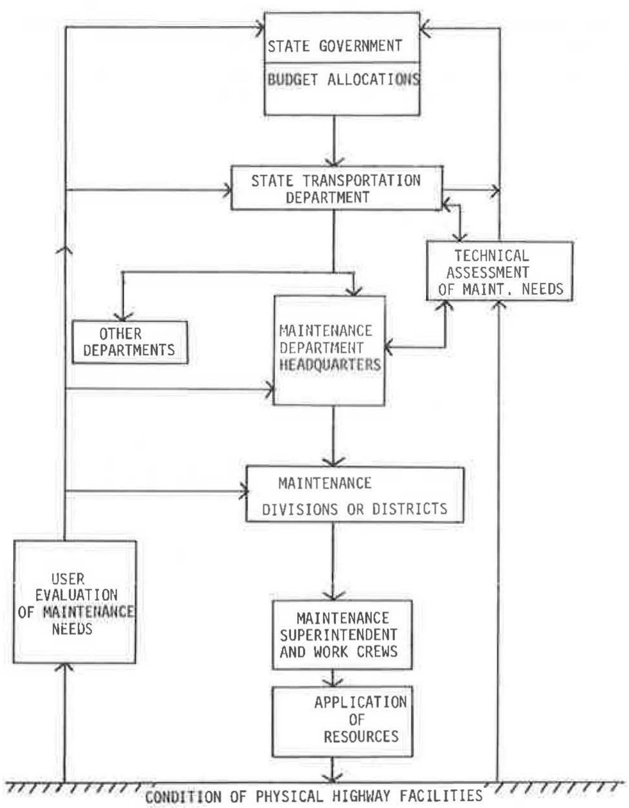
Table 2. Organizational roles, highway quality, and maintenance information needs.

Organizational Element	Maintenance Role	Decision Variables	Data Needs and Presentation Formats
National, state, and local government and legislature	Funding allocations to reflect competition between sectors for funds, general transportation priorities, and highway, regional, classification, and other financial programs	Funding available Public acceptance of highway conditions regarding safety, convenience, economical transport, and uniform highway quality Geographical apportionment Trade-offs between capital and non-capital expenditures National, regional, and local policies and priorities	Definition of highway quality or condition to readily reflect changes in available funding Annual comparison of highway quality for key items such as pavement and bridges Annual expenditures associated with quality levels Data summarized and condensed to show principal features needed, with detailed background information available if needed, impacts of program on users and general public clearly stated
Transportation agency administration	Similar to above but with greater weight given to needs based on technical performance standards	Similar to above but also including technical and administrative determinants of program effectiveness and costs and implementation within specific jurisdictions	Similar to above but generally in greater detail
Maintenance management headquarters	Administration and allocation of resources within maintenance jurisdiction	Policy guidelines for highway quality Available funds and resources New methods and procedures Evaluation of performance and effectiveness Response to district needs and coordination between jurisdiction or other districts Budget apportionments	Management information for monitoring performance and maximizing maintenance effectiveness with regard to quality versus funding; budget computation analysis and evaluation
Maintenance district or section management	Similar to headquarters but with primarily district or section emphasis	Similar to headquarters but primarily with district or section emphasis including detailed priority and work schedule requirements	Similar to headquarters but primarily with district or section emphasis related to specific maintenance activities and labor, equipment, and materials use
Local, state, national, and international technical, research, and professional organizations	Organizations playing an advisory role in defining and substantiating uniformly applicable approaches to highway quality, measurement, analysis, and evaluation	Methodologies and approaches for establishing and defining highway quality; relating quality to funding, maintenance procedures, user needs, local, regional, and national maintenance policies and standards; and recognizing essential differences due to geographical, economic, cultural, and government characteristics	Consistent terminology and recognition of principal features of technical, economic, and management tools to assist comparison of key performance indicators

capital, maintenance, and user costs together with facility specification variables to determine a quality level that offers the least cost; and (c) by imposing a threshold level on the element because of a lack of adequate funding or other resources required to carry out the necessary maintenance. In this last, uncontrolled situation there is considerable danger of the threshold quality's falling below the critical level. The third level is fiscal policy measures that include the above approaches to a greater or lesser degree. A critical quality, q_c, exists when the element becomes unserviceable in terms of its function as a highway component. Examples of highway segments in this category are those where

1. Posted reductions in speed are required,
2. Detours are required,
3. Significant accident hazard exists,
4. Lane or lanes are fully or partially closed,
5. Vehicle weight must be reduced,
6. Imminent or unpredictable structural failure is likely,
7. Undue costs accrue to the direct users and the general public, and
8. Any situation exists where the agency concerned could be considered not to have provided adequate professional diligence, judgment, and care in protecting the public from injury, if a substandard condition is allowed to persist.

Figure 2. State highway department information flow.



Macro-Quality

Macro-quality of an element can be described as the extent to and the manner in which micro-quality is distributed throughout the inventory of that element. Because of this, macro-quality, Q, can be expressed in several ways that can assist the analysis of highway quality. These include (a) a frequency distribution of the micro-quality levels with the element, (b) average and median values and appropriate measures of dispersion, and (c) the proportion of the element that exists above or below some specified quality level (such as specified threshold levels).

Figure 3. Micro-quality concepts.

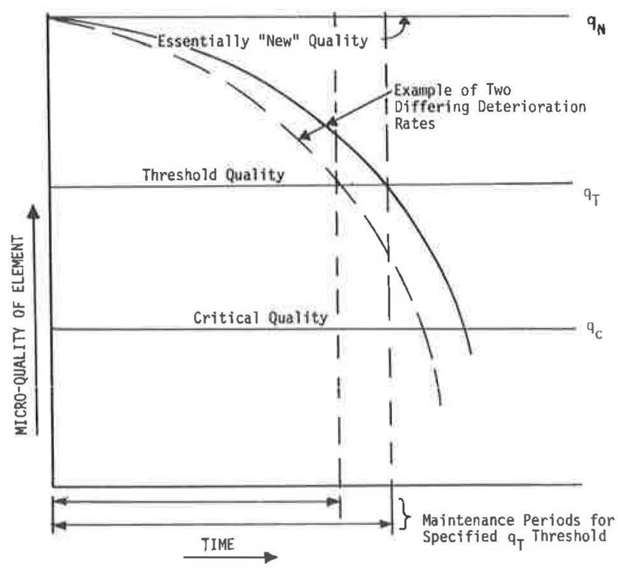


Table 3. Examples of micro- and macro-quality.

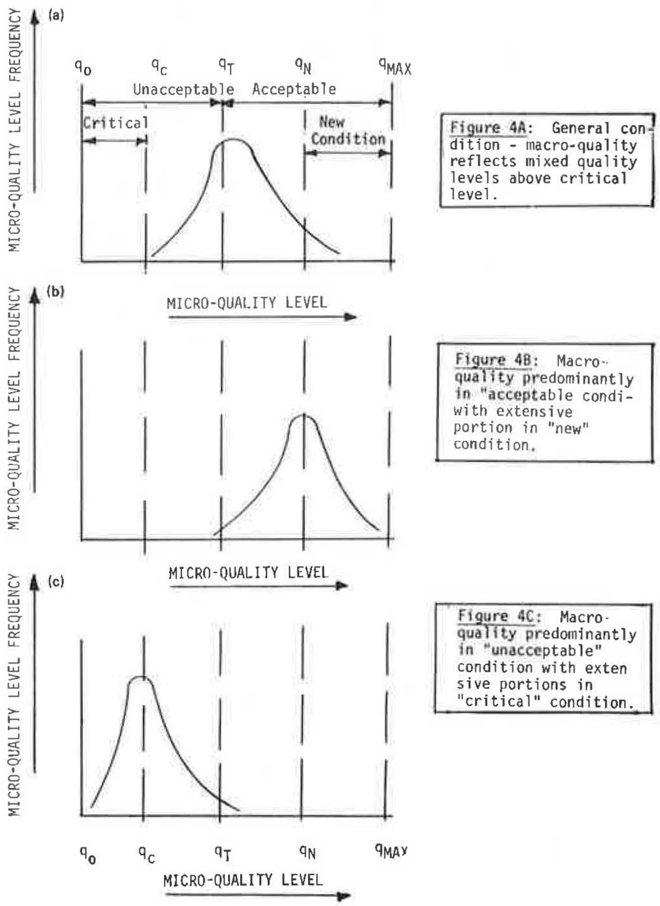
Maintenance Item	Micro-Quality Measurement	Macro-Quality Measurement
Pavement surface	PSI*, alternatives: roughess or failure severity	Area of pavement existing at or below a given PSI or PSI threshold
Guardrail	Measure of distortion or misalignment of individual segments	Length of misaligned segments
Drainage ditches	Depth of standing water or other obstructions	Length of drainage for water deeper than a given standing-water or obstruction depth
Roadside grass	Height of grass	Area of grass taller than a given height
Bridges	Cross-sectional area of critical structural members and other criteria of structural adequacy	Number of system bridges or possibly number of spans having deficient structural members

*PSI is present serviceability index.

Generally, if the micro-quality of a specific element is normally distributed (other distributions are also possible), the various terms and relations can be illustrated as shown in Figure 4.

In Figure 4a the area under the curve lies between zero quality, q_0, and q_{MAX}; there is 100 percent of the inventory of the element; the acceptable proportion of the inventory of the element is that shown under the curve between the micro-quality levels q_T and q_{MAX} (this is the proportion of the inventory above the micro-quality threshold level q_T); and the unacceptable proportion of the inventory of the element is that shown under the curve between q_0 and q_T. This is divided into two segments: the portion that is critical (q_0 to q_C) and the proportion that requires maintenance but has not yet reached a critical stage (q_C to q_T).

Figure 4. Comparison of micro- and macro-quality.



Figures 4b and 4c illustrate hypothetical cases of new and extensively deteriorated highway elements, respectively. In the latter case a significant portion of the element lies within the critical zone (q_0 to q_C). Also, if the threshold quality lies significantly below the critical value ($q_T \leq q_C$), then the entire inventory of the element in question may need immediate attention.

Micro- and macro-quality can be related to pavement performance by considering, for instance, that the micro-quality distribution for "premium" pavement would lie to the right of the distributions for pavements with normal design standards, other conditions being equal.

For any highway element, the numerical value of macro-quality will increase as the value of the threshold quality (a micro-quality) decreases. In quality-control terminology, the lower the quality acceptance level, the greater the acceptable quantity.

In practice, macro-quality can be expressed in terms of the deterioration and remedial work required in terms of work units (area or volume, for instance) of each inventory item to bring the item to as nearly new a condition as is reasonably possible. The quality of the sample segment can thus be expressed as a direct function of the extent of the maintenance or repairs needed.

For example, if there are 1000 linear meters of guardrail in a segment (U_s) and, based on the assessment observations, 100 linear meters of it is found to be in need of repair (U_D), the quality index (Q_I) for that item within the sample segment is

$$Q_I = (1 - U_D/U_s) \times 100 = (1 - 100/1000) \times 100 = 90 \text{ percent} \quad (1)$$

Thus, direct measurement of deficiencies and of the total inventory of each element provides a direct assessment of the highway quality expressed as a proportion of each element's inventory. This method of express-

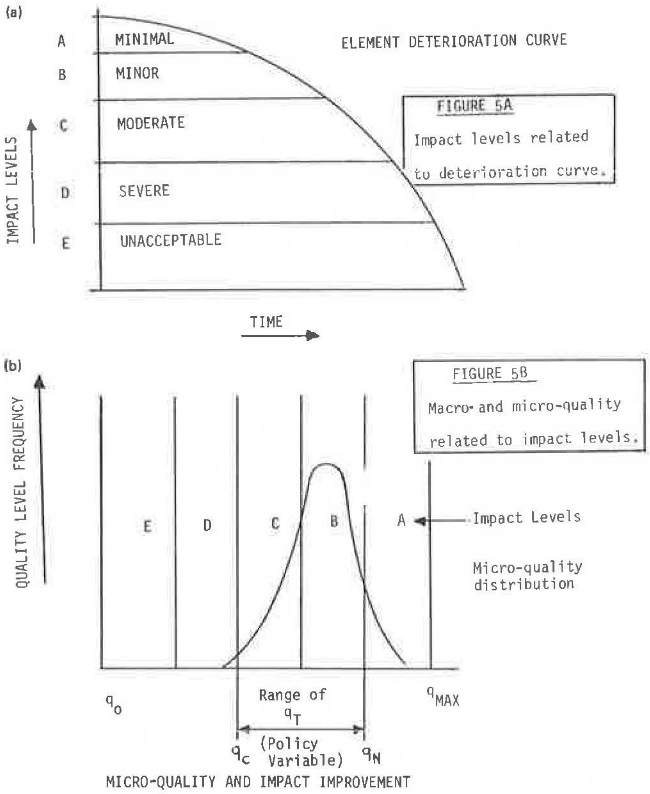
Table 4. Initial listing of maintenance impacts.

Level	Rating	Highway Condition	User Impacts
A	Minimum	Ranges from new condition to minor deviation from design and operational specifications	Highest level of service attainable in terms of safety, riding comfort, aesthetics, and operational effectiveness
B	Minor	Ranges from minor deviation from specified design conditions to occasional and isolated instances where deterioration is apparent but does not need immediate attention	Occasional instances of reductions in riding comfort, operational effectiveness, and aesthetics; no deterioration in safety aspects
C	Moderate	Ranges from isolated instances of deterioration to locations where maintenance should be performed within 12-month period to avoid adverse significant user impacts or loss in investment	Significant perception of deterioration in aesthetics and some perception of reduced riding comfort and operational effectiveness
D	Severe	Ranges from locations where deterioration is noticeable in a significant number of elements, generally most severe in roadside elements but also in traveled way	Significant perception of deterioration in riding comfort and operational deterioration such as need for reduced speed; perceptible accident potential exists
E	Unacceptable	Physical quality ranges from a significant number of locations needing scheduled maintenance to locations where deterioration requires emergency repair or closure of the facility to the public for safety reasons	Accident potential and riding comfort induce extensive loss of operational efficiency due to lane closures, surface deficiencies, debris, or other obstruction in right-of-way

ing quality assists direct comparison of deterioration, remedial work needed in terms of work units, and the Q_I, which permits direct numerical comparisons of highway quality between various jurisdictions and in different time periods.

Furthermore, the assessment of the macro-quality of each element provides a direct numerical value of the maintenance work to be done in terms of work units. When multiplied by appropriate performance standards and equipment and materials costs, the quality assessments thus provide an initial cost estimate, based upon the highway's condition, for objective budget estimates and maintenance planning.

Figure 5. Highway quality and user impacts.



USER IMPACTS

Closely related to highway quality and maintenance is the concept of user impacts. Deteriorated pavements and other conditions cause physical damage to vehicles, increase accident probability, and induce less than optimum route choice. In turn, these factors can lead to many undesirable situations ranging from loss of productivity to excess energy consumption and associated costs.

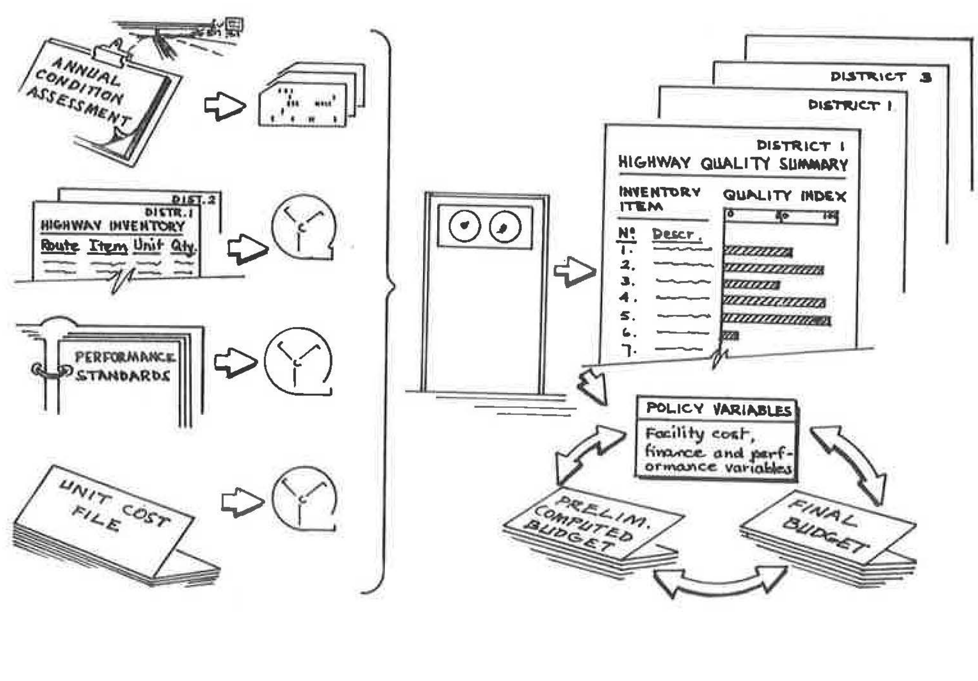
An initial attempt at delineating qualitative descriptions of maintenance impacts is shown in Table 4. This describes a scale of impacts from A through E, ranging from the impacts associated with a recently constructed and properly maintained road (level A) to those where extensive operational deficiencies and significant potential for accidents exist (level E).

Some of the key relations between micro- and macro-quality and maintenance impacts are shown in Figures 5a and 5b. These diagrams illustrate conceptually how the numerical values that could be assigned to different qualities resulting from specific maintenance policies are likely to affect highway users. This also provides a basis for formulating expressions describing total costs.

In Figure 5a, the relation between micro-quality and the various impact levels is shown. Level A is shown to occur above q_N, while, at the other extreme, level E is shown below the critical quality level, q_C. The threshold quality, q_T, a variable depending on specific policy decisions, can occur throughout the range of impact levels. From the point of view of preservation of investment and user comfort and convenience, it will usually be preferable to set q_T somewhere within the range of maintenance impact level C, described here as a moderate impact. Deferred maintenance policies may set $q_T \leq q_C$ within impact levels D or E (severe or unacceptable, respectively).

Figure 5b shows how the quality and impact levels as well as the macro-quality of the highway can be related. The threshold level, q_T, is shown at the same impact level as in Figure 5a. For the distribution of quality throughout the system, the area under the curve

Figure 6. Highway quality assessment and budgeting process.



for each impact level indicates the proportion of the inventory that exists at that level. Thus, the amount of quality deterioration and the consequent maintenance effort required to bring the total inventory of each element up to an acceptable level can be determined.

MAINTENANCE, BUDGETING, AND POLICY DECISIONS

The concepts presented here have been aimed at providing a structure, with appropriate definitions and hypothesized relationships, within which highway quality, maintenance, and user impacts can be quantified. Although not identical to this approach, particularly in the concepts of micro- and macro-quality and user impacts, several maintenance management systems have been implemented that feature a formal highway quality assessment procedure to provide a basis for both future budgeting and maintenance action and for preparation of numerical and graphic descriptions of the highway quality.

For instance, the Ohio Department of Transportation has used an assessment process for some years (6, 7) that relies on a system of recordable conditions measured in units that can be associated with the extent of maintenance needed and, subsequently, to a district and statewide annual maintenance budget.

A quality-assessment procedure now being investigated for the maintenance management system of the Massachusetts Department of Public Works is based on the quality index described earlier. In this system the threshold quality level is described in appropriate micro-quality terms that can be directly related to specific maintenance activities (8). A further development in Massachusetts is the introduction of work load and cost models responsive to many of the variables, including design, and traffic and environmental factors (9) mentioned earlier.

The Ohio approach measures or identifies samples of the micro-quality condition of selected elements and compares the proportion of their occurrence between maintenance jurisdictions and over time. It is not directly linked to the work load but provides an indicator of highway condition as a guide for budgeting. In the Massachusetts system the proposed measurement of quality would estimate specific amounts of deterioration of the element related to the total inventory. The mechanism for converting this to a proposed budget is still under consideration.

In general, as portrayed in Figure 6, an annual quality assessment, when combined with the highway inventory, performance standard, and unit cost files, can produce a highway quality summary for each district. The information can also be used to compute first a preliminary budget and, through a series of iterations and modifications, a final budget that is responsive to policy for funding allocations and desired level of highway quality.

Probably the greatest potential advantage of the micro- and macro-quality concepts is that the quality index, or a similar measure, indicates how much inventory is deficient and, therefore, the amount to be budgeted to ensure the required standard. For example, if the quality index for guardrail in a district is 0.91 (or 91 percent of the inventory is of acceptable quality) for a given year, based upon measurement or estimates, and if a satisfactory index is 0.99 (as determined by policy), the required budget to achieve the policy objectives for this element will be

$$[Q_I\,(\text{policy}) - Q_I\,(\text{existing})] \times \text{inventory extent} \times \text{maintenance cost per unit} \qquad (2)$$

or

$$[0.99 - 0.91] \times \text{inventory extent} \times \text{maintenance cost per unit} \qquad (3)$$

CONCLUSIONS AND NOTES ON FURTHER RESEARCH

In presenting the issues and concepts here, I have attempted to add to current knowledge about the need for and quantification of highway quality. Some of the key elements of current concerns have been placed in an analysis format in order to better define a quantitative approach consistent with the needs and roles of a wide range of people and organizations, including highway maintenance departments, policymaking and decision-making agencies, and highway users in general.

Future research directions that could be beneficial to the technical and administrative aspects of developing acceptable maintenance management procedures include

1. Investigation of consistent or standardized information formats for various organizational elements concerned with maintenance (in particular, the preferred means of presenting information and cost implications in a meaningful way to policymakers to assist in the funding and budgeting process);
2. Continued acquisition and analysis of data to adequately quantify micro- and macro-quality relations and the means by which these, or other concepts, can assist in the maintenance process; and
3. A continuing analysis of maintenance impacts to ensure that the varied effects of specific policies on different classes of road users, and on the general public, can be adequately documented.

In particular, highway quality assessment techniques and further exploration of the quality and impact relations indicated in Figures 3, 4, and 5 should prove advantageous from the point of view of defining numerical relations for computational and presentation purposes. Recent implementation of maintenance management systems by many organizations will significantly assist this effort.

ACKNOWLEDGMENT

I wish to acknowledge with thanks the background information on maintenance management techniques provided by R. Keefe and the Maintenance Department staff of the Massachusetts Department of Public Works. I also thank R. Zook of the Ohio Department of Transportation and M. Markow of CMT Inc. Thanks are also due to L.G. Byrd, R. Thompson, and J. Kerkering of Byrd, Tallamy, McDonald and Lewis for commenting on certain aspects of the concepts presented here. However, I am solely responsible for the contents of the paper.

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**J.G. Schoon was with Byrd, Tallamy, McDonald and Lewis when the concepts of micro- and macro-quality were being developed.*

A Systems Approach to Maintenance Station Location

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The California Department of Transportation (Caltrans) has developed a procedure for identifying appropriate locations for facilities needed to support the highway maintenance mission. The traditional approach has failed to answer the questions of whether the facility is really necessary and is in the best location, whether the adjoining stations are affected, and what the fiscal impacts of possible alternate locations are. The procedure developed by Caltrans considers the trade-offs between capital costs and operating costs over the project's life and emphasizes changes in expected travel costs as a function of maintenance station location. These costs can then be weighed against the social and administrative aspects of deciding what facilities are needed and where to build them. Computerized network simulation is used to estimate travel-time impacts, while capital costs are evaluated by using discounted cash flows. A field application of the procedure, as a portion of the siting-decision process for a new facility, Beckwourth, is discussed, along with results observed after a year's application.

Twenty-five percent of California's 325 maintenance stations are older than 30 years; almost 20 percent of its stations are 40 years old or older. Although age alone does not determine the obsolescence of a facility, it is a major consideration. The aggregate age of California's facilities gives a partial insight into the magnitude of the problem that the California Department of Transportation (Caltrans) must face. The present dollar cost of modernizing the system could easily approach $100 million. This total grows daily as more stations join the ranks of the obsolete and as inflation continues its upward march.

Historically Caltrans' practice has been to identify specific deficiencies in maintenance stations and to address these specifically through a project. Most commonly the correction proposed is either reconstruction of the facility or construction of a new one nearby. The notable exception has been in the larger metropolitan areas, where the emerging trend is to develop centrally located service centers.

Appreciating the magnitude of the problem, Caltrans' management took a second look at the task. Over the past 30-40 years the highway system has evolved and changed considerably from the system that the maintenance stations originally served. From this second look it became apparent that the older facilities are no longer in the best locations to effectively support the maintenance mission.

In early 1976 the California Highway Commission challenged a project to locate a new facility in the remote community of Covelo in northwestern California. Responding to this challenge required a comparison of the total system cost of supporting the highway from the proposed local operating base in the Covelo area against the cost of supporting the highway from the next proximate bases at Willits or Leggett.

It was necessary to estimate the total costs for the various siting decisions. The maintenance-facilities siting model, developed to satisfy this objective, contains two major elements: the operating cost element and the capital cost element. Changes in the costs of maintenance operations as they relate to the location of the maintenance stations are examined in the operating cost element. The impact of capital expenditures, both present and future, are considered in the capital cost element. The facility siting model brings these elements together in a format that permits management to make the critical trade-off (see Figure 1).

The method of analysis that was developed to meet this purpose is the topic of this paper.

MAINTENANCE OPERATING COST ELEMENT

This element is used to simulate the normal highway maintenance function. The work done in each highway section is studied and the existing crew travel patterns analyzed. From the information gained, we can estimate what our costs might be if we were to relocate.

By working with reasonably short, fairly uniform stretches of highway linked together into a network, the actual road system may be simulated. If the time consumed by crew travel, their travel speed, and the travel distances are known, then an estimate of travel frequency can be made. In turn, these calculated travel frequencies can be used to estimate the total travel time needed by crews to come from a new location.

Terms

Throughout the discussion of the operating cost element, certain terms are used repeatedly. These terms are defined as follows:

Figure 1. Facilities siting model.

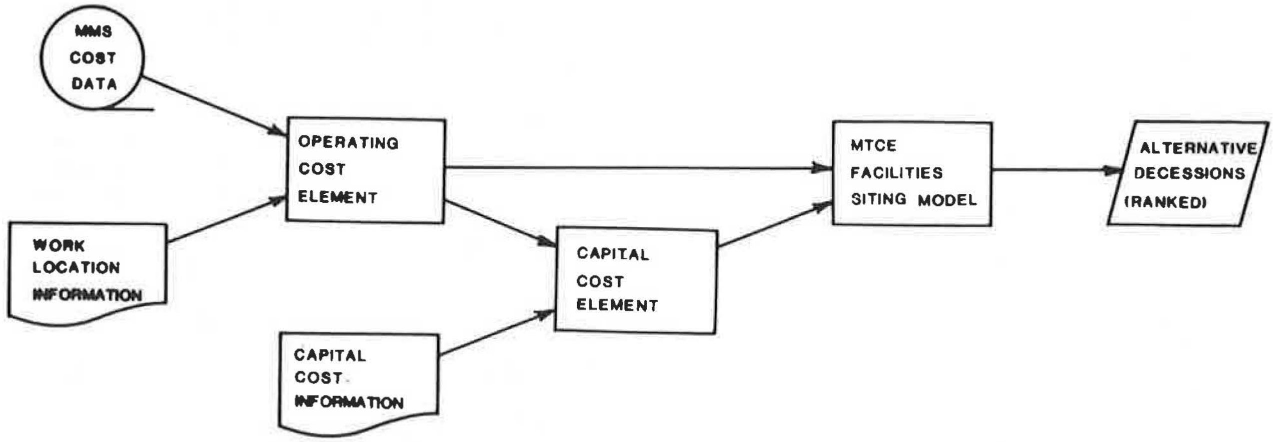
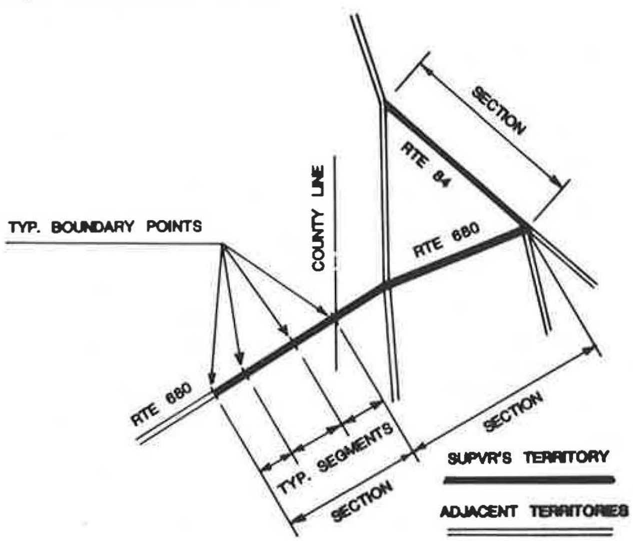


Figure 2. Network subdivisions.



1. Highway section: A highway section is the smallest cost-accounting unit within California's maintenance management systems (MMS).
2. Segment: A segment is an arbitrary but logical subdivision of a highway section and is characterized by its relatively high degree of uniformity of both the terrain and the required maintenance effort.
3. Boundary point: A boundary point is the end of any segment. Boundary points are identified by (a) a change in the character of the roadway terrain, (b) a change in the makeup of the roadway maintenance requirements, or (c) a maintenance station location.

Figure 2 illustrates these definitions.

Work Groups

Work groups are a convenient method of organizing similar work-related inputs in a meaningful manner. The structure and number of work groups may be varied to fit the different crew types. Some work group examples typical of a road maintenance crew are group 1, all of the flexible pavement maintenance activities except pothole repairs and similar labor intensive work; group 6, all snow- and ice-control activities; and group 9, hand repair of flexible pavements (the flexible pavement maintenance is excluded from group 1).

Weighting Factor

The weighting factor is a subjective measure of the maintenance effort expended within each segment of a highway section. Each work group is separately evaluated. Experienced local supervisors and managers estimate the relative effort per kilometer expended or expected to be expended in each segment relative to all other segments in a highway section. These estimates are used to allocate both the total maintenance effort and the travel effort between the segments of the section.

Work inputs are now being reported relative to post mile locations. (The customary term is retained throughout this paper.) As this post mile is accumulated over the coming years, these subjective weight factor estimates will be phased out and replaced by objectively derived data.

Maintenance Management System

The Caltrans MMS identifies and accumulates the work and support costs and assigns them to the highway section maintained by a single supervisor. It does not, however, subdivide the section. Commonly a supervisor's section will contain several different stretches of a road, each with its own maintenance needs. Each segment must be identified and a basis of work allocation established both by work type and quantity. Lacking recorded data between work and post mile, the section is subdivided and the work assigned in accordance with the supervisor or superintendent's judgment and knowledge. This is done in the field.

OPERATIONS ELEMENT

The operating cost element progresses through three distinct phases (exclusive of the field gathering of information). In phase 1 existing work and travel patterns are analyzed; in phase 2 the impacts of proposed changes on the systems elements are estimated; in phase 3 the network for each pattern of stations to be reviewed is reconstructed.

The output of this element becomes, in turn, the input for the facilities siting model. In addition, information about the total work load at each proposed location becomes input information for the capitalized cost element; that is, the derived data yield information about needed crew size. Crew size determination permits an accurate estimate of the facilities that will be required.

Three groups of input information are needed by the operating cost element. First, the station's location together with locations of alternatives are described, which establishes the critical relations between the station sites and the highway section. Second, information showing the subdivision of the section into segments and assigning work to the segments by type and quantity is given. The third input provided is the categorized work hours obtained from MMS records.

Phase 1: Analysis of Existing Work Patterns

The first phase of the element analyzes the established work patterns. In California, all maintenance costs are reported to the highway section (the portion of a state highway within the responsibility of a single supervisor) and must be allocated back to the segment level by subjective means. The person responsible for the day-to-day work planning reviews the highway and provides weighting factors for each type of work performed by the crew.

The work reported in MMS is allocated to the various segments in proportion to the weighting factors; travel support is allocated in proportion to both the weighting factor and the actual travel distance. The average travel speed for each work group is derived from the MMS recorded work hours and kilometers of travel. Travel frequencies are developed from the actual distances, time spent, and derived speed.

The analysis process provides five-year average values for production effort, travel support, and travel frequency for each segment. Travel frequencies are estimated in one-way trips.

Phase 2: Estimating Travel Time Impacts

By using the travel frequency estimates just developed for each segment together with the information describing each alternative location, the travel effort for a location of interest can be estimated. The combined travel and production estimates yield an estimate of the total maintenance effort required to support each segment of the highway from that location, whether it already exists or is being planned.

The travel and total effort estimates are also presented as five-year averages.

Phase 3: Network Simulation

The systemwide impacts of the various patterns of station location are tested by simulating highway operation by using sets of selected sites.

More complex networks are first simplified by deciding which station is responsible for each primary or backbone route. The maintenance responsibility for lateral routes is that assigned to the station found responsible for the primary route at the lateral's junction.

The cumulative production and travel-demand functions are graphically displayed by plotting the values for each successive segment. Separate plots are developed for each discrete set of station sites. The plots of cumulative total effort and travel effort suggest where service boundaries can be located. Under ideal conditions, the point of equal single-trip travel time and the points of equal travel and total effort would be the same spot. While we have yet to find that ideal highway, our experience to date has been that these three indicators will not differ widely. Taken together they establish the general location for the service boundary.

From a practical point of view, once the location has been established, the exact boundary will be determined by field consideration. We have found that most section boundaries are characterized by a well-defined landmark and a suitable place to turn the equipment around.

When the selection of service boundaries is completed for each station site under consideration, the maintenance force required at each station can be estimated. The station estimates of the maintenance effort in work hours per year are translated to dollar costs by applying appropriate hourly rates for labor and equipment. Likewise, staffing needs can be readily estimated from the estimates of annual work hours. The latter information is extremely helpful when establishing the type and size of facility needed to support the maintenance area.

MAINTENANCE STATION CAPITAL COST ELEMENT

Station- or plant-related costs are the subject of this element. Its objective is to present the cost data in a manner that will allow management to make tradeoffs with the previously modeled operating costs. Consideration is also given to the facility's operating costs, even though these are not capital costs.

When the operating cost models were developed, discrete sets of station sites were examined, and costs were estimated for each of these patterns. In addition, estimates were made of the staffing and work load that would have to be supported from each site. For each condition examined in the operating cost model it is proper to develop a companion capital cost model.

The first, most critical step in developing the capital cost model is to write a schedule of the capital outlays required to implement each pattern. To do this one must estimate all of the cost factors expected to arise during the study period.

Each site being considered in the location study process requires a capital cost analysis. A few sites may require alternate studies that cover more than one possible development plan.

CAPITAL COST MODEL

In the capital cost model, all planned or anticipated expenditures over a 30-year study period are included, starting with the first expenditure. The time between the performance of the study and the beginning of the study period is treated as lead time. To properly evaluate each expenditure, an estimate of when each expense will occur is as critical to the analysis as the dollar cost itself.

The 30-year time span of the study was not chosen for its convenience. We have a significant number of stations that have been replaced or reconstructed. In reviewing the service lives of these stations, we found the median age to be 30.0 years (average 33.2 years, most common 27.0 years). The 30 years' expected life span is also used as a guide for estimating when existing buildings should be replaced.

One of the outputs of the operating cost model was a location-by-location estimate of the total maintenance effort needed to support the highway system. These estimates, when translated into work years, are used to select appropriately sized buildings and related improvements for each station.

The staffing estimates will indicate the basic building size needed at any given site. Once the building size has been estimated, it will be necessary to identify those supplemental facilities that will be required at each site—the number and size of storage bins, the absence or presence of storage areas, warehousing, and emulsion tanks—which are all determined by the character and quantity of the work to be supported by the facility.

To facilitate the trade-off analysis, the station-related costs need to be stated in terms compatible with the results of the operating cost analysis. The operating costs previously developed are expressed as annual expenditures. Therefore, the station costs are also annualized.

COST FACTORS

Five major categories of costs are treated in the capital cost element. At any given station, some of these costs may not be applicable. In some cases additional costs may be identified. Common and unusual costs are listed below.

Common Costs	Unusual Costs
Land	Employee housing
Value of existing facilities to proposed solution	Costs associated with personnel shifts
Investment in new facilities	Unique community costs
Value of any facilities replaced	
Remaining value of all land and improvements at end of study period	

Land Values

Land values include both the value of existing sites that will be used in the future and the costs of acquiring new sites. In developing the land costs, the costs of road improvements, utilities, and other undepreciable work such as land leveling or site clearing are included. The cost base for estimating land values is the expense of obtaining new sites or the estimated market value of existing sites that will be continued in service.

Existing Facilities Retained

The next major cost consideration is the value of any existing facilities that will be continued in service. This consideration concerns only the improvements on the land, not the value of the land, which has already been treated. There are three common methods of estimating the value of the facilities to be perpetuated: the fair market value, the alternate-use value, and the salvage value. Each of these methods of valuation should be reviewed and the appropriate method selected. The costs of upgrading, remodeling, or rearranging are not included in this category but are considered as new facilities investments.

New Facilities Investments

The investment required for new facilities is the most significant of the capital cost categories. Within this category are considered not only the costs of new improvements at new sites, but also the cost of additions, modifications, or extensions of existing facilities at existing sites. Planned future capital improvements are also included in this category.

Building costs are estimated by using standard industry techniques. Special features unique to maintenance stations are best estimated from historical costs of similar facilities or apparatus.

Costs that will not arise at the beginning of the study period but will have to be paid in succeeding years are estimated in base-year dollars. However, the year in which the improvement will be required must also be identified. The finished product of this schedule preparation should be a long-range capital improvement plan for the site that covers the entire 30-year study period. Because some of the capital outlays are deferred outlays that arise at some future time during the study, it is necessary to calculate the probable salvage value of each element of the site's master plan at the final year of the study.

Existing Facilities Replaced

When an existing facility will no longer be used as a maintenance station, the residual value of that station is considered in the analysis. This is normally treated as a credit or cash inflow. The credit to be taken for a facility to be replaced is the estimated market value of the improvements, the salvage value of the improvements, or the value represented by the improvements when they are converted to another use.

In some special cases, there may be no cash inflow. One case of this type would involve federal land occupied under withdrawal or special-use permit. This land cannot be sold. In some cases, the value may be negative if the improvements must be removed.

Residual Value of Investments

All the investments discussed up to this point will have a residual value at the end of the 30-year study period. Because plant investments lose value with age, their depreciated value must be estimated. These residual values are treated as credits or cash inflows occurring in the last year of the study period.

Maintenance stations are special-purpose developments and rarely can be sold, even when new, at a price equal to their cost. For this reason, Caltrans has avoided using straight-line depreciation as a method of estimating residual value. Depreciation methods that show more rapid loss of value in the earlier years of a station's life are considered more realistic.

Unusual Costs

In more remote areas of the state, housing frequently must be provided for the employees. These costs are generally similar to the stations' other costs but are handled separately. When presenting the results of the economic study, the costs of housing and any differences in housing costs between locations are pointed out.

The companion social-economic study, which goes along with the location study, may reveal cost impacts affecting either Caltrans employees or the communities in the study area. Significant impacts on the local tax base or school system, the costs of employee relocations, or any similar effects are considered in the study. If the personnel or community costs are one-time expenses related to the implementation of a proposed course of action, then these costs are estimated and capitalized. Costs of a continuing nature are combined with the annualized capital costs.

Station Maintenance and Upkeep

Station upkeep and operations are not capitalized costs, but, because of their relation to the maintenance stations rather than to the highways, they are included in the capital cost element. Costs included in this category are such items as utilities, repairs due to normal wear and tear, and custodial work.

The magnitude of these costs is estimated by past costs projected into the future or by regional norms. Regional norms have been established for each of the five geographical areas of the state as shown in Table 1. The operating and maintenance costs are added to the annualized capital costs.

ECONOMIC ELEMENT

When the master plan of capital development for a site has been completed, the net present worth of all investments and investment credits is calculated. This net present worth plus the net present worth of all future expenditures is then translated into an equivalent annualized capital cost so that it may be combined with other annual costs that have been developed.

Caltrans' current practice in the economic analysis is to use a discount rate of 10 percent, which was selected after consideration of a number of factors. The rate represents a compromise between the return that would be expected on a dollar invested in the highway system, a dollar of state highway funds invested in nonhighway improvements, the rate of return demanded by California public utilities, and current federal practice.

After capitalized cost estimates are developed for each station combination in the operating cost analysis, these annualized costs are combined with the estimated annual station operating and maintenance costs to develop the station's total specific cost. The station's specific costs are then in turn combined with the costs for other stations to develop the capital costs for the entire network. This process is repeated for each pattern of stations investigated in the operating cost analysis portion of the model.

The results of the capital cost model are now in a format that can be integrated with the results of the operating cost model to generate the total maintenance station location model.

MAINTENANCE FACILITIES SITING MODEL

In the previous elements a wealth of specific information relating to the costs of maintaining a state highway system and the capital requirements to support that maintenance effort have been developed. All of this information is now brought together to disclose how each alternate network arrangement will affect the total system.

California has chosen to preserve existing service locations and work assignments as its benchmark for the measurement of change. The cost base used is the total of the operating costs for the maintenance effort and the station-related costs. These costs represent the total variable costs associated with the system. The fixed costs of system support such as training, safety, and supervision are not developed because they are equal components of all solutions.

The potential solutions are placed into classes based on the number of service locations to be used. In this manner network configurations proposing the use of three service sites are separated from potential solutions proposing the use of two, or perhaps four, service locations.

Working in turn with each potential solution within a given class, the maintenance cost and station-related costs are tabulated and the change in cost from the benchmark is determined. The alternatives within the class may then be ranked by the effects of their total cost. This process is repeated for each class studied (see Table 2).

Unless the number of solutions is small, a doubled ranking system is very helpful in reaching a suggested solution. First, all the solutions in a single class are ranked by relative savings. Second, the most attractive solutions or alternatives are identified and ranked. The second ranking compares the preferred solutions of each class. This process highlights the most preferred or the most economical solution.

Up to this point any discussions of the noneconomic factors that always surround decisions of this type have been carefully avoided. These factors are treated in a separate socioeconomic report whose function is to carefully examine the superior alternatives. The report will examine, in considerable depth, the impacts each alternative will have on local communities and on the lives of the employees. Although the social effects of the decision are the subjects of a separate study, the economic study should be sensitive to the potential impacts of all solutions. If one of the solutions carries an obvious and severe social penalty, then the analysis should explore the economic aspects of that penalty. It should not make a social judgment but simply provide the information necessary for managment to make its decision.

THE DOYLE-BECKWOURTH CASE STUDY

By mid-1976 our limited model had advanced to the stage where field testing was indicated. The theory was apparently sound because we had used two very limited but real situations in its development. The long-delayed project to replace an obsolete station in the small community of Doyle offered us the opportunity we needed. The manager was approached and agreed to the trial.

The station at Doyle, a community of 175 people, was established in about 1945 by using buildings moved in from another location. The source and age of the main building are unknown, but its type of

Table 1. Regional norms for station costs.

Geographical Region	Operating and Maintenance Costs: Unit ($/year per square foot)	Operating and Maintenance Costs: Total ($/year)	Coefficient of Reliability (R)
Coastal	$591 \times (\text{area})^{0.723}$	$591 \times (\text{area})^{0.277}$	0.49
Valley[a]	$1678 \times (\text{area})^{0.664}$	$1678 \times (\text{area})^{0.136}$	0.80
	$846 \times (\text{area})^{0.664}$	$846 \times (\text{area})^{0.336}$	0.74
Foothills	$2096 \times (\text{area})^{0.900}$	$2096 \times (\text{area})^{0.100}$	0.79
Mountains	$85.78 \times (\text{area})^{0.472}$	$85.78 \times (\text{area})^{0.5}$[illegible]	0.61
Desert	$67.27 \times (\text{area})^{0.456}$	$67.27 \times (\text{area})^{0.544}$	0.90

[a] The first line is crew costs, the second supervisor costs.

Table 2. Summary of changes in annual costs.

Alternative Number	Proposed Station: Pattern	Proposed Station: Location	Station Costs ($)	Highway Operating and Maintenance Costs ($)	Total Changes ($)	Intrapattern Ranking	Interpattern Ranking
0	Three stations	San Lucas, Soledad, and Priest Valley	Base	Base	Base	3	
1A		San Lucas, Soledad, and Priest Valley	-	-1 100	-1 100	2	
1B		San Lucas, Soledad, and Junction US-198 and US-25	-4 000	+1 000	-3 000	1	4
4A	Two stations	Kings City and Priest Valley	-42 900	+9 800	-33 100	3	
4B		Kings City and Junction US-198 and US-25	-46 900	+11 300	-35 600	2	2B
5B		Greenfield and Junction US-198 and US-25	-46 900	+11 200	-35 700	1	2A
3C	One station	San Lucas	-82 800	+28 700	-54 100	1	1
4C		Kings City	-89 300	+36 200	-53 100	2	
5C		Greenfield	-89 300	+45 400	-43 900	3	

construction would indicate that it was originally built in the late 1920s or early 1930s. It is obsolete.

The present Beckwourth station was built in 1932 and, although expanded in 1959, is also obsolete.

To keep both of these stations functional would require a capital expenditure of nearly $650 000 in the near future, which would continue the existence of both small crews. These four- and five-person crews were not really capable of economical production under current traffic and safety requirements. The need to take corrective action was identified as far back as 1972 when a budget request was first submitted.

The Location Study

With the cooperation of local and regional managers, a full-scale study of the Doyle-Beckwourth needs was undertaken in the second half of 1976.

The scope of this study was far broader than anything attempted during the earlier development stages. The study treated 178 centerline kilometers (110 miles) of state highways. Three maintenance crews became directly involved in the study, and the costs from seven separate highway sections divided into 31 separate segments had to be considered. During the course of the study a total of 10 solution strategies were investigated. Five of the strategies were

1. Reconstruction to preserve the status quo,
2. Relocation of the crews to a common plant,
3. Crew consolidation and relocation,
4. Joint use of a single yard with another state agency, and
5. Various boundary conditions coupled with other strategies listed above.

The preferred solution included the aspects of (a) joint facilities development with the Department of Water Resources, (b) crew consolidation, (c) boundary reassignment, and (d) relocation. Multiple considerations required very carefully prepared plans, but beyond that no special problems were encountered.

The solution recommended to management was combining the crews into a single, larger crew to construct joint operational facilities with the Department of Water Resources in Beckwourth and to sell both existing stations.

The economic implications of these decisions were that areawide travel costs would be increased by $11 000/year, that plant construction costs would be about $375 000 instead of the $650 000 needed to continue the existing pattern of stations, and that the combined operating and capital costs of the offered solution would be $14 000/year less than the combined costs of two stations and crews.

The local managers agreed to accept the offered solution, and early in 1977 the crews were combined and the necessary service area adjustments were made. Operations were temporarily set up in the existing plant at Beckwourth pending the construction of new facilities nearby.

Study Evaluation

After operation for a period of one year with the Beckwourth and Doyle crews combined into a single crew, the results were evaluated. The results were both surprising and gratifying.

During the trial period preliminary architectural plans were prepared, and project budget estimates were developed. The architect's estimate for the project was $380 000, within $5000 of the conceptual estimate. Some upward movement of the estimate is expected because of unusually high inflation and minor project additions.

The study had projected a rise of $11 000/year in the costs of providing highway services without any increase in the service level. The study had assumed little or no change in productivity. The first year's results showed that, although there was an increase in travel time, it was not as great as had been expected.

An unexpected finding was an extremely significant increase in productivity. The year's operating costs decreased by $20 000 despite the increase in travel costs. Local management's analysis attributes this decrease in costs to three factors: increased efficiency because of crew augmentation, modification of work methods made possible by a larger crew, and a reduction in the quantity of nonproductive effort.

Throughout the study area no reduction in service levels occurred, even though the total staff serving the area was reduced from 10 to 9 people by the elimination of one supervisor when crews were combined. In fact, winter snow- and ice-patrol activities have actually increased on more than 56 centerline kilometers (35 miles) of the system along US-395. Before the merger of the crews, patrols were provided 8 h/day, 5 days/week with night and weekend service provided on an on-call basis. With the larger service area, it became economical to provide patrol service 7 days/week, 20 h/day.

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Systematic Development of a Highway Maintenance Simulation Model

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The number of interactions involved in the operation of the common industrial or governmental organization of today makes effective management very difficult, especially when the system is constantly changing. One effective method of examining the various aspects of such a system is by means of simulation. This paper reports research required to perform the initial phase and several follow-up stages in the development of a highway maintenance simulation model. This model is expected to provide management personnel in a state highway maintenance program with the opportunity to consider realistic alternatives and to analyze results of various possible actions before physical changes or irrevocable policy decisions are made. The model uses information such as work activities, labor power, equipment, materials, work-crew alternatives, road network consideration, weather characteristics, and scheduling alternatives. The model should give administrative personnel a means of considering a wide variety of typical highway maintenance dilemmas. Situations that only experience and rule-of-thumb reasoning explained in the past can thus be examined through the eyes of statistical indicators.

The number of interactions required to operate an industrial or governmental organization complicates the job of effective management. This is especially true when the system at hand is constantly changing. Simulation provides an effective tool for considering the various aspects of such a system.

This paper deals primarily with the research needed in order to perform the initial and several follow-up stages in the development of a highway maintenance simulation model.

The simulation model being developed is expected to allow highway maintenance management personnel to consider realistic alternatives and to analyze the results of various possible actions before they make any physical changes or irrevocable policy decisions.

PREVIOUS WORK

In 1967 the office of research and development of the Bureau of Public Roads (BPR) sponsored a study on the application of systems analysis to highway maintenance. The study was conducted by the National Bureau of Standards in two phases. Phase 1 was essentially a broad examination of highway maintenance and the identification of problem areas where systems analysis techniques appeared to offer some promise. At the end of phase 1, it was recognized that, in order to realize the greatest benefit from the project, it would be necessary to channel the remaining study resources into a single problem area; the one selected was the development of a simulation model for highway maintenance.

The phase 2 effort (1), however, was not sufficient to develop a working simulation model to its full potential. The model was designed with extensive detail in certain areas and showed excellent potential in some ways, but the program had one significant shortcoming: The simulation model would not operate (run) to the extent that it was intended. The major error seems to have been including too much detail too soon, given the project's time restrictions.

A number of other studies have been conducted that deal with specific portions of the overall highway maintenance problem, such as weather conditions (2,3), road networks (4), job-scheduling techniques (5), maintenance station locations (6), and roadside mowing operations (7). However, none of these addresses the highway maintenance problem as a whole.

SCOPE AND LEVEL OF DETAIL

The purpose of the simulation model is to aid the users to better understand the response and behavior of the highway maintenance system under different conditions.

For example, suppose that highway maintenance management personnel are considering purchasing some maintenance equipment. Reports show that equipment types 5 and 7 are needed more than the other equipment types. The question then arises of whether management should allocate the money for purchasing equipment type 5 only, or equipment type 7 only, or a combination of both, and, if so, how many.

In such a situation the decision maker's goal is to purchase and use sufficient amounts of each equipment type that the total contribution to the system's performance will be as large as possible. In reality, there is only one sure way to know exactly what contribution the addition of three pieces of equipment type 5 will have on the overall maintenance system. That way is to buy them and observe how the system functions with these additional equipment units over a period of time. But the result may be negative or the improvement slight, which indicates that another course of action might have been better. Simulation allows the user to try alternate approaches and to analyze probabilistic results through the model without the risk of physical involvement.

Another example may help to clarify the concept further. Suppose highway maintenance management personnel would like to have some idea of how the additional maintenance jobs could be worked after various combinations of new equipment were purchased. The model can be run for every logical combination of equipment. By examining the performance output, the user can decide which is the preferred choice. It is important to understand that the simulation model itself is not expected to find the optimum solution for any particular problem, but rather to provide sufficient statistical results that describe the state of the system over a period of time for each of the possible alternative courses of action.

ASPECTS OF THE MODEL

The program was developed with the following three primary goals to ensure the practicality and applicability of the model:

1. The model should be flexible in design to allow the input to define any specific maintenance data values and variations required in considering a highway maintenance situation.
2. The model should contain enough detail for good predictions on the district level but little detail above that amount.
3. The model should be applicable to both districtwide and parishwide maintenance operations.

The simulation development process consists of defining the interrelations between the physical elements and the decision processes that comprise the highway maintenance system. In order to represent a system of the level of complexity of this physical situation, a sizable number of elements and factors must be considered. These include various aspects of the work activities, road network factors, and several other special provisions such as weather, scheduling, and emergencies. A more complete listing of the program's elements is given in the list below.

1. Work activities: type of activity, location in the district or parish, seasonality of the activity, weather conditions, severity of defect, frequency and distribution of the number of occurrences for each type activity, and resource needs;
2. Personnel: personnel types, skills, availability of each type, base locations, and cost by personnel type;
3. Equipment: equipment types, personnel required for each equipment type, base locations, availability of each type, and cost by equipment type;
4. Materials: materials types, base locations, availability of each type, and cost by material type;
5. Work-crew alternatives for each activity (listed by work activity type): number of each personnel type, number of each equipment type, and performance rate of the alternative;
6. Road networks: type of surface, rural or urban, average number of occurrences for each type of work activity, and point-to-point travel considerations; and
7. Other considerations: weather characteristics, scheduling alternatives, emergency activities, performance characteristics, absenteeism, overtime, and contract work.

The final simulation model is expected to be able to appropriately incorporate the details involved with each of these considerations and interrelations into a realistic approximation of the actual system. The process is designed to be direct. That is, the user is required to enter variables via a prescribed input format; he or she is asked to specify certain program controlling parameters and, after the program has been executed, is provided with a varied set of statistical indicators that are an evaluation of the system's actions.

OBJECTS OF THE MODEL

In order to approach the problem properly, the objects of the model must be clearly defined. As a general statement, the overall object of the model is to be able to effectively consider the types of problems commonly encountered by highway maintenance administrators that deal with work crew, equipment, and material decisions. To address this situation more specifically the model must include sufficient input capabilities, sufficient computational breadth and depth, and sufficiently differentiating output to reasonably consider and display a wide variety of highway maintenance administrative dilemmas. These problems are such that no available means can effectively differentiate between alternatives. To better describe the type of problem the simulation is intended to address, a series of examples is given below:

1. Evaluate changes in work crew sizes and what effect the addition of two equipment operators would have.
2. Evaluate quantities and types of equipment, for example, whether it would be better to add two trucks of size A or three trucks of size B.
3. Evaluate work scheduling policies, for example, whether long- or short-duration activities should be chosen first when setting schedules with scarce resources.
4. Evaluate different maintenance strategies, for example, which policy is better in the long run for repairing a road defect.
5. Evaluate alternative material, personnel, and equipment base locations, for example, how much of material A should be kept on hand and where it should be located.

Because the situations are so varied and multiple objects naturally exist, the modeling object becomes one of incorporating into the model the capability of dealing with each of a wide variety of possible situations.

MODELING APPROACH

Although it is a slight overstatement to say that there are two types of computer programs—right ones and wrong ones—in a real sense this is very nearly true. One of the primary pressures on any computer-oriented research is the pressure to get the program running. In fact, the larger the problem the higher the risk and the greater the pressure. These factors are intensified if there is a fixed time constraint such as a contract due date on the research.

This section describes the approach used to handle the level-of-detail versus time-constraint problem encountered in this research.

Steps

The procedure used is essentially a three-step process

Figure 1. Model concept.

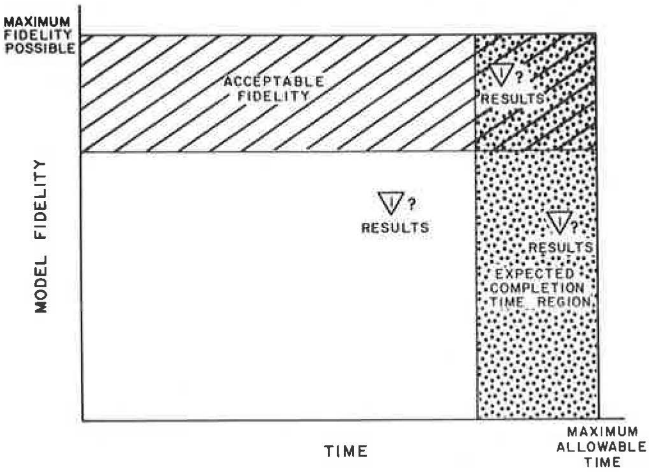
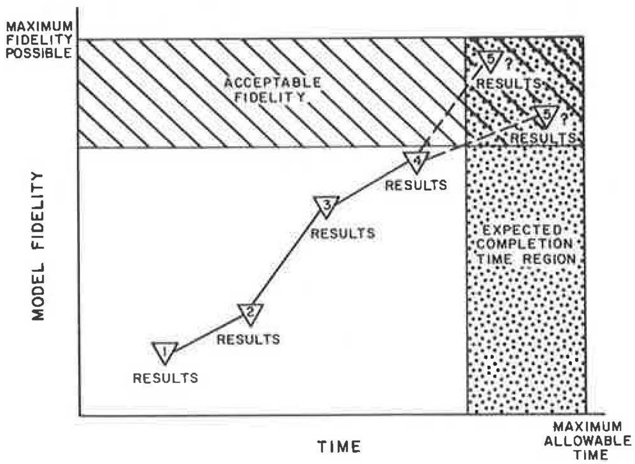


Figure 2. Evolutionary modeling approach.



through which the model evolves into its final form. The steps are

1. Construct an initial, basic (highly abstract, low detail) model;
2. Fully document and preserve the model as a benchmark for future reference and comparative purposes; and
3. Make rapid, distinct, evolutionary changes in the model in order to increase the level of detail (remove abstraction) and improve the fidelity of the model.

These concepts are discussed one at a time in what follows.

Concept

In order to model any system, the physical process must be well defined. However, since it is virtually impossible to completely and accurately describe the process, especially within some limited time constraints, it is sound practice to simplify the model by omitting or assigning constant values to some of the system's variables. The more variables that are suppressed, the higher the degree of model abstraction. As such, a more abstract model would not be expected to represent the real-world situation effectively. The model's fidelity is its ability to reproduce the actual system's results and would likely be rather low. There are some definite advantages to such an approach, however.

First, a working model can be developed in a much shorter time period. Although small problems can often be completed in a relatively brief time, it is very common in the case of larger, more complex problems for the first good run to take several months to achieve (Figure 1). Such a situation is not conducive to positive short-term reporting or to high morale.

Second, the success of the initial venture (Figure 2), without regard to the level of abstraction, is certain to produce a psychological boost to the modeling group and the management personnel group who have supported the project.

There are invariably people within the management decision-making chain who are either opposed to the idea of modeling or skeptical that it can be accomplished. Early reporting of positive results has the effect of attracting the uncommitted management people and strengthening the position of the supportive group. Such results will often produce a change in atmosphere for those who are involved in the project and make data collection and interaction more pleasant and productive.

In the case of the highway maintenance simulation, the final model should reflect all operations, weather conditions, material, equipment, personnel, travel, and the costs associated with the interactions of these units. However, rather than include all these factors from the outset, the initial model was designed to include only five types of operations (rather than the true number of about fifty): good or bad weather conditions, groupings of material and equipment types, a reduction of the various types of equipment operators and work specialists into the single category of "people", and a simplification of the travel calculations. The completion time for such a reduced initial model was much shorter than the completion time for the full model, allowing for the occurrence of the associated benefits discussed previously.

The initial working model thus becomes the first benchmark. Subsequent successful revisions of the model serve to provide higher-level benchmarks, once they have been tested and found to be operating properly. So, rather than make larger significant changes in the model (which may involve a large amount of time), small, rapid, distinct changes are produced. Each of the evolutionary stages represents a working model, complete insofar as the assumptions have described the situation. Each new stage represents a goal, while each new benchmark model represents a goal accomplished.

The approach described is a procedure that has been used effectively throughout the project to protect against the possibility of undesired consequences, such as time limitations and the negative psychological effect of not having any solid indicator of development.

MODEL DESCRIPTION

Assumptions for Initial Benchmark Model

As described previously, the first step in the modeling process was to define a benchmark model with several assumptions and to work on this simplified version of the model before the full scope of details was considered (in single-file order). The assumptions to be made were chosen in such a manner that the sense (i.e., skeleton structure) of the proposed model was not destroyed, but rather so that future development and programming difficulties were reduced. Significant effort was expended in detailing the assumptions so that later extensions would not cause unnecessarily severe difficulties in the programming. These assumptions are given below.

1. There are only five possible work activities instead of the approximately fifty actual work activity types.

2. Differences in the highway types are ignored, although actually there are three types: Interstates, state highways, and farm-to-market roads.

3. Weather is considered to be either good or bad instead of rainy, windy, icy, snowy, foggy, and so forth.

4. There is only one season during the year instead of four.

5. The time increment is considered to be by half days as opposed to hourly, which was also considered.

6. There is only one type of personnel, one type of equipment, and one type of material instead of about six types of personnel, ten types of equipment, and several types of material.

7. Emergency activities occur at the beginning of a period and have a duration of one period, where an emergency activity is an unexpectedly occurring work activity that must be worked immediately.

8. There is only one resource base location, and all the resources in the district (personnel, equipment and materials) are allocated from that point, whereas in reality there may be more than one resource base location.

9. Once a particular crew is assigned to a job, the crew will continue with the assignment until the task is completed.

10. Activities will be assigned to crews on the basis of least cost (for the performance of that activity only).

11. An activity already begun in a previous period has a higher priority in the scheduling process than another activity of the same type that has not yet begun. Also, the highest-priority work activity of all is emergency activity, which has the capability of preempting any ongoing job.

12. The leftover resources for any period fall into two basic categories, productive and nonproductive. They are considered as follows:

   a. In a productive activity a slack-time activity is assumed. There are work activities considered productive that require specific crew sizes and have definite equipment needs but that are "saved" to be worked on when no other productive jobs are able to be performed. In the benchmark model, these jobs are called slack-time activities and are performed when the conditions stated above exist.
   b. In a nonproductive activity a leftover resource is assumed. The final leftover resources that cannot even be assigned to a slack-time activity are referred to as leftovers.

13. The number of occurrences per week for all activities is assumed to be Poisson distributed, and the time between occurrences is assumed to be distributed exponentially.

14. The district or parish is divided into four sections, each of which has a certain distance (represented by a travel time in hours) from the resource location base.

Macroprogram Logic

The initial benchmark model was programmed in two simulation languages, GPSS/360 (8) and GASP IV (9). The macroprogram logic is basically the same in both language versions. Also, because the macrolevel logic does not change later when extensions to the model are made, as additions and modifications are performed, the program flowchart simply takes on more detail, while the direct, initial logic remains virtually unchanged.

After development of working models in both computer simulation languages, the choice was made to perform the remaining modifications by using GASP IV only. This decision was based primarily on the fact that GASP IV, as a FORTRAN-based language, provides a greater degree of programming flexibility and capabilities equal to those of GPSS/360.

In reality, the maintenance work system is initiated by the maintenance supervisor, who drives a truck on the highways of the district spotting defects along the way. As a result, he or she develops a list of work activities that will ideally be worked during the coming week. The simulation model is initiated in a similar manner, by generating the next week's work activity list by using the random number generator and the distributional forms characterizing the occurrences of defects of each type. Space restrictions prohibit a lengthy description of the program itself, but the macrolevel flowchart shown in Figure 3 gives a logical view of the programming approach.

Program Input

The same basic input values are required for both versions of the benchmark model. These include parameters for several probability distributions of work activities, emergency personnel and equipment requirements, defect severity, classification, and weather condition variations. Input is also necessary to specify resource availabilities, various costs, travel times, and activity and crew characteristics. A more detailed input description is given in the list below.

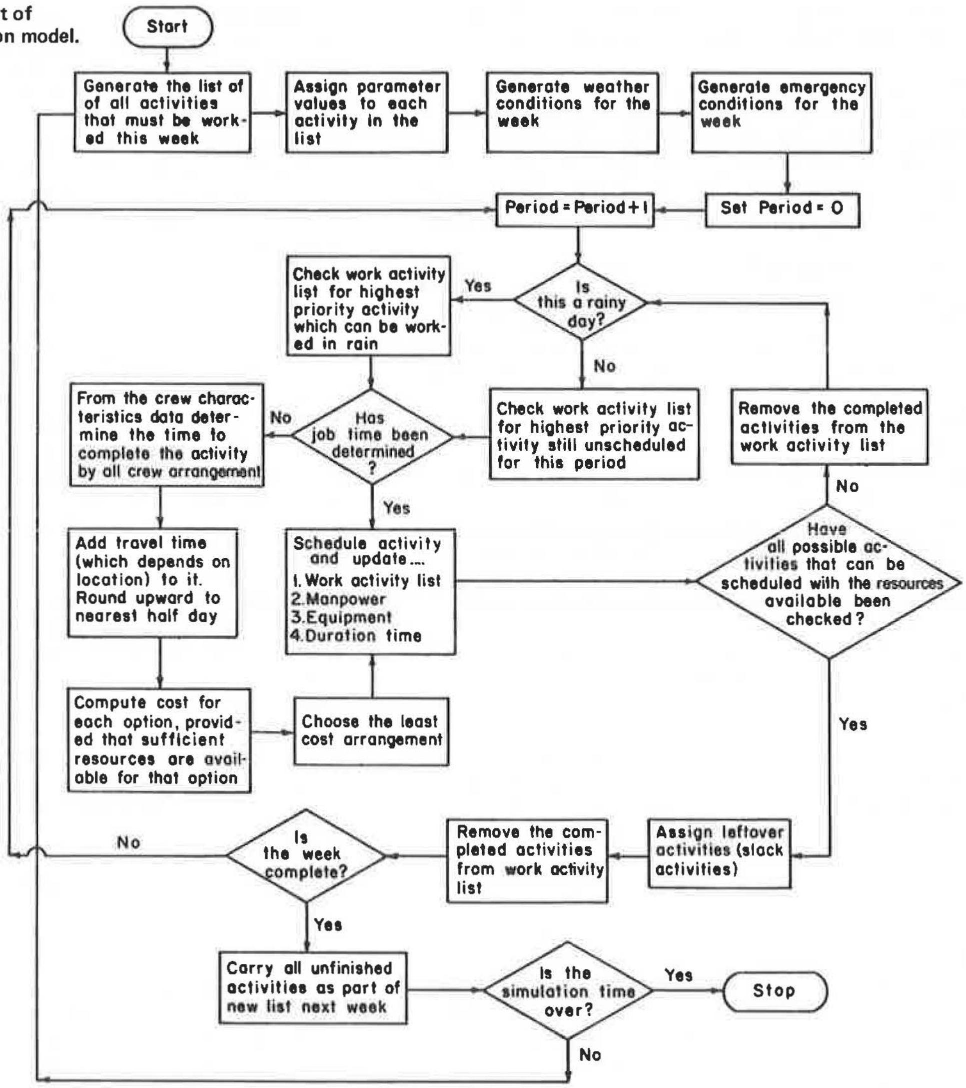
1. Parameters for several probability distributions: occurrence of each work activity (including emergencies), defect severity for each work activity (including emergencies), defect location for each work activity (including emergencies), weather condition parameters, personnel needs for emergency activities, and equipment needs for emergency activities;
2. Resource availabilities at the base location;
3. Cost of various resources per period;
4. Travel times from resource bases to defect locations; and
5. Crew characteristics for each job option: personnel requirements, equipment requirements, and performance rate.

Program Output

The output from the initial benchmark model consists of several statistical indicators that describe the behavior of the maintenance system under the prescribed conditions. The following statistics are collected:

1. Leftover (unused) personnel and equipment levels at the end of each period after slack crews have been assigned, both of which indicate the level of resource use;
2. Proportion of time the preferred crew option is assigned to the job and the proportion of that time the alternate crew was scheduled, given that the preferred crew was not able to be scheduled;
3. Time elapsed from the activity's generation until the activity is begun (i.e., successfully scheduled);
4. For each work activity, the time spent in the system (i.e., time from generation until completion);
5. Time required to accomplish the task once the activity is begun; and
6. The number of crews assigned to the standby (i.e., productive) activity each period, which gives a

Figure 3. Macro-level flowchart of highway maintenance simulation model.



numerical measure of the level of resources not assigned to expected work activities each period but nevertheless used to perform some other productive job.

Each of the statistics plays a unique role in the evaluation of a simulation model.

Example

In order to better understand the role of the model, its input, and its output, a brief example is presented. In fact, the results discussed were taken from the GASP IV version of the benchmark model, but nearly identical values could have been acquired by using the GPSS/360 version. For the sake of brevity, not all input and output values are discussed.

Resource availabilities used as input to the model include 50 personnel units and 28 equipment units. The time between defect occurrences of each type was assumed to be exponential with mean times between occurrences ranging from 5 to 11 periods. The time between occurrences of emergencies was also assumed to be exponential, with an average time between emergencies of 4 periods. Other input was entered and the program executed.

An interpretation of the program's statistical results is presented next. The analysis given is primarily a look at the meaningful statistics collected.

After all activities were considered and the leftover resources were assigned to the slack-time activity crews, on the average about eight units of personnel were left idle (or nonproductively used) every period. Out of the 28 equipment units, approximately 16 on the average were left idle every period. In fact, 8 of the equipment units were never used (minimum leftover units = 8.0). This indicates that the district had more equipment units than were needed. A poor balance apparently exists between the personnel and equipment unit availabilities.

On the average, almost three full crews were assigned to unexpected (but productive) work activities each period. At least at first glance this seems to be a rather large number. In 92 percent of the cases, the activities were scheduled to be worked by their preferred (i.e., least-cost) crew. However, in only 9.2 percent of the cases in which the preferred crew could not be scheduled could the second crew be assigned. Clearly, in the case when the best crew is unable to be assigned, the second preference crew is also normally unable to be assigned.

With the present resource availabilities, many of the activities were started immediately after they were generated. On the average, time from generation to starting work was less than 1 period. However, there were cases in which an activity was started 9 periods after it was generated, indicating that, although it was unusual, some jobs still had to wait. Once the activity was started, 4.74 periods were needed (on the average) to finish it and (on the average) it remained in the system for 5.24 periods after its generation. However, there was a case in which an activity (of low priority, no doubt) took 49 periods to finish.

The decisions to be made by examining these results depend on the highway maintenance management personnel and the realistic options available. However, one possible conclusion is that the district under consideration has more equipment units than necessary.

Also, it should be pointed out that simulation, in order to be effective, often requires numerous executions of the simulation model, that is, numerous examinations under varying parameter conditions. This discussion has been concerned with only a single run, which indicates an incomplete analysis. However, this approach was presented in order to show the type of results generated by the simulation program and to provide a sense of the typical analysis process.

Model Extensions

As described in the section on modeling approach, once the initial benchmark model is operative, extensions that improve the program's fidelity are the next logical step. The following conceptual extensions are considered as one-at-a-time additions to the initial benchmark model.

There may be more than one type of emergency, but emergency activities may last more than one period. Some changes and additions may be made regarding the statistics collected in the benchmark model.

There may be more than one resource location base. This seemingly innocent option adds significant complexity to the model. The reason for this additional complexity lies in the combination aspects of more than one resource base location. Since resources can come from either base location, both the economic and feasible aspects of the problem must be considered.

A standard performance report as output from the model may be included. A system as involved as those included under highway maintenance activities cannot be adequately analyzed with only the basic statistics presented previously. In order to improve the user's understanding of the system, a number of indicators that measure the system's performance were added in the form of a performance report. The report is a slightly modified version of a performance report developed by the Louisiana Department of Transportation and Development.

Expansion of the level of detail regarding personnel, equipment, and material is required. The initial benchmark model considered all personnel to be of one type, all equipment to be of one type, and all necessary materials to be readily available and stored along with the equipment. Of course, this level of simplification is not adequate to describe a realistic system. Later versions of the model include several types of personnel, several equipment unit types, and several material types. In addition, considerations for scheduling activities include an inventory check and an ordering policy.

Additional consideration is needed regarding seasonality for both weather and work activities. The initial benchmark model considers only a single season, with corresponding work activity parameters changed for each of the four seasons and the capability of modifying the work activity parameters as the seasons change. The need for this level of flexibility is obvious when one considers that many activities, such as mowing, are highly seasonal.

Numerous miscellaneous changes in the model will accompany these major modifications. Program units, even those that use the efficient approach of evolutionary change, are rarely ever totally independent. This means that modification occurs throughout the program, even for relatively minor changes in approach. These changes include such items as filing array modifications and variations in the methods of statistical collection. These are not normally thought of as model extensions but have a way of becoming just that.

SUMMARY

The research effort on the highway maintenance simulation model described in this paper is not yet complete. Much remains before the final implementation of the complete system is finished. But the method of development and work plan are readily apparent. This paper deals with the development, the completed steps, the partially completed steps, and the steps to come. The approach is very direct.

After the conceptual model design was completed and what information was expected from the final model was determined, a series of simplifying assumptions were made in order that a first-level, benchmark model could be defined. The simulation of the simplified situation was set as the next project goal. In fact, because the most appropriate simulation language was initially a question mark, the first-level model was programmed in two languages, GPSS/360 and GASP IV. Later, after thorough consideration, GASP IV was chosen as the language to be used in subsequent evolutionary stages.

While progress was being made in programming and debugging the initial model, plans were made regarding expansion of the model. Several of these expansion phases have now been completed, while work on others is still being carried on. The final model, scheduled for completion in mid-1979, will include each of the extensions described in this paper and will be used to address questions that could only be speculated about prior to the model's development.

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Countywide Traffic Signal Maintenance Program

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Creation of an effective traffic signal maintenance program requires gathering and analyzing a large amount of data on existing conditions and on the history of maintenance activities. A model has been developed that allows the testing of various maintenance strategies based on historical data from the system being simulated. The computer program, adaptable to almost any computer, does not require user expertise in programming. Its outputs include summary reports, which are an excellent basis for management control and planning. Labor and budget requirements for achieving various levels of accident reduction can be calculated. The model is a valuable tool both for program budgeting and for short- and long-range planning.

Developing an effective traffic signal maintenance program requires gathering and analyzing data on both the existing conditions of the system and its history of various types of maintenance activities. While such data are generally available in files and charts, retrieval and analysis can be time consuming unless the information is processed by digital computer. The benefits that can be gained from even the simplest analysis of signal maintenance data are numerous and can lead to economic savings, higher levels of service, increased productivity, and decreased liability. The law, as it relates to traffic signal maintenance, is that there is a duty to maintain the lights in a traffic control signal and that a failure to do so may lead to liability if it is a proximate cause of an injury. The erosion of sovereign immunity and the gradual increase in financial liabilities to the community have drawn attention to the maintenance of traffic signal systems.

In most areas, maintenance of the traffic signal system is left to one unit of government, be it state, county, or city. The increase in labor, material, and equipment costs in recent years has caused all such units to take a second look at increased productivity and the maintenance of proper levels of service at stable levels of spending. The effect of these spending reviews has been for those in charge of local traffic signal systems to attempt to reevaluate their current procedures in terms of various alternate maintenance strategies. The problem here, however, lies in the facts that sufficient, easily accessible data files are not available and that analysis techniques remain generally at a level too low to allow significant results or information to be gained or a sound engineering evaluation to be made.

To date, several communities have begun the implementation of computerized maintenance reporting systems that lend themselves to the analysis of maintenance-related data and the possible development of model parameters. One survey of the maintenance management of traffic signal equipment and systems (1) concluded that deficiencies in maintenance lead to signal malfunctions or breakdowns that cause delays to the traveling public, increased accident potential, increased fuel consumption, and air pollution. Thus, it is important to have a program that includes routine and preventive maintenance to ensure that problems be kept to a minimum. The lack of the ability to use such data once they are collected can lead to the improper operation of the maintenance program.

BACKGROUND AND SETTING

The Macomb County Road Commission is responsible for 2250 km (1400 miles) of highways in southeastern Michigan (northeastern suburbs of Detroit). The county covers an area of 1253 km^2 (482 miles^2) and encompasses 15 cities and 11 townships, all within the metropolitan region of Detroit. The county has a traffic signal system of approximately 500 traffic signal locations. The signals, which are under the jurisdictions of the various cities, the county, and the state highway department, are all maintained by the Macomb County Road Commission.

Traffic signal maintenance performed by the commission consists of the following types:

1. Routine maintenance: work items that must be performed on a regular basis to ensure the continued operation of the equipment;
2. Preventive maintenance: work items that should be performed at scheduled intervals to minimize the probability of failure of the signal equipment;
3. Emergency repairs: work required to restore traffic signal equipment to its original state after a service failure; and

Figure 1. Work order form.

CBO Date: __________

Nº 32100

MACOMB COUNTY ROAD COMMISSION

TROUBLE AND WORK SHEET

Reported by: __________ At: ______ A.M. P.M. Date: ______

Location: __________ Location Number: ______

Reported trouble: __________

Given to: ______ At: ______ A.M. P.M. Truck Number: ______ By: ______

Arrived at location: ______ A.M. P.M. Date: ______

Condition found: __________

Nature of repair: __________

9. CONTROLLER MAINTENANCE	20. RESET TO CBO	31. ROUTINE LAMP CHANGING
10. SIGNAL INSTALLED	21. RESET CLOCK FOR D.S.T.	32. PEDESTRIAN SIGNAL OUT
11. SIGNAL STUCK	22. RESET CLOCK FOR E.S.T.	33. CASE SIGN OUT
12. SIGNAL TWISTED	23. CLOCK INCORRECT	34. CASE SIGN DAMAGED
13. SIGNAL DAMAGED	24. TIMING INCORRECT	1. VISOR BENT
14. SIGNAL OUT	25. CHECK INTERCONNECT	2. POLE HIT
15. SIGNAL DOWN	26. CONTROL BOX OPEN	3. GUY WIRE DOWN
16. SIGNAL LOW	27. CONTACT BROKEN	4. SPAN WIRE DOWN
17. BAG SIGNAL	28. FLASHER BROKEN	5. OVERHEAD SIGN INSTALLED
18. NO BELL POWER	29. BULB OUT	6. OVERHEAD SIGN MAINTENANCE
19. NO EDISON POWER	30. LENS BROKEN	7. NO PROBLEM FOUND
		8. OTHER

Left operation: ______ A.M. P.M. Date: ______

☐ OK Perm. ☐ OK Temp. ☐ Check Timing

Parts used: __________

4. Maintenance work: work caused by relocation of signals, or scheduled or unscheduled work caused by functional inadequacy of the installed equipment or the need for physical changes in the installation brought about by pavement reconstruction or changes in signalization standards.

The development of a traffic signal maintenance program that integrates all types of maintenance at a minimum cost and also allows a budget and personnel analysis would aid in the efficient use of resources and would minimize accident liability.

Recent studies in highway maintenance have been devoted almost entirely to increasing the effectiveness of either the individual maintenance operation or the management of the maintenance organization. The problem is that highway maintenance involves a broader range of items including equipment and material types, characteristics of individual components of the system, system degradation, and system user delay. The maintenance strategy that will give the lowest total cost will not necessarily give the lowest component costs.

A study was therefore initiated to develop a reporting system to gather maintenance data that could be used to analyze the current maintenance effort and to develop a computer model for simulating the current maintenance strategy and testing alternative strategies.

METHODOLOGY

To enable the development of a model of the maintenance system, it was first necessary to develop, test, and implement a data-collection system.

In 1973 the Macomb County Road Commission instituted a signal maintenance reporting system that allows the necessary detailed data files to be built and maintained. Since that time, data for each traffic signal device under the maintenance jurisdiction of the Road Commission have been collected. The collection consists of reports of every authorized maintenance or service and repair call at all the traffic signal devices.

The reports include date and time of the reported trouble, date and time of arrival of the service technician, condition of the traffic control device, nature of the repair, and condition the location was left in. The reports are prepared by the service technicians that visit the site and are completed on a form suitable for data-processing use (Figure 1). The reports are submitted to the traffic engineer's office, where they are reviewed and the data are punched onto computer cards.

Currently three reports are being prepared from these data: a detail report listing service calls by location, a summary report of service call types by location, and a summary report of various trouble and service types (Figure 2).

Figure 2. Sample maintenance report.

```
                    LOCATION NAME
09 - CONTROLLER MAINTENANCE          2 TOTAL TROUBLE CODE
13 - SIGNAL DAMAGED                  1 TOTAL TROUBLE CODE
22 - RESET CLOCK FOR E S T           1 TOTAL TROUBLE CODE
23 - CLOCK INCORRECT                 1 TOTAL TROUBLE CODE
29 - BULB OUT                        3 TOTAL TROUBLE CODE
31 - ROUTINE LAMP CHANGING           2 TOTAL TROUBLE CODE
                           1974   1975
                              5     12 TOTAL LOCATION TR-SH
   COLE/PHLOX       TO 10 MILE RD         085
07 - NO PROBLEM FOUND                1 TOTAL TROUBLE CODE
08 - OTHER                           1 TOTAL TROUBLE CODE
14 - SIGNAL OUT                      1 TOTAL TROUBLE CODE
22 - RESET CLOCK FOR E S T           1 TOTAL TROUBLE CODE
31 - ROUTINE LAMP CHANGING           1 TOTAL TROUBLE CODE
                           1974   1975
                             13      5 TOTAL LOCATION TR-SH
   GRATIOT          TO REMICK             086
07 - NO PROBLEM FOUND                2 TOTAL TROUBLE CODE
08 - OTHER                          11 TOTAL TROUBLE CODE
09 - CONTROLLER MAINTENANCE          2 TOTAL TROUBLE CODE
12 - SIGNAL TWISTED                  1 TOTAL TROUBLE CODE
22 - RESET CLOCK FOR E S T           1 TOTAL TROUBLE CODE
27 - CONTACT BROKEN                  2 TOTAL TROUBLE CODE
31 - ROUTINE LAMP CHANGING           1 TOTAL TROUBLE CODE
                           1974   1975
                             12     20 TOTAL LOCATION TR-SH
   COMMON           TO GRATIOT            087
08 - OTHER                           2 TOTAL TROUBLE CODE
09 - CONTROLLER MAINTENANCE          1 TOTAL TROUBLE CODE
31 - ROUTINE LAMP CHANGING           2 TOTAL TROUBLE CODE
                           1974   1975
                              5      5 TOTAL LOCATION TR-SH
   CONNER           TO SHERWOOD           088
```

At the time that the signal maintenance reporting system was being initiated, an inventory of traffic signal devices was also being conducted. The inventory consisted of reviewing each location and determining various physical items that characterize each location, such as street location, location number, number of dials, number of circuits, cam intervals, and type of clock and flasher.

To evaluate various maintenance strategies and to determine basic system functioning parameters, the basic information required includes knowing the average number of trouble and service calls per location per year, how the average number of trouble and service calls varies with different levels of controller maintenance and lamp replacement, and how lamp life varies with respect to controller characteristics and maintenance levels.

The first object of this study was to review the basic data files and to determine what relations exist and what types of analysis and data requirements would be necessary for further study. As such, the data contained in the trouble and work report file and the location inventory file were reviewed and a number of items were chosen for review.

1. Total number trouble and work calls per location for 1974 and 1975,
2. Total number controller maintenance visits per location for 1974 and 1975,
3. Total number lamp burnout visits per location for 1974 and 1975,
4. Total number lamp replacement visits per location for 1974 and 1975,
5. Number of timing dials per location,
6. Number of circuits per location,
7. Existence of a flasher unit at a location,
8. Existence of a clock unit at a location,
9. Secondary voltage provided to the controller, and
10. Wattage rating of the location.

The analysis of the data began with a determination of the mean and standard deviation of each variable. Then a correlation analysis was conducted to evaluate the relations among variables that are commonly assumed to be related. This approach was used because we felt it would save time to test these common assumptions.

The variables that were assumed to be related were

1. Number of 1974 trouble and service calls versus 1974 controller maintenance, 1974 lampouts, and 1974 lamp charges;
2. Number of 1975 trouble and service calls versus 1975 controller maintenance, number of dials, number of circuits, number of clock units, secondary voltage at controller, and power consumption of location;
3. Number of 1974 lampouts versus secondary voltage at controller; and
4. Number of 1975 lampouts versus secondary voltage at controller.

The results of the correlation of the unsegregated data did not indicate very high levels of relations for any of the pairs of variables. It was felt that a more detailed analysis of the data base was necessary.

Next the data were segregated based on (a) the number of circuits at a location, (b) the wattage rating at a location, and (c) the number of timing dials at a location. These three items were chosen because we felt that they gave an indication of the complexity of the signal installation.

A study of these characteristics indicated a difference between locations of one circuit that consumed less than 700 watts of power and those of six or more circuits that consumed 700 or more watts. Based on this review, the data set was segregated.

Concurrently with this basic study, a number of regression analyses were performed to determine the relations among the variables of the data set. Again, variables were chosen based upon common assumptions of the signal maintenance field, in an effort to reduce the number of computer runs. Next, by using the following information, we calculated total maintenance calls per location per year, controller maintenance calls per location per year, lamp replacement visits per location per year, total nonmaintenance calls per location per year, and trouble and work calls per location per year. The existing data were plotted.

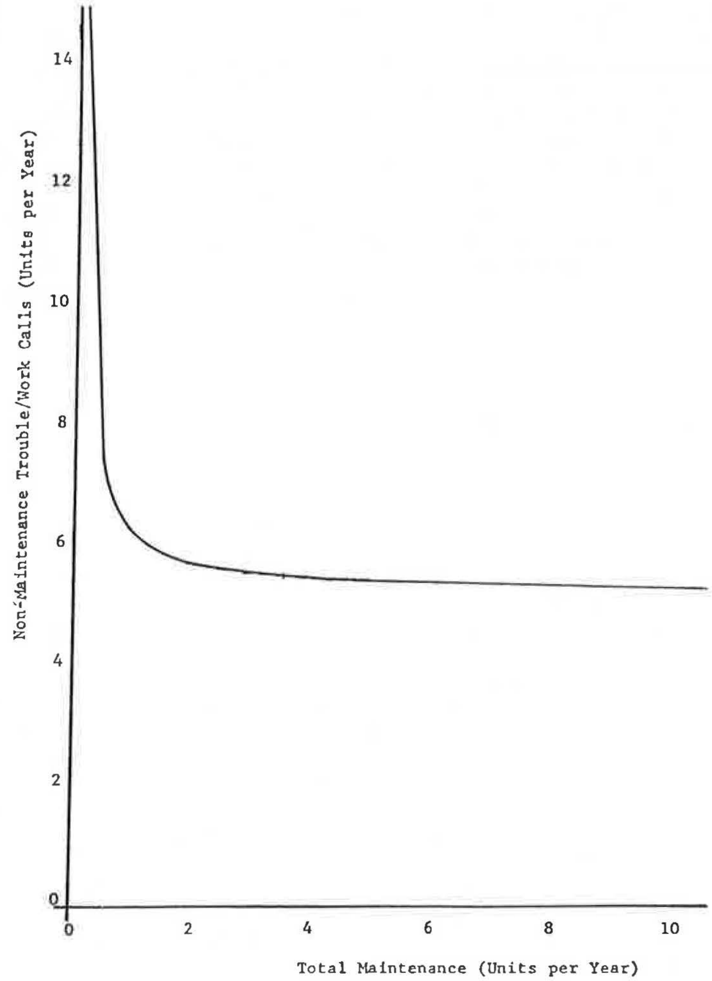
Although it was recognized that the number of data points was too small to establish valid relationships at this time, the assumptions being tested related location trouble to amounts of maintenance. Thus it was possible to determine whether further work would be worthwhile.

After plotting, an attempt was made to fit a curve to the data. The results provided a hyperbolic-type curve (Figure 3) that related maintenance to trouble calls and indicated that increasing or decreasing maintenance to extremes becomes self-defeating, either burdening the system with excessive breakdowns or excessive maintenance.

THE MODEL

In order to evaluate various traffic signal maintenance strategies and various types of signal systems in different locations in an efficient and timely manner, we

Figure 3. Maintenance versus nonmaintenance calls curve.



decided to devise a model that, from the input of various system parameters, would project accurate maintenance requirements. Such projections would be produced in a form that would enable the user to tailor the analysis for any particular traffic operations organization by using the model.

The major system components consist of the following sequential tasks:

1. Entrance and initialization,
2. Maintenance requirement generator,
3. Maintenance queue component,
4. Work time generator, and
5. System clock and termination component.

These major components provide for the general control of the program and system configuration.

Entrance and Initialization

Task 1 provides for the initialization of the system clock and the designation of the traffic signal system. The traffic signal system is initiated by the input of individual data that describe the locations by parameters that have previously been determined to be characteristic of the system. That is, the signal location could be described by the number of electrical circuits, the power consumption, the number of lamps, and other similar items.

Maintenance Requirement Generator

Task 2 provides for the setting up of the various maintenance strategies that can be tested by the model. The maintenance requirement generator responds to the input of the various types of maintenance calls and the conditions under which each type will be responded to. The maintenance requirement generator performs three separate functions in this process. First, based on the designated maintenance characteristics of the signal system, a maintenance call is generated. Second, the call is assigned to a particular location, and, finally, the actual type of the maintenance call is determined. The functions are sequenced in this particular manner so that the maintenance call will be appropriate for the time at which it is occurring and also is compatible with the characteristics of the particular location that it is assigned to. It is during the second and third functions that an iterative process may occur under certain circumstances, where the characteristics of the location may preclude the occurrence of a maintenance call at that particular time. In that case a new location would be designated and checked.

Maintenance Time Generator

The work time generator provides for the calculation of travel and actual work time based on the location of the device to be serviced and the type of maintenance work to be performed. The generator uses travel time data supplied for each location and input as part of the location description.

The times are from the point when the maintenance service crew responds to the point when they arrive at the particular signal location.

To generate maintenance service calls and maintenance types, a method using discrete random deviates was devised. This allowed for the input of data for occurrence and type of maintenance service call that would reflect the characteristics of the system being modeled. This method also allows the input data to be modified to reflect some theoretical or future distributions.

USE OF THE MODEL

Maintenance of the traffic signal requires activities in several categories that include routine maintenance, preventive maintenance, emergency repairs, and reconstruction. Equipment malfunctions, which are more likely to occur when there is a lack of routine and preventive maintenance, can result in increased accident potential, increased fuel consumption, and environmental pollution. Signal maintenance programs include such work items as frequent visual inspections, relamping, signal head cleaning, detector inspection, and control equipment inspection.

Selection of a maintenance policy that includes all the various categories of maintenance and various maintenance programs can be approached as a problem of minimizing the cost of maintenance. Also, the level of maintenance depends on how fast malfunctions and breakdowns are detected and corrected. The dependence of both of these items on maintenance personnel and the procedure they use is critical.

The maintenance strategy used for signal maintenance involves two major areas. The first is the way various categories of maintenance are mixed in an attempt to minimize catastrophic failures. If maintenance work were subdivided into catastrophic and noncatastrophic types, the general relation given below could be described.

$$CF = f(NCF) \qquad (1)$$

where CF is the level of catastrophic failures and NCF is the level of noncatastrophic failures.

In the case of this study, the routine, preventive, and reconstruction categories of maintenance would be grouped as noncatastrophic failures, while emergency repairs would be classed as catastrophic failures. In the case of most signal systems, a variety of signal types and configurations is used, along with different physical conditions of installation. The physical characteristics of a signal installation contribute to the amount of catastrophic failures and therefore Equation 1 can be changed to the more specific form given below.

$$CF = f(NCF, PC) \qquad (2)$$

where PC is a factor that describes the physical characteristics of the signal.

The second area involves the actual dispatching of maintenance personnel and the procedures they use in the field. Some typical schemes used would be assigning work to a crew immediately on notification, holding work until a crew becomes available, or determining action to be taken according to the type or time of occurrence of the failure.

Deficiencies in maintenance lead to signal malfunctions or breakdowns that result in additional costs to the motoring public in both direct and indirect ways. It is important to have a signal maintenance program that includes routine and preventive maintenance that will minimize these costs.

The amount of noncatastrophic or routine maintenance performed and the procedures used to correct catastrophic failures directly affect the cost to the public. Both items can be varied to alter these costs. The amount by which each of these items is varied affects the cost to the public directly. Unfortunately, because the effects of maintenance are long term, the modification of the particular maintenance procedures being followed cannot be tested beforehand or even after a short trial period.

The model discussed in this study was used to test the effects of varying signal maintenance strategies by applying statistical tests to actual data and data generated by the model to determine whether significant changes could be detected. Tests were performed for variations in the distribution of catastrophic failures by type and time of occurrence as various maintenance strategies were applied to the system.

Two maintenance strategies were tested during the course of this study. The first consisted of routine and preventive maintenance equal to four trips per signal location per year, plus the catastrophic failure strategy below.

1. A full-time service and repair person was assigned to service catastrophic failures. During the normal working hours this person is assigned to bench work and is available for duty at any time. During all other hours of the day and on weekends he or she is on call for duty as needed. During these on-call periods a minimum call-out time is paid for whether it is needed or not.
2. As soon as notice of a catastrophic failure is received the repair person is dispatched to the site and remains there until the signal is functioning properly.
3. In all but the most extreme cases (i.e., signals completely destroyed by storm or accident), the failure is serviced by the repair person only.
4. In the case of this strategy, catastrophic failures included such occurrences as pole hit, span wire down, signal struck, signal twisted, signal damaged, signal out, signal down, signal low, no electrical power, control box open, contact broken, flasher broken, lamp out, lens broken, pedestrian signal out, case sign out, and case sign damaged.

The second maintenance strategy consisted of routine and preventive maintenance equal to four trips per signal location per year, plus the catastrophic strategy below.

1. A full-time service and repair person was assigned to service catastrophic failures during normal working hours. During periods when not on duty servicing a call the repair person is assigned to bench work.
2. As soon as notice of a catastrophic failure is received during normal working hours, the repair person, if available, is dispatched to the site and remains there until the signal is functioning properly or the regular shift ends. When the regular shift ends before completion of repairs, work resumes at the start of the next regular shift.
3. During all other nonregular shift hours in the case of the more dangerous types of failures (e.g., pole hit, span wire down, signal stuck, signal damaged, signal down, and case sign damaged), the service repair person goes to the location to move debris to the side of the road and shut off electrical service.

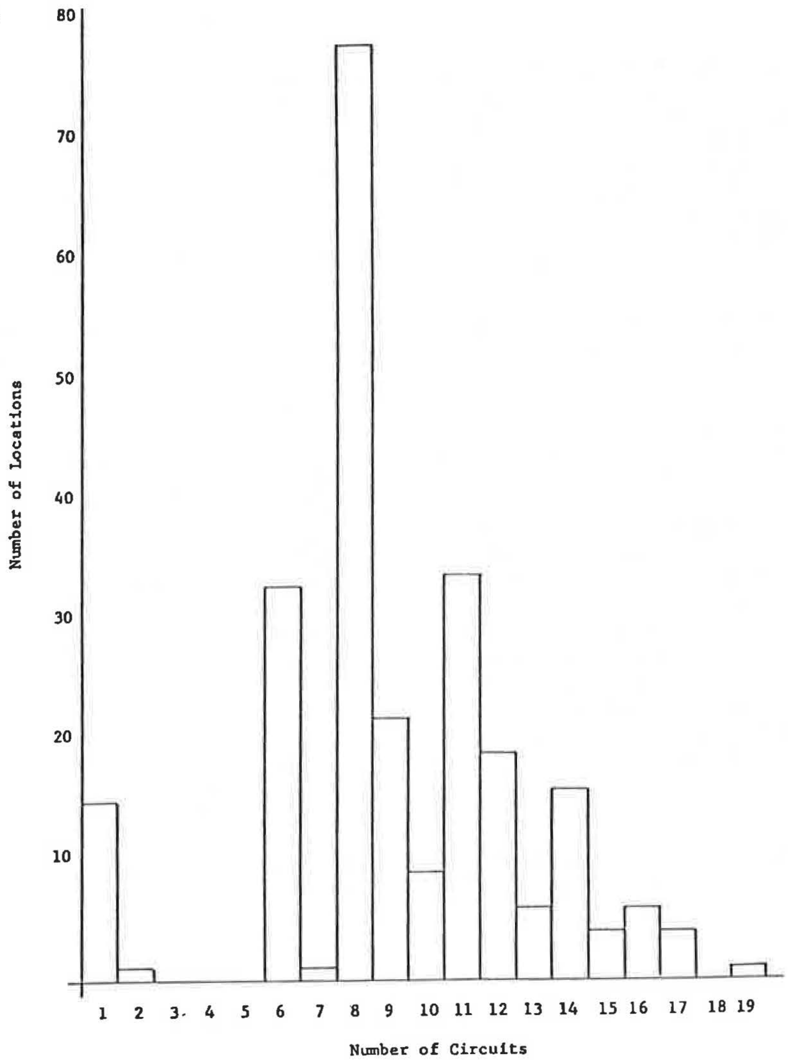


Figure 4. Circuits and locations.

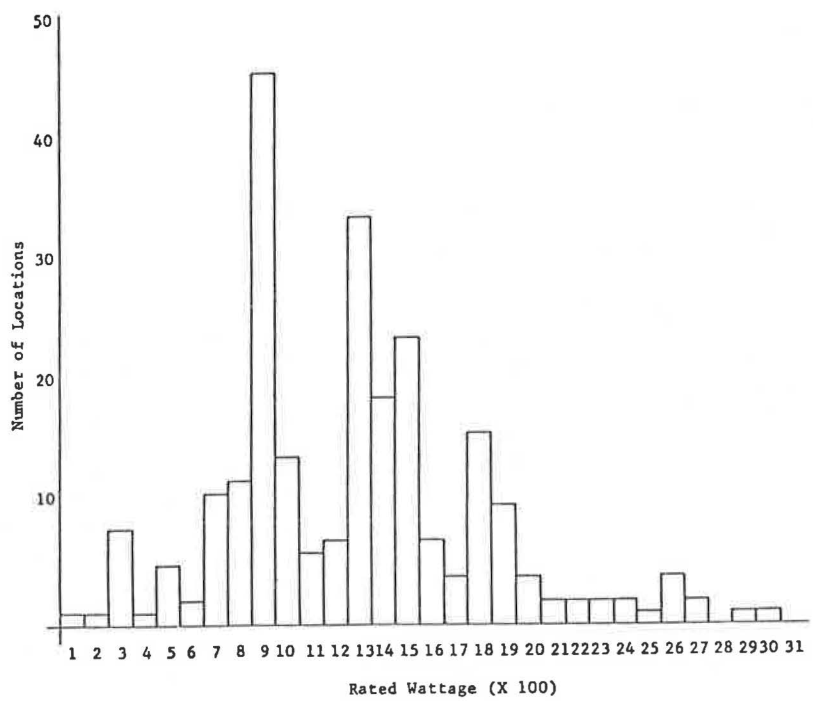


Figure 5. Wattage and locations.

Repairs would take place starting at the beginning of the next regular shift.

4. For the failure classifications signal twisted, signal out, signal low, no electrical power, control box open, contact broken, flasher broken, lamp out, lens broken, pedestrian signal out, and case sign out, the repair person would not report to the location during nonregular shift hours, and repairs would be scheduled starting at the next regular shift.

5. Reports of catastrophic failure would be screened by the dispatch personnel and handled accordingly.

The first, or full, maintenance strategy described is one that is commonly used for signal maintenance. The second, or limited, maintenance strategy, is derived from the first and has as its major difference the reduction in catastrophic-failure service.

Many agencies engaged in full maintenance strategies periodically consider the limited strategy because of economic factors. An agency engaged in a full maintenance program might, for example, have to pay the service and repair person for a 3-h minimum period even if he or she worked only a portion of that period (i.e., any period less than 3 h).

Obviously, for some periods of time, the cost of a full maintenance program would be excessive when only the economic factors were considered. But the real question lies in the minimum cost when economics, excessive delay, increased accident liability, and other associated costs are all accounted for.

RESULTS

The results from use of the model indicate that the second maintenance strategy (restricted night service) resulted in overall increases in the length of time to complete a repair to 4.3 h. The amount of overtime charged to the emergency repair of signals would be reduced by 3.5 h by use of the second strategy.

The results were obtained by running year-long maintenance simulations for a system consisting of 500 signals. System parameters reflecting the equipment configurations were as indicated in Figures 4 and 5.

CONCLUSIONS

The model developed in this study provides a useful tool for both monitoring traffic signal maintenance work and testing proposed maintenance strategies. The computer program is flexible and adaptable to almost any size computer. This program was originally developed and tested on an IBM 1130, 8K system.

A case study comparing two maintenance strategies indicated that significant changes in the factors affecting signal maintenance costs and maintenance levels could be achieved by making relatively minor strategy changes.

The model has the potential to be used for both short- and long-range planning and can contribute significant input to program budgeting by using systemwide data.

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Priority Assignment for Bridge Deck Repairs

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This paper presents, in considerable detail, an approach used to assign priorities to bridge decks for protection, rehabilitation, or replacement. The system was developed by integrating traffic use (level of service) with existing deck condition. High priority is assigned to critically deteriorated decks in heavy and moderate traffic volume locations. Medium priority is assigned to exceptionally good decks in heavy and moderate traffic volume areas to prevent chloride-induced corrosion of the rebars and subsequent spalling. Low priority is assigned to the remaining bridge decks in a descending fashion from high- to low-volume areas. The key elements needed to draft and develop the priority schedule are reviewed and discussed. The rationale for selecting protection systems to be installed and the deck preparation required for various initial deck conditions is presented. Last, a brief review of policy implementation is provided.

Perhaps the single most perplexing problem to confront bridge design and maintenance engineers in the past decade is corrosion-induced spalling of the deck. Various systems have been developed and implemented in an attempt to prevent spalling on new decks and to rehabilitate existing ones. Many bridge decks with 10-15 years of service have experienced spalling severe enough to require major repair or complete rehabilitation. As is often the case, projected maintenance needs often exceed budget limitations. There are too many bridges to fix and not enough money to go around.

Minnesota, along with many other northern central states, has been especially aware of the growing deck deterioration problem. Geographic location and somewhat severe winters necessitate extensive salting to maintain bridges and roadways in good winter driving condition. Consequently, the heavy deicer applications have resulted in an early awareness of spalling as more maintenance efforts have been concentrated on deck repair.

Installation of protection systems designed specifically to correct chloride-induced corrosion of the reinforcing steel and subsequent spalling began in 1971 and 1972. At that time, however, there was something less than consensus among staff and operations and maintenance personnel on exactly what the problem was and how it should be corrected.

Initial guidelines, which amounted to little more than a list of approved membranes selected from a study (1) and some recommendations for deck preparation before system installation, were implemented as a stopgap measure in November 1974. These, it was felt, would buy time until the problem could be more fully reviewed and a comprehensive policy developed to correct it.

During the closing months of 1975, a task force made up of personnel from the offices of bridge design and construction, materials, research, and standards was assembled to review the state of the art for both problem and solution technology and to develop a new policy for bridge deck repair and protection. The following approach to assigning priorities to decks for repair is one of the cornerstones of that policy.

OBJECTIVE

The objectives of this paper are to present in a clear and detailed manner the approach used to (a) select bridge decks in need of repair by means of a systematic and rational procedure that takes into account as nearly as possible the many variables involved, (b) identify the elements needed to develop a realistic and practical policy of this type, (c) select protection systems installed on various decks, and (d) review the policy's implementation and exceptions.

Minnesota began a program of annual bridge inspection to determine physical condition and identify deficiencies in 1970. By 1973, the inspection procedure had been upgraded to include detailed information on items such as percentage of deck areas patched with either bituminous (temporary) or concrete (permanent) patches that showed spalling or delamination. These checklist items were then lumped together as unsound concrete. A condition code number, based on current inspection inventory rating, was also incorporated into the process.

TRAFFIC CATEGORY GROUPING

The first approach to developing a workable format that would identify bridges for early deck repair resulted in agreement among all parties that repair should be reserved for those bridges with the most severe deck condition (largest amount of unsound concrete). It was further agreed that traffic use should be considered in deciding which severely deteriorated bridges should be repaired first, second, third, and so on.

It was around the simple concept that repair should be dictated by deck condition and traffic use that the format evolved. Furthermore, it was agreed that the concept of use versus condition would be best incorporated into a meaningful policy if kept simple. With this in mind, the Minnesota group agreed on the division of traffic categories. This assignment was not arbitrary. Rather, it generally reflected three levels of service.

Category A encompasses all bridges on urban Interstate systems with volumes of 10 000-100 000 vehicles per day average daily traffic (ADT). It is significant that those roadways and bridges that carry the highest volumes of traffic, as a general rule, are those that are subject to the most frequent and heaviest amounts of salting. Subsequently, they have also exhibited earlier and more severe deterioration than bridges in less heavily trafficked areas.

Category B (2000-10 000 ADT) encompasses all bridges located on rural Interstate highways and state trunk highways. These bridges are not salted as often and exhibit less severe premature deterioration than those in category A.

Category C (less than 2000 ADT) encompasses all remaining bridges on lower-volume state trunk highways. They are generally salted less and are in better condition with regard to incidence of surface spalling than bridges in categories A and B.

DECK CONDITION GROUPS

Several task force sessions were devoted to reviewing the state of the art relative to probability of successful permanent repair versus initial deck condition. This review showed that only very few factual data were available to support various methods and procedures for repairing or rehabilitating decks.

Research by others (2-6) using half-cell potentials and chloride analysis of simulated concrete decks has suggested that corrosion and spalling may continue even after special protection systems are in place if care has not been taken to remove all salt-laden concrete or areas of active corrosion (defined by half-cell testing) before system placement. Field investigations of actual structures performed by California and Iowa (6,7) indicate that this concept, although theoretically sound, was not firmly supported by field data and observations.

Iowa reports that high-density concrete overlays installed on decks contaminated above the chloride threshold have not shown significant spalling since placement.

Stratfull (6) has identified structures where half-cell potentials fall below the accepted corrosion threshold even though chloride at the rebars is in the range of roughly three times that needed to cause corrosion. He attributes this occurrence to insufficient moisture for the corrosion cell to remain active. In addition, review of repairs on five decks showed corrosion potential reductions on the order of 50 percent of the pre-repair level. Stratfull did caution, however, that this reduction did not necessarily reflect on the probability of continued corrosion in areas where contaminated concrete was not removed.

Other investigations (8) of special concrete deck protection systems, some now in place for five and six years on decks with threshold-level chloride, show only minor evidence of continued spalling at present. Thus it would seem that the current understanding of the corrosion phenomenon and possible solution technology should call for considerable flexibility in a policy intended to deal with the situation.

After much discussion, task force members decided to use four deck condition groups. Initially, they were identified subjectively by the levels of deterioration listed below.

		Deterioration	
Group	Rating	Percentage	Code No.
1	Slight	0-5	9
2	Moderate	5-20	7-8
3	Severe	20-40	5-6
4	Critical	40+	4 or below

Further review led to defining the percentage of unsound concrete, as identified earlier, that was associated with each level of deterioration. Finally, the code designation used in annual inspections was assigned to its respective group. One ought to keep in mind that there is nothing absolute about assigned percentage of unsound area or code condition. Condition and traffic

Table 1. Bridge and area assignments by deck condition and traffic category.

	Category A		Category B		Category C	
Group	No. of Bridges	Area Affected (m^2)	No. of Bridges	Area Affected (m^2)	No. of Bridges	Area Affected (m^2)
1	14	51 740	91	115 346	52	44 935
2	97	775 182	641	506 539	556	254 436
3	111	207 120	214	209 078	236	100 503
4	13	48 014	7	2 819	10	25 662

Note: 1 m^2 = 1.2 yd^2.

use were grouped, categorized, and integrated as shown in Table 1.

As all bridge inspection reports are logged in a central computer inventory system, the next step in policy development was fairly easy. A program was written to identify all bridges by number and surface area and to assign them to their respective positions in the matrix. A more definite picture of current and future needs began to develop. When this task was complete, the next one, that of assigning priorities for programming and scheduling work, began.

PRIORITY ASSIGNMENT FOR CONTRACT REPAIR

As was mentioned previously, assigning the first priority was easy. Those bridges with critical deck spalling in traffic category A should be repaired first and were appropriately identified as priority one. In a similar manner, critical bridges in category B were assigned priority two. It was in assigning priorities three and four that major disagreement among task force members surfaced. Part of the group felt that priority three should be assigned to severely deteriorated (group 3 bridges in category A), while others felt that priority three should be delegated to protecting the slightly deteriorated bridges in category A.

It seemed reasonable to implement the old axiom that an ounce of prevention would in fact be worth a pound of cure. If a deck was in excellent condition with only a minimum amount of chloride contamination, then there was no good reason not to protect it from further salting and eventual deterioration by adding an additional 50 mm (2 in) of special concrete. This would provide the additional cover needed to prevent salt from ever reaching the rebars in threshold level quantities during the expected life of the structure.

Disagreement persisted until an economic analysis was performed to better understand the cost-benefit ratio for each course of action. In addition, chloride analysis was performed on those decks in category A group 1 to ensure that threshold chlorides had not reached the level of the rebars. Major items for consideration in cost-benefit analysis were cost of removing concrete and preparing the deck for new overlay, cost of new overlay per square meter at the specified thickness, and approximate life expectancy of the system on the deck being repaired. It seemed reasonable to expect that, for a given system, the life expectancy would be the longest if the deck to which it was applied was in the best possible condition. Extending this concept further led to developing crude estimates of system life and to assessing costs based on dollar per square meter of deck per year of service. Such figures, though based on little more than engineering guesses, provided a relative ordering of system costs versus anticipated performance. With the cost-benefit study complete, it was apparent that assigning priority three to category A group 1 was justified by a ratio of at least 2:1 and in some instances 3:1.

After reviewing cost-benefit data, priorities three and four were thus assigned to group 1 traffic categories A and B, respectively. Priority five was assigned to group 4 category C. The priority assignment shown below continued in a similar manner until all groups were completed.

	Priority Assignment		
Group	Category A	Category B	Category C
1	3	4	10
2	6	7	11
3	8	9	12
4	1	2	5

EXCEPTIONS

As is often the case with policy development, exceptions arise that must be dealt with. There were several in our case, and these will now be reviewed.

The first exception involves bridges in which the deck is a portion of the main structural support member. This includes concrete box girders, slab spans, and deck girder bridges. Because decks on these structures cannot be removed without supporting the structure on falsework, the amount of unsound concrete in the severe category was changed to 20-60 percent and critical assessment was reserved until 60 percent or more of the surface is unsound. Every effort should be made to protect these decks before deterioration begins or to repair them as soon as programming allows. Within any category, these structures should receive priority over other bridges.

Another exception occurs when a bridge that does not necessarily warrant immediate repair (but in all probability will during the foreseeable future) is located near bridges being repaired as a strip project. In this case, it is economically justified to include the random bridge in the strip project, as opposed to repairing it several years later as a single project. Also, from a traffic control standpoint, there is less adverse public reaction to multiple restrictive lane closures year after year on the same section of highway.

The last exception is also associated with traffic conditions in that, when some bridges are repaired, it is more time efficient to close the bridge to all traffic and make detours. Other structures that might by priority assignment require repair are delayed to accommodate detoured traffic.

REPAIR SYSTEM SELECTION

Presenting an approach for assigning repair or rehabilitation priorities would be incomplete without some discussion of protection system selection. There is also a need to review the various deck preparations, or, more specifically, concrete removal procedures with regard to extent and depth.

The two classes of systems currently used for deck protection and rehabilitation are membranes with bituminous overlays and special concrete overlays. The three basic deck preparation methods are

1. Scarify, spot remove, patch, and overlay;
2. Remove 100 percent of the concrete to the top of the upper rebar mat and overlay; and
3. Remove entire deck.

Predicting probable system performance was difficult enough with systems installed on new decks. There was early consensus on the contention that traffic

Table 2. Summary of 1976 policy for contract bridge deck restoration.

		Deterioration		Category A				Category B				Category C			
Group	Rating	Percentage	Code	No. of Bridges	Area (m^2)	Priority	Procedure	No. of Bridges	Area (m^2)	Priority	Procedure	No. of Bridges	Area (m^2)	Priority	Procedure
1	Slight	0-5	9	14	51 737	3	Spot removal and concrete overlay	91	115 348	4	Spot removal and concrete or membrane and bituminous overlay	52	44 936	10	Spot removal and concrete or membrane and bituminous overlay
2	Moderate	5-20	7-8	497	775 183	6	Spot removal and concrete overlay	641	506 593	7	Spot removal and concrete overlay	565	254 436	11	Spot removal and concrete or membrane and bituminous overlay
3	Severe	20-40	5-6	111	207 121	8	100 percent removal to reinforcing bars, minimum spot removal below bars, concrete overlay	214	209 078	9	Spot removal and concrete overlay	236	100 502	12	Spot removal and concrete or membrane and bituminous overlay
4	Critical	40+	4 or lower	13	48 014	1	Program new deck	7	2 819	2	Spot removal and concrete overlay	10	25 663	3	Spot removal and concrete or membrane and bituminous overlay

Note: $1\ m^2 = 1.2\ yd^2$.

volume is directly related to the level of chemical use. More highly trafficked areas are salted more heavily and frequently than lower-volume areas. Pursuing this rationale led to recognizing that some decks require the maximum protection possible, while others need considerably less protection. In short, system selection should be based initially on anticipated exposure to deicing chemicals.

A second and more elusive aspect of probable system performance was the influence of initial deck condition. It was mentioned earlier that only limited data were available to support a decision regarding which system to install on a deteriorated deck.

It seemed reasonable to expect that a specific system installed on a new deck may well out-perform the same system installed on a badly deteriorated deck. There was also a very real possibility that the extent of concrete removal preceding overlay placement could influence system performance.

In an attempt to balance the benefits accrued from protecting relatively good in-service decks against the risk associated with premature protection system failure, the following format for deck preparation and system selection was developed.

Group 1

Priority 3
Spot removal and concrete overlay
Priority 4
Spot removal and concrete overlay or membrane and bituminous overlay
Priority 10
Spot removal and concrete overlay or membrane and bituminous overlay

Group 2

Priority 6
Spot removal and concrete overlay
Priority 7
Spot removal and concrete overlay
Priority 11
Spot removal and concrete overlay or membrane and bituminous overlay

The decision to use concrete overlays in high-volume areas is based in part on the marginal performance of early membrane and bituminous overlay systems and partially on the apparent long-term durability of concrete overlays in Iowa. In addition, using scarification for decks with less-than-threshold chlorides at rebar level and spot removal on decks with a few spalls seemed reasonable in terms of cost. This procedure was thus selected for implementation in all traffic categories for deck condition groups 1 and 2.

For decks where deterioration has advanced to the severe stage, group 3, it is generally agreed that total removal to the top of the upper mat of rebars is the most effective procedure. Concrete overlays were again selected as the system most likely to provide the best long-term, cost-effective protection, as shown below.

Group 3

Priority 8
100 percent removal to reinforcing bars and minimum spot removal below bars, concrete overlay
Priority 9
100 percent removal to reinforcing bars with minimum spot removal below bars, concrete overlay
Priority 12
100 percent removal to reinforcing bars and minimum spot removal below bars, concrete overlay

Group 4

Priority 1
Program new deck
Priority 2
Program new deck
Priority 5
Program new deck

For those bridges classified as critical, total deck removal and replacement is economically justified. When this situation arises, the replacement deck is given the same protection as a new deck. New decks are designed with protection systems intended to provide the longest maintenance-free life for the level of traffic and exposure anticipated. New decks in category A are constructed with epoxy-coated rebars in the top mat of reinforcing steel and a special concrete overlay—in effect, a dual system. Decks in category B receive either epoxy-coated rebars, a special concrete overlay, or a membrane and bituminous overlay. Finally, new bridges built in areas subject to low traffic volumes will have decks designed with a high-quality minimum water/cement ratio concrete and 76 mm (3 in) of clear cover over the top mat of rebars.

For cases where decks are carrying low traffic volumes but are still subject to heavy deicing chemical application, consideration should be given to placing a system corresponding to the next higher traffic volume category. Cases of this type arise in urbanized areas and intersections and ramps.

IMPLEMENTATION

Early in 1976 implementation of the new policy (see Table 2) began with its being incorporated into bridge repair and rehabilitation plan preparation. During that year approximately 100 bridges were either built or repaired. Considerable attention and effort were focused on rehabilitating bridges assigned priorities one and two. By 1977, bridges assigned priorities three and four were protected in accordance with provisions of the new policy. As deficiencies or omissions in the policy were identified during the first year of implementation, revisions were necessary and were made early in 1977. No major problems developed, and all changes were minor in nature.

One of the major advantages of this policy is that it delegates repair effort to decks where the need is greatest (priorities one, two, and four). Another feature of the approach is that it provides a fairly accurate picture of the distribution of decks (and surface area) by condition and traffic use. Reviewing the distribution gives considerable insight into where present and future repair efforts will need to be focused. The number of decks and their surface areas involved are categorically defined. A basis for predicting future funding needs is also now established.

Other significant benefits provided by the policy are found in the rationale of protecting good bridge decks now instead of repairing them later (priorities three and four). Specific advantages and several disadvantages associated with this aspect of the policy are listed below.

Advantages

1. Structures can be protected with today's dollars at a much lower cost than that required to repair them after deterioration begins.

2. Duration of lane closures can be minimized by limiting concrete removal before protection. Normal closures take half the time it would take to repair and overlay.

3. Effectiveness of this procedure is superior to any repair or rehabilitation short of removing the entire deck.

4. The problem deterioration is being controlled to the highest degree possible by attacking the affected group of structures from two directions, the top (newer decks) and the bottom (critical decks).

Disadvantages

1. The public uproar caused when motorists see workers apparently repairing "new" decks is significant (an obvious and glaring example of make-work).

2. Current funding of bridge repairs is often inadequate to cover the costs of repairing critically deficient bridges, let alone trying to protect the newer ones.

3. A program of testing and evaluation for identifying which bridges should be protected is a prerequisite to initiating this policy.

SUMMARY

Since implementation, nearly 250 bridge decks have been built, protected, or rehabilitated in accordance with the provisions of the original policy. By using a system that allocates a certain portion of the annual construction budget to protecting in-service structures in good condition, in addition to rehabilitating critically deteriorated decks, we are in effect burning the candle from both ends. It is overly optimistic to expect complete success with such an approach. What is assured, however, is that premature deterioration of structures that can be saved will be prevented. This in itself will serve to compress the deteriorating decks into a manageable group.

Integral to the success of this policy is the annual reassessment of deck conditions based on a reliable inspection program and an inventory rating system. Protection system selection should be largely based on anticipated level of service and use of chemical deicers. Repair or rehabilitation procedures should be based on the present physical condition or should be expected to fully extend the remaining service life.

Every effort should be made to integrate the bridge deck repair and protection policy with any existing bridge replacement program. It has been noted, however, that by and large most of the decks requiring repair of damage due to spalling seldom belong in a replacement program. Successful implementation hinges on providing some flexibility where anticipated or unusual exceptions occur.

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Abridgment

Solar Energy: Hedge Against the Future

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If solar energy has an answer to some of the transportation industry's problems, both economic and energy oriented, we need to find it out. Solar is already a $75 million a year industry in California, and nationwide it involves nearly 6000 manufacturers and distributors.

The major problems encountered in solar applications seem to stem from simple mechanical problems of leakage and control malfunctions. Many engineers with solar experience stress the importance of simplicity in designing controls and layout (1,2). All of this means that any solar commitment should be made with well-researched performance specifications and carefully and specifically designed integration of solar into the existing structural plans. It is recommended that an engineering consultant with current experience in solar systems be employed whenever a solar system is being designed. Also, cost estimates for solar should compensate for the tendency of contractors to bid conservatively in this unfamiliar field.

FUEL COSTS

A general industry rule of thumb predicts a 10 percent increase in energy costs per year during the next 20 years. The U.S. Army Corps of Engineers uses a 20 percent increase per year until 1983, when it drops to 5 percent a year.

Use of gas and electricity has exhibited a fairly consistent pattern according to a five-year analysis of three Oklahoma field divisions. Cost of that use is a different matter, however, when the average annual increase in fuel bills over the five-year period is 17 percent or 30 percent as it was in 1976 and 1977. When cost is computed according to increases per million kilojoules, the increase is even greater—from 22 to 36 percent each year.

MUSKOGEE ASPHALT STORAGE TANK

The Oklahoma Department of Transportation (DOT) Research Division has been investigating solar energy for three years. With state funding only, a heated asphalt storage tank was designed for one of Oklahoma DOT's field division headquarters in Muskogee (3). The first in the nation, it began operation in April 1977. The 38 m^3 (10 000 gal) tank has successfully maintained the asphalt emulsion at an 18-60°C (65-140°F) temperature for two years. In fact, the temperature has never dropped below 23°C(75°F). The emulsion is about 65°C (150°F) when it is delivered from the supplier, so only six flat-plate solar collectors [10 m^2 (108 ft^2)] were required.

The Muskogee solar tank uses a 45.4-dm^3 (12-gal) fluid system to circulate the solar heat from the collector to a heat exchanger inside the storage tank. The fluid used is a combination of 40 percent ethylene flucol and 60 percent water (similar to antifreeze). It flows in 18.4-mm (0.75-in) copper pipes directly from the collectors to the heat exchanger unless the solar radiation drops or the collector temperature is less than that of the asphalt. In that case it automatically circulates through the auxiliary heater, which is a regular 22.7-dm^3 (6-gal) camper hot-water heater, into the asphalt tank.

The heat exchanger used copper tubing at Muskogee but later installations will use finned aluminum on copper to provide better heat distribution.

In summer the fluid remains in the solar system with a 103.4-kPa (15-lbf/in^2) pressure-relief valve for safety purposes. A 6.2-W ($^1/_{12}$-hp) pump circulates the fluid.

A feature added later involves an electric heat tape with a 15-min timer. It was placed on the take-out valve to heat the asphalt that coagulates at cold temperatures. This improvement was made after the discovery that the 51 mm (2 in) of sprayed-on urethane foam insulation on the tank was flammable when a torch was used to heat the valve.

The $4600 cost of the solar part of the installation, which includes insulation, solar system, and labor but not the tank itself, has been recovered in less than two years through reduced operating expenses. Heating a similar tank in 1977 cost $2900 and used 32 m^3 (8500 gals) of propane. Cost of heating the solar tank during 1978 was $70, which is the cost of the fuel used by the electric hot-water heater that is the standby heat source on cold and/or cloudy days. In February 1977 the auxiliary heater operated 16 days in a row at full capacity at a cost of $12.

The contrast between those two costs is striking, and the winter of 1978 was exceedingly severe. The benefits of solar energy need to be compared to the cost of the local source of energy. At Muskogee, propane costs $0.11/$dm^3$ ($0.40/gal), whereas the electricity costs approximately $0.035/kW·h. If one's storage tanks are presently heated by a cheaper fuel, the savings realized from a solar system may not be as dramatic and will take more years before payoff is achieved.

Solar savings at Muskogee are not all monetary. Maintenance crewmen are enthusiastic about not having to get up in the middle of a January night to check the pilot light on the propane burner. The dependability of the solar system has saved uncounted hours of labor and time and has helped morale.

The insulation of the 38-m^3 storage tank was a most important part of the solar system in Muskogee. As in all solar designs, the use of "passive" solar is the first consideration. Solar heat or energy is hard earned and every effort must be made to keep and treasure each unit: Plumbing runs should be as short as possible; all piping should be heavily insulated; solar collectors should not leak.

An optimum 51-76 mm (2-3 in) of spray-on urethane foam will provide important savings. To prevent ultraviolet deterioration, a Hypalon coating over the insulation is used.

The success of the Muskogee installation has led Oklahoma DOT to start construction on three additional solar-heated tanks with six retrofits planned for 1979. The use of solar to heat MC asphalt tanks involves the use of higher-temperature solar collectors of the evacuated-tube or concentrating type. Such collectors can produce temperatures in the 149°C (300°F) range.

The Oklahoma emulsion storage tank is designed to maintain the asphalt within specified temperature ranges rather than heat it quickly. It has a much lower capital investment than the Texas and Arizona solar asphalt storage tanks, which cost two to three times as much (4).

FIELD DIVISION HEADQUARTERS

In a more venturesome solar research project, the Oklahoma DOT plans to supply heat, hot water, and air conditioning to a new $1.7 million 2880-$m^2$ (32 000-ft^2) field division headquarters building scheduled to be let in May 1979. The plans also call for solar heating in the 2592-m^2 (28 800-ft^2) warehouse and shop area. Auxiliary heat will be natural gas.

The present estimate is approximately $300 000 above the cost of a normal heating and cooling system. As a means of sharing the cost of the solar system at the Buffalo, Oklahoma, field headquarters, Oklahoma DOT applied to the U.S. Department of Energy (DOE) for an award under their demonstration projects program for commercial solar applications. The project was one of 83 DOE awards made under the 1978 offering and involves a 50 percent sharing of the solar cost. The remaining half will be provided by state transportation funds. It also provides Oklahoma with the benefit of DOE experiences in the previous 222 demonstration projects.

The Buffalo project design calls for about 450 m^2 (5000 ft^2) of liquid flat-plate collectors arrayed on the ground near the two-story office structure. The mechanical room will be located in the warehouse along with a 38-m^3 (10 000-gal) above-ground storage tank. A 22.5-t (25-ton) reciprocating chiller and a 22.5-t (25-ton) absorption chiller will be used. One way or the other, the transportation industry has to cut its fuel and overhead costs. Be it pioneering solar research or plain ingenuity, there are a multitude of ways to save money and energy. Now is the time to start these projects.

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