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6 Reports

Tire and Equipment Replacement,
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Foreword

One of the problems posed to managers is the determination of the most economical replacement policy for groups of items which may be tires, equipment, traffic lights or something else. A solution involves an estimation of life spans and a calculation of predicted failures as a function of the age of the group of items.

It is particularly difficult for the representative of a public authority to weigh the merits of vendor claims that a high acquisition cost is justified by an expected longer life with less maintenance. Two papers in this RECORD offer a means by which public authority representative can sort "fact from fancy."

Doom offers a procedure which may effect a direct saving of 52 percent of former costs as well as indirect benefits in the form of reduced "downtime" on the purchase of tires.

A number of innovations are reported by Slubicki and Shen, but their approach to acquisition of equipment on the basis of estimated least cost is of particular interest. Their solution neatly eliminates the problem of deciding how to proportion a budget allocation for equipment between different types of equipment by including all types of equipment on one priority list.

The maintenance engineer, through advances in the fields of systems analysis and computer technology, has tools available whereby he may analyze all factors related to maintenance operations and most efficiently utilize available men, money and equipment. Yet, analysts and researchers can only offer a glimpse of potential advances in the art of maintenance management until vastly improved maintenance cost data collection and reporting systems are developed and widely used. Smith and Oppenlander afford a glimpse of this potential in their report of a comprehensive traffic signal and flasher maintenance program for an Indiana maintenance district. Use of the program optimizes the use of resources yet insures the proper and safe operation of the system.

Millions of dollars and scores of researchers are involved in a search for the causes of bridge deck deterioration and for corrective treatments. It is easy, in such massive efforts, to overlook successful procedures because they may be routine, of long standing and so effective as to be taken for granted. For nearly 30 years, Massachusetts has used a successful membrane waterproofing on new concrete bridge decks that are to be covered by bituminous concrete and on restoration of bridge decks that have deteriorated to the point of requiring repairs. During that time, Massachusetts has constructed approximately 1000 bridges and reconstructed approximately 80 bridges using a membrane waterproofing. Although Hagenbuch concludes ". . . waterproofing is (not) the panacea for all our bridge deck problems" it is interesting to learn that he has found no indications in his state, that any serious bridge deck deterioration has occurred. Significantly, Massachusetts is not immune from trouble on bridges which have not used the membrane waterproofing technique. Bridge designers and maintenance engineers might well take note of this impressive case history as they scan multi-million dollar bridge deck repair bills.

Previous studies have shown various solutions of linseed oil and other materials to be effective antispalling compounds on concrete. Kubie, Gast, and Cowan concluded that linseed oil emulsions are equally effective and eliminate the fire hazard arising from the use of other linseed oil compounds. Maintenance engineers may also be interested in aspects of the study relating to times at which recoating is advisable.

Maintenance budget requirements are commonly projected ahead for relatively short periods of time, say one or two years, but methods are available for predicting needed pavement maintenance for much longer periods of time. One of the techniques, developed in Oklahoma, is reported by Hartronft. The procedure estimates resurfacing requirements over a period of five years making use of visual condition surveys and Benkelman beam testing. Maintenance engineers should find the method relatively simple, easy to understand and straightforward in its application to their needs.

Contents

Performance Purchasing of Tires in Virginia

IRA F. DOOM, Virginia Highway Research Council

This paper describes a study on how to purchase replacement tires for the Virginia Department of Highways and its consequences as they affected the purchasing program. The purposes were (a) to determine the objectives of the tire buying program and to evaluate the effectiveness of the program in achieving these objectives, and (b) if upon completion of evaluation there was believed to be need for improvements, to state where these needs existed and how they might be fulfilled.

The Department's tire buying objectives are to satisfy its needs at the least cost consistent with desired safety; and the method used in pursuit of this aim was to buy "first line" tires at the lowest bid price on the assumption that these tires were comparable to original equipment tires. A study of available records indicated that although there was no evidence that application of these procedures was not providing the desired safety there was substantial evidence that the use of the lowest bid price technique was not the least cost method of procuring tires for a more desirable end result. It was further suggested that the definition of lowest cost be changed from lowest bid price to least cost per tire mile of service. Two methods viewed as possible devices to achieve least cost per mile of service were the use of laboratory testing to insure more uniform quality of tires, and the use of performance data to express the quality of tires in terms of miles of service.

Necessary requirements for effective incorporation of performance data into a competitive bidding system (specifically, least cost per mile bidding) were developed.

As a result of the study, a three-year performance purchasing contract was made with the successful bidder. Anticipated benefits are direct savings of 52 percent of former cost ($441,000) and indirect savings from reduced downtime and tire shipments directly to the areas of use. Including cuts, blowouts, and normal road hazards, guaranteed average mileage is 35,000 for automobile tires and 60,000 for truck tires. The ultimate success of performance purchasing of tires in Virginia will be determined by prospective suppliers' bids on a new contract beginning January 1, 1969.

•THIS paper describes a study initiated in 1964 on how to purchase replacement tires for the Virginia Department of Highways and the consequences of this study as it affected the Department's purchasing program.

The purposes of the study were (a) to determine the objectives of the Virginia Department of Highways' tire buying program and to evaluate the effectiveness of the program in achieving these objectives, and (b) if, after the evaluation was completed, there

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was believed to be need for improvement, to state where these needs existed and how they might be fulfilled.

PRELIMINARY RESEARCH

In approaching the subject of tire procurement, the first step was to define the problem. There were two basic objectives of the Department's tire buying program: (a) to purchase tires that could be safely used on the vehicles on which they were installed, and (b) to obtain these tires at the least cost.

Management said that while there were other methods of tire procurement, the technique used by the Department was to buy "first line" tires at the lowest bid price on the assumption that these tires are comparable to original equipment tires. Management did not feel, however, that the use of this method was achieving the least cost objective, and some concern was expressed regarding the safety of the tires being used. When asked what "first line" meant, there was reference to the General Services Administration's minimum tire carcass strength and endurance standards and the Tire Buying Guide, which lists the first line tire of each supplier. However, the most frequent comment made was that, "The first line tire of one supplier may not actually be equivalent to the second line tire of another!"

Examination of complaint records and conversations with mechanics in the field indicated there had been no serious injuries or loss of life attributable to unsafe tires, but there was considerable grumbling about tires that were "put on one day and taken off the next." An examination of the performance records of State Police tires (Table 1) indicates there was as much as 20 percent variation in the average mileages delivered by tires.

More importantly, Table 1 indicates that the lowest bid price first line tire is not in fact the cheapest tire in terms of cost per mile of service. Records of average mileage delivered by original equipment and replacement tires indicate that on the whole there is an even wider performance difference between tires.

Conclusions drawn from the foregoing investigations were: that the Department's desired safety objective was probably being achieved through then existing purchasing procedures, and that the Department was probably paying more for tires in terms of cost per mile of service than was necessary.

As a result, the definition of lowest cost was changed from lowest bid price to least cost per mile of service. The objectives of the tire study were redefined to include the development of procedures within the competitive bidding system which would insure that the purchase of tires would continue to be of the desired safety level, and would deliver the least cost per mile of service consistent with this safety level.

It was felt that the safety objective could be achieved through specifying at least first line tires. Approaches considered to be potentially helpful in solving the problem of how to purchase tires at the least cost were the use of laboratory testing to insure more uniform quality of tires, and the use of performance data to express the quality of tires in terms of miles of service.

TABLE 1

REPORT OF THE VIRGINIA STATE POLICE ON TIRE PERFORMANCE
(August 1, 1961-February 1964)[a]

Brand Name	Size	Number Used	Avg. Price Per Tire ($)	Avg. Miles Per Tire	Cost Per Mile ($)
A	670 × 15	3,978	12.28	10,627	0.00115
B	670 × 15	2,234	11.53	8,426	0.00136
C	670 × 15	2,181	12.60	10,192	0.00124
D	670 × 15	1,500	12.13	10,585	0.00114
E	670 × 15	1,227	15.15	8,649	0.00175

[a] Specific brand names are withheld at the request of the State Police and the Purchasing and Equipment Divisions.

Since the General Services Administration (GSA) of the U. S. Department of Commerce made and administered first line tire specifications, this agency was contracted to find out just what its tire specification requirements were and how tires were tested for determining compliance with these requirements. The tests for first line tires were designed to measure the strength of the tire as determined by the inch-pounds of energy necessary to push a 1 ½-in. plunger through it, and the endurance was tested by cutting the tire slightly, installing it on a test wheel, and measuring the rate of cut growth. If a tire required more than the set standard of inch-pounds to be broken by the plunger, and another tire of the same size and brand had a rate of cut growth below the established maximum, this brand tire was viewed by GSA as a first line tire. Under then existing procedures, manufacturers could test their own tires and send a certified statement of the results to GSA.

It was pointed out by an official of the Bureau of Standards that enforcement standards under these procedures were inadequate. He also pointed out that the Bureau of Standards had conducted tire tests for other agencies with the result that the minimum first line requirements had been met and greatly exceeded by almost all tire manufacturers; therefore those requirements were out of date and rather meaningless in terms of measuring the relative quality and performance of different brands of tires. It was also suggested that since first line tire requirements were expressed in strength and endurance terms they would not—even if the standards were increased—express the quality of tires in terms of miles of service.

More recently, the government has initiated strengthened tire quality control procedures and requirements of rubber manufacturers; but, as in the past, these procedures do not express quality in terms of miles of service.

On reexamining the existing evidence, it was felt that these points had been substantiated by records and other test reports on the varying performances of different brand first line tires on test tracks. An example of one of these reports is given in Table 2 in which Brand B, the lowest mileage performer, is the same brand that was the lowest mileage performer in Table 1. Analysis of results from tests conducted between 1945 and 1955 indicated, however, that the performance of tires varies over the years in both absolute and relative terms, and a purchasing policy based on past performance could well lead to paying higher prices for lower quality tires. If tires could be purchased on the basis of a guaranteed cost per mile of service, however, performance data would be effectively incorporated into existing competitive bidding procedures.

PERFORMANCE PURCHASING

General requirements considered necessary to cost per tire mile bidding were the development of a plan which would be feasible to both the State and the tire suppliers, and the determination of which tires should be included in the plan, and how much the State was paying for these tires in terms of costs per tire mile of service.

In attempting to fulfill these requirements, local representatives of the various tire suppliers were contacted and the author went to Akron, Ohio, to discuss the requirements

TABLE 2

TIRE LIFE MILEAGE CALCULATION—FEDERAL SPECIFICATIONS ZZ-T-381J OF 7-13-59 TESTS CONDUCTED BY INDEPENDENT TIRE TESTING COMPANY

Tire Brand	Mileage	Non-Skid Loss (0.001) Centerline	Brand Average Skid Loss	Average Original Skid Depth	Average Calculated Mileage
A 037MH662	12,000	0.209	0.209	0.341	19,600
037MH652		0.209			
B 3552E01	12,000	0.261	0.263	0.357	16,300
3552E02		0.266			
C 6BAC8451	12,000	0.165	0.174	0.362	24,300
6BAC8452		0.184			
D 009308Q896	12,000	0.174	0.183	0.358	23,500
137052Q896		0.192			

with management of the tire companies. The concept of the "representative scrap pile" was presented; more specifically, it was suggested that over a sufficient period of time (two years or more) the performance of tires scrapped would be representative of the performance of tires purchased. A period of two years is required because the average mileage yielded by the tires removed first is far lower than the overall average performance of all tires. Since this concept appeared valid the problem of how to keep accurate tire records inexpensively became the next obstacle to overcome.

The suggestion was made that residency mechanics could fill out a tire card showing serial number of the tire on and off, the reason for removal, the vehicle number, and the vehicle mileage. This card could be sent to the Highway Department's central office where electronic data processing equipment could be used to prepare a summary of the mileage delivered by each scrapped tire regardless of where in the State the tire was put on or removed. However, it was noted that many tires have identical serial numbers, which along with making previous approaches questionable, would eliminate the feasibility of this course of action.

It was then recommended that the Districts could be given branding irons to identify each tire and that insurance of completion of tire record cards would be provided by forwarding these cards to the districts, where the district shop clerks could check to see that the number of cards filled out corresponded to the number of tires issued—if there was a variance the residency and district mechanics could then be so advised. Tire performance could be accurately and inexpensively measured in this way.

After the validity and practicality of the record-keeping procedures had been agreed upon, effort was directed toward developing a plan by which price and quality could be properly evaluated.

The first element of quality is the average mileage that the tires will run. Tire suppliers agreed that since tire records would give an accurate picture of performance they would be willing to guarantee average mileage performance on an individual size basis. Because of "downtime" considerations, the mileage guaranteed for automobile tires would be no less than 15,000 miles and that for trucks no less than 20,000 miles. This guaranteed performance would include tires removed for reasons of normal wear and cuts and blowouts. The latter provision is most important since what really matters to the State is not how far a tire will run under ideal conditions, but the tire's overall performance in actual use, which includes cuts—particularly in mountainous areas.

An important aspect of tire pricing aside from the initial bid price is the average value of the scrapped carcass of each tire. This average depends on the worth of recappable carcasses, the worth of carcasses that are not recappable (is much less in most instances), and the percentage of carcasses which are recappable. Conversations with management of the Highway Department's Purchasing and Equipment Divisions, employees in the field, and people who actually recap the tires indicated that the percentage of the recappable scrapped tires was quite low—30 percent at most for State truck tires. Examination of piles of scrapped tires in the district shops substantiated this estimate. Furthermore, results of the performance of recapped truck tires indicated that on the average they had to be removed within 9,000 miles. In other words, in order to determine the cost per tire of a number of same sized tires the initial price the average mileage, and the value of the scrapped carcass would have to be considered

With these thoughts as a frame of reference, procedures were developed for a tire mileage bidding plan. These procedures included:

1. Preparation of the bid,
2. Advertising for the bid,
3. Award of the contract,
4. Evaluation of performance, and
5. Provisions for adjustment at the end of the contract in case the overall actual cost per mile delivered was above the overall cost per mile bid.

For each size tire under the program the supplier would quote a gross price, guarantee average mileage performance, and guarantee to buy back every scrapped carcass at a specified price. In effect, the bid would amount to a guaranteed cost per mile per tire. For example, the bid for automobile tires might be a gross price of $15.00 with a guarantee to buy back every scrapped carcass for $5.00, leaving a net price of $10.00 per tire. In the bid the supplier might guarantee that the average mileage delivered by these tires would be 20,000 miles, making the effective guaranteed cost per mile for automobile tires 0.500 mill.

To make certain the tire cost per mile guarantee would be met, evaluation procedures were implemented. The first provision was that there must be a sufficient time lag between the award period and the record-keeping period to evaluate the performance of tires furnished by the supplier at the end of the award period. Otherwise, good tires might be furnished initially and poor tires supplied later in the contract. It was believed therefore that the award period should be two years while the record keeping or evaluation period should be four years. Under such an arrangement, the supplier would be held accountable for performance and scrapped carcasses of tires furnished during the latter part of the contract.

Suppose that after four years the average mileage delivered by automobile tires was not 20,000, but 15,000 miles. In this case, the delivered cost per mile would be substantially above the guaranteed cost per mile (0.667 mill vs 0.500 mill) unless sufficient adjustment was made by the supplier to reduce the actual cost per mile delivered to the guaranteed cost per mile bid. To accomplish this, an adjustment plan was developed. It works as follows: Assuming the average performance of the scrapped tires is 15,000 miles, what net price is necessary to achieve an actual cost per mile of 0.500 mill?

$$1 \text{ mill} = \frac{1}{1000} \quad \text{of } \$1.00$$

In other words, if 15,000 ÷ x = 0.500 mill, what does x equal? The answer of course is $7.50. Since in this example the State paid a net price of $10.00 for every automobile tire, it would be entitled to a rebate of $2.50 for every tire purchased. If, for example, 5,000 automobile tires had been purchased, the State would receive $12,500. This adjustment procedure would be applied to each size tire in the bid.

In fairness to the supplier, performance greater than that guaranteed in one size tire should be allowed to compensate for performance less than guaranteed in another size tire using the same formula. In no case, however, would the State pay the supplier, even if the overall performance of tires furnished under the program was greater than that guaranteed.

The effect of these adjustment provisions would be to give mutual incentive to the supplier and the State to reduce the cost per mile delivered to the State as much as possible, because (a) if the overall actual costs per mile were greater than the guaranteed cost per mile, the supplier would have to reimburse the Department for the difference; and (b) the Department would get any additional savings if the overall cost per mile delivered was less than the overall cost per mile bid (this savings would come in the form of lower present costs and lower bid costs in the future).

Because this mileage bidding plan would require considerable cooperation between tire suppliers and the State, it was felt that the award of tire purchases should be restricted to one supplier. This award would be determined by evaluating the cost per mile bid for each size tire according to past usage patterns. For example, if it was decided to put only 825 x 20 tires and automobile tires under such a program, and 825 x 20 tires represented 75 percent of the total expenditures for these two tires, a 75 percent weighting would be given to the cost per mile bid for 825 x 20, and a 25 percent weighting to automobile tires.

Before tire usage data could be examined in detail, one other feature was necessary in the development of a plan by which performance purchasing could be implemented. This was to provide assurance to the State and the suppliers that every reasonable effort would be exercised to lower delivered costs per mile; and that actual cost per mile delivered would conform to guaranteed cost per mile bid either through performance or adjustment subsequent to the evaluation period. The first part of this procedure was to recognize that tire mileage delivered depends not only on the quality of the tire but on the equipment and tire maintenance practices of the State, and that the supplier should have certain rights as well as obligations under a cost per mile guarantee. Therefore it was suggested that if such a program was put into effect the Department and any other participating agencies should agree to make a reasonable effort to:

1. Maintain the air pressure suggested by the supplier in tires furnished by that supplier,
2. Keep wheels on the vehicles of these agencies in alignment and brakes properly adjusted, and
3. Follow recommendations of the supplier on installation and removal practices, and the particular type of tire which should be installed.

It was agreed after suppliers had examined the Department's maintenance practices that "reasonable effort" would be defined as "continuance or improvement of present maintenance practices." The State should also exclude from carcass payment requirements, but not scrap pile mileage records, all carcasses removed at less than $^1/_{64}$-in. tread depth, and exclude from mileage records all carcasses removed at more than $^1/_8$-in. tread depth unless the tire was blown, cut, or removed because of damage due to road hazards (not including fire or tires "run flat"). To insure that the supplier would conform to the guarantee, it was suggested that he be required to post a surety bond of $50,000, which would be returned to him after satisfactory performance using the adjustment procedures previously described.

With the details of the mileage bidding plan worked out, an analysis had to be performed regarding which tires might be put under such a program and determining the cost per mile the State was paying for these tires under the former low bid price for first line tire procedures. This determination was made because the State should accept no bid in which the cost per mile bid for any size tire equaled or exceeded what the Department was then paying.

After examination of initial purchase price figures for the period July 1962 to June 1964, it was found that principal tire expenditures were made for the tires in Table 3. It was believed that only those tires in Group 1 should be included in any mileage bidding program because the grader and tractor tires shown in Group 2 are installed on vehicles which do not have odometers, thereby making it impossible to determine the average mileage delivered by these tires, and the "other trucks" tires shown in Group 2 represent numerous sizes, but small expenditures per size.

A small number of the tires purchased in both groups were delivered to State agencies outside the Highway Department and that the larger sizes have higher recappable values, so the figures were used only to determine which size tires effort should be concentrated upon.

TABLE 3

TIRE EXPENDITURE PATTERNS OF THE VIRGINIA DEPARTMENT OF HIGHWAYS
(July 1962—June 1964)

Group	Tire Description	Number Bought	Dollars Spent	% of Total Expenditures
1	Automobile	16,475	$155,839	17.94
	670 × 15 (truck)	2,850	30,017	3.45
	710 × 15 (truck)	1,550	23,696	2.72
	650 × 16 (truck)	3,650	46,804	5.38
	825 × 20 (truck)	9,792	306,604	35.29
	900 × 20 (truck)	1,125	44,845	5.16
	9-22-5 (truck)	950	35,540	3.63
			$639,345	73.57
2	Grader and tractor		170,131	19.58
	Other trucks		59,113	6.80
			$868,589	99.95

Source: Kardex records of the Purchasing Division of the Virginia Department of Highways.

TABLE 4

ESTIMATED NET PURCHASE COSTS FOR TIRES

Tire Description	Automobile	670 × 15 (Truck)	710 × 15 (Truck)	650 × 16 (Truck)	825 × 20 (Truck)	900 × 20 (Truck)	9-22-5 (Truck)
Average price paid	$9.45	$10.53	$15.28	$12.82	$31.31	$39.86	$33.20
plus							
Average recapping costs	0.00	0.46	0.46	0.46	0.85	0.85	0.85
equals							
Total purchase costs	9.45	10.99	15.74	13.28	32.16	40.71	34.05
minus							
Average scrapped carcass value (recappable and non-recappable)	1.00	1.00	1.00	1.00	5.00	5.00	5.00
equals							
Net average purchase cost	8.45	9.99	14.74	12.28	27.16	35.71	29.05

Note: Average recapping costs per tire are low because so few are recapped. The average value per scrapped carcass is thought to be realistic because of the low percentage of recappable carcasses and lower prices paid for most of the recappable carcasses of the Department's past tires.

Source: Kardex records of the Purchasing Division, invoice billings and tire recappers.

The next task was estimating the cost per tire mile that the Department paid for the tires described in Group 1 of Table 3. It was decided this problem should be approached in the following manner:

1. Estimate the net purchase cost per tire for each tire size,
2. Estimate the average mileage delivered by each tire size, and
3. Divide the estimated net purchase cost by the estimated average mileage and obtain the estimated delivered cost per mile.

The estimated net purchase cost for each tire and the method of computation of these estimates are given in Table 4.

In estimating average mileage, records of replacement tire performance were taken from several of the Highway Districts throughout the State—specifically the Richmond, Fredericksburg, Lynchburg, Salem and Staunton Districts. Though not used in estimating cost per mile for replacement tires, performance of original equipment tires is also given in Table 5 because it is believed there will be considerable interest in the different average mileages delivered by original equipment and replacement tires.

The figures in Table 5 are only approximations and so the estimated costs per mile for each tire in Table 6 can only be approximate. These statistics represented the best guess as to what the Department was paying for its tires in terms of cost per tire mile of service. It was suggested that if the estimating procedures and estimates were reasonable, then in implementing the tire mileage bidding plan, no bids above these estimates should be awarded.

TABLE 5

ESTIMATED AVERAGE MILEAGE DELIVERED BY ORIGINAL EQUIPMENT AND REPLACEMENT TIRES[a]

Tire Description	Avg. Mileage, Orig. Equip.	Avg. Mileage, Replace.	No. Tires, Orig. Equip. Sample	No. Tires, Replace. Sample
Automobile	25,461	13,744	214	299
670 × 15 (truck)	25,491	16,432	216	472
710 × 15 (truck)	28,121	22,521	110	43
650 × 16 (truck)	21,967	16,740	222	114
825 × 20 (truck)	32,411	19,257	607	460
900 × 20 (truck)	36,929	18,850	80	119
9-22-5 (truck)	Not available	20,369	0	296

[a] Original equipment tires installed 1957-64; replacement tires, 1960-64; record-keeping period ended in 1964.

Source: Tire records from Richmond, Fredericksburg, Lynchburg, Salem, and Staunton Districts.

TABLE 6

ESTIMATED COST PER MILE NOW PAID FOR REPLACEMENT TIRES

Replacement Tire Description	Estimated Net Purchase Costs	Estimated Average Mileage	Estimated Costs Per Tire Mile
Automobile	$ 8.45	13,744	0.615 mill
670 × 15 (truck)	9.99	16,437	0.608 mill
710 × 15 (truck)	14.74	22,521	0.656 mill
650 × 16 (truck)	12.28	16,740	0.734 mill
825 × 20 (truck)	27.16	19,257	1.410 mills
900 × 20 (truck)	35.71	18,850	1.894 mills
9-22-5 (truck)	29.05	20,369	1.426 mills

Source: Tables 4 and 5.

The fulfillment of requirements deemed necessary to the implementation of performance purchasing of tires has been presented. Inasmuch as the presentation included techniques as well as specific recommendations, it is felt that a summary, in outline form of the mechanics of such a program is in order.

PROCEDURES

Preparation of Bid Specifications

1. Gross bid price for each size tire. Guarantee to buy back the scrapped carcass of this tire at a specified price. The difference between the two prices is the net bid price for each size tire.
2. Guarantee average mileage for each size tire with a minimum guarantee of 15,000 miles for automobile tires and 20,000 miles for truck tires.
3. $\frac{\text{Net price}}{\text{Guaranteed average mileage}}$ = Guaranteed cost per mile

Awarding the Contract

1. Bid would be awarded to one supplier for two years. Record-keeping period would be for four years.
2. Cost per mile bids would be weighted on basis of past net purchase expenditures for each size tire, except that bids would not be awarded in cases where any single cost per mile bid was above that shown below:

	Percent Weighted	Cost Per Mile
a. Automobile	24	0.615 mill
b. 670 x 15 (truck)	5	0.608 mill
c. 710 x 15 (truck)	4	0.656 mill
d. 650 x 16 (truck)	8	0.734 mill
e. 825 x 20 (truck)	47	1.410 mills
f. 900 x 20 (truck)	7	1.894 mills
g. 9-22-5 (truck)	5	1.426 mills

Purchasing

1. Tires would be shipped direct to districts and to the Department's central warehouse in Richmond.

2. Release would be issued against a blanket purchase order designating the location to which shipment is to be made, gross billing price, and required delivery date in addition to type of tires ordered.

Receiving

1. Receiving district or other designated receiving location would be furnished advance copy of order release.
2. Upon receipt of tires the bill of lading would be checked against number of tires received.
3. Any differences would be noted to enable claim to be filed against carrier in case of shortages.
4. Sizes received would be checked against purchase release. If supplier shipping errors result in the receipt of sizes which cannot be used, return would be arranged for, transportation collect, to supplier warehouse.
5. Receipt of tires would be acknowledged and any discrepancies from order would be noted. If sizes other than those shown on purchase orders are received, and such sizes are usable by the district, these differences would be noted to enable Richmond to obtain price corrections from the supplier.

Branding

1. After acknowledgment of receipt of tires, all acceptable tires would be branded with identifying numbers and entered to stock cards. Each district would be supplied branding irons and numbers would be branded on tires, say from 1 - 9999. In addition each district would have an identifying prefix number, for example, as follows:

Bristol	-1	Salem	-2
Suffolk	-5	Fredericksburg	-6
Lynchburg	-3	Richmond	-4
Culpeper	-7	Staunton	-8

2. Examples of first numbers used by the districts would be Bristol District—1-0001, Salem 2-0001, Lynchburg 3-0001.

Record Keeping

1. Tire Installation to Vehicle—Each time a tire is taken from inventory and mounted on a vehicle the residency or district mechanic would see that the following information is put on one of the tire cards supplied to the district and residency garages:
   a. Pool number of vehicle
   b. Vehicle mileage
   c. Identifying number of tire put on vehicle
   d. Identifying number of tire taken off vehicle (if unbranded tire is removed, the manufacturer's name should be shown)
   e. Size and type of tire installed and removed
   f. Reason for removal and whether tire is to be held for future use or sent to scrap pile
   g. Date
   h. Name of residency or district.
2. Disposition of Tire Cards by Residency or District Garage—Tire cards would be forwarded daily to district shop office along with issue sheets. At the district the number of tire cards would be checked against the issue sheets. If there is a variance, the residency or district mechanic would be so advised.
3. Disposition of Tire Cards by District—After verifying all tire cards against issue sheets for all residencies and district garages, district shop office would forward daily all tire cards to Electronic Data Processing Division in Richmond.

a. Upon receipt of tire cards from District offices EDP would set up to introduce the following information into a system:

   1. Identification number of tire mounted on vehicle
   2. Identification number of tire removed from vehicle
   3. Vehicle number
   4. Vehicle mileage
   5. Size of tire
   6. Reason for removal—A code system would be established to enable determination of includable versus non-includable tires for average mileage purposes.

b. EDP would perform the following from information supplied by the tire records:

   1. Retain all data on tires mounted on vehicles until tires are removed from service and sent to scrap pile.
   2. For each tire subtract tire mileage on from tire mileage off to determine actual miles tire delivered.
   3. Sort tires into groupings of tire size to enable average mileage delivered by each size to be computed.
   4. Sort tires by district code if desired.
   5. Accumulate tire mileages for any one tire regardless of the number of charge cards issued for that tire.

c. EDP would publish periodic reports on the average miles delivered by each size tire.

Maintenance Practices

Since the tire mileage actually delivered depends upon the equipment and tire maintenance practices of the State, and since the supplier should have certain rights as well as obligations under a cost per mile guarantee, agencies participating in this program should make every effort to:

1. Maintain air pressure suggested by the supplier of the tires furnished.
2. Keep the wheels on the vehicles involved in alignment and the brakes properly adjusted.
3. Follow recommendations of the supplier on proper tire installation, removal, scrap practices, and the particular type of tire that should be installed on the vehicle.
4. Exclude from carcass payment requirements, but not scrap pile mileage records, all carcasses that have been removed at less than $\frac{1}{64}$-in. tread depth as measured from the center of tire.
5. Exclude from mileage records all carcasses that have been removed at more than $\frac{1}{8}$-in. tread depth unless the usefulness of the tire has been eliminated through normal road hazards (cuts, blowouts, etc., but not fire or tires that have been "run flat").
6. Consider "every reasonable effort" to mean continuance or improvement of present maintenance practices.

Disposition of Scrapped Tires

1. Whenever possible, at least monthly, the residency shops will ship all tires permanently removed from service to the district shops. Branded tires must be segregated from older unbranded tires being removed.
2. Branded tires would be shipped to the central warehouse where they would be picked up by the supplier.
3. A receipt for the number of each sized scrapped tire returned to the supplier would be given to the State. The number of tires times the guaranteed scrap price of each size would then be deducted from the next billing for new tires delivered to the State or paid in cash to the State, whichever is preferred.

Evaluation of Supplier's Guarantee

1. Based on actual versus guaranteed performance of tires.
2. Performance of all tires viewed as being represented by performance during the record-keeping periodas shown by average mileage reports of Electronic Data Processing Division.

Method of Computing Adjustment Owed the State Where Actual Average Mileage Delivered Is Less than Guaranteed Average Mileage for Any Size Tire

1. Average mileage delevered by each size tire under the contract is obtained from Electronic Data Processing Division.
2. Price of each size tire required to deliver bid cost per mile based on actual average mileage of this tire would be computed.
3. Net price paid for each size tire (gross price—scrap price received) minus price required for tire would be required adjustment per tire.
4. This adjustment for each size would be multiplied by number of tires bought of that size to determine total required adjustment for each size tire.
5. Over performance of one size tire would be allowed to compensate for under performance of another size on the basis of procedures described in 1 - 4 above, up to the point of a zero adjustment required by the State.
6. In no case would the State be required to compensate the supplier for overall over performance.
7. An example of how to compute required adjustment per tire follows:

Net Price Paid	Average Mileage Guaranteed	Guaranteed Cost Per Mile	Actual Mileage	Price Required	Adjustment Per Tire
$10.00	20,000	0.500 mill	15,000 mi	$7.50	$2.50

RECOMMENDATIONS

It was felt by the author that the tire mileage bidding program as described should be adopted. It was believed that a practical way had been developed to incorporate price and quality into the competitive bidding system.

Existing costs per mile paid for the sizes of tires that could be included in such a program were computed to insure that implementation of this program would take effect only if these costs could be reduced. All indications were that the tire suppliers would bid under most of these estimates. It was suggested that this bidding procedure would also result in certain intangible benefits, such as improved tire maintenance practices caused by the mutual interest of the State and supplier in achieving lower costs per tire mile, and the possible reduction of downtime indicated by the intent of most suppliers to bid on premium rather than first line tires.

As has been stated, the mutual interest in cost reduction would come about because (a) if the overall costs per mile delivered are greater than the guaranteed costs per mile the supplier will have to reimburse the difference, and (b) the State would get any additional savings if the overall cost per mile delivered is less than the overall cost per mile bid—this savings would come in the form of lower present costs and lower bid costs in the future. Because of this mutual interest the services, knowledge, and experience of the suppliers would also be provided for in the bid cost per mile.

It was suggested that perhaps the greatest defect other than tire quality in the present competitive bidding process is the absence of the service element when evaluating alternative suppliers. Service would be an integral part of the suggested program.

By allowing cost per mile bids for first line tires and above a method had been provided by which the price/quality of premium tires could be related to the price/quality of first line tires in terms of a common measurement. Futhermore, if proven economical in terms of cost per mile, any bid to supply the higher priced premium tires would have to contain a guarantee of substantially greater average mileage. If this guarantee was met the reduction of downtime in the field would result in considerable savings. Although suppliers were not required to offer premium tires, some of them did.

Before such a program could be implemented it was felt that certain additional steps should be taken. These were to:

1. Familiarize all district equipment superintendents and residency mechanics with the record-keeping aspects of the program.
2. Establish appropriate tire cards and coding procedures for electronic data processing.
3. Furnish branding irons to the eight districts (and any other participating agencies) so that tires could be properly identified for record-keeping purposes.
4. Delay the time period between the award of the bid and the purchase of tires from the successful bidder for a period of at least 30 days so that the State and supplier could develop a good working relationship.

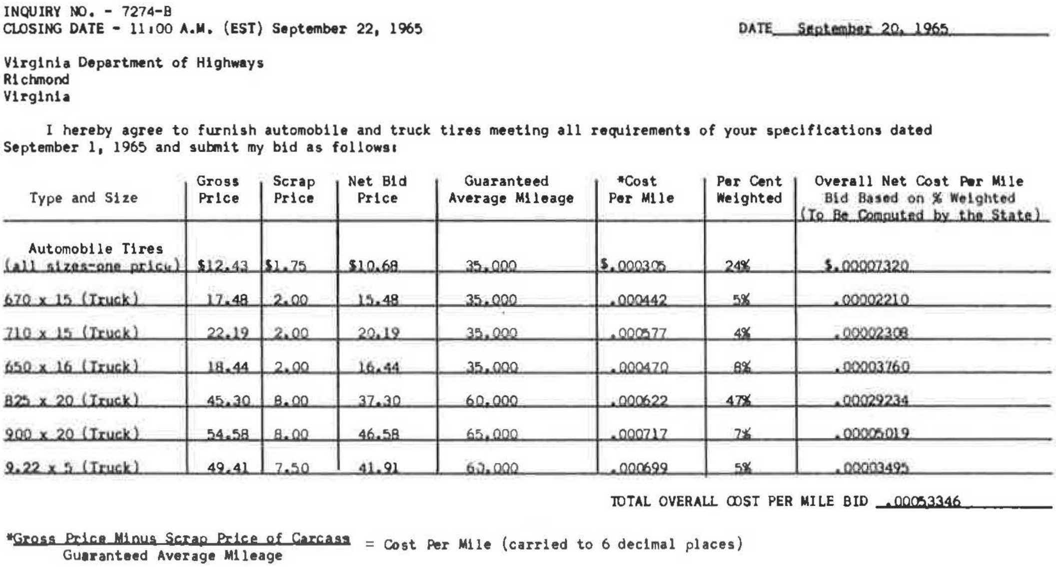
"Performance bidding" ideas developed in this report may be useful in purchasing batteries, spark plugs, filters, and even vehicles, as well as other types of equipment.

RESULTS

A research report entitled "The Tire Buying Study" was released to management of the Virginia Department of Highways in July 1965. It has been stated that it was decided to implement the recommendations almost as submitted, except to offer bid proposals for a 3-yr contract and a 5-yr record-keeping period instead of the suggested 2-yr contract with a 4-yr record-keeping period.

Inquiry No. 7274 B was issued by the Virginia Department of Highways on September 1, 1965 to all interested tire suppliers for a 3-yr contract for most of Virginia's tire replacement needs.

Bids received as a result of this inquiry are shown in Figures 1 through 6.



INQUIRY NO. - 7274-B
CLOSING DATE - 11:00 A.M. (EST) September 22, 1965

DATE September 20, 1965

Virginia Department of Highways
Richmond
Virginia

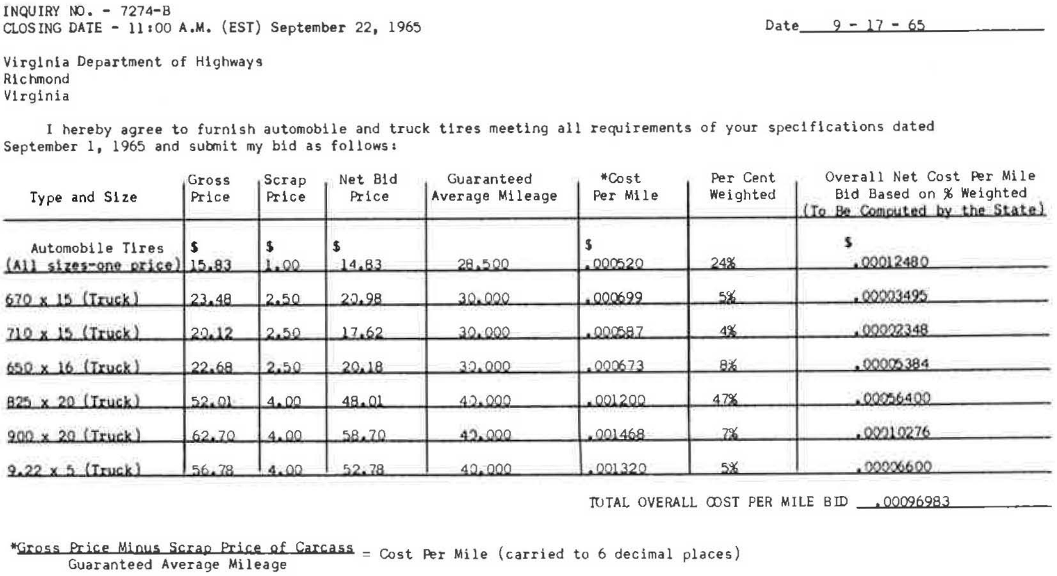
I hereby agree to furnish automobile and truck tires meeting all requirements of your specifications dated September 1, 1965 and submit my bid as follows:

Type and Size	Gross Price	Scrap Price	Net Bid Price	Guaranteed Average Mileage	*Cost Per Mile	Per Cent Weighted	Overall Net Cost Per Mile Bid Based on % Weighted (To Be Computed by the State)
Automobile Tires (all sizes-one price)	$12.43	$1.75	$10.68	35,000	$.000305	24%	$.00007320
670 x 15 (Truck)	17.48	2.00	15.48	35,000	.000442	5%	.00002210
710 x 15 (Truck)	22.19	2.00	20.19	35,000	.000577	4%	.00002308
650 x 16 (Truck)	18.44	2.00	16.44	35,000	.000470	8%	.00003760
825 x 20 (Truck)	45.30	8.00	37.30	60,000	.000622	47%	.00029234
900 x 20 (Truck)	54.58	8.00	46.58	65,000	.000717	7%	.00005019
9.22 x 5 (Truck)	49.41	7.50	41.91	60,000	.000699	5%	.00003495

TOTAL OVERALL COST PER MILE BID .00053346

*$\frac{\text{Gross Price Minus Scrap Price of Carcass}}{\text{Guaranteed Average Mileage}}$ = Cost Per Mile (carried to 6 decimal places)

Figure 1.



INQUIRY NO. - 7274-B
CLOSING DATE - 11:00 A.M. (EST) September 22, 1965

Date 9 - 17 - 65

Virginia Department of Highways
Richmond
Virginia

I hereby agree to furnish automobile and truck tires meeting all requirements of your specifications dated September 1, 1965 and submit my bid as follows:

Type and Size	Gross Price	Scrap Price	Net Bid Price	Guaranteed Average Mileage	*Cost Per Mile	Per Cent Weighted	Overall Net Cost Per Mile Bid Based on % Weighted (To Be Computed by the State)
Automobile Tires (All sizes-one price)	$ 15.83	$ 1.00	$ 14.83	28,500	$ .000520	24%	$ .00012480
670 x 15 (Truck)	23.48	2.50	20.98	30,000	.000699	5%	.00003495
710 x 15 (Truck)	20.12	2.50	17.62	30,000	.000587	4%	.00002348
650 x 16 (Truck)	22.68	2.50	20.18	30,000	.000673	8%	.00005384
825 x 20 (Truck)	52.01	4.00	48.01	40,000	.001200	47%	.00056400
900 x 20 (Truck)	62.70	4.00	58.70	40,000	.001468	7%	.00010276
9.22 x 5 (Truck)	56.78	4.00	52.78	40,000	.001320	5%	.00006600

TOTAL OVERALL COST PER MILE BID .00096983

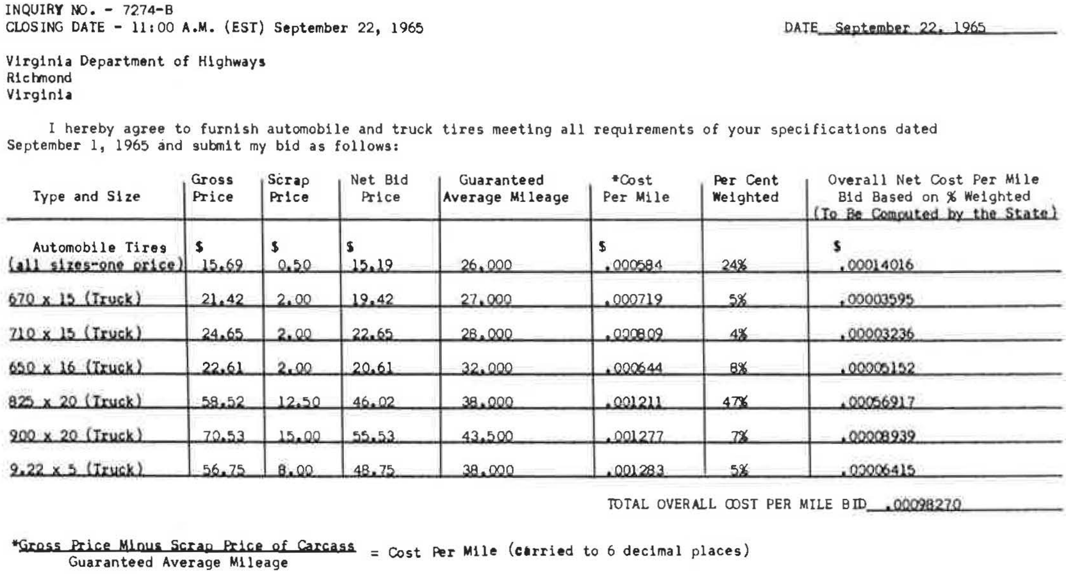
$^*\dfrac{\text{Gross Price Minus Scrap Price of Carcass}}{\text{Guaranteed Average Mileage}}$ = Cost Per Mile (carried to 6 decimal places)

Figure 2.

The successful bidder for the 3-yr contract was United States Rubber Company, or as it is now called, Uniroyal. Estimated benefits of this contract to Virginia are shown below:

Computation of Direct Savings

1. Former cost per mile 1.131 mills
   Cost per mile under contract 0.533 mill



INQUIRY NO. - 7274-B
CLOSING DATE - 11:00 A.M. (EST) September 22, 1965

DATE September 22, 1965

Virginia Department of Highways
Richmond
Virginia

I hereby agree to furnish automobile and truck tires meeting all requirements of your specifications dated September 1, 1965 and submit my bid as follows:

Type and Size	Gross Price	Scrap Price	Net Bid Price	Guaranteed Average Mileage	*Cost Per Mile	Per Cent Weighted	Overall Net Cost Per Mile Bid Based on % Weighted (To Be Computed by the State)
Automobile Tires (all sizes-one price)	$ 15.69	$ 0.50	$ 15.19	26,000	$ .000584	24%	$ .00014016
670 x 15 (Truck)	21.42	2.00	19.42	27,000	.000719	5%	.00003595
710 x 15 (Truck)	24.65	2.00	22.65	28,000	.000809	4%	.00003236
650 x 16 (Truck)	22.61	2.00	20.61	32,000	.000644	8%	.00005152
825 x 20 (Truck)	58.52	12.50	46.02	38,000	.001211	47%	.00056917
900 x 20 (Truck)	70.53	15.00	55.53	43,500	.001277	7%	.00008939
9.22 x 5 (Truck)	56.75	8.00	48.75	38,000	.001283	5%	.00006415

TOTAL OVERALL COST PER MILE BID .00098270

$^*\dfrac{\text{Gross Price Minus Scrap Price of Carcass}}{\text{Guaranteed Average Mileage}}$ = Cost Per Mile (carried to 6 decimal places)

Figure 3.

INQUIRY NO. - 7274-B
CLOSING DATE - 11:00 A.M. (EST) September 22, 1965

DATE September 22, 1965

Virginia Department of Highways
Richmond
Virginia

I hereby agree to furnish automobile and truck tires meeting all requirements of your specifications dated September 1, 1965, and submit my bid as follows:

Type and Size	Gross Price	Scrap Price	Net Bid Price	Guaranteed Average Mileage	*Cost Per Mile	Per Cent Weighted	Overall Net Cost Per Mile Bid Based on % Weighted (To Be Computed by the State)
Automobile Tires (all sizes-one price)	$ 10.06	$ 2.06	$ 8.00	15,000	$ 0.000333	24%	$ .00012792
670 x 15 (Truck)	12.72	2.96	9.76	20,000	0.000488	5%	.00002440
710 x 15 (Truck)	14.21	3.21	11.00	20,000	0.000550	4%	.00002700
650 x 16 (Truck)	13.67	3.09	10.58	20,000	0.000529	8%	.00004232
825 x 20 (Truck)	39.47	15.57	23.90	20,000	0.001195	47%	.00056165
900 x 20 (Truck)	56.19	16.25	39.94	20,000	0.001997	7%	.00013979
9.22 x 5 (Truck)	41.45	7.50	33.95	20,000	0.001697	5%	.00008485

TOTAL OVERALL COST PER MILE BID .00100293

*Gross Price Minus Scrap Price of Carcass / Guaranteed Average Mileage = Cost Per Mile (carried to 6 decimal places)

Figure 4.

Savings per mile 0.598 mill

2. Expenditures in dollars under former system (three-year period) 834,000
Expenditures in dollars under contract 393,000
Savings in dollars (three-year period) 441,000

Anticipated savings of contract is 52 percent of former costs

Computation of Indirect Savings

1. Downtime
Average mileage under former system on automobile tires 15,000

INQUIRY NO. - 7274-B
CLOSING DATE - 11:00 A.M. (EST) September 22, 1965

DATE September 22, 1965

Virginia Department of Highways
Richmond
Virginia

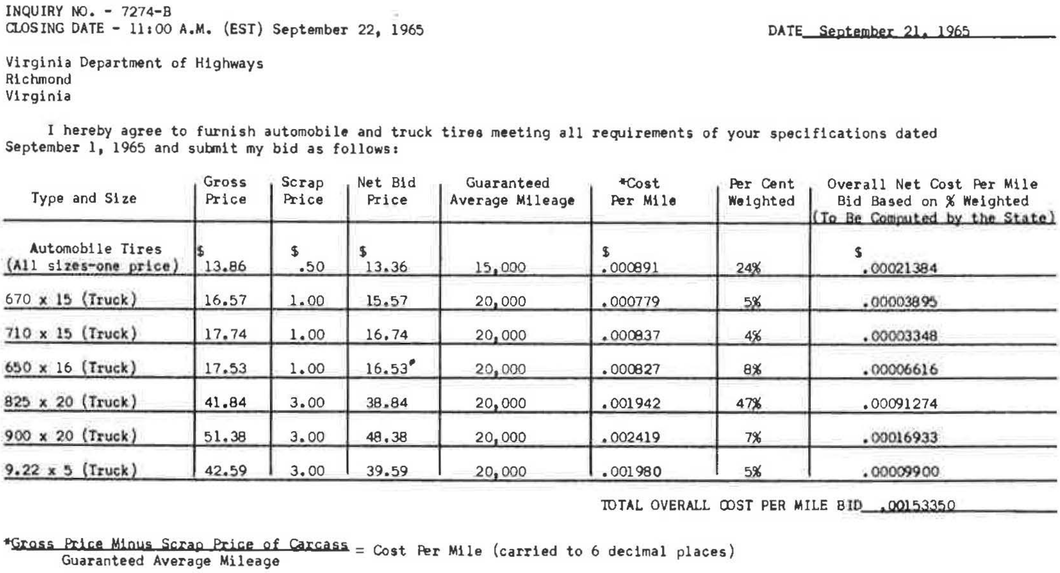
I hereby agree to furnish automobile and truck tires meeting all requirements of your specifications dated September 1, 1965 and submit my bid as follows:

Type and Size	Gross Price	Scrap Price	Net Bid Price	Guaranteed Average Mileage	*Cost Per Mile	Per Cent Weighted	Overall Net Cost Per Mile Bid Based on % Weighted (To Be Computed by the State)
Automobile Tires (all sizes-one price)	$ 30.50	$ 1.00	$ 29.50	35,000	$ .000843	24%	$ .00020232
670 x 15 (Truck)	27.70	6.70	21.00	25,000	.000840	5%	.00004200
710 x 15 (Truck)	30.16	6.96	23.20	25,000	.000928	4%	.00003712
650 x 16 (Truck)	26.86	6.86	20.00	25,000	.000800	8%	.00006400
825 x 20 (Truck)	79.09	20.00	59.09	35,000	.001688	47%	.00079336
900 x 20 (Truck)	91.83	22.50	69.33	35,000	.001981	7%	.00013867
9.22 x 5 (Truck)	78.23	20.00	58.23	30,000	.001941	5%	.00009705

TOTAL OVERALL COST PER MILE BID .00137452

*Gross Price Minus Scrap Price of Carcass / Guaranteed Average Mileage = Cost Per Mile (carried to 6 decimal places)

Figure 5.



INQUIRY NO. - 7274-B
CLOSING DATE - 11:00 A.M. (EST) September 22, 1965

DATE September 21, 1965

Virginia Department of Highways
Richmond
Virginia

I hereby agree to furnish automobile and truck tires meeting all requirements of your specifications dated September 1, 1965 and submit my bid as follows:

Type and Size	Gross Price	Scrap Price	Net Bid Price	Guaranteed Average Mileage	*Cost Per Mile	Per Cent Weighted	Overall Net Cost Per Mile Bid Based on % Weighted (To Be Computed by the State)
Automobile Tires (All sizes-one price)	$ 13.86	$ .50	$ 13.36	15,000	$ .000891	24%	$ .00021384
670 x 15 (Truck)	16.57	1.00	15.57	20,000	.000779	5%	.00003895
710 x 15 (Truck)	17.74	1.00	16.74	20,000	.000837	4%	.00003348
650 x 16 (Truck)	17.53	1.00	16.53*	20,000	.000827	8%	.00006616
825 x 20 (Truck)	41.84	3.00	38.84	20,000	.001942	47%	.00091274
900 x 20 (Truck)	51.38	3.00	48.38	20,000	.002419	7%	.00016933
9.22 x 5 (Truck)	42.59	3.00	39.59	20,000	.001980	5%	.00009900

TOTAL OVERALL COST PER MILE BID .00153350

$$^{*}\frac{\text{Gross Price Minus Scrap Price of Carcass}}{\text{Guaranteed Average Mileage}} = \text{Cost Per Mile (carried to 6 decimal places)}$$

Figure 6.

Guaranteed average mileage under contract	35,000
Average mileage under former system on truck tires	20,000
Guaranteed average mileage under contract	60,000

2. Distribution
   Under the former system all tires were shipped to the Department's central warehouse in Richmond and distributed to the districts as needed. Under this contract all tires will be shipped direct to the districts and central warehouse as needed. Considerable savings will be realized in freight and handling.
3. Administrative Cost
   Under the former system bids were obtained periodically for anticipated needs of approximately 60-90 days. This constitutes considerable cost in the preparation, mailing, and awarding of bids and preparation and requisition of purchase orders. By the contractual method bids will be obtained only once every three years and only one purchase order will be issued for each district annually.
4. Under the present contract the successful bidder agreed to furnish trained maintenance personnel whenever needed at no additional cost to the State.

At this time implementation of performance purchasing of tires is well under way. Uniroyal representatives have visited all the districts and have made several recommendations regarding improvement of the State's tire maintenance practices. Two principal suggestions were the proper matching of tires and the recurrent checking of tire inflation. Procedures have been initiated to implement these suggestions.

The author has participated in the inspection of scrapped tires. These inspections have given indications of causes of unnecessary tire wear and led to the recommendation regarding tire inflation. The inspections have, perhaps more importantly, shown to both the supplier and the State the significance of mutual interest in the success of the contract.

The inspections have also shown Virginia the correctness in awarding the bid on the basis of the average mileage of all tires; not just ones with "normal run-out."

Record keeping has generated some problems—mostly in the area of appropriate timing of delivery of tire cards to and their processing by the Electronic Data Processing Division in conjunction with receipt and inspection of scrapped tires in Richmond. These problems have not jeopardized the contract, but are pointed out so that other States may be aware of their existence and solution.

Tire card processing is now being more properly synchronized with tire inspections by holding the cards at the districts until the scrapped tires are shipped to Richmond for inspection or by the use of alternative procedures. The timing and updating of tire card computer runs and scrapped tire inspections have also been more closely dovetailed.

Even so, a few records of mileage of scrapped tires received are omitted but this was anticipated by both the State and prospective suppliers in the concept of the use of the scrapped sample as being representative of the performance of all tires purchased. In brief, the wisdom of the suggestion of the use of scrap sample tires as being representative of all tires and the awarding of bids based on the guaranteed average mileage of all tires (not just those with "normal run-out," but those with cuts and damage from normal road hazards) has been confirmed by experience.

There is no question that Virginia will receive substantial savings under this contract, but the real measure of success cannot be determined until a new contract is awarded. This is because true performance purchasing (not just the label or provisions of initial cost scrap value) has been tried by a state for the first time.

After suppliers' experience with and/or observation of this contract, they will make some sort of decision as to what they would bid for the next contract. This bid will more accurately reflect the long-run savings to the State achieved by performance purchasing of tires.

Of course, the State must also make a decision as to the worthiness of proposing future performance bids for tire needs.

It is the author's opinion that a new contract would be more expensive (more in line with the second low bidder's offer on this contract) but will still result in savings of about 20 to 30 percent of former costs.

Appendix

Tables 7 through 11 represent the source data for estimated average mileages delivered by original equipment and replacement tires shown in Table 5. Tables 12 and 13 describe the location of vehicles and the use of tires throughout the eight districts of the Department. Table 14 is included to give a most conservative estimate of the costs of ordering tires through the central warehouse in Richmond rather than having them shipped direct to the districts; and Table 15 is the source data for the weighting of cost per mile bids for each size tire given in the section on "Procedures." Table 16 is a report of tests conducted by the National Bureau of Standards in May 1965 on three different brands of 825 x 20 tires that the Department had in stock.

TABLE 7

AVERAGE MILEAGE DELIVERED BY ORIGINAL EQUIPMENT AND REPLACEMENT TIRES IN RICHMOND DISTRICT[a]

Tire Description	Avg. Mileage, Orig. Equip.	Avg. Mileage, Replace.	No. Tires, Orig. Equip. Sample	No. Tires, Replace. Sample
Automobile	27,001	10,663	20	44
670 × 15 (truck)	26,846	18,617	72	38
710 × 15 (truck)	32,299	20,937	44	10
650 × 16 (6-ply)	23,491	11,303	36	5
825 × 20 (10-ply)	37,867	18,799	256	112
900 × 20 (10-ply)	35,510	14,131	11	3
9-22-5	Not available	19,617	0	20

[a] Original equipment tires installed 1957-64; replacement tires, 1960-64; record-keeping period ended in 1964.

Source: Tire records in Richmond District.

TABLE 8

AVERAGE MILEAGE DELIVERED BY ORIGINAL EQUIPMENT AND REPLACEMENT TIRES IN FREDERICKSBURG DISTRICT[a]

Tire Description	Avg. Mileage, Orig. Equip.	Avg. Mileage, Replace.	No. Tires, Orig. Equip. Sample	No. Tires, Replace. Sample
Automobile	Not available	Not available	0	0
670 × 15 (truck)	29,025	20,247	40	84
710 × 15 (truck)	18,324	18,676	4	3
650 × 16 (6-ply)	Not available	Not available	0	0
825 × 20 (10-ply)	Not available	Not available	0	0
900 × 20 (10-ply)	Not available	15,657	0	4
9-22-5	Not available	22,172	0	6

[a] Original equipment tires installed 1957-64; replacement tires, 1960-64; record-keeping period ended in 1964.

Note: These statistics are presented as they are all that are available. Since the number of tires supplied for each size is so small (except for 670 × 15), the average mileages must be regarded with a jaundiced eye (except for 670 × 15).

Source: Tire records in Fredericksburg District.

TABLE 9

AVERAGE MILEAGE DELIVERED BY ORIGINAL EQUIPMENT AND REPLACEMENT TIRES IN LYNCHBURG DISTRICT[a]

Tire Description	Avg. Mileage, Orig. Equip.	Avg. Mileage, Replace.	No. Tires, Orig. Equip. Sample	No. Tires, Replace. Sample
Automobile	25,214	12,340	3	25
670 × 15 (truck)	24,798	15,058	48	125
710 × 15 (truck)	30,071	25,109	17	15
650 × 16 (6-ply)	19,098	19,092	36	19
825 × 20 (10-ply)	27,419	23,891	122	114
900 × 20 (10-ply)	35,193	19,374	15	24
9-22-5	Not available	17,841	0	109

[a] Original equipment tires installed 1957-64; replacement tires, 1960-64; record-keeping period ended in 1964.

Source: Tire records in Lynchburg District.

TABLE 10

AVERAGE MILEAGE DELIVERED BY ORIGINAL EQUIPMENT AND REPLACEMENT TIRES IN SALEM DISTRICT[a]

Tire Description	Avg. Mileage, Orig. Equip.	Avg. Mileage, Replace.	No. Tires, Orig. Equip. Sample	No. Tires, Replace. Sample
Automobile	28, 186	15, 533	115	113
670 × 15 (truck)	18, 653	11, 223	25	114
710 × 15 (truck)	15, 922	Not available	7	0
650 × 16 (6-ply)	22, 781	14, 384	48	36
825 × 20 (10-ply)	27, 261	17, 800	120	116
900 × 20 (10-ply)	38, 273	15, 514	26	41
9-22-5	Not available	20, 796	0	101

[a] Original equipment tires installed 1957-64; replacement tires, 1960-64; record-keeping period ended in 1964.

Source: Tire records in Salem District.

TABLE 11

AVERAGE MILEAGE DELIVERED BY ORIGINAL EQUIPMENT AND REPLACEMENT TIRES IN STAUNTON DISTRICT[a]

Tire Description	Avg. Mileage, Orig. Equip.	Avg. Mileage, Replace.	No. Tires, Orig. Equip. Sample	No. Tires, Replace. Sample
Automobile	31, 535	15, 408	76	117
670 × 15 (truck)	24, 373	19, 695	31	111
710 × 15 (truck)	25, 690	21, 760	38	15
650 × 16 (6-ply)	22, 059	17, 988	102	54
825 × 20 (10-ply)	30, 856	16, 648	109	118
900 × 20 (10-ply)	37, 170	20, 321	28	47
0-22-5	Not available	24, 318		

[a] Original equipment tires installed 1957-64; replacement tires, 1960-64; record-keeping period ended in 1964.

Source: Tire records in Staunton District.

TABLE 12

A DESCRIPTION OF TYPES AND NUMBER OF VEHICLES BY DISTRICT AND SIZE TIRES[a]

(March 1965)

Vehicle Description	Size Tire Used	Bristol	Salem	Lynchburg	Richmond	Suffolk	Fredericksburg	Culpeper	Staunton	Richmond Central Office Equipment Depot & Central Warehouse	Other Agencies (Statewide)	Total
Automobile	Auto	43	43	29	43	65	30	57	44	254	832	1440
Station wagon	710 × 15	22	14	14	20	17	9	18	17	31	NA	162
½ Ton (pick-up)	650 × 16 or 670 × 15	123	118	77	114	90	100	117	122	79	NA	940
2 Ton	825 × 20	169	150	134	177	97	116	195	138	52	NA	1228
2½ Ton	825 × 20	33	41	46	38	27	64	54	45	29	NA	377
3 Ton	900 × 20 or 9-22-5	22	8	7	17	4	14	31	19	2	NA	129
Total		417	374	307	409	300	333	472	385	447	832	4276

Note: Trucks above 3 tons in weight total 124 in number and are distributed throughout districts.

The number of vehicles except for cars that are not included in this table because of outside agencies is estimated to be no more than 10 percent of total of 4276. This statement applies to tire purchases for possible mileage bidding program.

Source: Equipment Division Records.

TABLE 13

NUMBER OF TIRES[a] THAT PASSED THROUGH DISTRICT WAREHOUSES

(July 1962—June 1964)

Tire Description	Culpeper	Richmond & Hampton Roads	Salem	Lynchburg	Suffolk	Fredericksburg	Staunton	Bristol	Totals
650 × 16	167 (9.36)	144 (8.07)	360 (20.17)	125 (7.00)	186 (10.42)	302 (16.92)	280 (15.69)	221 (12.38)	1,785 (100.00)
670 × 15	984 (14.91)	598 (9.06)	1,200 (18.18)	928 (14.06)	585 (8.86)	767 (11.62)	661 (10.02)	877 (13.29)	6,600 (100.00)
710 × 15	241 (23.56)	151 (14.76)	48 (4.69)	44 (4.30)	232 (22.68)	121 (11.83)	126 (12.32)	60 (5.87)	1,023 (100.01)
750 × 14	629 (10.11)	418 (6.72)	936 (15.04)	704 (11.31)	1,364 (21.92)	518 (8.33)	724 (11.64)	929 (14.93)	6,222 (100.00)
800 × 14	136 (37.26)	NA	NA	NA	137 (37.53)	69 (18.90)	NA	23 (6.30)	365 (99.99)
825 × 20	1,785 (16.43)	1,103 (10.15)	2,088 (19.22)	1,605 (14.77)	732 (6.74)	898 (8.27)	1,524 (14.03)	1,129 (10.39)	10,864 (100.00)
900 × 20	206 (18.81)	74 (6.76)	144 (13.15)	89 (8.13)	121 (11.05)	130 (11.87)	145 (13.24)	186 (16.99)	1,095 (100.00)
9-22-5	190 (18.54)	96 (9.37)	192 (18.73)	154 (15.02)	69 (6.73)	115 (11.22)	92 (8.89)	117 (11.41)	1,025 (100.00)
	4,338 (14.97)	2,584 (8.92)	4,968 (17.14)	3,649 (12.59)	3,426 (11.82)	2,720 (9.39)	3,552 (12.26)	3,547 (12.24)	28,979 (99.33)

[a] 800 x 14 and 750 x 14 are automobile tires, 670 x 15 and 710 x 15 are truck and automobile tires grouped together; remaining size are truck tires.

Note: Percentage figures are percent of particular size tire that passed through each district.

Source: District Kardex Records.

TABLE 14

ESTIMATED DISTRIBUTION COSTS FOR 20,000 TIRES PURCHASED FROM OCTOBER 1, 1963 TO OCTOBER 31, 1964

Space Storage Cost Per Tire (30 days)	Handling Cost Per Tire Per Tire Handled	Average Interest Cost Per Tire (30 days)	Average Distribution Costs Per Tire	Total Distribution Cost for 20,000 Tires
$0.02	$0.40	$0.06	$0.48	$9,600

Notes: 1. Space cost is based on a Richmond real estate appraiser's estimate of $0.50 per sq ft per year as the going rate for inventory rental space and the assumption that tires are stored in the central warehouse for an average of 30 days.

2. Handling costs are based on estimates derived from the Equipment Division data that it costs between $0.30 and $0.50 to handle a tire depending on its size.

3. Interest rates are based on an assumed 4½ percent per year for dollar payment prior to the use of goods at a price of $17.50 per tire ($350,000/20,000).

4. No estimate is made for transportation costs as management feels that the trucks will be moving from the field to Richmond and back anyway. If average transportation costs were based on Virginia Intra State Tariff rates of over 5,000 lb average transportation costs per tire would be $0.72.

TABLE 15

ESTIMATED PURCHASE COSTS AND DERIVATION OF ESTIMATES

Tire Description	Automobile	670 × 15 (Truck)	710 × 25 (Truck)	650 × 16 (Truck)	825 × 20 (Truck)	900 × 20 (Truck)	9-22-5 (Truck)
Number bought	16,475	2,850	1,550	3,650	9,792	1,125	950
minus							
Number delivered to outside agencies	659	114	62	146	98	0	0
equals							
Number used	15,816	2,736	1,488	3,504	9,694	1,125	950
Initial purchase cost	$155,839	$30,017	$23,696	$46,804	$306,604	$44,845	$31,540
minus							
Dollar value delivered to outside agencies	6,234	1,201	948	1,872	3,066	0	0
equals							
Total initial purchase cost for tires used	149,605	28,816	22,748	44,932	303,538	44,845	31,540
plus							
Estimated recapping and repair costs for tires used	0	1,257	685	1,608	8,240	960	800
equals							
Total purchase costs for tires used	149,605	30,073	23,433	46,540	311,778	45,805	32,340
minus							
Total recappable and scrapped carcass value	15,816	2,736	1,488	3,504	48,470	5,625	4,750
equals							
Net cost for tires purchased and used	133,789	27,377	21,945	43,036	263,308	40,180	27,590
Divided by							
Number purchased and used	15,816	2,736	1,488	3,504	9,694	1,125	950
equals							
Net cost per used tire	8.45	9.99	14.74	12.28	27.16	35.21	29.05

NOTES: 1. It is assumed that beginning and ending inventories are the same when determining number of tires used.

2. It was estimated that 490 of automobile, 670 × 15, 710 × 15 and 650 × 16 tires were sent to outside agencies. 190 of 825 × 20 and no 900 × 20 and 9-22-5 were sent to these agencies.

3. The average value per scrapped carcass of all tires was estimated to be $1.00 except for heavier truck tires (825 × 20, 900 × 20, and 9-22-5) which were valued at $5.00. This low value is felt to be realistic because of the low percentage of recappable carcasses and lower prices paid for recappable carcasses of the Department's present tire suppliers.

Source: Kardex records of the Purchasing Division, invoice billings, and tire recappers.

TABLE 16

REPORT OF NATIONAL BUREAU OF STANDARDS ON RESULTS OF TESTS CONDUCTED IN MAY 1965, ON THREE DIFFERENT BRANDS OF 825 × 20 TIRES

Tests				
Manufacturer				
Endurance test:				
Running time, hr, at:				
100% load	7	7	7	7 min.
120% load	16	16	16	16 min.
140% load	24	24	24	24 min.
Total cut-growth, %	43	5	14	600 max.
Breaking energy, in.-lb	13,110	14,597	19,926	10,875 min.

[a] Required results based on Interim Federal Specifications ZZ-T-00381j, dated July 13, 1959.

Note: The tires comply with the requirements for these tests.

High-Speed Data Processing for Fleet Management

J. G. SLUBICKI and K. Y. SHEN, Ontario Department of Highways

This report is concerned with the application of high-speed data processing in the management of a fleet of vehicles involved in highway maintenance. Specifically, documentation techniques, cost usage and maintenance cost control, replacement methods and budgeting are discussed. The method of formulation of a unique replacement priority list is given and finally, some of the user's experience and the expected future potential of the system is reported.

•IT is hardly necessary to outline the equipment management problems of a growing fleet in an expanding operation. The number of vehicles has increased into hundreds and thousands, the number of garages has multiplied, and management is faced with problems not previously encountered. The memory, often cherished and glorified, of the old superintendent, who knew his fleet and people, is still very much alive. The superintendent of days gone by knew every truck, mechanic, and operator in his fleet. Today we do not know every truck, neither do we know every mechanic by his first name—especially in the faraway garage—and, as a result it is often doubted that we know the front-end of a truck from the rear.

But, with due respect for the old man's memory, his ability and experience, his fleet was small, compared with those of today and these are only a fraction of the fleets of tomorrow. When vehicles are numbered in the thousands, a new approach is necessary; old methods and tools are inadequate.

In a large fleet, dispersed over a large geographical territory, the distance between management and the vehicle grows. This distance can be measured both in miles and in the steps of the organization ladder.

The manager makes decisions based on information that reaches the top of the organization pyramid through all the in-between positions. With an increasing number of in-between steps, the information has more chance of being preselected and opinionated.

One method, frequently applied, is to delegate authority to lower levels. This results, for all practical purposes, in dividing the fleet into several independent smaller fleets. This may be acceptable, but no doubt some of the advantages of the big fleet operation will be lost.

The Department of Highways, Ontario, selected a different approach. The high-speed data processing methods described in this paper were designed to overcome the difficulties of managing a large fleet, and to utilize the advantages of a big operation.

SYSTEM DEVELOPMENT

Data collection for the high-speed data-processing (HSDP) system began in 1954 and by the time it was fully introduced, a 10-yr background of essential information was available. The accumulation and proper selection of data is a prime requisite of any successful data-processing system. It is a well known paradox of data processing that, whereas the processing and computing can be accomplished in seconds, the time required to make a change in a system may take months or even years.

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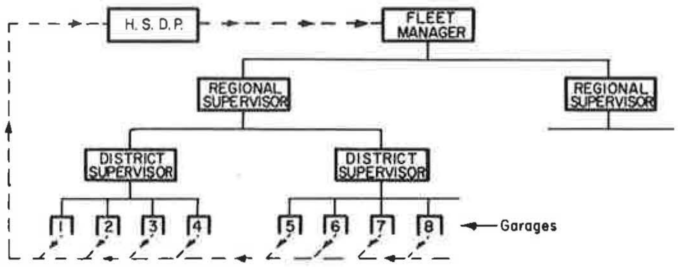

Figure 1. Communication path using high-speed data processing.

The records kept for a particular vehicle must be comprehensive and cover the entire life of the vehicle. All repairs, and their costs, must be documented from the day the vehicle is introduced into the fleet until it is replaced.

Two methods of recording data are in use in HSDP, one of these utilizes a component breakdown where each major component is assigned a reference number, the other assigns a reference or documentary system that considers each vehicle as an entity. Although the first method seems to be gaining some popularity, it has certain limitations in the control of a diversified fleet, with its variations in sizes and types of equipment. This inevitably results in such vast accumulations of data referencing numbers, that it becomes unwieldy and difficult to handle. The second system, in which complete vehicles are considered as units, lends itself much more readily to further development of computations, such as devising a replacement method and budgeting study.

In the system under discussion the data-processing center receives input information from each district. This information is received direct and does not follow the normal organizational ladder. The information on all vehicles is recorded in the same way, regardless of location. Figure 1 illustrates a typical information flow diagram.

The information received by the processing system must be supplied in a form that is acceptable to the system and it must be available at the time required. Management decisions can only be based on the results of processing, which reduces the flood of accumulated data to a more meaningful and manageable size. In the system described, processing is divided into the following four categories: documentation, cost and usage control, replacement study, and budgeting.

DOCUMENTATION

The first listing, and the one requiring the least amount of processing, is the accumulation of data, documenting the history of each vehicle. This consists of (a) the list of running data, (b) yearly accumulation (Table 1), (c) life accumulation, and (d) accumulation for accounting purposes. Each month, a list of running data is produced for each garage. However, this information has little value due to the length of the list.

Once a year an accumulated total is produced in book form. The accumulation provides, for each truck, yearly mileage, hours of operation, gas used, cost of repairs, cost of labor, and total cost of operation (Table 1). Also, once a year a listing of total figures for the life of each vehicle is produced.

A separate accumulation is compiled each year for accounting purposes, indicating the price, the yearly depreciation, and the depreciated value of each vehicle. Following the accepted commercial practice, depreciation is based on the age of the vehicle only, with no regard for its physical condition. Each district garage supervisor receives a copy of all of these accumulations for the vehicles under his jurisdiction.

COST AND USAGE CONTROL

To reduce the accumulations to a more manageable size, a control method known as "management by exception" is used. All exceptions to the rule are singled out and

TABLE 1

A TYPICAL YEARLY ACCUMULATIVE SHEET

Vehicle				Gasoline		Motor Oil		Truck Miles		Parts Cost	Labor Cost	Aux. Parts	Aux. Labor	Total Cost
Yr.	No.	Cl.	Mk.	Gals.	Amt.	Qts.	Amt.							
62	471	031	11	3658	1748.10	104	22.68	1898	31217	297.48	654.00	15.75	24.00	2848.79
62	472	031	11	5233	2435.81	165	34.77	2055	39824	1014.08	842.00	29.15	16.00	4407.98
65	527	031	40	2916	1343.19	98	24.44	1436	27466	258.46	394.00	60.75	376.00	2484.84
63	751	031	11	2752	1168.44	142	44.35	965	22950	771.20	932.00	160.73	838.00	3943.51
63	755	031	11	4615	2106.14	190	42.80	2090	35484	671.71	796.00	5.40	56.00	3734.05
63	790	031	11	4154	1982.34	152	38.21	1783	36442	1015.68	884.00	127.65	44.00	4092.93
63	799	031	11	4780	2192.42	126	30.04	2235	38744	907.18	912.00	25.24	32.00	4098.88
63	800	031	11	4174	1921.30	113	29.55	1637	38317	490.27	576.00	7.49	12.00	3043.68
63	826	031	11	3687	1753.42	139	30.22	1869	31503	1178.81	1160.00	13.01	68.00	4271.59
63	827	031	11	3478	1662.94	107	22.95	2373	31540	568.59	966.00	3.35	16.00	3325.97
63	829	031	11	3359	1598.73	123	28.46	1866	32269	866.28	892.00	6.53	28.00	3477.50
63	837	031	11	4413	1426.91	133	34.10	2194	37970	599.26	564.00	110.05	44.00	2778.32
63	845	031	11	3194	1511.14	82	18.51	2056	26815	818.46	660.00	15.55	40.00	3118.69
65	517	033	20	2286	733.25	62	13.88	792	18357	60.54	176.00	56.36	72.00	1112.03
65	524	033	20	3495	1222.50	141	29.72	1075	27360	87.66	184.00		8.00	1531.88
61	684	033	40	1901	658.50	57	12.51	608	17446	162.19	236.00	246.59	76.00	1391.79
63	815	033	32	3427	1189.39	120	26.66	1016	26769	353.53	520.00	177.37	40.00	2306.95
57	109	040	32	664	252.83	31	6.40	378	4058	89.39	132.00	18.27	20.00	518.89
64	239	050	28	2818	961.33	92	20.62	742	15970	212.10	200.00	40.70	258.00	1692.75

brought to the attention of management. In the processing system, the following items are controlled in this manner: fuel consumption, extent of use and repair costs.

Fuel Consumption

Fuel consumption depends on the type of operation, i.e., highway surface patching requires considerable engine idling and the mileage figures for a vehicle engaged in this type of work would be quite different from those obtained from routine highway patrolling. Thus, it is difficult for the head office to correlate fuel consumption with the numerous duties each vehicle performs; this can only be done at the district level and the responsibility is consequently assigned to district managers.

Each month the district supervisor receives a miles-per-gallon figure for the past month for each truck under his jurisdiction. He is also supplied with an average fuel consumption figure for each type of vehicle in the entire fleet which enables him to compare his vehicles with those in other districts. Fuel consumption is computed in the normal way by dividing miles driven by the number of gallons used during the control period.

Usage Control

A similar method is adopted for usage control. In this case however, control is effected by the head office and the method of tabulating is different. A "usage limit" is established for each group of vehicles of a specific type and this is set at approximately one-half of the fleet average for the type of vehicle involved. Once again employing the exception principle, all vehicles having a total usage figure below the usage limit are listed as exceptions. The circumstances are then investigated with a view to transferring these vehicles to other more pressing assignments.

When these vehicles are listed as exceptions the following information is supplied: assigned code number, location, number of similar vehicles at location, fleet average usage, and actual vehicle usage (in miles or hours depending on the type of equipment involved). A typical example of this type of list is given in Table 2.

Maintenance Cost Control

In this rather complex listing the limit is not established as a value but as an equation, i.e.,

$$C = f(M) \tag{1}$$

where C = cost and M = mileage. This approach to maintenance cost control is the result of prior experience in which it has been established that maintenance cost is

TABLE 2

EQUIPMENT USAGE DISTRICT NO. 16
(April 1966 to March 1967)

Type of Equipment	Number	Average (hours or miles)	Hours or Miles Worked
Stk-W-hoist-trucks, 3-ton—3 in district	61-284-033	18, 360	8, 269
Dump trucks, 5-ton—7 in district	57-248-051	11, 637	3, 896
	66-516-051	11, 637	6, 026
	67-552-051	11, 637	5, 878
	67-559-051	11, 637	2, 327
Fixed trucks, 6-ton—4 in district	57-264-062	8, 273	4, 181
Motor graders Class 1—3 in district	59-103-101	546	357
	56-115-101	546	282
Motor graders Class 4—2 in district	51-179-104	801	325
	51-206-104	801	277

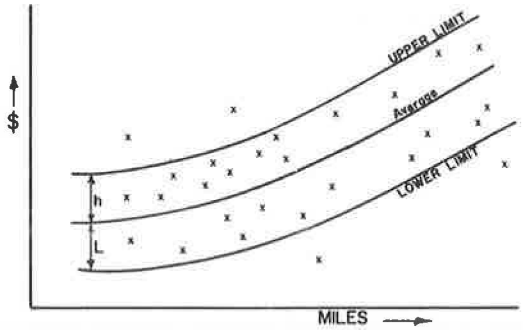

Figure 2. Repair cost limits.

related to mileage only. Repair costs accumulated from the day the vehicle was introduced into the fleet, must be taken into account. Cost-per-mile, calculated over a short control period is of little value, since any repair that immobilizes a vehicle increases the cost-per-mile figure immensely.

Equation 1 is a simplification because the age of the vehicle is omitted. Age is reflected, however, in the mileage since all vehicles in a group travel approximately the same mileage and the "exceptional" vehicle is singled out by "usage control."

In the following description, a graphical presentation is given for convenience—the computer program utilizes mathematical equivalents. Figure 2 shows total repair costs (parts and labor) on the vertical axis; total miles driven are shown along the horizontal axis.

In Figure 2, average repair costs are represented by the middle curve; upper and lower limits by the upper and lower curves respectively. In the computer program, the equation for the average costs is computed using the regression technique and it assumes a parabolic shape due to the rising costs when the vehicle has been driven more miles. The upper and lower limits are drawn by assuming a value h and ℓ.

$$\begin{aligned} \text{Average curve } y &= ax^2 + bx + c \\ \text{Upper limit } y &= ax^2 + bx + (c + h) \\ \text{Lower limit } y &= ax^2 + bx + (c - \ell) \end{aligned}$$

The upper and lower limits are established in order to single out approximately 10 percent of all vehicles in each class. All vehicles above the upper limit and all those below the lower limit are listed.

When a vehicle is listed, the difference between the upper cost limit for the vehicle (C_u) and the total repair cost C_1 is subtracted from the vehicle's recorded maintenance costs. The corrected record shows the vehicle's actual mileage and maintenance costs equal to C_u. The same procedure is used for vehicles with maintenance costs below the lower limit, but in this instance the difference is added. This correction was introduced to avoid listing of a vehicle as a result of expenses that occurred prior to the last checking period. Figure 3 shows two vehicles that would be listed. Vehicle 1: the repair cost C_1 is above the acceptable limit C_u for a vehicle with M_1 number of miles; the correction subtracted for future control is $(C_1 - C_u)$. Vehicle 2: the repair cost C_2 is below the lower limit C_L; the average cost is C_{2A} and the correction added to records is $(C_L - C_2)$.

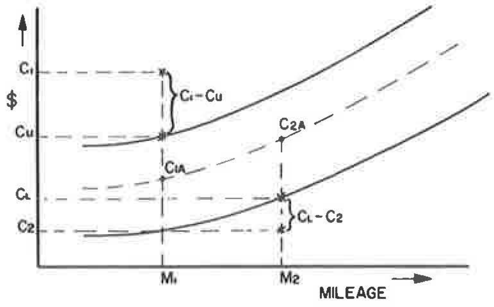

Figure 3. Amount of record adjustment for listed vehicles.

This output includes vehicle code number, location, miles driven, total maintenance cost, corrected maintenance cost, upper limit for this mileage, amount over the limit and the amount spent during last control period. Lists are revised by the head office and then sent to the districts. Each vehicle listed must be investigated and the results sent to the head office. A

TABLE 3

LIST OF VEHICLES HAVING UNUSUAL EXPENDITURES

Vehicle Number			Dist.	Miles or Hours	Act. Cost ($)	Adj. Cost ($)	Tolerable Cost ($)	Amt. Over ($)	Amt. Under ($)	Average Cost ($)	Act. Dollar Cost Over Last 6 Months
*63	120	051	17	52829	3700	4033	4060		27	5831	481
*56	124	051	10	87730	19270	13830	11966	1864		9618	2483
66	127	051	7	9390	2181	2181	2173	8		1118	1137
66	132	051	8	7521	2343	2343	1940	403		916	2343
*54	134	051	9	90594	18104	12658	12324	334		9929	334
*62	139	051	9	31458	8018	4955	4932	23		3513	894
*62	140	051	2	80804	6307	6308	6633		325	8866	671
64	144	051	2	50138	3124	3124	3812		688	5539	232
*60	164	051	6	57931	11914	10106	8241	1865		6385	2252
*61	171	051	6	33255	6879	5322	5156	166		3707	466
66	174	051	19	8956	2487	2487	2119	368		1071	2487
*58	182	051	1	115037	6767	9706	9783		77	12581	362
*61	191	051	6	26835	5966	4710	4354	356		3011	769
*64	193	051	17	50201	2437	3194	3818		624	5546	240
*57	216	051	6	100820	16382	13887	13602	285		11038	893
*57	223	051	1	100860	6787	8386	8479		93	11043	251
*60	226	051	16	64803	9549	9533	9100	433		7130	1421
*64	233	051	19	61984	3578	4741	4902		161	6824	1401
*58	235	051	8	74475	15648	10326	10309	17		8180	739

*These vehicles previously listed.

typical example of a list produced by computer, showing vehicles above the upper limit and below the lower limit, is given in Table 3.

USER'S EXPERIENCE AND FUTURE POTENTIALS

Documentation

The usefulness of all information collected and stored in its original form requires no explanation or justification. The information is used by the head office when checking the present status or past history of a vehicle. No transfer, major repair, or special installation can be approved without checking records. Any future development depends on records and information stored over a period of years.

Cost and Usage Control

Cost and usage control is one of the most successful programs. When this program was implemented several years ago, it was discovered that some units which were expensive to maintain, cost so much more than the remainder, that the average maintenance costs were visibly affected. By eliminating these problem units, the fleet maintenance costs were reduced and the average cost for the whole group was lowered.

High maintenance costs can usually be attributed to one of three causes: (a) unsatisfactory repair—when the same repair work has to be done a second time within a very short period; (b) improper operation—or the result of improper operation because operators have not received sufficient instruction; or (c) vehicle not suitable for the type of operation. The districts are required to resolve these problems, but if they are unable to do so, a qualified representative is sent from the head office to investigate and recommend the required action.

Many examples of the success of this procedure (over the last few years) can be cited, for example:

1. The type of vehicle used by surveyors was changed. Although the purchase price of the new vehicle was higher, overall costs were reduced and savings in operational costs were effected.
2. Courses of instruction were introduced in specific districts which dealt with such problems as split-shifting of snowplow drivers and the maintenance of generator units supplied to isolated camps.
3. Inspection and road testing procedures were improved.

The overall success of this program can be attributed to several factors. The first is the relative simplicity of the procedure. The second, which cannot be overestimated, is the fact that all personnel involved become conscious of the need to make proper decisions, which are likely to be challenged by the data-processing techniques applied. As a consequence, all staff, at all levels of the organization, become very aware of expenditure and their decisions are made accordingly.

Finally, this procedure has been surprisingly well received by district supervisory staff. The district supervisor does not feel so bad when told that some of his vehicles are expensive to operate when he can be complimented on the operation and efficiency of other units.

The efficient, inexpensive-to-operate vehicle is also subject to investigation. By analyzing those units that operate below average cost, it becomes apparent, quite frequently, that one factor is contributing towards the successful operation. It may be the make of the machine, a better trained or more conscientious operator, or a smaller number of operators assigned to one machine. If one factor were to be singled out which contributes most to low cost operation it would be the conscientious operator fully responsible for his unit; the one man-one machine operation. In many operations, shift work cannot be avoided, but the price paid for assigning more than one man to a machine is a higher maintenance cost. Information of this kind is utilized by management to reduce overall expenditures.

No method is without its problems and this one is no exception. The first difficulty is the time required to introduce a change. The whole life of a vehicle must be recorded.

When a change in recording is required, it takes time (equivalent to the life of a unit) to collect all the required information. If, for example, a vehicle in a certain group is replaced every four years, and it has been decided to collect additional information not recorded before, it will take four years to collect the necessary data. The importance of selection of information cannot be overemphasized.

The second difficulty is the human resistance to analytical thinking. The question "Why is this truck expensive?" is only too often answered "Because we had to install a new engine." Obviously, that is not correct. The cause of the engine failure is important, and not the fact that it had to be replaced. A broad look on the whole operation of the truck is necessary.

The third difficulty is the time lag between the expenditure and the inquiry. At present, the list is computed twice a year, embracing six months. An expenditure that shifted a vehicle above the upper limit and which occurred at the beginning of the check period, will not be recorded by HSDP until six months later. The collecting of information for the last month in the check period takes four weeks; the computing, two weeks. As a result, the list is computed eight months after the expenditure. The inquiry sent to the district will ask, "Why eight months ago did you have to repair this truck?" This is an extreme example of an expenditure occurring at the beginning of the check period, but it illustrates the time lag problem. Defining the difficulties is half the battle, then an effort can be made to overcome them.

Corrections in selection of information take a long time. It is hoped that modifications introduced a few years ago will result in an improved accuracy of the method. For the time being, no future changes are anticipated. Analytical thinking and the proper and effective use of available information is a matter of instruction and education. It is a never ending task, but the results are very satisfactory and gratifying.

In the not too distant future the Department will be using an IBM 360 random-access computer, and new possibilities will be available. It is intended to secure direct access to the computer from each garage. It is too soon to tell how it will be done, since we are in the planning stage only. The object is to delete all in-between paper forms. The information should be transferred directly from the work-order, dispensing pump slip and time sheet, into the computer. Having done this, the program can be run weekly. The head office will be in a position to ask the critical question "why?", within ten days of the completion of the work-order.

REPLACEMENT STUDY

Description

The replacement study was the focal point of the system's development. The objective was to establish when a particular piece of equipment can be replaced most economically. From a fleet management point of view, because there are financial restrictions, it is desirable to know how much money will be lost if that piece of equipment is not replaced.

If the units of a fleet of vehicles tend to have widely varying costs and mileages, or if there are only a few vehicles, individual analysis is the only possible method. However, if a fleet follows a fairly close pattern, not varying too widely from the average, it is possible to consider a statistical approach. This is true of vehicles in the following classes: station wagons, 3-ton dump trucks, ½-ton express vehicles, 2-ton trucks, 5-ton vehicles, 6-ton vehicles, graders, wheeled tractors, and power loaders.

The department adopted the statistical approach. All the vehicles were grouped by types, such as station wagons, 3-ton trucks, and graders, and analysis was done within each group. Fortunately, the number of vehicles in each major type used was in the hundreds, which provided sufficient statistical stability (from the "t" test tables, stability appears at about 50 observations).

In some cases, such as graders and power loaders, analysis revealed that a statistical model was not too useful. These vehicles cost a great deal, and last a long time. As a result, the costs of these vehicles follow a straight line pattern, rising slowly for the whole life of the vehicle. Therefore, these vehicles are analyzed on the basis of

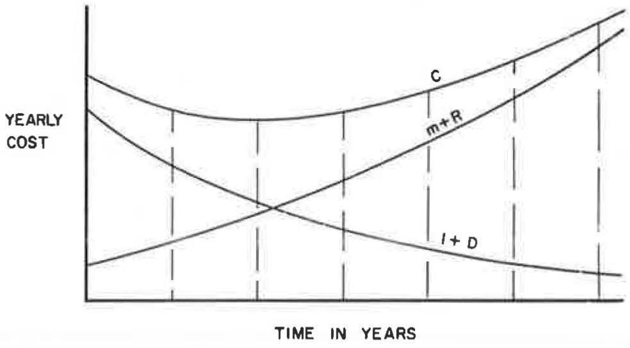

Figure 4. Relationships between operating time and vehicle cost.

increasing maintenance cost per hour. However, in most of the cases considered, for example cars, station wagons, and all kinds of trucks, the statistical approach proved very useful. A prediction model for each type, using the multiple regression method, was established. These models are used to carry out a replacement study. Although it was recognized that the models developed are only valid for our operating environment, the method used to derive these mathematical models is applicable in any other agency with similar management problems.

Briefly this method allows the prediction of the optimum replacement age of individual vehicles, based on group characteristics which are described by a mathematical model.

Concept

The operation problem of a unit of equipment can best be illustrated by the operation of a vehicle which is familiar to our daily life. The operating cost of the vehicle for a certain period of time may be broken down into the following elements:

I = interest on the current value of the vehicle,
D = depreciation of the vehicle,
m = maintenance cost including labor, parts and overhead, and
R = downtime loss.

All of these elements vary from year to year and the sum will be called C. Figure 4 illustrates the cost pattern. This concept can be made applicable to industrial concerns by including other factors as required, such as taxation, which are not applicable to government organizations.

Figure 5 shows that to replace a vehicle at the bottom of the C (yearly cost) curve would mean the loss of the most economical operating time, since the new vehicle will start again at the high level instead of operating at the low. This is why we define the minimum of the $\overline{C}$ (average yearly cost) curve as the optimum replacement age.

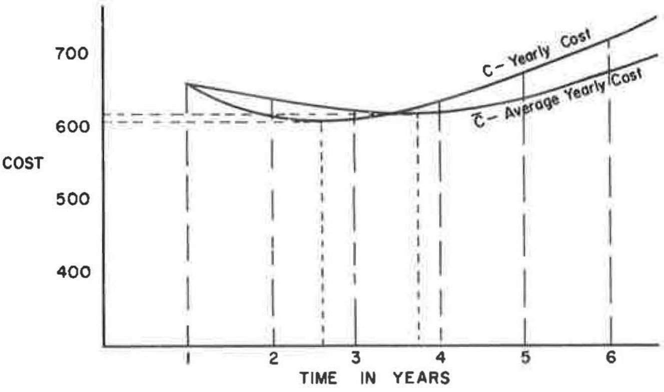

Figure 5. Optimum replacement time.

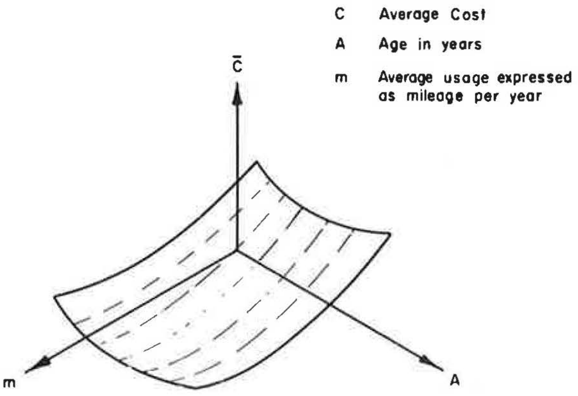

Figure 6. Relationship between cost, age and usage.

Method

In developing the model to predict the minimum $\overline{C}$, close observation of the data showed that mileage and age are the main factors influencing the cost. These factors are both fairly easy to measure. Many forms of the relation $\overline{C} = f(mA)$ were extensively examined.

From the foregoing, it is obvious that there will be an age at which the yearly cost will be a minimum. But we are concerned not just with that particular year, but also with minimizing the total operating cost over the life of the vehicle. Therefore it is easier to work with the average yearly cost, which is defined as

$$\overline{C} = \frac{\text{total operating cost}}{\text{age in years}}$$

From the definition, $\overline{C}$ varies as follows:

$$\text{1st year:} \quad \overline{C} = C_1 \text{ first year's cost}$$

$$\text{2nd year:} \quad \overline{C} = \frac{C_1 + C_2}{2}$$

$$\text{3rd year:} \quad \overline{C} = \frac{C_1 + C_2 + C_3}{3}$$

Again from the cost curve, the C-values vary, at first getting smaller, later becoming larger and larger. There will be one C-value which is a minimum.

The relationship between the yearly cost C and the average yearly cost $\overline{C}$ is illustrated by Table 4.

In Figure 5, $\overline{C}$ reaches a minimum later than C. For the model, it can be shown mathematically that this relation is always true.

The results of these examinations revealed that the best general model applicable to most types of equipment such as station wagons and trucks, takes the form:

$$\overline{C} = a_0 + \frac{a_1}{A} + a_2A + a_3A^2m$$

TABLE 4

RELATIONSHIP BETWEEN YEARLY COST AND THE AVERAGE YEARLY COST $\overline{C}$

Age (yr)	Yearly Cost (C)	Total Cost	Avg. Yearly Cost ($\overline{C}$)
1	700	700	700
2	600	1300	650
3	550 min	1850	617
4	600	2450	612 min
5	650	3100	620
6	700	3800	633

where

$\overline{C}$ = average yearly cost,
A = age in years,
m = rate of usage which equals total mileage (M) divided by age, and
$a_0, a_1, \ldots$ = coefficients to be determined statistically.

In one example, the actual equation now being used for 3-ton dump trucks is:

$$\overline{C} = 2865 - \frac{761}{A} - 298A + 0.00127A^2m$$

This relationship can be thought of as a three-dimensional surface (Fig. 6).

Some explanation should be given for the variable m which we call the rate of usage. When a vehicle is operated for more than one year, m becomes an average rate of usage. The average would reflect the actual yearly usage if the mileage every year was the same. Then the same value could be used in the model to predict for the next year. However, we find that the usage of a vehicle decreases significantly as it gets older. As a result, the predicted cost for the next year would be too high if this year's average m were used. Instead, the value of m is modified to make it more realistic.

Briefly, vehicles of each age within a certain type are grouped and their average usage at that age is determined. This predicted mileage is added to the actual mileage to date, and the sum is divided by the actual age plus one year. The quotient gives the modified m to be used in the model for prediction.

Replacement Priority List

Two computer programs are used in the process of obtaining a replacement priority list for major types of vehicles. One is the multiple regression program used in constructing the model; the other uses the model to process mileage and age data on the vehicles, and produces the required list. The list contains three groups of information:

1. Historical data included from the given information, for easy reference.
2. Processed information based on group characteristics showing the optimum replacement age, predicted operating cost for the next year, and money loss expected if the vehicle is not replaced.
3. A priority rating based on a relative index formed by adjusting the money loss predicted for next year on a group characteristics basis, with its own operating characteristics. It is possible to have two vehicles of the same type and age, with similar usage, and therefore their predicted money losses will be the same. However, the one whose past operating costs have been higher will stand higher on the priority list.

The list will be used by management subject to available financial resources. A sample priority list is given in Table 5. All the vehicles on the replacement priority list have reached or passed their optimum replacement age. The comparison is carried out using the actual age increased by one year. The cut-off point is such that vehicles which have not reached replacement age will not appear on the priority list.

Currently, types of vehicles are grouped in six categories to which the model is applicable. The equation is as follows:

$$\overline{C} = A_0 + A_1/T + A_2T + A_3T^2m$$

The associated parameters for these types are shown in Table 6.

The department's replacement method draws a lot of attention, because it produces the answer to the two critical questions:

1. How many trucks in a group should be replaced?
2. Which vehicles should be replaced first (priority order)?

The replacement procedures adopted are as follows: the number of trucks to be replaced is determined by computation and budget allocations. When the vehicles are on order, but prior to delivery, equipment inspectors are dispatched to the districts. Each

TABLE 5

TYPICAL COMPUTED PRIORITY RATING LIST

Historical Data						Group Characteristics				Individual Adjustment	
Vehicle Number	Dist.	Total Hour or Mileage	Age	Total Op. Cost	Avg. Yearly Op. Cost	Optimum Replacement Age	Optimum Avg. Yearly Op. Cost	Predicted Op. Cost Next Year	Money Loss[a]	Relative Index For Individual Priority Rating[b]	Individual Priority Rating
64 351 3	17	87279	3.0	2547	849	2.9	960	1218	258	1107	45
63 676 3	20	106961	4.0	3258	814	3.0	939	1221	282	1096	46
64 146 3	14	60389	3.0	3053	1017	3.4	875	924	49	1066	47
64 119 3	19	79400	3.0	2598	866	3.0	938	1125	187	1053	48
63 675 3	20	105405	4.0	3110	777	3.0	936	1166	230	1007	49
64 276 3	17	65736	3.0	2757	919	3.3	895	975	80	999	50
64 771 3	14	92428	3.0	2336	778	2.8	973	1168	195	974	51
64 327 3	17	125002	3.0	2407	802	2.4	1043	1203	160	962	52
64 775 3	19	67067	3.0	2608	869	3.3	899	989	90	958	53
64 551 3	20	68690	3.0	2444	814	3.2	905	1006	101	915	54
62 509 3	20	96187	5.0	3521	704	3.6	859	1056	197	901	55
64 774 3	19	69410	3.0	2348	782	3.2	907	1013	106	888	56
61 443 3	20	144105	6.0	4333	722	3.1	917	1083	166	887	57
62 503 3	20	105770	5.0	3475	695	3.4	883	1042	159	853	58
64 776 3	19	53592	3.0	2308	769	3.6	848	866	18	787	59
63 672 3	20	88556	4.0	2686	671	3.3	893	1007	114	785	60
64 777 3	17	49019	3.0	2260	753	3.8	828	833	5	758	61
63 673 3	20	86259	4.0	2441	610	3.3	886	915	29	638	62

[a] Money loss = predicted op. cost next year - optimum avg. yearly op. cost.

[b] Relative index for individual priority rating = predicted op. cost next year - optimum avg. yearly op. cost + avg. yearly op. cost.

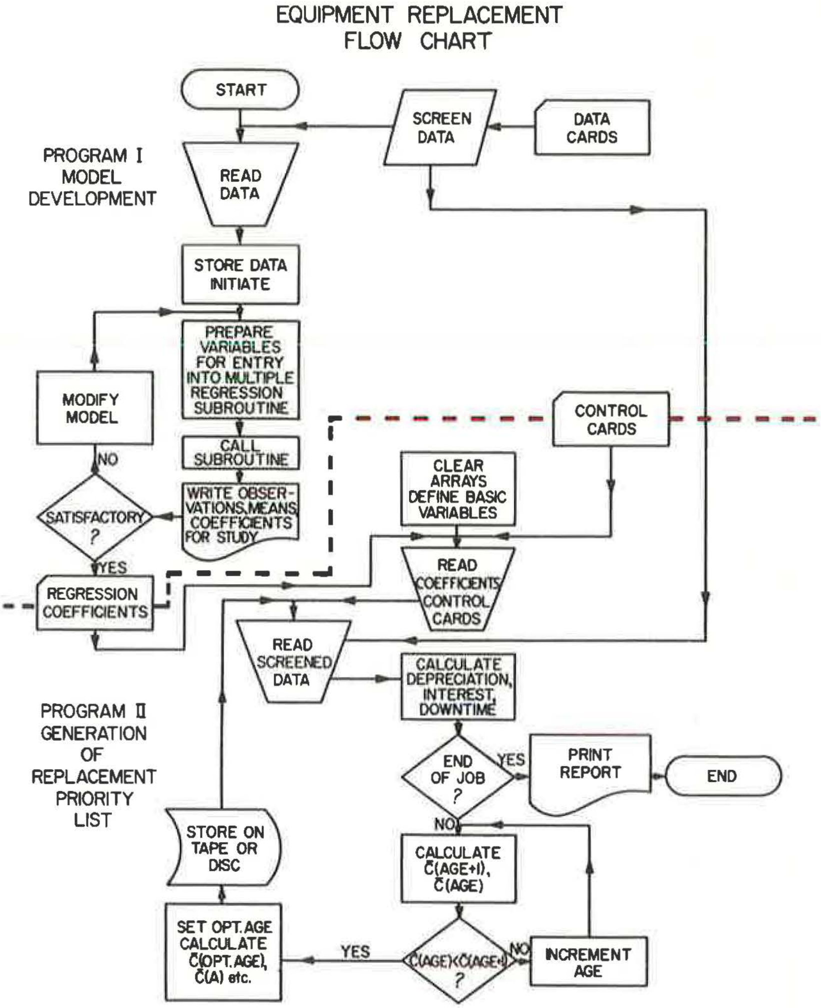

Figure 7. Flow chart: the logic of computation.

inspector is supplied with the computed replacement list for a specific district. The local equipment supervisor is required to produce his own replacement list, based on experience and knowledge of the vehicles. The matching of the two lists, and verification by a physical inspection of all vehicles designated for replacement, results in a final replacement list. Each replacement must be discussed and agreement reached with the local equipment supervisor.

The vehicles on the computed list can be substituted with others, but the number of replacement vehicles in each district is not changed. By comparing the computed list with the final list resulting from a physical inspection, the accuracy of computation can be determined. At present, the changes amount to 10 to 15 percent, which is considered satisfactory. It is expected that with improved data collection, greater accuracy will be achieved.

BUDGETING

In the method developed, the computer is required to perform one more task—the preparation of the budget estimates. The main difficulty in preparing budget estimates is the time factor, since the Government operates on a budget that is voted yearly. The

TABLE 6

SAMPLE PARAMETERS FOR THE MATHEMATICAL MODEL

Vehicle Description	Code	A_0	A_1	A_2	A_3
Station Wagons (south and north)	001	1811	-540	-237	0.00121
½ Ton Express (south and north)	003	850	564	-128	0.00128
2 Ton Express (south and north)	02X	2593	-828	-454	0.00256
3 Ton Dump Trucks (south)	031	3154	-592	-420	0.00139
3 Ton Dump Trucks (north)		2865	-761	-298	0.00127
5 Ton Dump Trucks (south and north)	05X	3368	-479	-179	0.00091
6 Ton Dump Trucks (south and north)	06X	4826	153	-354	0.00196

fiscal year is from April 1 until March 31 of the following year. The equipment section must prepare the budget estimates for the next year in June and July. At that time the last data available are as of March 31. The estimate is an anticipated amount that is hoped will be allocated to the section the following April, to fulfill commitments in the ensuing summer. In other words, it is necessary to look more than one year ahead. This is done by theoretically aging the vehicles one year and then computing the replacement list.

The procedure is as follows: All vehicles that are to be replaced this year are selected from the March data. At this stage, the expected mileage and repair costs are added to each vehicle. Then the position of each vehicle is compared with the mathematical model of its group. As a result, the number of vehicles to be replaced in each group is known, and the amount that will be lost by not replacing the vehicle is also realized. The amount required to purchase the new vehicle is also shown.

The list will be headed with a vehicle that will cost the department, say, 600 dollars if not replaced. The last vehicle in the list will be that showing a one dollar loss. Since it is unpractical to replace a vehicle in order to save one dollar, a limit must be established. The limit is not fixed but it must be above 100 dollars. In other words, a vehicle is not replaced if the predicted loss does not exceed 100 dollars. With regard to the accuracy of this procedure and the verification of results, it is pointed out that for the budget estimate, only the number of vehicles to be replaced is important—the identity of the trucks is of little consequence. The computation will produce a list of vehicles by numbers. The chance is that even a deviation in identification may produce a relatively accurate list as to the number of vehicles.

The last process in the computation, applicable both in producing replacement lists and budget estimates, is the total replacement list. The objective is to produce one

TABLE 7

ESTIMATED MONEY LOSSES

Vehicle Type	Purchase Price ($)	Estimated Loss ($)
Grader No. 111	20,000	500
Truck No. 121	10,000	350
Truck No. 122	10,000	300
Small Truck No. 131	3,000	200

TABLE 8

PRIORITY LIST

Vehicle Type	Purchase Price ($)	Estimated Loss ($)	Ratio	Priority
Truck No. 131	3,000	200	$\frac{200}{3000} = 0.066$	1
Truck No. 121	10,000	350	$\frac{350}{1000} = 0.035$	2
Truck No. 122	10,000	300	$\frac{300}{1000} = 0.030$	3
Grader No. 111	20,000	500	$\frac{500}{2000} = 0.025$	4

list which includes all types of equipment. When the budget allocation is smaller than the estimate (which is often the case) it must then be decided how to proportion the money between different types of equipment—is it more economical to spend 20,000 dollars to purchase a grader, six station wagons, or so many 3-ton trucks?

The total replacement list solves this problem, by including all types of equipment on one priority list. The first on the list may be a grader, the second a station wagon, followed by two 3-ton trucks, etc. This list is produced by estimating the amount of money that will be lost by not replacing a unit and proportioning the amount to the capital expenditures (Table 7). It is apparent from Table 7 that it would be more economical to purchase two trucks for a total of 20,000 dollars and thereby save 650 dollars, than to purchase one grader for the same amount and save only 500 dollars. The priority list is based on a decreasing purchase-price-to-loss ratio (Table 8).

For convenience, the running total of purchase prices is included on the list. Now the procedure is simple: if for example, 100,000 dollars is available, the replacements will include all units from the top of the list down to the unit opposite which the running total of purchase prices equals 100,000 dollars. If 200,000 dollars, all units down to the running total of 200,000 dollars will be replaced. Since the optimum number of units that should be replaced is known, the difference between the number replaced and the optimum number results in a money loss which can be determined by summing up the excess cost of operation of all units that should have been replaced, but were not.

As may be noted, the priority for any particular vehicle relative to others of the same type may differ in the budget list as compared with the replacement priority list, because in the budget list, money loss, based on group characteristics, is used as a basis, whereas in the replacement list individual characteristics modify the group predicted money loss in forming a relative rating. Since the budget deals with the group as a whole, the use of group characteristics for prediction is valid. The replacement priority list attempts to deal with the individual case. Therefore, a refinement of the group information, geared to the individual, attains greater accuracy and at the same time yields a different order in the list.

The replacement list is used in November, utilizing data accumulated to the end of September. The information is current, which accounts for the accuracy of the results.

This is not the case with the budget estimates. The necessity of projecting ahead for more than a year makes the computation less reliable. At present, the result of budget estimate computations is checked by other methods, such as comparing with past experience, average age of vehicles in each group, depreciation and depreciation ratio.

The department is developing a new method which, if successful, will provide a more accurate check on the replacement policy. This will be known as the fleet condition factor (FCF). The condition of each vehicle will be determined by a number. For example, No. 100 will indicate a new unit, No. 0 a fully depleted unit and No. 50 a unit 50 percent depleted. The number will be a function of age and mileage, and will not be identical with the depreciation. The average FCF will reflect the condition of the whole fleet. By comparing the FCF at the beginning and the end of a fiscal year an assessment of the adequacy of replacement can be made; e.g, if the FCF in 1965 equaled 51 and in 1966 was 49, this would indicate that the replacement made was not sufficient to maintain the overall fleet condition level.

It is expected that an optimum condition level for each group of vehicles in the fleet can be determined. Apart from major changes in the composition of the fleet, this method will allow determination of budget requirements for the next year by comparing with the last year's achievements.

As of today, this method is in the development stage, and has not yet been used.

ACKNOWLEDGMENTS

This study was initiated by C. G. Saunders in 1955; it was subsequently developed and applied by the staff of the Equipment Section of the Department of Highways, Ontario. The formulation and calibration of the mathematical models was carried out by the scientific programming staff of the Electronic Computing Branch, under the Director, A. E. Goodwin, who played an active role in the study. The help of W. G. Cooke, Superintendent of Equipment is also acknowledged.

Economic Model for the Maintenance of Traffic Signals

THOROLD G. SMITH and J. C. OPPENLANDER, Joint Highway Research Project, Purdue University

The purpose of this investigation was to develop a comprehensive traffic signal and flasher maintenance program, using systems analysis techniques, that was both economical and practical for the Crawfordsville maintenance district in Indiana. All phases of the corrective and preventive maintenance operations were analyzed to determine the optimal maintenance program. The optimum lamp replacement program, involving the determination of the proper time duration for the most economic group lamp replacements, was obtained for actual conditions. The shortest routes for preventive operations were ascertained for several maintenance alternatives, and the most economic option was revealed. In addition, the staff necessary for effective maintenance of traffic signals and flashers was specified for this state highway district.

Preventive maintenance is advisable for traffic signals and flashers because it affords economic advantages and reduces the probability of failure, thereby improving traffic safety. The procedures developed in this analysis can be applied to any maintenance organization that has responsibility for traffic signals and flashers.

•A major responsibility of highway engineers is to provide for the public a highway system capable of accommodating vehicle and pedestrian travel in a safe, efficient, and economic manner. In developing this highway system, the engineer is responsible for the planning, design, construction, operation, and maintenance of that system.

In many instances the maintenance function is relegated to a minor position. Limitations in the available resources, coupled with the expansion of the planning, design, and construction operations to keep pace with the increasing traffic demands, have resulted in a situation where funds and efforts, which are necessary for the maintenance of existing facilities, have been diverted to other tasks. In addition, past experiences indicate some difficulty in interesting engineers in the area of maintenance operations. The result is a shortage of qualified men and other resources in a field on which the continued operation of the highway system is predicated.

In the past, maintenance engineers have used rule-of-thumb warrants, personal experience, or component analysis to determine the maintenance program that utilizes the expected budget allowances. Recent advances in the fields of systems analysis and computer technology have provided the engineer with the tools necessary to analyze various maintenance situations. A complete analysis of all related factors enables the maintenance engineer to optimize the use of available men, money, and equipment and to insure the proper and safe operation of the system.

The traffic engineer is concerned with a maintenance program applicable to traffic signals and flashers. Signal reliability is a necessity because failures create hazards to life and property and increase the maintenance costs by requiring men and equipment for emergency repairs. A preventive maintenance program reduces the number of traffic signal failures and insures the accurate operation of the controllers. However, the

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formulation of such a program is beyond the intuitive comprehension of any individual because of the numbers and locations of the traffic signals involved. Systems analysis techniques and high-speed electronic computers permit the formulation of a traffic signal and flasher maintenance program that relates each component to the total operation of the system.

The purpose of this investigation was to develop a comprehensive traffic signal and flasher maintenance program that was both economical and practical for a typical maintenance district in a state highway department. All phases of the emergency and preventive maintenance operations were analyzed to determine the best maintenance program. The optimum lamp replacement, involving the determination of the proper time intervals for scheduling group lamp replacements and the most economic lamp life, was ascertained. The shortest routes for preventive maintenance operations were determined for several maintenance alternatives, and by comparing the anticipated annual costs, the most economic option was revealed. The staff necessary for effective traffic signal and flasher operation was ascertained for the maintenance activities performed by state personnel (6).

A scientific maintenance program enables the traffic engineer to discharge his principal assignment of providing safe, efficient, and economic travel by insuring that the traffic signals and flashers are dependable and operating in accordance with the predetermined schedules. The investment in traffic control devices is protected by eliminating the deterioration of equipment and the resulting costly failures caused by a policy of neglect. In addition, traffic signals that are clean, well painted, and in proper working condition provide the traffic engineering profession with a medium for establishing good public acceptance.

REVIEW OF LITERATURE

The subject of maintenance appears frequently in industrial trade magazines but rather infrequently in traffic engineering literature. This literature review is confined to those articles which apply directly to the problems of traffic signal and flasher maintenance.

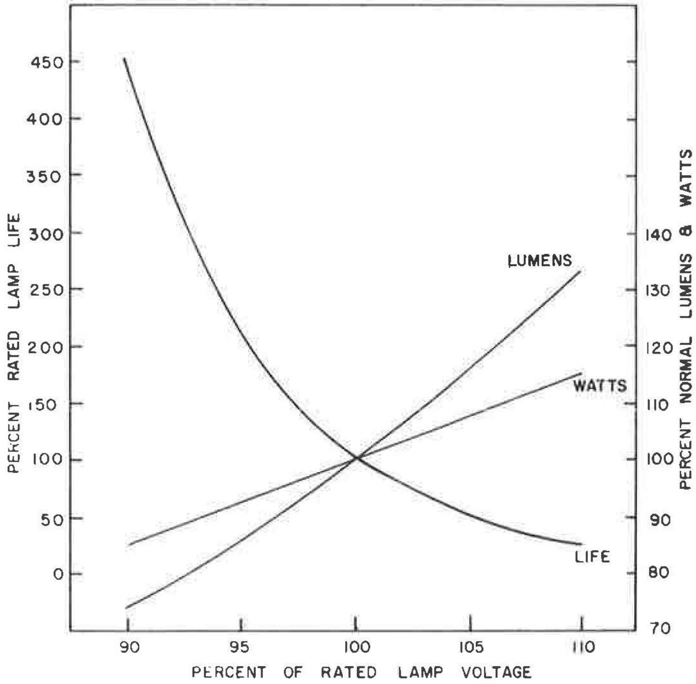
Several papers and reports have been written on the subject of traffic signal maintenance. These publications have generally been prepared as guides or suggestions in the formulation of routine maintenance programs.

A primary concern of most maintenance programs is determining the optimal period for the replacement of traffic signal lamps. The American Association of State Highway Officials (AASHO) recommends a regular lamp replacement schedule that is less than the rated (average) lamp life. The factors involved in the economic determination of scheduling group lamp replacements are the following:

1. Failure probabilities for lamps with different rated lives,
2. The effect on lamp life of the difference between the voltage at the lamp socket and the rated voltage for the lamp, and
3. The reduction of lamp life expectancy due to the vibrations in normal operation and lamp handling (4).

F. J. Meno concurs with the AASHO policy and reports that if the optical units (lenses, lamps, and reflectors) are regularly cleaned, it is possible to apply up to 5 v less than the rated lamp voltages without suffering poor visibility. This policy has the effect of lengthening the actual rated lamp life under field conditions (5). The relationship of voltage to lamp life, wattage, and lumens of outputs is illustrated in Figure 1 (3).

The controller is the next item to be considered in a comprehensive traffic signal maintenance program. Controllers must be periodically serviced to assure effective operation. AASHO stipulates that controllers shall be carefully cleaned and serviced at least as frequently as specified by the manufacturers and more frequently if experience proves it necessary (4). Each unit in the signal system including all master controllers should receive a yearly in-shop overhaul. This complete renovation includes cleaning, lubricating, and replacing all worn parts. The controllers are then tested to determine their reliability and operating characteristics (2). Controllers are most reliable when cleaned and checked for wear at least every six months (5).



LIGHTING MAINTENANCE MANUAL, Champion Lamp Works

Figure 1. Effect of voltage on incandescent lamp life, lumens and wattage.

To maintain the effectiveness of the traffic signal as a traffic control device, it is necessary to consider periodic cleaning of the lamps, reflectors, and lenses. Optical units that are not regularly cleaned have a 60 to 80 percent reduction in visibility over a period of years (5). In air that is relatively free from dust and corrosive industrial exhausts, the loss of light may be considered similar to the performance of closed street light fixtures. AASHO suggests that the optical units should be cleaned at least once every six months and that the lenses and reflectors should always be cleaned when the lamps are replaced, unless the last regular cleaning has been very recent (4).

The last phase in a comprehensive maintenance program is to schedule periodic painting of the traffic signal equipment at intersection locations. Painting is necessary to protect the traffic signal from rust and corrosion and to assure that the traffic signal appears clean and well maintained. All traffic signal appurtenances above the ground should be painted at least once every two years, and the painting should be more often if it is needed to prevent corrosion and to maintain a good appearance (4).

PROCEDURE

The traffic signal maintenance activities in a selected maintenance district were observed to determine the time patterns of maintenance characteristics. Maintenance of traffic signals was formulated into a system of related components to permit the development of an optimum traffic signal maintenance program in the study district. Statistical estimations and various statistical tests were used to appraise the findings and to develop the necessary relationships.

Site Selection

The Crawfordsville maintenance district in Indiana was selected for this problem of scheduling traffic signal maintenance. This maintenance district contains the three principal urban centers of Terre Haute, Lafayette, and West Lafayette. The remainder

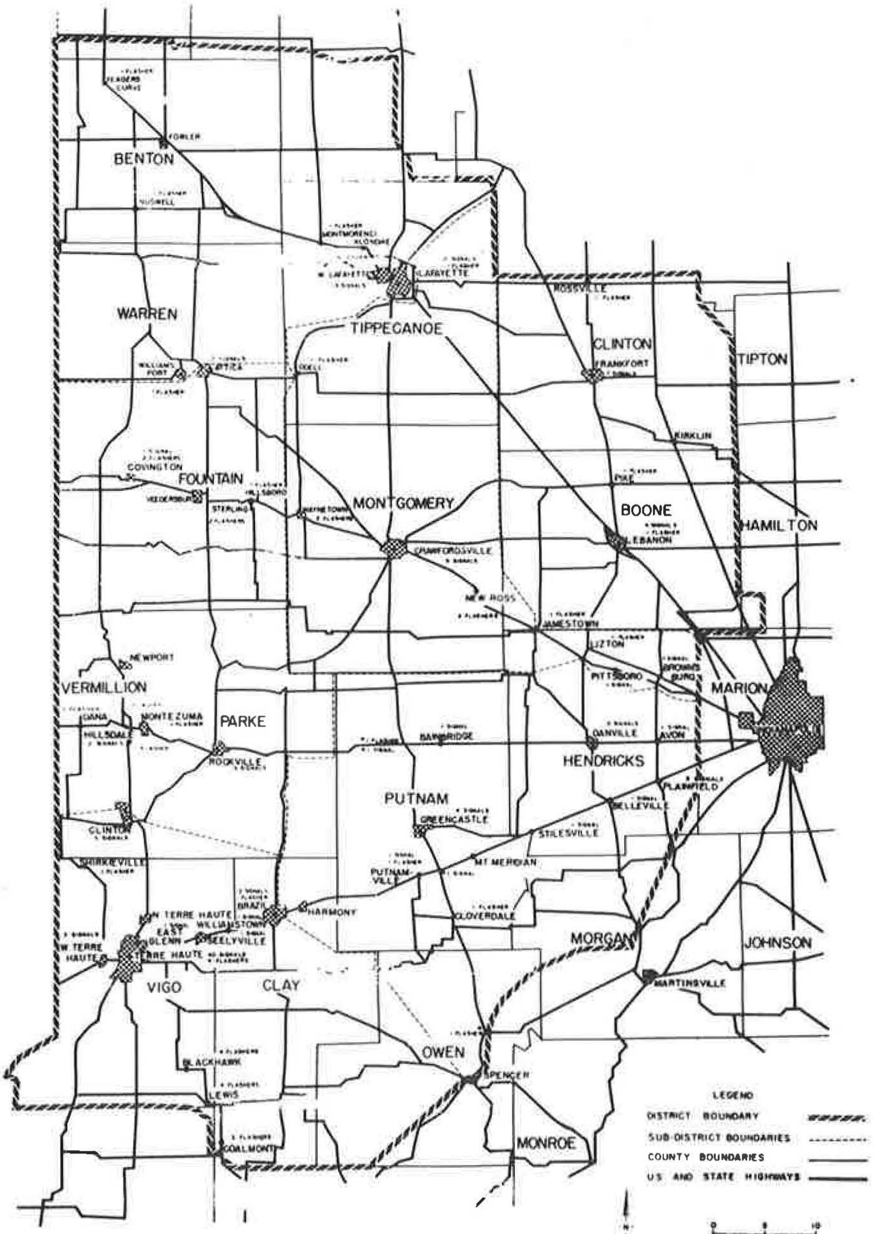


Figure 2. Traffic signal locations—Crawfordsville maintenance district.

of this district is predominantly rural with a number of small cities and towns. Both preventive and emergency maintenance activities are performed in the three major cities by contractors, except in West Lafayette where state forces are responsible for the preventive maintenance.

The distribution of traffic control devices in this maintenance district is presented in the following outline and is shown in Figure 2.

1. Lafayette—21 signals and 1 flasher;
2. Terre Haute—40 signals and 4 flashers;

3. West Lafayette—13 signals;
4. Remainder of the district—56 signals and 42 flashers.

Data Collection

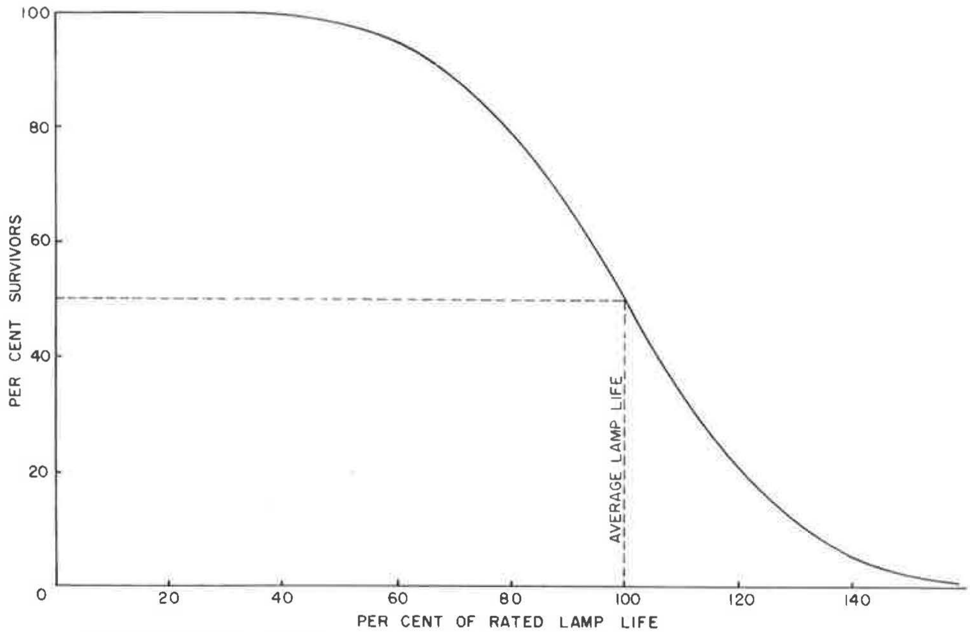
Because little information was available on the maintenance of traffic signals, data were collected on the personnel and equipment used, the distance traveled, the work performed, the type and number of parts replaced, and the time required for the daily maintenance of traffic signals in the Crawfordsville district. These data were analyzed to give estimates of the observed maintenance conditions. Models approximating the actual maintenance were formulated, and the optimum traffic signal maintenance program was determined by using these mathematical representations.

Lamp Replacement

Two steps were involved in building a model that predicts the optimal lamp replacement time. A probabilistic expression was first developed to approximate the expected traffic signal lamp operation. Several assumptions were made to formulate this expression. All traffic signal lamps, regardless of the rated life, have the same type of failure curve; therefore, lamp mortality curves that are based on percentage of rated life can be used for all traffic signal lamps (6).

The actual life of a lamp used in the field was assumed to have a service life that is 10 percent less than the rated life. These ratings are based on lamp tests conducted under ideal laboratory conditions, which vary considerably from those experienced in the field. Power surges and vibrations caused by handling, wind, and traffic are the principal causes of the differential between the rated lamp life and the actual life. To account for this variation, the rated lamp life is often reduced by 20 percent if the field conditions are very severe and by 10 percent if these conditions are normal (6).

The mortality curve, as developed by the General Electric Company (Fig. 3) was assumed to be normally distributed with a mean of 100 percent for the rated life and with a standard deviation of 25 percent. A χ^2 test was used to determine if this curve



CORRESPONDENCE, GENERAL ELECTRIC COMPANY MARCH 25, 1965

Figure 3. Estimated mortality curve (based on total average product).

followed a normal distribution. The results of this test produced a calculated χ^2 of 0.0043. This value is not significant at the 5 percent level with 27 degrees of freedom. Therefore, the mortality curve of traffic signal lamps was considered as a normal distribution in the rest of this investigation. In addition to the assumption of normality, the life of a lamp was assumed to be independent from that of other lamps.

With these assumptions the following model was developed:

Notations:

X = cost per replacement cycle per lamp;
X_t = cost per hour of operation per lamp;
t = lamp replacement period, in hours;
c = cost of replacing a lamp in group replacement;
k = cost of replacing a lamp at failure;
T_i = lamp life in hours of ith lamp when $T \cap N\ (100,\ 25)$ and the lamp lives are independent;
$A_n = T_1 + T_2 + \dots + T_n < t$;
$B_n = T_1 + T_2 + \dots + T_n + T_{n+1} > t$; and
$B'_n = T_1 + T_2 + \dots + T_n + T_{n+1} < t$.

Postulate:

In all cases the occurrence of event B'_n is predicated on the occurrence of event A_n, or B'_n is included in A_n.

Corollary:

$$P(A_nB_n) = P(A_n) - P(B'_n)$$

Derivation:

$$X = c \text{ if } T_1 < t$$
$$X = c + K \text{ if } T_1 < t < T_1 + T_2$$
$$\vdots$$
$$X = c + nk \text{ if } A_n \text{ and } B_n \text{ occur}$$

$$X = cP(T_1 > t) + \sum_{i=1}^{n} (c + ik)\ P(A_iB_i)$$

$$X = cP(T_1 > t) + \sum_{i=1}^{n} (c + ik) \Big(P(A_i) - P(B'_i)\Big)$$

$$X = cP(T_i > t) + c \sum_{i=1}^{n} \Big(P(A_i) - P(B'_i)\Big) + \sum_{i=1}^{n} ik \Big(P(A_i) - P(B'_i)\Big)$$

$$c = cP(T_1 > t) + c \sum_{i=1}^{n} \Big(P(A_i) - P(B'_i)\Big)$$

$$X = c + \sum_{i=1}^{n} ik \Big(P(A_i) - P(B'_i)\Big)$$

Computational Form:

$$
\begin{aligned}
X_t = \frac{c}{t} + \frac{1}{t}\ \{ & k\,[P(T_1 < t) - P(T_1 + T_2 < t)] \\
& + 2k\,[P(T_1 + T_2 < t) - P(T_1 + T_2 + T_3 < t)] \\
& + \ldots + nk\,[P(T_1 + T_2 + \ldots + T_n < t) \\
& - P(T_1 + T_2 \ldots + T_n + T_{n+1} < t)]\}
\end{aligned}
$$

The above replacement model determines the hourly cost for a single lamp. The use of elementary probability indicates that the cost per hour for n lamps is equal to the expression, nX_t.

The second step in the formulation of the replacement model is to determine the group and the failure replacement costs. The cost of traffic signal lamps is an important consideration in calculating the replacement costs. Lamps in the 60 to 69 w range with rated lives of 2000 to 8000 hr are of primary interest to maintenance personnel in the Crawfordsville district. The prices of these lamps vary linearly with the rated lamp life as shown by the function:

$$Y = 0.0010X + 28.50$$

where Y = cost per lamp in cents and X = rated lamp life in hours.

Governmental agencies are given a discount of about 50 percent when large quantities of traffic signal lamps are purchased. As a result of this discount, the function estimating the lamp cost for the State of Indiana can be expressed as the following relation.

$$Y = 0.0005X + 14.25$$

The cost of replacing a lamp in a group replacement program was then determined. In the Crawfordsville district 1896 lamps are presently maintained by state personnel. The total time required to change lamps on a group replacement program, including travel time, is 130 hr. The development of this group replacement program is presented in the section on "Results." The cost of replacing a lamp in a group replacement program for the district is given in Table 1.

The cost of changing a lamp at failure is the next step in preparing information for the lamp replacement model. The mean distance of the lamps from the district maintenance office was calculated. In determining the average distances for the Crawfordsville district, the lamps were classified by their uses. From Crawfordsville, the average distance is 36.26 miles for the lamps used in flashers, and the mean distance of the lamps in traffic signals is 30.66 miles. A weighted mean of 31.20 miles was calculated by pooling all lamps used to estimate the average distance of lamps from maintenance headquarters.

TABLE 1

LAMP REPLACEMENT COSTS

Group Replacement Costs	
Cost of labor (2 men at \$2.45 per hour) × 130 hr	\$ 637.00
Cost of equipment (1 truck at \$5.00 per hour) × 130 hr	650.00
Cost of lamps (current price) (\$0.16 per lamp) × 1896 lamps	303.36
Total cost of group replacement	\$1,590.36
Total cost of group replacement per lamp	\$ 0.84
Failure Replacement Costs	
Cost of labor (2 men at \$2.45 per hour) × 1.84 hr	\$ 9.02
Cost of equipment (1 truck at \$5.00 per hour) × 1.84 hr	9.20
Cost of lamp (current price) \$0.16 per lamp	0.16
Total cost of changing a lamp at failure	\$ 18.38

An estimation of the travel time is required to determine the costs for lamp replacement at failure. The relationship expressing the distance traveled in minutes is

$$Y_C = 1.437X + 7.775$$

where Y_C = travel time in minutes, and X = distance traveled in miles.

For a mean travel distance of 31.20 miles the one-way travel time is 52.7 min, and the total two-way travel is 105 min. The expected time required to change a single lamp at failure was found to be 5 min. Therefore, the total time spent changing a lamp that has failed is 110 min or 1.84 hr. The cost of replacing a lamp failure is given in Table 1.

To complete the preparation of information for the lamp replacement model, realistic estimations were needed for the number of hours that lamps burn under field conditions. The annual burning times for traffic signal lamps in various uses are summarized in Table 2. These time estimates are based on above average conditions of usage for traffic signals and flashers located in the Crawfordsville maintenance district.

TABLE 2

LAMP BURNING TIME ESTIMATES FOR VARIOUS TRAFFIC SIGNAL AND FLASHER USES

Lamp Use	Percent of Time	Hour per Year
Flasher	58	5080
Traffic signal:		
Red	50	4380
Green	42	3680
Amber	8	700

Optimal Route Sequencing for Preventive Maintenance

The optimal sequencing of preventive maintenance is determined by a model that simulates the activities of the maintenance crews. This technique is predicated on realistic estimations of various factors that describe the work patterns of the maintenance personnel.

The maintenance model is composed of several principal parts. The first section estimates the time required to perform the various maintenance functions. As evidenced from the field observations, a primary preventive maintenance operation includes changing the signal lamps, cleaning the lenses and reflectors, and cleaning and oiling the controller. The expected work time for this preventive maintenance on a traffic signal installation is 40 min with a standard deviation of 24 min. For a flasher installation, this maintenance is expected to take an average of 13 min with a standard deviation of 9 min.

Another operation is painting the traffic control installation. The average work time for painting a traffic signal installation is 133 min with a standard deviation of 40 min. Painting a flasher complex takes an average of 37 min with a standard deviation of 13 min.

Data were not available for the combined tasks of signal head and controller maintenance and of painting the traffic control installation. The expected work times were determined by assuming that the controller and signal head maintenance and the painting operation are independent. Therefore, the expected work time for the traffic signals becomes 173 min with a standard deviation of 47 min. For the flashers, the average work time is 50 min with a standard deviation of 13 min.

Because 50 percent of the maintenance operations require more than the average work time, the 85th percentile work time was considered satisfactory for scheduling the maintenance operations. The estimated work times that were used for signal head and controller maintenance are 65 min for traffic signals and 23 min for flashers. For painting, the estimated work time is 175 min, and the corresponding value for flashers is 50 min. When the controller and signal head maintenance is combined with the painting operation, the expected work times are 220 and 64 min, respectively, for traffic signal and flasher installations.

The second section of the maintenance model estimates the travel times. The relationship of travel distance and travel time was determined for trips of various purposes. All travel resulting from the failure of a traffic signal to operate properly was considered an emergency trip. A regression analysis was performed on the data for emergency trips, and the following relationship was established:

$$Y_E = 1.352X + 7.836$$

where Y_E = travel time in minutes, and X = distance traveled in miles. This regression equation (Fig. 4) has a coefficient of determination of 0.78.

All regular maintenance trips were classified as routine. The least-squares fit for the routine trip data resulted in the following linear equation:

$$Y_R = 1.485X + 8.542$$

where Y_R = travel time in minutes, and X = distance traveled in miles. The coefficient of determination for the routine trip analysis is 0.83, and the relationship is shown in Figure 4.

The curves for the emergency and routine trips were found to be similar. Therefore, the data for these trips were pooled to determine a better estimate of the travel characteristics. Regression analysis of the routine and emergency data produced the following expression:

$$Y_C = 1.437X + 7.775$$

where Y_C = travel time in minutes, and X = distance traveled in miles. The combined expression is shown in Figure 4, and the coefficient of correlation is 0.90. This resultant linear equation was used to determine the emergency and routine travel times in the rest of the investigation.

The return-home trip is another travel classification. This trip originates at the last location of work and terminates at the maintenance shops. The regression expression for the return-home trip is

$$Y_{RH} = 0.802X + 36.810$$

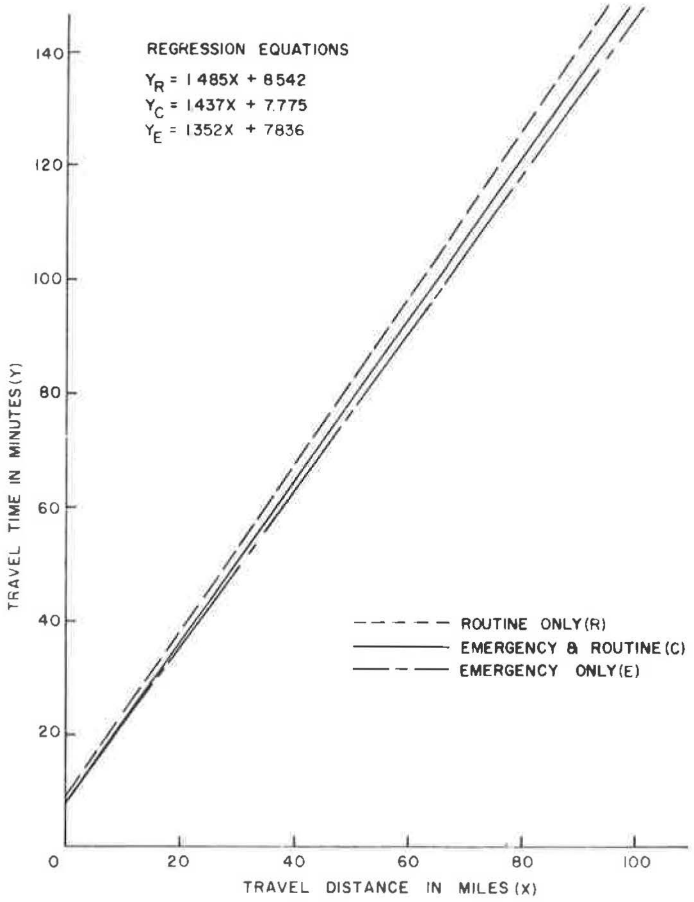


Figure 4. Regression lines for estimation of travel times for various trip purposes.

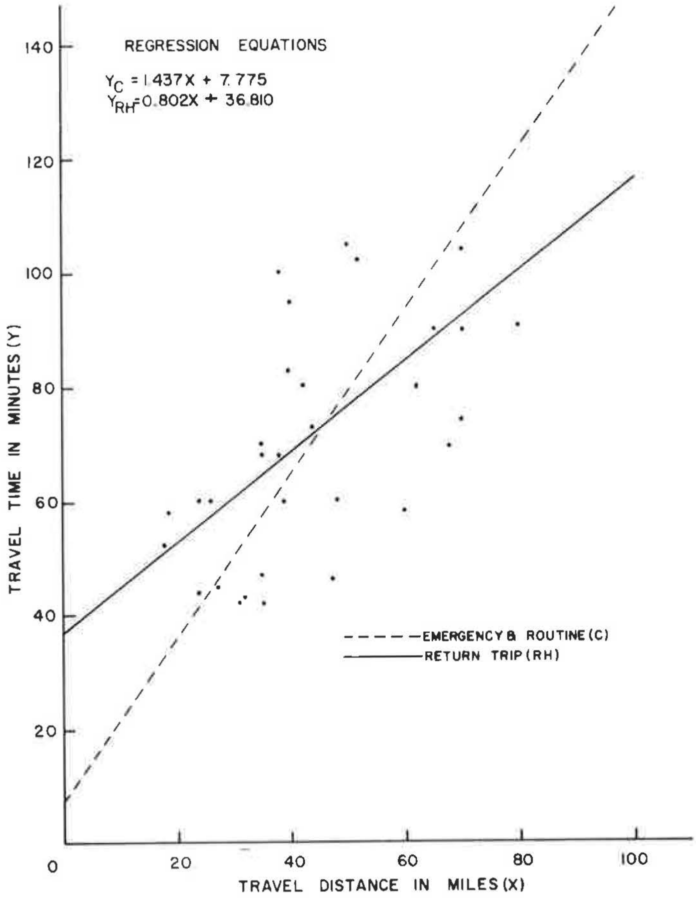


Figure 5. Regression line for the estimation of travel time for the return-home trip.

where Y_{RH} = travel time in minutes, and X = distance traveled in miles. The linear equation for the return-home trip is shown in Figure 5 and has a correlation coefficient of 0.58.

Because high travel times for short distances and low travel times for long distances were reported in the sample of return-home trips, this expression was not considered valid for inclusion in the development of a scientific maintenance program. A return-home trip equation, which assigns time for travel commensurate with the distance traveled, was desired to permit more efficient use of the time available for signal and flasher maintenance. Therefore, the best available estimate of travel time is the expression determined for the pooled emergency and routine trip data. This relationship is shown by the dashed line in Figure 5. Reasonable agreement is evident with the data collected on travel times and distances for the return-home travel.

The third phase of the maintenance model involves the selection of the minimum path for a proposed routine maintenance schedule. Preparation of information for the minimum path algorithm is predicated on several conditions. The locations of all traffic signals and flashers within the study area must be known. These locations were identified, and those signals clustered in a city or town were grouped to form a node (signal node) with signals and flashers. This grouping was performed because the signals in a community are so close that any attempt to find an optimal routing within the city would produce only marginal benefits. The order of maintaining the signals within a town is left to the discretion of the work crew. However, the number of signals maintained in a day

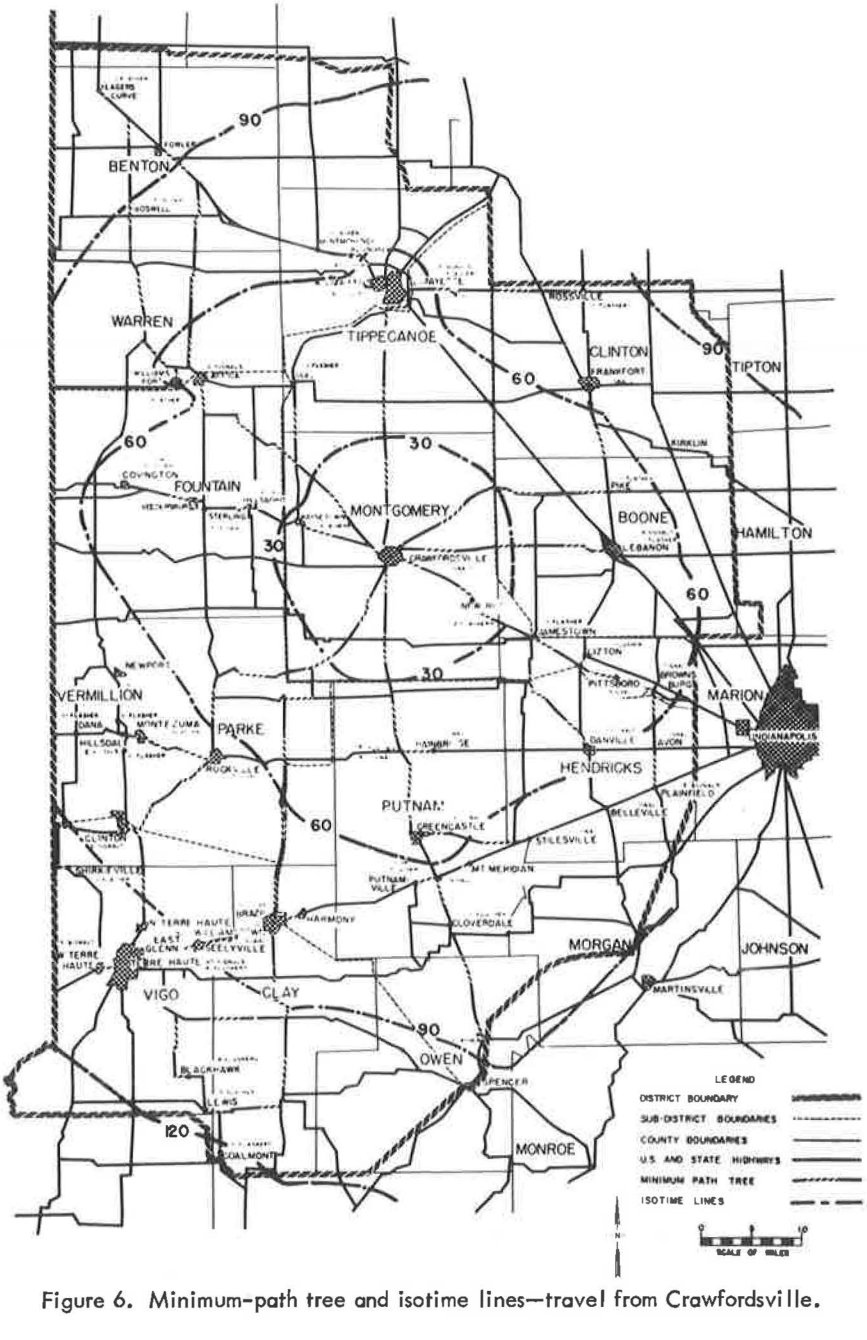


Figure 6. Minimum-path tree and isotime lines—travel from Crawfordsville.

is specified to permit the maximum utilization of the working day. The isolated traffic signal and flasher locations were considered as signal nodes with either one traffic signal or one flasher.

The output of the minimum-path analysis was divided in two parts. A series of minimum-path trees from each signal node to every other node in the district was first obtained. These trees were used to determine the shortest routes among signal nodes. Isotime lines were computed from these trees to provide time estimates from nodes of interest. The minimum-path tree and isotime lines emanating from Crawfordsville are shown in Figure 6.

The second part of the output was a matrix of the shortest distances to and from all signal nodes. A traveling salesman algorithm, using the matrix of shortest distances, considered each proposed maintenance tour and determined the best routing sequence for the two signal maintenance programs that were investigated in this operational study. The first program schedules signal head and controller maintenance at 6-month intervals with painting planned as a separate operation on a 2-year schedule. The second alternative schedules signal head and controller maintenance three times in a 2-year period, and a fourth routine maintenance cycle in this 2-year period combines painting with signal head and controller maintenance.

Several trial solutions were made for the alternate signal maintenance programs. All possible combinations of signals and flashers were not tested because of the large number of required calculations. Although optimality is not guaranteed for the maintenance alternatives, the results of this testing procedure approach optimal solutions because the minimum-path tree and isotime lines emanating from Crawfordsville were used to guide the selection of signal node groups. The groups of signal nodes, called daily tours, constituted the numbers and locations of traffic signals and flashers that are maintained in a single day for a proposed maintenance schedule. A complete maintenance schedule is composed of all daily tours.

After the analysis of the daily tours was completed, the proposed solutions were altered to optimize more fully the available working time. This process was continued until the feasible solution could no longer be improved. The best solution for each maintenance alternative was selected using the following criteria:

1. The work was completed in the minimum number of days,
2. The distance traveled was a minimum, and
3. Maintenance was scheduled to utilize the available time in a work day.

Then, the total cost for each alternative was determined and compared on an annual-cost basis.

Staffing

A vital part of a comprehensive signal maintenance program involves the determination of the staff necessary to insure proper signal operation. The optimal lamp replacement periods and the maintenance sequencing can be determined, but if there is an insufficient maintenance staff, the proposed maintenance program is not utilized to its fullest advantage.

The staffing was determined for those locations within the Crawfordsville maintenance district which are maintained by state personnel. Lafayette, Terre Haute, and West Lafayette were not included because the signal maintenance is performed in these cities by contractors. If the maintenance responsibilities are delimited in this manner, it is reasonable to assume that the traffic signals and flashers are uniformly distributed throughout that portion of the maintenance district being considered. The average distances of signal installations from Crawfordsville were used to estimate the travel distances for the emergency operations. The mean distance from Crawfordsville for traffic signals is 30.66 miles, and the average distance is 36.26 miles for flashers.

The average times required for travel to the site of a failure were computed from the derived formula as 52.7 min for traffic signals and 60.1 min for flashers. Two-way travel times were used in this investigation for two reasons: (a) the travel to and from the failure site is part of the total time required for the emergency maintenance operation; (b) when two failures are corrected without returning to Crawfordsville between the operations, the total travel time is approximated by two round trips. Therefore, the round-trip travel times assigned for the traffic signal and flasher repair operations are 105.4 and 120.2 min, respectively.

The total field times required to perform the repair operations are necessary in analyzing the staffing problem. The work times for repairing the traffic signals and flashers are 48.3 and 23.2 min, respectively, and the total field times for the repair operations are 154 min for traffic signals and 143 min for flashers. In addition, the average field time for changing a lamp that has failed was previously calculated as 110 min.

TABLE 3

PROBABILITY OF THE NUMBER OF EXPECTED FAILURES PER DAY FOR VARIOUS MALFUNCTIONS

Failure	Probability of the Number of Expected Failures per Day				
	0	1	2	3	4
Traffic signal	0. 698	0. 251	0. 045	0. 006	–
Flasher	0. 834	0. 122	0. 044	–	–
Lamps	0. 964	0. 036	–	–	–
Traffic signals, flashers and lamps	0. 559	0. 302	0. 114	0. 023	0. 002
Traffic signals and lamps	0. 673	0. 267	0. 052	0. 008	–

The daily rate of traffic signal failures for the maintenance district was determined to be approximated by a Poisson distribution with a mean of 0.0063 failures per day per signal. The 57 signals considered in the staffing problem have a failure rate of 0.359 failures per day. The expected daily traffic signal failure probabilities are given in Table 3.

An inconsistency was observed in determining the failure pattern for flashers. All flasher failures were observed in the period starting July 1 and ending October 1. Because an estimate pertaining to the number of flasher failures is necessary for determining the number of days not available for preventive maintenance, it was deemed satisfactory in this study to use the observed pattern of failures for a 90-day period and to assume that there would be no failures during the remaining 275 days of the year. The flasher failure probabilities observed for this time interval are also given in Table 3.

The probability of a lamp failure was computed by analyzing the data for existing conditions. The 17 lamp failures were observed to be dispersed randomly throughout the year. The resulting failure pattern distribution is given in Table 3.

The summation of traffic signal, flasher, and lamp failure probabilities was determined by estimating the probabilities of every possible combination of failure. In a similar manner, the failure probabilities were obtained for the situation when only traffic signal and lamp failures are expected (Table 3).

A weighted mean which represents the daily average repair time was determined by using the failure probabilities and the expected field repair times of 154 min for traffic signals, 143 min for flashers, and 110 min for lamps. The results of these calculations are as follows:

Failure	Daily Average Repair Times
Traffic signals, flashers and signal lamps	85.9 min
Traffic signals and signal lamps	58.8 min

The staff required to correct the expected signal failures could be determined by an economic analysis if a failure penalty were determined. However, no penalty was assessed because of the difficulty in assigning realistic costs for accidents and delays caused by signal failures. The staff required to satisfactorily perform the necessary maintenance operations was determined by considering the following factors:

1. The failure probabilities (Table 3),
2. The average daily repair times,
3. The anticipated time required to perform the preventive maintenance operations, and
4. The suitability of certain seasons for preventive maintenance operations.

The total time available for the preventive maintenance operations was calculated, and a decision was made concerning the staff required to perform the maintenance operations in the time allocated.

RESULTS

All phases of the emergency and preventive maintenance operations for the Crawfordsville district were analyzed to determine the optimal maintenance program. The optimum lamp replacement program, involving the determination of the proper time intervals for scheduling group lamp replacement and the most economic lamp life, was ascertained from the results of the lamp replacement model. The shortest routes for preventive maintenance operations were determined for several maintenance alternatives, and by comparing the anticipated annual costs, the most economic option was revealed. The staff necessary for effective traffic signal and flasher operation was obtained for those installations maintained by state personnel.

Lamp Replacement

The lamp replacement model was designed to produce results applicable to both the general lamp replacement problem and the conditions observed for the Crawfordsville maintenance district. The optimal lamp replacement periods were determined for various ratios of replacement costs (group replacement versus replacement at failure). The optimal lamp replacement times were analyzed by regression methods to determine a curve that estimates the observed conditions. The optimum lamp replacement intervals were best predicted by the significant terms in the following relationship:

$$Y = 32.82 + 1.54X - 0.31 \times 10^{-1}X^2 + 0.31 \times 10^{-3}X^3 - 0.11 \times 10^{-5}X^4$$

where Y = the ratio of optimum replacement time to rated lamp life × 100, and X = the ratio of group replacement cost to replacement cost at failure × 100. This regression curve (Fig. 7) was fitted to the observed data with a standard error of estimate equal to 1.10 percent.

The relationship expressing the optimum replacement period as a function of the ratio of replacement costs can be used to determine the best group replacement time for lamps used in traffic signals and flashers. The general usage of this function is restrained by the manner in which the lamp failures are corrected. The assumption concerning lamp failures used in this analysis is that lamps are immediately replaced upon failure.

Annual cost calculations were performed for various rated lamp lives using the replacement model. The lamps with longer rated lives have lower annual maintenance costs than those with shorter rated lives. The following example demonstrates the validity of the observed results concerning annual maintenance costs:

1. Compare two lamps where lamp A has twice the rated life of lamp B.
2. Change all lamps at 50 percent of the rated lamp life.

If the costs per replacement cycle for lamps A and B are

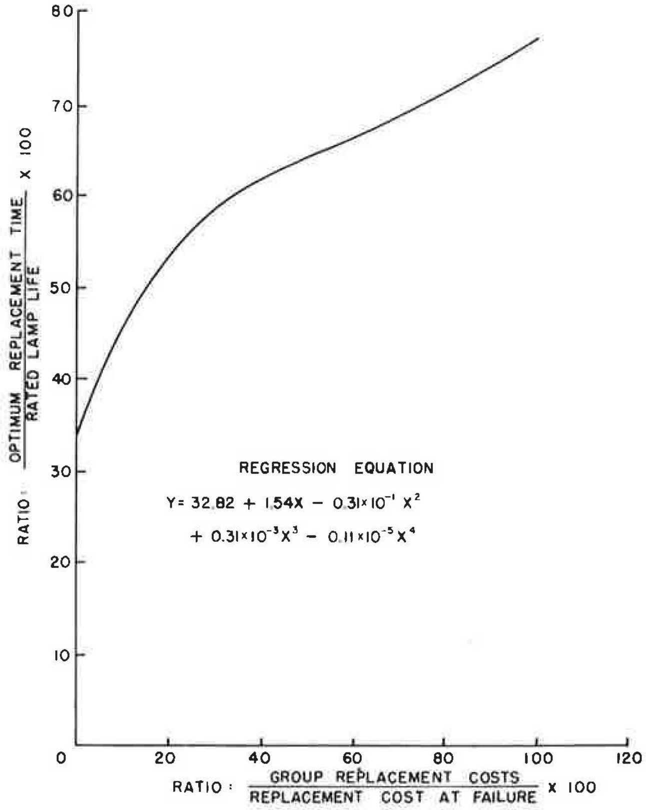


Figure 7. Regression line for estimating the optimum lamp replacement time.

equal, a valid comparison of the maintenance costs is obtained by prorating these costs for each lamp type over a given unit of time. Therefore, the maintenance costs using lamp B are twice those of lamp A, because bulb B requires two maintenance cycles for every cycle of bulb A.

If the maintenance policy is set at a fixed replacement interval, the results are similar to those noted in the previous case. For this situation, the group replacement costs are equal for lamps A and B because the same number of replacements are scheduled for each time interval. The difference in maintenance costs originates from the number of expected lamp failures for these two types of bulbs. Fewer bulb failures develop for the longer rated life than for the shorter lamp life. Therefore, the total costs of the maintenance cycles are less when lamps of longer rated lives are used, but lamps with shorter rated lives are more economically employed when the anticipated burning times are very short. This finding is based on the fact that the anticipated savings in lamp failure costs resulting from using longer life lamps are not completely offset by increased purchase prices of these bulbs.

The analysis of the maintenance conditions was performed for several lamp replacement alternatives. Two rated lamp lives of 6000 and 8000 hr were considered in this investigation. The 8000-hr lamp was studied because it has the longest rated lamp life that concurred with the voltage and wattage requirements of the study district. The 6000-hr lamp was included in the analysis because the 8000-hr lamp is not acceptable by AASHO standards. The lamp in question was rated at 575 lumens, and AASHO indicates that 665 lumens are necessary for 8000-hr bulbs (1).

These lamps were applied to several group replacement programs. The first lamp replacement alternative closely approximates replacing the individual lamps used in traffic signals (red, green, and amber) and flashers at the optimum intervals determined by Figure 7. Analysis of this replacement option necessitated the reappraisal of the group replacement costs which were established in the procedure for estimating the total cost of replacing all lamps in the same preventive maintenance cycle. Certain elements of the group replacement program, which includes travel time and controller maintenance, are performed regardless of the number of lamps replaced at a signal location. Because the optimal replacement period for lamps used in flashers and in the red position of traffic signals was approximately the same, the total travel time for the best routing sequence was used for every maintenance cycle. However, the computations were performed by distributing the total travel time in proportion to the number of traffic signals and flashers in the study district.

The times for changing lamps and for controller maintenance were allocated in a manner consistent with the anticipated work for each maintenance cycle. The maintenance time for flashers was unchanged because the complete maintenance operation was performed for each scheduled cycle. The traffic signals required allocations of maintenance times because all lamps are not scheduled for replacement in each preventive cycle. Controller maintenance was allotted as 55 percent of the work time, and 15 percent was apportioned to each lamp use changed (red, green, and amber). The work times required for each traffic signal operation were computed by adding the controller maintenance times to the total for the lamp uses replaced.

The total costs for the preventive maintenance operation were calculated by adding the proper travel times to the anticipated work times, and this sum was multiplied by the hourly cost of men and equipment ($9.90 per hour) for maintenance performed by state personnel. These computations are tabulated as follows:

Use		No. of Lamps	Group Replacement Cost ($)	Cost per Lamp ($)	Percent Rated Life
Flashers		170	404.00	2.38	48
Traffic signals:	One lamp	513	567.25	1.10	42
	Two lamps	1,026	822.50	0.83	41
	Three lamps	1,539	1,158.75	0.76	40

TABLE 4

ANNUAL COST OF OPTIMUM REPLACEMENT PROGRAM USING SEVERAL RATED LAMP LIVES

Lamp Use	8000-Hr Lamp		6000-Hr Lamp	
	Lamp Change Interval (yr)	Cost Per Year ($)	Lamp Change Interval (yr)	Cost Per Year ($)
Flasher	1. 0	777. 70	0. 5	914. 20
Traffic signal:				
Red	1. 0	948. 38	0. 5	983. 16
Green	1. 0	637. 38	0. 5	989. 06
Amber	4. 0	109. 13	3. 5	149. 60
Total annual cost		2, 472. 59		2, 945. 02

The technique for determining the optimum replacement schedule and the annual cost of this policy are summarized in the following.

1. Determine the ratio of group replacement costs to replacement costs at failure for the Crawfordsville maintenance district.
2. Apply the replacement cost ratio to the optimum replacement curve to determine the percentage of rated life for the replacement period.
3. Use the optimum percentage of rated life to determine the number of hours that the lamps should be permitted to burn before replacement.
4. Use Table 2 and the optimum burning times to calculate the replacement intervals for lamps used in flashers and traffic signals. These calculations were rounded to the nearest 6 months.
5. Apply the expected lamp burning times to the replacement model to calculate the anticipated annual costs. The results of these annual cost calculations for the optimum lamp replacement program are summarized in Table 4.

Two additional lamp replacement programs were considered in this investigation. The first program schedules lamp replacement every 12 months, and the second alternative plans group replacement at 6-month intervals. The annual costs of these maintenance programs were determined by applying the group and failure costs to the lamp replacement model (Table 5).

The results of the computations summarized in Tables 4 and 5 reveal several significant facts. The 8000-hr lamp is designated as the best lamp for use in the Crawfordsville maintenance district if the criteria for judgment are based solely on economic considerations. In addition, the lamps used in flashers and those used in the red and green positions of traffic signals should be changed every 12 months. The bulbs used for the amber indication in traffic signals need only be replaced every 4 years. However, if the lamps used in the amber position are changed each year, the annual cost is increased by only 0. 42 percent.

The most economical replacement program for the 6000-hr lamp is recommended because the 8000-hr lamp considered in this evaluation does not meet AASHO specifications. The lamps used in the red and green positions of traffic signals and those used in flashers should be replaced at 6-month intervals. The lamps used in the amber indication are most economically replaced every 42 months. The annual cost of the group replacement program is increased by 6. 38 percent when amber replacements are scheduled every 6 months. Because this additional cost is quite small, all lamps should be replaced on a 6-month schedule.

The actual determination of the optimal lamp replacement policy involves more than economic considerations. The following factors must be considered, and their importance must be carefully weighed with respect to the final results on the system of traffic control.

TABLE 5

ANNUAL COST OF SEVERAL FIXED TIME INTERVAL LAMP REPLACEMENT PROGRAMS

Lamp Use	Cost of Replacement Programs			
	Change Lamps at 6-Month Intervals		Change Lamps at 12-Month Intervals	
	6000-Hr Lamp ($)	8000-Hr Lamp ($)	6000-Hr Lamp ($)	8000-Hr Lamp ($)
Flasher	392. 20	307. 10	1, 440. 50	516. 70
Traffic signal:				
Red	996. 50	893. 26	2, 422. 00	979. 13
Green	911. 40	878. 16	1, 380. 00	667. 13
Amber	833. 70	843. 21	418. 36	422. 13
Total annual cost	3, 133. 80	2, 921. 73	5, 660. 86	2, 585. 04

TABLE 6

SUMMARY OF RESULTS OF MODEL ANALYSIS FOR CHANGING LAMPS AND CONTROLLER MAINTENANCE FOR TRAFFIC SIGNAL AND FLASHER INSTALLATIONS

Total Number of Hours Worked		Set					
Less Than	Greater Than	1 1522.00 Miles 17 Days	2 1522.60 Miles 17 Days	3 1507.60 Miles 17 Days	4 1597.00 Miles 17 Days	5 1519.90 Miles 17 Days	6 1606.30 Miles 17 Days
	8:30	0	0	0	0	0	0
8:30	8:10	0	0	0	0	0	0
8:10	8:05	0	1	1	0	0	0
8:05	7:45	10	7	10	12	9	11
7:45	7:30	4	5	1	3	4	4
7:30	7:00	2	3	2	1	3	1
7:00	6:00	0	0	3	0	0	1
6:00		1	1	0	1	1	0

1. As the period between lamp replacements increases, the number of expected failures becomes greater.
2. Fewer failures are expected per unit of time for increasing lamp lives.
3. Hazards to the motorist increase as the number of signal failures increases.
4. With longer burning times less light is emitted because of the condensation of filament vapors on the lamp envelope (1).
5. Less light is emitted with increasing time between the cleaning of the optical units.
6. As less light is emitted from the signal, the potential hazard to the motoring public becomes more pronounced. This factor is critical for the red position because it indicates the stop condition and eye sensitivity is lower in that portion of the light spectrum (6).

Optimal Route Sequencing for Preventive Maintenance

This portion of the maintenance problem is concerned with the optimal scheduling and sequencing of routine preventive maintenance operations. The model analysis was separated into three parts to consider several possible alternatives. The first phase considered the optimal routing for preventive tasks concerned only with signal lamp and controller maintenance. Then, the shortest sequence of signal nodes was developed for the painting operation. The last alternative necessitated the selection of the shortest route for scheduling signal lamp, controller, and painting maintenance. The results of the model analysis for the three preventive maintenance operations are summarized in Tables 6, 7, and 8.

The best group of tours for each maintenance alternative was selected using the following criteria:

1. The work was completed in the minimum number of days;
2. The distance traveled was a minimum; and

TABLE 7

SUMMARY OF RESULTS OF MODEL ANALYSIS FOR PAINTING TRAFFIC SIGNAL AND FLASHER INSTALLATIONS

Total Number of Hours Worked		Set						
Less Than	Greater Than	1 3879.5 Miles 47 Days	2 3523.6 Miles 46 Days	3 3773.5 Miles 46 Days	4 3422.0 Miles 42 Days	5 3451.3 Miles 41 Days	6 3378.4 Miles 41 Days	7 3424.9 Miles 41 Days
	8:30	0	0	0	0	1	0	0
8:30	8:10	0	0	0	1	3	0	0
8:10	8:05	0	0	0	1	0	3	3
8:05	7:45	4	3	7	30	36	34	36
7:45	7:30	8	4	7	6	0	3	0
7:30	7:00	21	23	18	2	0	0	1
7:00	6:00	10	15	13	1	0	0	1
6:00		4	1	1	1	1	1	0

3. Maintenance was scheduled to utilize the available time in a working day.

TABLE 8

SUMMARY OF RESULTS OF MODEL ANALYSIS FOR CHANGING LAMPS, CONTROLLER MAINTENANCE, AND PAINTING TRAFFIC SIGNAL AND FLASHER INSTALLATIONS

Total Number of Hours Worked		Set				
Less Than	Greater Than	1 4269. 1 Miles 53 Days	2 4244. 8 Miles 53 Days	3 4152. 4 Miles 51 Days	4 4146. 5 Miles 51 Days	5 4131. 2 Miles 51 Days
	8:30	0	0	0	0	0
8:30	8:10	2	0	5	2	0
8:10	8:05	1	2	2	3	5
8:05	7:45	36	38	40	45	44
7:45	7:30	8	8	2	0	1
7:30	7:00	4	3	2	0	0
7:00	6:00	0	1	0	0	0
6:00		2	1	0	1	1

The optimal selection for changing the lamps and for controller maintenance is Set 5, in which the total time required to perform the maintenance operation is 121 hr and 52 min. Set 6 is the best routing for painting the traffic signal and flasher installations. This option requires 322 hr and 3 min to complete the maintenance cycle. Set 5, which requires 405 hr and 8 min per cycle, is the optimum schedule for combining the lamp and controller maintenance with the painting operation.

The three optimum maintenance sets were combined in accordance with AASHO preventive maintenance specifications. AASHO recommends that lamps and controllers be maintained every 6 months and that the traffic signal and flasher installations be painted at 2-yr intervals (4). Two maintenance alternatives result from the AASHO policy. One routine schedules signal head and controller maintenance at 6-month intervals while painting is planned as a separate operation on a 2-yr schedule. The other arrangement requires that signal head and controller maintenance be performed three times in a 2-yr period. A fourth maintenance cycle in this 2-yr interval combines painting with lamp and controller maintenance. Annual costs were calculated for the two alternatives by multiplying the anticipated hours required annually for each option by the hourly costs of men and equipment (Table 9).

The annual cost of alternate two is slightly less expensive than the first alternative. However, alternative two is not recommended because it lacks sufficient flexibility for use in a system where failures occur randomly and where good weather cannot be guaranteed. When the painting operation is scheduled separately from the lamp and controller maintenance, the time required for painting can reduce the slack time in the work load if weather conditions are satisfactory. The painting operation can be scheduled during these slack periods because the continued and accurate operation of the traffic control devices is not critically dependent on this phase of maintenance. The optimal sequencings of the more flexible first alternative are presented in Table 10 for the routine signal head and controller maintenance and in Table 11 for the painting operation.

The proper operation of the maintenance sequencing is predicated on two procedural techniques. The nine traffic signals in Crawfordsville are necessary to absorb the unused work times because the maintenance scheduling has been performed with 85th percentile work times. Scheduling maintenance operations with the 85th percentile work times increases the possibility of the daily activities being completed in less than 8 hr. If this situation arises, the maintenance crews finish the work day by maintaining the traffic signals in Crawfordsville. At the end of the maintenance cycle those traffic signals in Crawfordsville that have not been maintained receive scheduled preventive maintenance.

TABLE 9

ANNUAL COST OF VARIOUS PREVENTIVE MAINTENANCE ALTERNATIVES

Alternative One		
4 lamp changes at 121. 82 hr per cycle	=	487. 28 hr
1 paint only at 322. 05 hr per cycle	=	322. 05 hr
Total preventive maintenance hours in 2-yr period	=	809. 33 hr
Total preventive maintenance hours in 1-yr period	=	404. 66 hr
Total annual preventive maintenance cost at $9. 90 per hr	=	$4, 000. 00
Alternative Two		
3 lamp changes at 121. 82 hr per cycle	=	365. 46 hr
1 lamp change and paint combined at 406. 13 hr per cycle	=	406. 13 hr
Total preventive maintenance hours in 2-yr period	=	771. 59 hr
Total preventive maintenance hours in 1-yr period	=	385. 80 hr
Total annual preventive maintenance cost at $9. 90 per hr	=	$3, 820. 00

The other consideration for the maintenance sequencing is concerned with the use of fractions of traffic signal and flasher installations for the painting operation. The lengthy work time required for the painting operation necessitated this procedure for scheduling work to insure that the time available

TABLE 10

OPTIMAL SEQUENCE OF TRAFFIC SIGNALS AND FLASHERS FOR LAMP AND CONTROLLER MAINTENANCE

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
1	5.00	1.00	Brazil	Clay
2	—	1.00	Williamstown	Clay
2	5.00	—	Brazil	Clay
3	1.00	—	East Glenn	Vigo
3	1.00	—	Seelyville	Vigo
3	2.00	—	Brazil	Clay
3	1.00	—	US-40; SR-43	Putnam
4	—	3.00	Blackhawk	Vigo
4	3.00	—	West Terre Haute	Vigo
5	—	1.00	Cloverdale	Putnam
5	—	1.00	US-231; SR-67	Owen
5	—	3.00	Coalmont	Clay
5	—	4.00	Lewis	Vigo
5	—	1.00	Blackhawk	Vigo
6	3.00	—	Clinton	Vigo
6	—	1.00	Shirkieville	Vigo
6	—	1.00	US-36; SR-71	Vermillion
6	—	1.00	US-36; SR-63	Vermillion
7	4.00	—	Greencastle	Putnam
7	1.00	1.00	Putnamville	Putnam
8	3.00	—	Rockville	Parke
8	—	1.00	US-35; SR-43	Putnam
8	1.00	—	Bainbridge	Putnam
8	1.00	—	US-36; SR-43	Putnam
9	—	1.00	Montezuma	Vermillion
9	1.00	—	Hillsdale	Vermillion
9	—	1.00	US-36; SR-63	Vermillion
9	1.00	2.00	Covington	Fountain
9	—	2.00	Sterling	Fountain
9	—	1.00	Hillsboro	Fountain
9	—	2.00	Waynetown	Montgomery
10	—	1.00	Odell	Tippecanoe
10	2.00	—	Attica	Fountain
10	—	1.00	Williamsport	Warren
10	—	1.00	Boswell	Benton
10	—	1.00	US-52; US-41	Benton
10	—	1.00	Montmorenci	Tippecanoe
10	—	1.00	Klondike	Tippecanoe
11	6.00	—	West Lafayette	Tippecanoe
12	6.00	—	West Lafayette	Tippecanoe
13	1.00	—	West Lafayette	Tippecanoe
13	—	1.00	Rossville	Clinton
13	1.00	—	Frankfort	Clinton
13	—	1.00	Pike	Boone
13	—	1.00	Lebanon	Boone
14	6.00	—	Frankfort	Clinton
15	4.00	—	Lebanon	Boone
15	—	1.00	Lizton	Hendricks
15	—	1.00	Jamestown	Boone
15	—	2.00	New Ross	Montgomery
16	1.00	—	Pittsboro	Hendricks
16	1.00	—	Brownsburg	Hendricks
16	3.00	—	Plainfield	Hendricks
17	2.00	—	Danville	Hendricks
17	1.00	—	Avon	Hendricks
17	1.00	—	Belleville	Hendricks
17	1.00	—	Stilesville	Hendricks

Note: The 9 traffic signals in Crawfordsville are used as safety valves.

TABLE 11

OPTIMAL SEQUENCE OF TRAFFIC SIGNALS AND FLASHERS FOR PAINTING OPERATIONS

Day	Number of Installations Maintained		Location of Traffic Signal or Flasher Installation	
	Traffic Signals	Flashers	Town	County
1	—	3.00	Coalmont	Clay
1	—	2.50	Lewis	Vigo
2	—	1.50	Lewis	Vigo
2	—	4.00	Blackhawk	Vigo
3	2.00	—	Plainfield	Hendricks
4	—	1.00	Jamestown	Boone
4	—	1.00	Lizton	Hendricks
4	1.00	—	Plainfield	Hendricks
4	—	2.00	New Ross	Montgomery
5	1.00	—	Belleville	Hendricks
5	1.00	—	Stilesville	Hendricks
6	1.00	—	Hillsdale	Vermillion
6	—	1.00	US 36; SR 71	Vermillion
6	—	1.00	US 36; SR 63	Vermillion
6	—	1.00	Montezuma	Vermillion
7	1.00	—	US 36; SR 43	Putnam
7	—	1.00	US 36; SR 43	Putnam
7	1.00	—	Bainbridge	Putnam
8	2.00	—	Clinton	Vigo
9	1.00	—	Clinton	Vigo
9	1.00	—	Rockville	Parke
10	1.00	—	Rockville	Parke
10	—	1.00	SR 63; Hillsdale	Vermillion
11	1.00	—	West Lafayette	Tippecanoe
11	—	1.00	Montmorenci	Tippecanoe
11	—	1.00	Klondike	Tippecanoe
11	—	1.00	Rossville	Clinton
12	2.10	—	Frankfort	Clinton
13	2.10	—	Frankfort	Clinton
14	2.10	—	Frankfort	Clinton
15	—	1.00	Pike	Boone
15	0.70	—	Frankfort	Clinton
15	1.20	—	Lebanon	Boone
16	0.80	—	Lebanon	Boone
16	—	1.00	Hillsboro	Fountain
17	2.00	1.00	Lebanon	Boone
18	2.00	1.00	Greencastle	Putnam
19	2.00	—	Greencastle	Putnam
20	1.00	—	US 40; Sr 43	Putnam
20	1.00	—	Danville	Hendricks
21	—	1.00	Waynetown	Montgomery
21	1.00	—	Avon	Hendricks
21	1.00	—	Danville	Hendricks
22	1.00	2.00	Covington	Fountain
22	—	2.00	Sterling	Fountain
22	—	1.00	Waynetown	Montgomery
23	1.00	1.00	Putnamville	Putnam
23	—	1.00	Cloverdale	Putnam
23	—	1.00	US 231; SR 67	Owen
24	2.25	—	West Lafayette	Tippecanoe
25	2.25	—	West Lafayette	Tippecanoe
26	2.25	—	West Lafayette	Tippecanoe
27	2.25	—	West Lafayette	Tippecanoe
28	2.25	—	West Lafayette	Tippecanoe
29	0.75	—	West Lafayette	Tippecanoe
29	—	1.00	US 52; US 41	Benton
29	—	1.00	Boswell	Benton
29	—	1.00	Williamsport	Warren
30	2.00	—	Attica	Fountain
30	—	1.00	Odell	Tippecanoe
31	1.75	—	West Terre Haute	Vigo
32	1.25	—	West Terre Haute	Vigo
32	0.50	—	East Glenn	Vigo
33	0.50	—	East Glenn	Vigo
33	1.00	—	Seelyville	Vigo
33	—	1.00	Brazil	Vigo
34	2.00	—	Brazil	Vigo
35	2.00	—	Brazil	Vigo
36	2.00	—	Brazil	Vigo
37	2.00	—	Brazil	Vigo
38	2.00	—	Brazil	Vigo
39	2.00	—	Brazil	Vigo
40	1.00	—	Rockville	Parke
40	—	1.00	Shirkieville	Vigo
40	—	1.00	Williamstown	Vigo
41	1.00	—	Pittsboro	Hendricks
41	1.00	—	Brownsburg	Hendricks

Note: The 9 traffic signal installations in Crawfordsville are used as safety valves.

each day is fully utilized. Because the signal operation is not dependent on the painting operation, it is possible to leave a signal installation partially painted and to return the next working day for the completion of this task.

Staffing

This part of the maintenance problem is concerned with determining the size of the state maintenance staff necessary for effective traffic signal and flasher operation. The traffic signal and flasher maintenance operations in Lafayette, Terre Haute, and West Lafayette were not included in the staffing analysis because the maintenance operations in these communities are handled on a contract basis.

The analysis of the staff necessary to provide adequate traffic signal and flasher maintenance was determined by considering the following factors:

1. The failure probabilities expressed (Table 3),
2. The average daily repair times,
3. The anticipated time required to perform the preventive maintenance operations, and
4. The suitability of certain seasons for preventive maintenance.

The days available per year for preventive maintenance were calculated by multiplying the probabilities of no failures occurring in a day times the number of days expected for each failure condition. From the number of days in a year, 90 days were subtracted because the winter season, extending from December 1 to March 1, 'was not considered satisfactory for preventive maintenance operations. The number of failures was not calculated for the winter season, because the entire period was removed from consideration for preventive maintenance operations. An additional 78 days were deducted for the weekends occurring during the remainder of the year. For the situation when flasher failures are expected, the probability of no failures is 0.559, and the length of the observed period of flasher failures was 90 days. Therefore, 40 days in this 90-day interval are not available for routine maintenance operations because of possible traffic signal, flasher, and lamp failures. The probability of no failures per day is 0.673 for the remaining 107 days of the year, and the time not available for preventive maintenance was calculated as 35 days. Any day in which a failure occurred was not considered available for preventive maintenance operations. As a result of these limitations, only 122 days are available for preventive maintenance.

The preventive maintenance operations require 17 days per cycle (Table 6) for changing the lamps and cleaning the controller and 21 days per year (Table 7) for the painting operations if a 2-yr painting cycle is employed. Depending on the lamp replacement policy of one or two cycles per year, 38 or 55 days are required per year, respectively, for the preventive maintenance operations. One maintenance crew can successfully perform the preventive and emergency maintenance operations for the Crawfordsville district.

Because the traffic signal maintenance personnel are also responsible for traffic signal modernization, installation of new traffic signals and flasher complexes, and rebuilding controllers and other signal appurtenances, a single two-man crew is not totally sufficient. A three-man maintenance team would provide a more effective maintenance crew. One man is charged with the responsibility of rebuilding the controllers and the other repair tasks requiring a high degree of technical skill. The remaining two men are assigned the preventive maintenance operations and the less difficult repair tasks.

SUMMARY OF RESULTS AND CONCLUSIONS

The following results and conclusions were derived from the analysis of traffic signal and flasher operations. The findings were classified under the categories of general conclusions and of results applicable to the Crawfordsville maintenance district.

General Conclusions

1. A scientifically determined maintenance program was formulated for traffic signals and flashers using systems analysis techniques. This program includes determining

the optimal lamp replacement interval, calculating the shortest route for performing the preventive maintenance, and staffing the work crew necessary to insure proper signal operation.

2. The use of a preventive maintenance program affords certain economic advantages and improves the safety of an intersection because the probability of a signal failure is reduced.

3. Lamps with long-rated lives are recommended because their operation is less costly and the anticipated numbers of failures per unit time are smaller than for bulbs with short lamp lives.

4. An adequate maintenance record system is mandatory for the economic and efficient scheduling of realistic traffic signal and flasher maintenance.

Results Applicable to Crawfordsville Maintenance District

1. The relationship expressing the distance traveled in minutes for a typical maintenance trip in the district is $Y_C = 1.437X + 7.775$.

2. The average work times for various preventive maintenance operations are:

Operation	Traffic Signal	Flasher
Change lamps	40 min	13 min
Paint	113 min	37 min
Change lamps and paint	173 min	50 min

3. The average lamp replacement costs are $0.84 for replacing a lamp in a group replacement program and $18.38 for replacing a lamp at failure.

4. The failure rate for traffic signals was reasonably represented by a Poisson distribution with a mean of 0.0063 failures per day per signal.

5. The optimum lamp replacement curve was used to indicate the proper interval for scheduling group lamp replacements.

6. In concurrence with the specifications of AASHO, the use of 6000-hr lamps with a group replacement schedule of 6 months is recommended for the most economical preventive maintenance program.

7. The painting and the lamp replacement and controller maintenance are scheduled as separate maintenance operations to provide sufficient flexibility in the scheduled preventive maintenance for unpredictable occurrence of failures and poor weather conditions.

8. The staff required in the Crawfordsville district for traffic signal and flasher maintenance should consist of one signal technician qualified to make major controller repairs and two technicians who perform the preventive maintenance and minor repair tasks.

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Protection for Concrete Bridge Decks by Membrane Waterproofing

JOHN J. HAGENBUCH, Massachusetts Department of Public Works

ABRIDGMENT

•IT IS standard practice in the Commonwealth of Massachusetts to use a membrane waterproofing on all new construction of concrete bridge decks that are to be covered by bituminous concrete. This is not new as it has been used back as far as the late 1940's. All restoration of concrete bridge decks that have deteriorated to the point of requiring repairs, include membrane waterproofing as a part of the restoration project. The first use of this method was tried in 1949.

Massachusetts has many bridges built prior to 1940 without adequate deck waterproofing that have a bituminous-concrete riding surface of various thicknesses. These are the decks that are presently reaching a state of deterioration requiring necessary repairs. In every instance there is considerable cracking in the bituminous concrete, and severe disintegration along the curb lines where the water collects between the concrete and the bituminous-concrete covering.

At first, 3 plys of impregnated cotton fabric were used between layers of a waterproofing asphalt or a coal tar pitch emulsion. In 1958 the Department revised the Specifications for membrane waterproofing and called for a 2-ply coated woven-glass fabric placed between five moppings of a coal tar pitch emulsion.

It is interesting to note that over the years the average contract bid price for this work has remained constant at approximately $3.00 per square yard.

Before placing of the membrane waterproofing all concrete surfaces are brought to a true cross section, free of rough spots, projections and other defects which might rupture or puncture the membrane. No waterproofing is allowed to be applied in wet or foggy weather and when the temperature is below 40 F.

The emulsion must be thoroughly agitated in its container and no adulterants of any nature may be added. All applications of the coal tar pitch emulsion are applied at a minimum rate of $\frac{1}{8}$ gal per sq yd. Each of the five applications must thoroughly dry before the next is applied. The first application of the emulsion is applied to a dampened concrete surface free of puddles. When the application is thoroughly dry the second coat is applied and the first ply of the coated glass fabric is laid. It must be brushed flat, free of wrinkles and bumps. This is followed by the third and fourth applications of the emulsion. The second ply of the coated glass fabric is laid on the fourth application of the emulsion at right angles to the first ply. This is followed by the application of the fifth and final coat of emulsion.

Where membrane waterproofing will be placed at steel expansion joints, scuppers, manholes or other metal projecting through the concrete, the membrane is turned up about $1\frac{1}{2}$ inches and sealed to the metal. When it is necessary to keep a section of the roadway open to traffic during the work, a 6-in. lap is left at the edge of each section of roadway to allow the joining of the adjacent section.

Bleeders, 2 in. in diameter, are installed at the curb lines, prior to the placing of the membrane waterproofing.

It is important that the membrane waterproofing be protected throughout all operations of placing the bituminous-concrete base course. No vehicles, including mechan-

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ical spreaders, are permitted on the bare waterproofing. The first course of bituminous concrete must be spread by hand.

Membrane waterproofing is paid for at the contract unit price per square yard of deck surface covered, complete in place. The contract costs for membrane waterproofing over the past five years has varied from a $1.80 per sq yd to $6.00 per sq yd, with the average cost being slightly under $3.00 per sq yd.

Observations during the past 20 years show satisfactory results from this method of waterproofing. No other method or materials have been found that will produce comparable results at such a reasonable cost.

Linseed Oil for the Preventive Maintenance Of Concrete

W. L. KUBIE, L. E. GAST and J. C. COWAN, Northern Regional Research Laboratory, U. S. Department of Agriculture

Information is presented on the use of boiled linseed oil solutions and emulsions as antiscaling compounds for concrete. These linseed formulations can be easily applied to concrete with conventional spraying equipment. With the emulsion drying 2 hr after application, serious loss of oil during a rain appears to be eliminated. When subjected to freeze-thaw cycles in the presence of salt, air-entrained concrete highways coated with linseed oil showed increased durability compared to uncoated controls. Tests also indicated that recoating is advantageous for long-term protection.

Laboratory freeze-thaw tests in water and 2 percent brine were conducted on concrete beams coated with linseed oil emulsions to evaluate its effectiveness as an antiscaling and curing agent. Coated beams showed no loss in 42-day flexural strength over moist-cured controls. Coated beams subjected to 300 freeze-thaw cycles in the presence of water and 2 percent brine were from 4 to 6 times as durable as uncoated beams.

Preliminary data indicate that linseed oil emulsions may serve as both a curing and antiscaling compound.

•EVIDENCE within the past 10 years suggests that air-entrained portland cement concrete as laid in the field is not the complete solution to freeze-thaw damage in the presence of salts (1). Numerous coatings for concrete have been tried, and in 1963, Furr (2) reported results of laboratory tests indicating that boiled linseed oil offered the best protection for concrete of all the sealants tested. In 1964, Grieb and Appleton (3) showed that linseed oil coatings increased the resistance of concrete to scaling. Snyder (4) in 1965 published a laboratory investigation in which many protective coatings were tried. His best results were with a solution of linseed oil. Both the 1964 and 1965 reports contained results of tests of linseed oil emulsions. Although these emulsions were less effective than solutions of boiled linseed oil, the test method kept the linseed oil coated surface continuously wet. In the field, a concrete surface would be wet for only relatively short periods with water, slush, or brine.

In 1965, Scholer and Best (5) under contract to the Northern Laboratory (NU) listed findings as:

1. Air entrainment does not completely protect concrete from freeze-thaw damage in the presence of salts.
2. Properly applied boiled linseed oil in mineral spirits does extend protection to air-entrained concrete during freeze-thaw cycles.
3. Periodic reapplication of linseed oil is desirable to maintain protection.
4. Application of boiled linseed oil after scaling of the concrete surface has started appears to prevent further deterioration.

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5. Reinforcing steel is not corroded as long as the overlying concrete is intact; it is the destruction of the concrete that allows corrosion of the steel to occur, not the corrosion of the steel that induces destruction of the concrete.
6. Linseed oil probably protects concrete by preventing the penetration of salt while slowing down the penetration (and escape) of water.
7. With sound aggregate in the concrete, it is the cement paste that is attacked initially under freeze-thaw conditions. When poor aggregate, such as porous Florence limestone, is used in concrete, it is the aggregate that is destroyed first.
8. A screeded surface of concrete is more vulnerable to attack than a formed surface.

In 1967, Kubie and Cowan (6) found that either an emulsion of boiled linseed oil in water or a solution of boiled linseed oil in mineral spirits was an effective antispalling compound on concrete. Both the emulsion and the solution gave the same protection.

Morris (7) stated in 1965 the present need for using linseed oil on concrete. He outlined procedures to be followed in applying 50 volume percent of boiled linseed oil in a mineral spirits solution.

This paper presents additional information on the use of NU emulsions as antiscaling compounds for concrete (6), and on the desirability of recoating from time to time to maintain protection. In studies financed by us, durability of concrete coated with NU linseed oil emulsion was tested by the U.S. Army Corps of Engineers, Mariemont, Ohio. Data from these durability studies are also included.

WATER SENSITIVITY OF BOILED LINSEED OIL FILMS ON CONCRETE

Rain soon after the application of boiled linseed oil may wash the film from the concrete surface. Also, the film laid down from an emulsion may be more easily removed than one laid down from a solution. To determine the water sensitivity of linseed oil films, 2 by 2 by 1-in. blocks of mortar were prepared from a 3:1 sand-cement mix. The water/cement ratio was 0.5. The blocks were cured under polyethylene sheeting for 2 weeks and then aged at room temperature for 2 weeks before coating. The blocks were soaked in either NU emulsion 39-2 (Table 1) or National Flaxseed Processors Association (NFPA) antispalling compound for 20 min, withdrawn, drained of excess fluid and allowed to dry in the laboratory for at least 2 hr. Coating weights absorbed by the blocks were from 0.350 to 0.543 lb of linseed oil per square yard for the emulsion and from 0.268 to 0.463 for the mineral spirits solution. These amounts are well above coating weights of 0.16 lb/sq yd recommended for use in the field. The coated blocks were soaked in 200 ml of distilled water for 72 hr and weighed after withdrawing and draining. The water was acidulated and extracted with petroleum ether for Series 1 to 3 and with xylene for Series 4 to 6 (Table 2). At drying times longer than 6 hr, no oil was lost from the blocks. Two hours of drying appears to be sufficient to eliminate any serious loss of oil either from the emulsion or solution coating. The first group of blocks (Series 1 to 3, average coating of 0.341 lb/sq yd) picked up an average of 3.0 percent water in 72 hr, which is equivalent to the uncoated controls. The second group (Series 4 to 6, average coating of 0.425 lb/sq yd) gained an average of 1.9 percent water, which is almost two-thirds of that gained by the control.

TABLE 1

FORMULAS OF EMULSION

Emulsion	NU Formula		
	38-1	39-2	49-1
Oil phase, 50 volume percent:			
Boiled linseed oil	97	97	67
←Z_2 bodied linseed oil	0	0	30
Saturated tallow alcohols	3	3	3
Water phase, 50 volume percent:			
Tap water	100	99.60	99.60
Sodium hydroxide	0	0.37	0.37
Dipicolinic acid	0	0.03	0.03

PROTECTION OF AIR-ENTRAINED CONCRETE IN THE FIELD

In November 1959, under the auspices of the NFPA and under the direction of Charles Morris, a new interchange from the Tristate Tollway to Kennedy Expressway, Southbound, at O'Hare Field near Park Ridge, Ill., was coated with two coats of 50 volume percent of boiled linseed oil in mineral spirits. It

TABLE 2

EFFECT OF DRYING TIME ON OIL LOSS FROM COATED MORTAR BLOCKS IMMERSED IN WATER

Series Number	Treatment	Rate (lb/sq yd)	Dry Time Before Immersion (hr)	Oil Removed (%)	Water Gain (%)
1a	Emulsion	0.350	2	0.10	3.2
1b	Lso/ms[a]	0.285	2	0.05	3.0
2a	Emulsion	0.405	4	0.00	3.1
2b	Lso/ms	0.277	4	0.03	3.5
3a	Emulsion	0.460	6	0.00	2.6
3b	Lso/ms	0.268	6	0.01	2.9
4a	Emulsion	0.424	2	0.06	2.1
4b	Lso/ms	0.299	2	0.02	2.1
5a	Emulsion	0.405	4	0.18	2.1
5b	Lso/ms	0.463	4	0.00	1.5
6a	Emulsion	0.543	6	0.00	1.8
6b	Lso/ms	0.416	6	0.02	1.7
Control					
1	None	0	-	0.00	3.0
2	None	0	-	0.00	3.5

[a] Lso/ms = boiled linseed oil in mineral spirits.

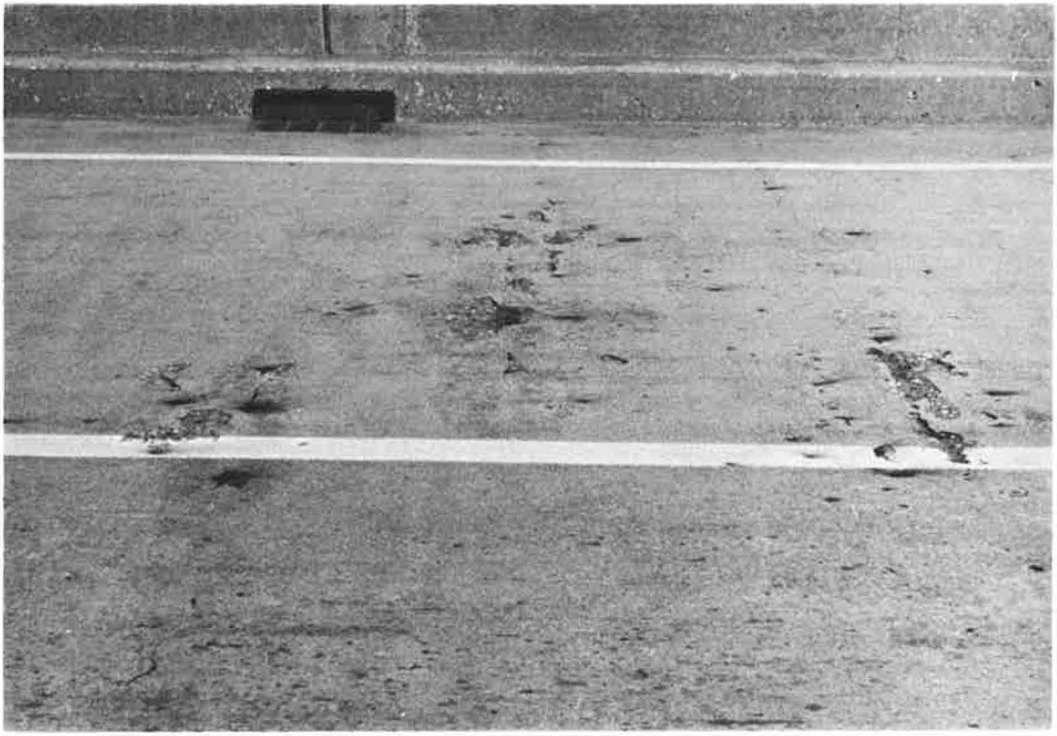

Figure 1. A section of an interchange near O'Hare Field, Chicago.

was estimated that the concrete was 4.5 percent air entrained. The first coat was made at the rate of 40 sq yd/gal of solution and the second, applied 2 days later, at the rate of 67 sq yd/gal. The total coating weight was 0.16 lb/sq yd of boiled linseed oil. Salt was applied as needed during the winter months.

Figure 1 is a representative area of this roadway taken approximately 6 years after the interchange was furnished and coated. The damaged area of an uncoated portion of roadway is in the background; in the foreground, there is relatively little damage on the coated portion.

This test demonstrated that coating air-entrained concrete with a boiled linseed oil solution increased durability of the pavement when subjected to freeze-thaw cycles in the presence of salt.

Tests have now been started to determine the usefulness of linseed oil coatings on structures other than roads. Floors of the Grant Park underground garage in Chicago had to be replaced after 11 years because of deterioration of the concrete. Salt carried in by automobiles presumably caused this deterioration. A new section of floor in the Grant Park garage was poured in 1965 and coated with linseed oil emulsion NU 39-2. By the summer of 1967, no deterioration of the coated floor could be detected.

In another test started in June 1966, the floor and ramp of the underground garage of the Security Savings and Loan Building in Peoria was sprayed with the NU boiled linseed oil emulsion 39-2. The coating rate was 50 sq yd/gal. To date, no deterioration of the garage floor has taken place.

RECOATING CONCRETE WITH BOILED LINSEED OIL EMULSIONS AND SOLUTION

Some areas of the parking lot at NU treated in 1962 (6) were recoated in September 1964. The areas originally treated with 50 volume percent of boiled linseed oil in mineral spirits were recoated with 0.10 lb/sq yd of boiled linseed oil from the same system. The areas originally coated with the NU emulsion 39-2 were recoated with 0.14 lb/sq yd of the same emulsion. From 1962 to 1967, no surface deterioration was apparent in recoated areas with either system. The areas treated in 1962 but not recoated are beginning to show scaling in a few spots. These tests indicated that to maintain protection for long periods of time recoating is advisable.

In May and June 1963, we tested two NU linseed oil emulsions, 38-1 and 39-2, (Tabl 1) as curing agents of the sidewalks on our laboratory grounds, details being previously published (6). Three different types of controls were used. In October 1965, we recoated with NU emulsion 39-2 half of each test area previously coated and coated for the first time all control areas. Surface deterioration has been prevented in areas where none had previously appeared, and no further deterioration has appeared in the once oil-treated areas.

LABORATORY STUDIES ON PROTECTION OF CONCRETE

During the past 3 years, I. Narrow and W. W. Roberts of the U. S. Army Corps of Engineers have performed a series of tests for us to determine the effects of using NU linseed oil emulsions on durability and strength of concrete and to attempt to relate these data to the scaling of concrete under freeze-thaw conditions. While these tests were primarily designed to evaluate the durability of concrete coated with linseed oil, some preliminary information on linseed oil coatings for curing as well as protection was obtained. Four mixes (Table 3) were used to make the concrete beams ($3\frac{1}{2}$ by $4\frac{1}{2}$ by 16 in.) needed for the evaluation tests. The composition of the beams varied slightly in air content and slump. The aggregate chosen contained 8 percent deleteriou material, including 3 percent chert.

Three NU linseed oil emulsions (Table 1) were used to coat the beams. All coating rates were approximately 200 sq ft/gal of emulsion (coating weight of 0.18 lb/sq yd of linseed oil). The five conditions used for treating and curing the beams are given in Table 4.

TABLE 3

COMPOSITION OF THE CONCRETE MIXES USED FOR MAKING TEST BEAMS[a]

Ingredients	Mix 1	Mix 2	Mixes 3-4
Cement, bags/cu yd	5.53	5.53	5.53
Water/cement, by weight	0.496	0.496	0.496
Fine aggregate, % volume	40	40	40
Slump, in.	3.5	3.0	2.75
Air, %	3.6	3.1	3.0
Aggregate:			
8 percent poor (3% chert), ¾-in. max.			

[a] Data obtained by U.S. Army Corps of Engineers.

Condition A: Beams kept 35 days in the moist room served as controls.

Condition B: Beams held 28 days in the moist room, dried 2 days in the laboratory, then coated on all surfaces with emulsion applied at a rate of 200 sq ft/gal, and cured in air for 5 days.

Condition C: Beams placed 1 day in the moist room, then coated, and dried in the laboratory for 34 days.

Condition D: Beams kept 14 days in the moist room followed by drying 2 days in the laboratory, then coated on all sides, and cured for 19 days in the laboratory.

Condition E: Top surface of beams coated as soon as free water disappeared, then beams cured in their molds for 14 days in the laboratory. The beams were then removed from the molds and their other five surfaces coated, after which they were cured for an additional 21 days in the laboratory.

All beams were immersed in water at 70 ± 5 F for a period of 7 days immediately before testing. Beams were coated with emulsion 38-1 under Conditions B-E; Conditions D and E were repeated with first emulsion 39-2 as the coating and them emulsion 49-1. Six beams were treated in each set of conditions.

Tests of flexure were run on three of the six beams used in each group (condition) immediately after the 7-day soak (42-day flexural strength test) and on the remaining 3 beams at the end of the freeze-thaw test. Testing was done according to the Corps of Engineers Method CRD-C-16 (ASTM C78-59), except that the troweled surface was in tension.

The freeze-thaw test comprised the cycling of three beams from each group under water or brine from a beam temperature of 40 F to 0 to 40 F in 2 hr according to the Corps of Engineers Method CRD-C-20 (ASTM C291-61T). Degradation of the beam was indicated by sonic measurements of the dynamic modulus. The freeze-thaw durability

TABLE 4

CURING AND COATING OF CONCRETE BEAMS WITH LINSEED OIL EMULSIONS[a]

Condition	Treatment (days)			
	Moist Room	Laboratory Before Coating	After Coating (50% RH, 70 F)	Water Soak (70 F)
A (control)	35	0	0	7
B	28	2	5	7
C	1	0	34	7
D	14	2	19	7
E, Step 1 (surface)	0	0	35	7
Step 2 (5 other sides)	0	14	21	7

[a] Data obtained by U.S. Army Corps of Engineers.

TABLE 5

PERCENT WEIGHT GAIN OF CONCRETE BEAMS DURING 7-DAY SOAK[a]

Mix	Condition				
	A	B	C	D	E
1	0.06	0.53	1.10	0.67[b]	1.57[b]
3	0.10	0.69	0.50	0.80[b]	1.80[b]
4	0.21	—	—	0.90[c] 0.80[d]	1.70[c] 1.60[d]

[a] Data obtained by U.S. Army Corps of Engineers.
[b] Coated with emulsion 38-1.
[c] Coated with emulsion 39-2.
[d] Coated with emulsion 49-1.

is reported as a Durability Factor (DFE_{300}), which is defined by the following:

$$DFE_{300} = PN/300$$

where P = ratio of dynamic modulus at N cycles to original modulus times 100, and N = number of cycles.

Table 5 gives the weight gain (percent) of beams during the 7-day immersion in water. The controls (Condition A) gained little weight, from 0.06 to 0.21 percent. Beams from other conditions gained appreciable weight, averaging from 0.61 percent for Condition B to 1.67 percent for Condition E.

Research in this area is particularly difficult because variations in concrete occur even when it is prepared under carefully controlled conditions. This variability is illustrated by comparing the composition of concrete from Mixes 1 and 4 (Table 3) and the average flexural strength of beams prepared therefrom (Table 6, Condition A). These beams were made from identical materials and by the same techniques, but the 42-day flexural strengths of mixes 1 and 4 differed by 20 percent. While comparison of results from the same mix is possible, it is difficult to compare results from different mixes.

The same three NU formulas (Table 1) were used for coatings in the tests of flexure. All beams under Condition A were uncoated moist-cured controls. Beam from Mixes 1 and 3 were coated with emulsion 38-1 under Conditions B through E (Table 6). There was essentially no loss in the 42-day flexural strength under Conditions B and D when compared with the moist-cured controls. Condition C gave a somewhat lower value for Mix 1 and a very low value for Mix 2. No conclusions can be reached on beams treated under Condition E. With the other two emulsions (39-2 and 49-1), only Conditions D and E were studied. Condition D approximates antiscaling work in the field and Condition E should give some information on the usefulness of linseed oil coatings for both curing and antiscaling. Compared to A, Condition D does not appear to affect the 42-day flexural strength adversely, whereas Condition E appears to lower strength somewhat.

The concrete controls and beams were coated with the three linseed oil emulsions and durability after 300 freeze-thaw cycles in water and in 2 percent brine is given in Table 7. All coated beams were more durable than the control (Condition A). Emulsion 38-1 and Condition D (typical for antiscaling tests in the field) produced the most durable specimens. The lower value for E was probably due to loss of water from these beams during curing (Table 6).

Table 7 also gives the durability of beams coated with emulsions 39-2 and 49-1 under Conditions D and E. The lower durability of specimens cured under Condition E compared to D was not evident with these emulsions. Results in water demonstrate that a fourfold increase in durability is gained

TABLE 6

AVERAGE FLEXURAL STRENGTH OF BEAMS AT 42 DAYS (PSI)[a]

Mix	Air Content (%)	Condition				
		A	B	C	D	E
		(a) Emulsion 38-1				
1	3.6	895	905	800	925	610[b]
3	3.0	802	835	577	793	648[b]
		(b) Emulsion 39-2				
2	3.1	805	—	—	805	805
4	3.0	723	—	—	772	666
		(c) Emulsion 49-1				
2	3.1	805	—	—	825	805
4	3.0	723	—	—	800	663

[a] Data obtained by U.S. Army Corps of Engineers.
[b] Perimeter of beams not sealed to mold.

under Conditions D or E (antiscaling or curing) compared to the full moist cure. A sixfold increase in durability results in 2 percent brine. Condition D usually gave the best durability.

Although none of the experiments proved which emulsion was the most effective, it is evident that a linseed oil film properly applied significantly increases the durability of concrete under freeze-thaw conditions. Results suggest that these films may retain enough moisture when used as a curing agent to develop full-strength concrete equal to the strength developed by a full moist-cure.

TABLE 7

DURABILITY FACTOR AT 300 CYCLES (DFE$_{300}$) IN WATER AND 2 PERCENT BRINE[a]

Mix	Air Content (%)	Freeze-Thaw Solution	Condition				
			A	B	C	D	E
		(a) Emulsion 38-1					
1	3.6	Water	18	45	60	79	54
3	3.0	Brine	11	72	42	80	57
		(b) Emulsion 39-2					
2	3.1	Water	8	—	—	34	33
4	3.0	Brine	14	—	—	86	79
		(c) Emulsion 49-1					
2	3.1	Water	8	—	—	35	40
4	3.0	Brine	14	—	—	87	79

[a] Data obtained by U.S. Army Corps of Engineers.

CONCLUSIONS

Linseed oil treatment increases durability of concrete.

Linseed oil treatment of partially deteriorated concrete reduces and helps to prevent further damage.

Linseed oil emulsions appear to be as effective in the field as linseed oil solutions. Also, emulsions eliminate the fire hazard arising with the use of mineral spirits.

The best method for applying linseed oil to new concrete for antiscalling should include a drying period before application and should be made at least 14 days after the pour.

ACKNOWLEDGMENT

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Overlays for Flexible Pavements for the 1968 Interstate Estimates

B. C. HARTRONFT, Oklahoma Department of Highways

Interstate funds for additional state construction were made available under the provision of IM 21-1-67 issued by the Bureau of Public Roads in January 1967. However, certain criteria were required to be met before a project could become qualified. Primarily these criteria were the project must have been authorized for construction prior to October 24, 1963; the condition of the pavement must exhibit visual evidence of physical stress; and a complete structural analysis of the pavement design must establish a need for additional thickness. These considerations are to provide a serviceability index of 2.0, 20 years after the date of authorization of the initial pavement construction project.

This paper explains the methods of determining conditions, determining structural adequacy, design analysis, and determining the thickness of overlay required for flexible pavements included in the 104(b)5 report for the 1968 Estimate of the Cost of Completing the Interstate System in Oklahoma.

A method is included to predict if a project will meet the criteria prior to 1972 even though the present condition does not qualify for immediate overlay.

Although this method of analysis was used for Interstate pavements, it is one which may be adopted (and has been used prior to this time) on any system.

•ALTHOUGH the design of pavements has been studied for hundreds of years, the design of overlays for pavements, until recently, has been a "seat of the pants" operation.

When the Bureau of Public Roads issued IM 21-1-67 in January 1967, Interstate funds were made available for additional stage construction. However definite criteria were required to be met in order that a particular project could qualify for these funds. Primarily these criteria were (a) the project must have been authorized for construction prior to October 24, 1963; (b) the condition of the pavement must exhibit visual evidence of physical stress; and (c) a complete structural analysis of the pavement design must establish a need for additional thickness. These considerations are to provide a service ability index of 2.0, 20 years after the date of authorization of the initial pavement construction project. It is evident these requirements reduce the latitude of guesswork in arriving at the thickness of overlay required.

Using these criteria, the sections of Interstate highways qualifying for immediate overlays can be defined. However another problem was presented to the several highway departments when the Bureau of Public Roads asked that an estimate of the cost of overlays through 1972 be included in the 104(b)5 report for the 1968 Estimate of the Cost of Completing the Interstate System. In essence, the department engineers needed a method of predicting which sections would meet the criteria within the next five years.

Paper sponsored by Committee on Maintenance of Bituminous Pavements and presented at the 47th Annual Meeting.

TABLE 1

VISUAL CONDITION SURVEY—TERMS

Terms	Percent of Area
Few, slight	<5
Some	5 to 15
Considerable	15 to 30
Extensive	>30

SURVEYS OF PAVEMENTS

Two types of surveys were made on each section of Interstate pavement authorized prior to October 24, 1963:

1. A visual condition survey (1, 2) to determine the rate of deterioration. The visual survey was conducted using the outline in Tables 1 and 2.

If maintenance has been performed, the maintained area will be rated in one of the preceding classifications as to its effectiveness. A note will be made in the remarks column of the condition survey form regarding the type of maintenance that has been formed. Other remarks included the general condition of the pavement structure.

Condition surveys of projects which had been recently resurfaced could not be expected to reflect the true rate of deterioration; therefore, particular cognizance was taken of undulation of shoulders and curb lines as indicators of distress and special Benkelman beam deflection testing was accomplished.

2. On all projects except those with soil-cement base courses, Benkelman beam tests (3) were run at 500-ft intervals. All Benkelman beam tests were conducted with a 9000-lb wheel load. In areas having a condition rating less than 90, the deflections were run at 250-ft intervals. Projects that had been resurfaced were tested at 1000-ft intervals, except where the deflections were greater than 0.022 in. These areas were isolated by testing in both directions at 250-ft intervals until the deflections returned to the 0.022-in. level.

In selection of a design wheel load for a given pavement, the volume and character of traffic, including some form of load repetition, is a major consideration. Earlier work in Oklahoma (4) had established an allowable deflection of 0.037 in. for a 9000-lb wheel load design using a 20-yr design life. Later testing established the relationship between 9000-lb wheel load and 15,000-lb wheel load deflections (Fig. 1). Using the assumption that the permissible deflection for a 20-yr design is 0.037 in. for the designed wheel load and considering the 15,000-lb wheel load design used for Interstate

TABLE 2

VISUAL CONDITION SURVEY—CLASSES AND RATING

Classes	Rating (%)	Remarks
Excellent	98-100	No apparent major or minor defects. No maintenance performed.
Superior	90-97	No base failures or other major defects and no structural maintenance has been necessary. Any one or all of the following characteristics may be present within a 0.2-mi extent: slight surface roughness, cracking, riding quality impaired but very slightly.
Good	80-89	No base failures. Any one or all of the following characteristics may be present within a 0.2-mi extent: some surface roughness, or cracking, slight raveling, or distortion.
Average	65-79	Few localized base failures, considerable surface roughness, or cracking, some raveling (especially in the outer wheel lanes and along the edges), some distortion.
Poor	50-64	Considerable base failures, extensive surface roughness, or cracking, surface raveled extensively throughout its width, or considerable distortion.
Failure	<50	Numerous and extensive base failures, extensive distortion, extensive traffic hazards due to failures and distortion, or routine and special maintenance repairs have not been effective.

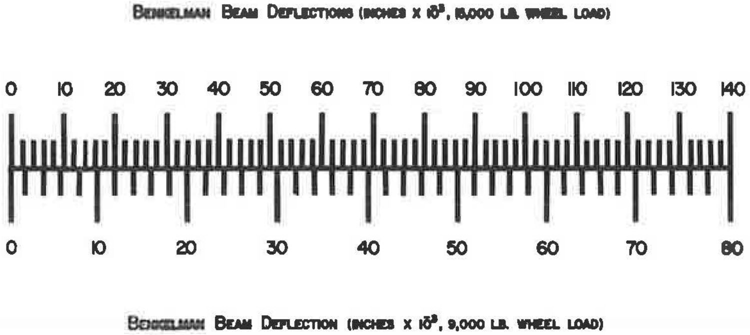


Figure 1. 9000-lb wheel load deflection vs 15,000-lb wheel load deflection.

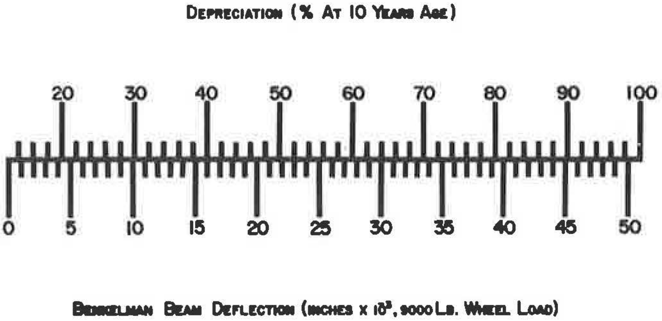


Figure 2. 9000-lb wheel load deflection vs depreciation for Interstate pavements (flexible).

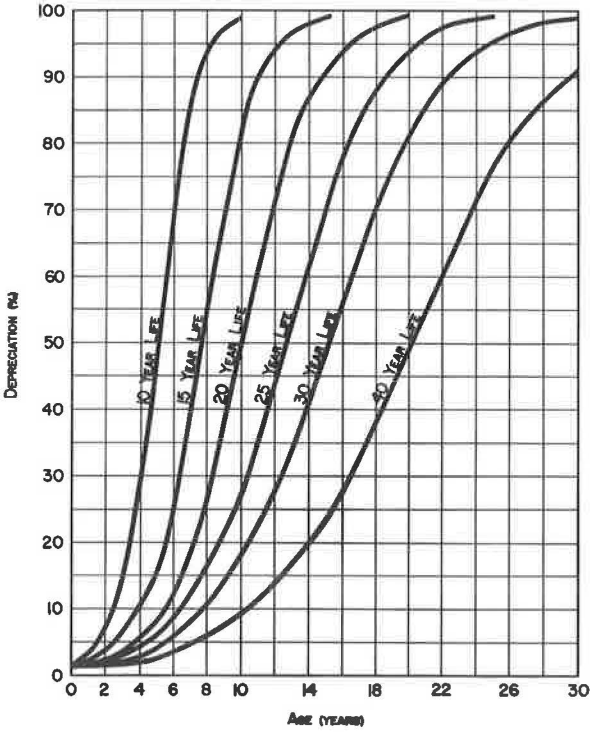
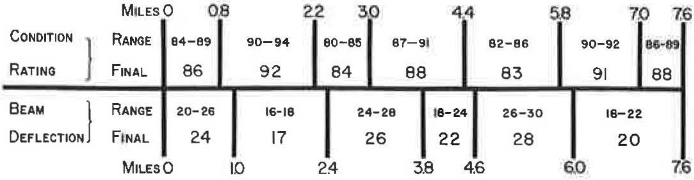


Figure 3. Life curves for flexible pavements.



Design Analysis Equivalent Base Thickness Increase 5 Inches

Extent	Condition		B. Beam		Design	Recommended
Miles	Rating	Overlay	Defl. (10^{3})	Overlay	Overlay	Overlay
0.0-0.8	86	1	24	3	3.3	3
0.8-1.0	92	0	24	3	3.3	3
1.0-2.2	92	0	17	0	3.3	0
2.2-2.4	84	5	17	0	3.3	4
2.4-3.0	84	5	26	3	3.3	4
3.0-3.8	88	0	26	3	3.3	3
3.8-4.4	88	0	22	0	3.3	0
4.4-4.6	83	6	22	0	3.3	5
4.6-5.8	83	6	28	5	3.3	5
5.8-6.0	91	0	28	5	3.3	5
6.0-7.0	91	0	20	0	3.3	0
7.0-7.6	88	0	20	0	3.3	0

Figure 4.

designs in Oklahoma, the allowable 9000-lb wheel load deflection should be 0.022 in. Extropolation of these values in conjunction with the results of the earlier research establish the relationship of the rate of depreciation to measured deflection for this system (Fig. 2).

Projects constructed with a soil-cement base were rated using the present serviceability index (5) rather than the Benkelman beam.

ANALYSIS OF CONDITION SURVEYS

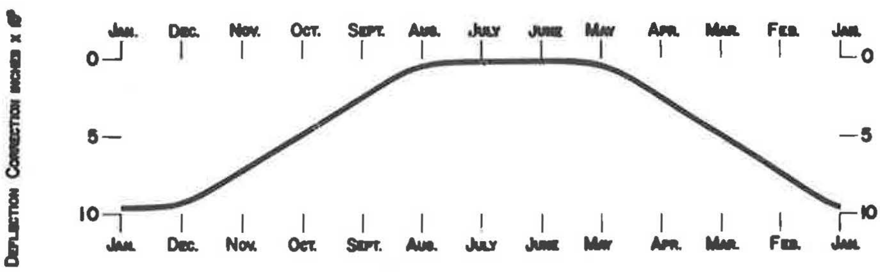
Using the pavement life curves (4) in Figure 3, the age of the pavement and the depreciation (100 - condition) the expected life of the roadway (with normal maintenance) can be projected. As an example: A pavement five years old exhibiting a condition rating of 85 would have an expected life of 15 years. In addition, the depreciation of the pavement at the end of 10 years would be approximately 82 percent. For projects which have been resurfaced, the date of overlay rather than date constructed is used to determine age. Referring to Figure 2, this project could be expected to experience a deflection level of about 0.040 in. when subjected to a 9000-lb wheel load. Further analysis of this information will be discussed in the section of this paper dealing with analysis of deflections.

For purposes of analysis, the condition rating for each portion of a project was recorded on a line chart (Fig. 4) using a suitable scale, generally 1 in. = 1 mile. Further, the conditions were grouped in appropriate ranges (i.e., a 4-5 percent spread) and a representative value selected, not necessarily the average, to use for determining the overlay required.

ANALYSIS OF BENKELMAN BEAM DEFLECTIONS

The beam deflections as taken in the field must be adjusted in accordance with the curve in Figure 5 to adjust for seasonal effects of temperature and general moisture conditions. This adjustment has been determined as a result of deflection studies during a 10-yr period. These corrections are added to the measured deflections. Deflections determined from condition do not require adjustment.

Further studies indicate that the deflection for a particular pavement will remain rather constant until the structure is overstressed and begins to fail. Because of this, deflection may be related to depreciation (Fig. 2). The results of the deflection tests (as adjusted) are recorded in the same manner as the condition on the line chart (Fig. 4).



For SABC With 4 ½" A.C. Surface Use ½ Of The Chart Correction

HMSA Base With 4 ½" A.C. Surface – Black Base With 4 ½" A.C. Surface – Full A.C. With 4 ½" A.C. Surface

Figure 5. Benkelman beam—seasonal effects.

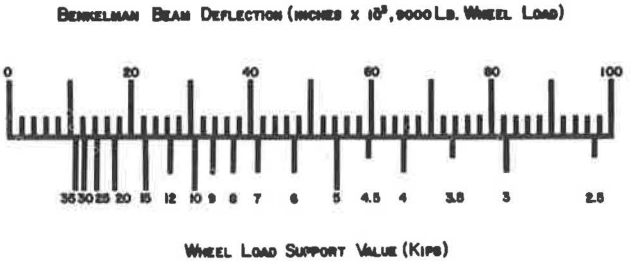


Figure 6. Relationship of Benkelman beam deflections to wheel load support value of flexible pavements.

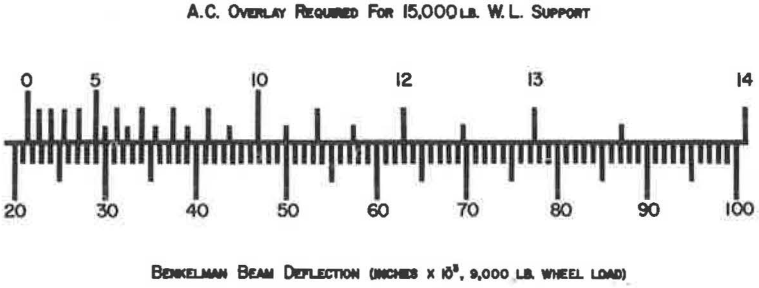


Figure 7. Asphaltic-concrete overlay requirement based on Benkelman beam deflections.

Deflections have been related to the allowable wheel load for a pavement (Fig. 6) and the ability of the overlay material to import additional strength to the structure has been established (4). From these relationships, the excess deflection may be used to establish the amount of overlay required to give adequate performance (Fig. 7).

DESIGN ANALYSIS

Using Oklahoma's Procedure for Pavement Design (6), the thickness required for 20-yr design life was developed and compared to the in-place thickness of the pavement including the thickness of overlays if the overlay thickness was 1½ in. or greater.

Questions may arise relative to the exclusion of overlay thickness less than 1½ in. This thickness, by past experience, has been accepted in Oklahoma as the least amount of overlay attributing additional strength to the initial structure (see Fig. 8). Some of

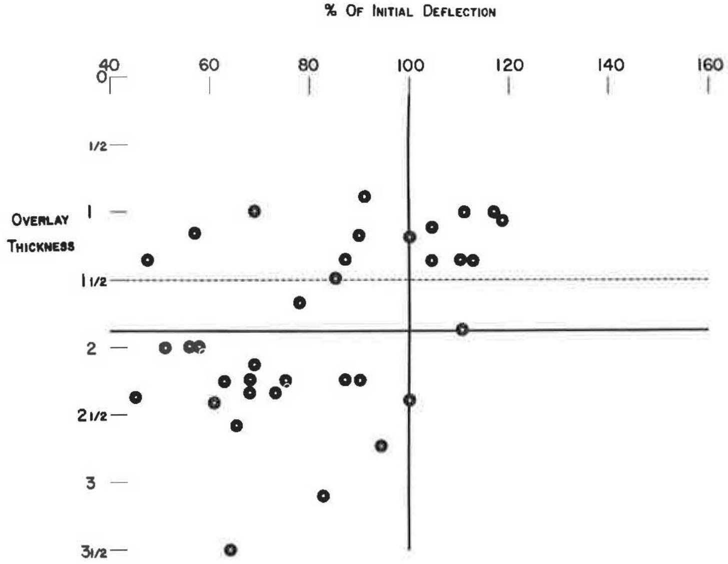


Figure 8. Overlay thickness vs deflection reduction (percent).

the scatter in this figure is accounted for by the inability to retake deflections in the same locations after the overlay had been placed, the variation in moisture conditions attributed to installation of additional underdrains, and the range of level of the initial deflections. In the areas of low initial deflection (0.020-0.025 in.) the decrease in deflection was not as noticeable as in the areas of higher initial deflection (0.040-0.050 in.).

The present design equation used by Oklahoma (4, 6) provides for increases in pavement thickness to account for traffic and climate. Because the design traffic was restricted to the year 1975 for projects authorized prior to October 1963 and the present procedure and authorization allows these designs to be updated to a 20-yr design, the increase in current pavement thickness over the in-place thickness is generally accounted for by the increase in traffic subsequent to 1975. Because the traffic effect is independent of soil type and because climate remains the same, it suffices to examine any point within the project for increase in design base thickness. The increase, if any, is recorded below the line chart in Figure 4.

Prior studies (4) indicate that asphaltic concrete has approximately 1½ times the equivalency of the base material used as a standard in Oklahoma. For this reason, the equivalent base thickness is divided by 1½ to establish the required thickness of overlay. This figure is recorded as the design overlay.

RECOMMENDED OVERLAY

After each extent of the project has been analyzed (as illustrated by the chart and table in Fig. 4), three of the parameters must be evaluated in combination to recommend the overlay thickness.

Although all projects receiving a recommendation for overlay do not qualify for immediate overlay based on present condition, the rate of deterioration can be examined and a determination made whether the "visual" condition of a particular project could be expected to meet the criteria for overlay by 1972. If it is determined that the project may qualify by 1972, it was included in the estimate of cost for completion of the Interstate System.

PRESENT SERVICEABILITY INDEX ANALYSIS

Sufficient data for determination of the serviceability-age relationship were not available to make a rational evaluation of the soil-cement base projects. Therefore, an arbitrary index level of 3.5 at this point in time was chosen as possibly qualifying the project for an overlay.

As further data become available, this portion of the procedure will be revised.

CONCLUSION

This procedure has been used for design of overlays in Oklahoma for several years and may be adjusted for various classes of highways and wheel loads. Methods similar to this have been used by others (7) with success. Each agency can, with modifications to adapt the information to its experience, use these parameters for such designs.

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