HIGHWAY RESEARCH RECORD

Number 359

Maintenance Operations and Applied Systems Engineering

8 Reports

LIBRARY
DEC 14 1971

Subject Areas

40	Maintenance, General
41	Construction and Maintenance Equipment
84	Urban Transportation Systems

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

WASHINGTON, D.C. 1971

ISBN 0-309-01975-3

Price: $2.40

Available from

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

SPONSORSHIP OF THIS RECORD

GROUP 3—OPERATION AND MAINTENANCE OF TRANSPORTATION FACILITIES

Harold L. Michael, Purdue University, chairman

Committee on Maintenance and Operations Costs (as of December 1970)

Lawrence Mann, Jr., Louisiana State University, Baton Rouge, chairman

William C. Adkins, John B. Benson, Matthew J. Betz, George A. Brinkley, Bertell C. Butler, J. L. Garner, W. L. Grecco, Foster P. Hicks, Roy E. Jorgensen, Roy W. Jump, C. O. Leigh, Dean L. Morgan, William G. Mortensen, Ian B. Packman, Gideon Schwarzbart, Ernest S. Valfer, Dillard D. Woodson

Committee on Maintenance Costs (as of December 1969)

Lawrence Mann, Jr., Louisiana State University, Baton Rouge, chairman

William G. Adkins, John B. Benson, Matthew J. Betz, George A. Brinkley, Bertell C. Butler, Tom Edwards, J. L. Garner, John M. Gibbons, W. L. Grecco, C. A. Grubb, W. G. Harrington, Foster P. Hicks, F. S. Hill, Roy E. Jorgensen, Roy W. Jump, C. O. Leigh, Edwin C. Lokken, Dean L. Morgan, William G. Mortensen, Ian B. Packman, Gideon Schwarzbart, Ernest S. Valfer, Jim West, Dillard D. Woodson

Committee on Roadside Maintenance

James F. Kelley, Massachusetts Department of Transportation, chairman

Brian E. Cox, Vern L. Dorsey, Robert H. Ellis, Wesley L. Hottenstein, James O. Kyser, vin C. Lloyd, Charles R. Miller, Thomas J. Mracek, Robert S. Ross, James A. Saunders, Alfred C. Scheer, E. E. Silva, Foster A. Smiley, Calvin A. Tottori, Ronald L. Zook

Committee on Snow and Ice Control

L. David Minsk, U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, chairman

S. M. Cardone, Francis Carr, Jr., Thomas M. Cleary, William E. Dickinson, Frederick H. Flagg, William D. Glauz, Charles W. Hoppes, J. G. Irving, Roy W. Jump, J. M. Kirtland, Richard W. Korzilius, William J. O'Brien, J. W. Reppel, David L. Richardson, P. A. Schaerer, Carl L. Schulten, Walker L. Shearer, Melvin E. Volz

Adrian G. Clary, Highway Research Board staff

The sponsoring committee is identified by a footnote on the first page of each report.

FOREWORD

The Highway Research Board Committee on Maintenance Costs has encouraged the use of economic theory, statistics, operations research, and systems techniques in planning and managing maintenance. Many maintenance supervisors have been unfamiliar with these tools. At the same time, only a small number of systems engineers have directed their attention toward maintenance problems. The committee had hoped to develop a manual, or at least a group of case study examples, that could be adapted by maintenance engineers to their operations. The papers by Betz and Butler in this RECORD were written as a part of the effort to develop such a manual. Although the committee has decided that this approach is not likely to prove fruitful at present, it is continuing to seek out and encourage reporting of related work. The paper by Tighe and Webber illustrating the use of a simulation model for planning snow and ice removal and Dunlay's paper reporting an attempt to develop a simultaneous equation econometric model of winter maintenance cost categories are outgrowths of that endeavor.

The importance of using every possible technique to control maintenance costs is clearly indicated in Tessman's paper, in which he projects financial requirements for highway maintenance in Minnesota through 1986. Unless worker productivity is raised or maintenance levels are lowered, the present functional cost of maintenance can be expected to double in less than 10 years and triple by 1986.

Three papers not directly related to economic analysis are also included in this RECORD. Bartlett, drawing on wide experience in the field of tree maintenance, suggests tree maintenance practices that should be followed to protect the public's investment in roadside development.

A paper by Young reports on the adaptation of articulated wheel loaders in snow removal. A lack of specialized maintenance equipment has created a demand for construction equipment, sometimes with modifications, that can be adapted to maintenance purposes. Young's presentation indicates that loader use can be extended from summer construction work into the winter season and thereby can decrease the unit cost for such equipment.

Anderson reports that rubber snowplow blades may be used without dislodging raised reflective traffic-lane markers. Such markers offer some significant advantages over painted lines, particularly in wet weather visibility, but they are not resistant to conventional steel-blade snowplows. It is encouraging to learn in this report that rubber snowplow blades make possible the use of raised markers in those areas where they were formerly not practicable because of their vulnerability to damage by steel plows.

CONTENTS

MINNESOTA HIGHWAY MAINTENANCE COSTS: A STUDY OF FINANCIAL REQUIREMENTS THROUGH 1986

Gerald Frank Tessman, Minnesota Department of Highways

The approach used in this study presents a reliable yardstick for determining within broad limits the extent of future resource requirements for highway maintenance. Despite efforts to improve technology and efficiency, the cost of maintaining the Minnesota state road system can be expected to soar in the next 16 years. The present total functional cost of maintenance ($39.7 million, formulated year cost, 1969) can be expected to double in less than 10 years and increase 195 percent by 1986. Gains through better administration, work methods, and equipment will be more than offset by rising costs associated with increases in traffic, increases in the total highway mileage (especially the growing proportion of freeways and expressways in the total system), addition of new activities, stricter requirements, and the increasing age of the state's Interstate and freeway systems. Rising labor compensation rates and cost of equipment and materials will further aggravate the situation and will, in fact, be the most influential factor.

•THE fact that highway maintenance costs are accelerating beyond the expectation of most state administrators comes as no shock to the highway engineer—he has prophesied it for years. But he can be likened to the age-old prophet of doom predicting the end of the world. Until he becomes specific—"the world will end Tuesday, May 8th"—and supports his contention with some logical analysis, he will not command much attention!

An objective quantification of future highway maintenance financial needs must be established if administrators and legislators are to be expected to take constructive action. Thus, it was the basic purpose of this analysis to quantify, within the normal constraints of fiscal projection processes, the future magnitude of the highway maintenance burden in Minnesota, specifically by 1975 and 1986. Our intent was to provide a more realistic basis for future highway management decisions, both administrative and political.

From the beginning of the study, we acknowledged that our findings would, in reality, be "structured speculation" regardless of the sophistication of the research techniques employed.

For each influential factor where both the relationship between cost and magnitude could be quantified and the future significance of the factor was known or could be formulated, we were faced with a factor for which an assumption had to be made. Examples of these assumptions are as follows:

1. There would be no major change in current trends concerning the development of mass transit systems that are compatible with planned highway transportation systems.
2. The highway department's identified highway construction needs would be met.
3. Technological changes in maintenance methods and equipment, although needed and expected, would be evolutionary, not revolutionary.

Sponsored by Committee on Maintenance and Operations Costs and presented at the 50th Annual Meeting.

Each assumption we made required a subjective judgment and thus is open to challenge on that basis. Nonetheless, we believe the approach used is realistic and consistent with the stated purpose of the study.

Our analysis began with an in-depth review of available literature concerning highway maintenance management research, specifically those reports dealing with the effect of various factors on maintenance costs. This was followed by a careful documentation and analysis of our own highway maintenance cost experience.

Because of circumstances peculiar to our record-keeping system, we chose to use cost accounting rather than expenditure records. Although cost data may vary from actual expenditures in any given year, especially for equipment and materials, over a period of time little, if any, total deviation was noted. The maintenance cost accounting system encompassed all of the activities traditionally considered as direct operational costs in accordance with the AASHO definition. A second projection level, the total functional cost of maintenance, was also developed, and I will comment briefly on it later in this report.

Maintenance costs on the state highway system for each year beginning in 1957 and continuing through 1969 were identified. These costs were related to a single measure of the magnitude of the maintenance work effort, namely, centerline miles of highways. To show explicitly the magnitude of fluctuations in cost over this 13-year period, the annual cost per mile was expressed as an index number with 1957-1959 serving as the base time period (Table 1). The index clearly shows the relative increase in the cost of all factors affecting highway maintenance over the cost that would result had these factors remained static. As can be seen, a fairly modest trend of increasing costs existed from 1957 through 1964. A significant change occurred between 1964 and 1965, and again between 1968 and 1969, with a somewhat stable period in between.

We sought to identify some basic factors that had a direct influence on the changes in the unit-mile cost for which (a) there existed or could be developed quantified measurements of past performance and (b) it would be possible to identify or project objectively a reasonable estimate of the future magnitude of the factor. The following factors were selected as totally meeting these criteria:

1. The increasing cost of labor, equipment, and materials, both in terms of trends toward greater utilization of more costly items or occupational classes and the influence of rising rates for these items over the past decade;
2. The effect of the changing mix of highway classifications within the total road network and the sheer technological complexity of maintaining the more sophisticated systems such as freeways (urban and rural) and expressways; and
3. The increase in road utilization in terms of rising traffic volumes.

The analysis of our highway maintenance historical cost data was basically a distillation process. For each of the factors, the extent or degree of influence was quantified and used to reduce the unit-mile cost of highway maintenance for each year. It was then possible to compute a new index that would show the change in the unit-mile costs for any given year if the specific factors under consideration remained constant.

TABLE 1

ANNUAL UNIT-MILE INDEX OF HIGHWAY MAINTENANCE DIRECT OPERATIONAL COSTS

Year	Cost Per Mile (dollar)	Index
1957	1,305.50	101.03
1958	1,338.96	103.62
1959	1,232.15	95.35
1960	1,328.55	102.82
1961	1,468.81	113.67
1962	1,522.89	117.85
1963	1,643.22	127.17
1964	1,785.12	138.15
1965	2,426.69	187.80
1966	2,425.97	187.74
1967	2,529.02	195.72
1968	2,289.13	177.15
1969	2,876.96	222.65
1957-59 avg.	1,292.14	100.00

The most prominent influence on maintenance costs proved to be fluctuations in the quantity and type of labor, equipment, and materials needed for direct maintenance operations and the effect of economic factors on the "going rate" for these resources. Inflationary pressure, specifically during the last 4 years, has played a significant part in the increase of maintenance costs. This inflationary pressure has primarily affected wage rates. Fortunately, because of the tremendous technological advances during the past decade, equipment and material costs have not increased as rapidly as the cost of labor.

Changes in the "going rates" for labor, equipment, and materials were computed and expressed in the form of index numbers for purposes of analysis. The recent increase in the cost of labor is clearly evident, and the 1969 compensation rates represent a 97 percent increase over the base period (Fig. 1). At the same time the increase in equipment costs has been very modest; costs have risen only about 13 percent over the base period (Fig. 2). The cost of maintenance materials is still below base-period levels despite a small but steady increase since 1965 (Fig. 3). An overall index (Fig. 4) was developed to express the composite impact of rising labor compensation and changes in equipment and material prices.

We have had to guard against the classification or interpretation of this change simply as inflation. Obviously, it represents more, as would easily be detected by comparing the labor index, for example, with the government's index for consumer prices.

A basic premise of this study has been the selection of a single measure of output, namely, centerline miles of highway maintained. In selecting this unit of measure, it was realized that not all centerline miles are equal in terms of maintenance complexity. Therefore, any change in this makeup from one year to another would obviously have a substantial effect on the average overall centerline mile maintenance cost.

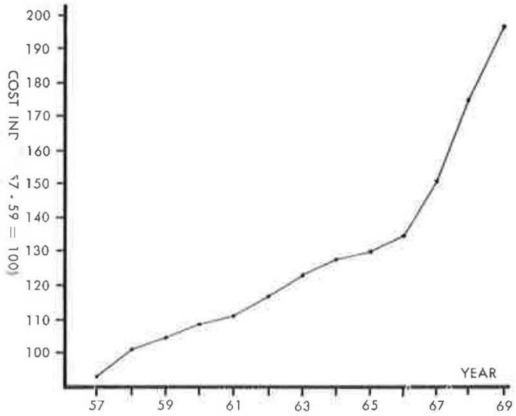


Figure 1. Labor compensation index.

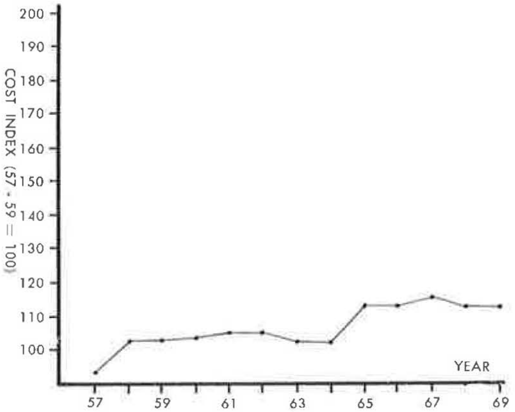


Figure 2. Equipment cost index.

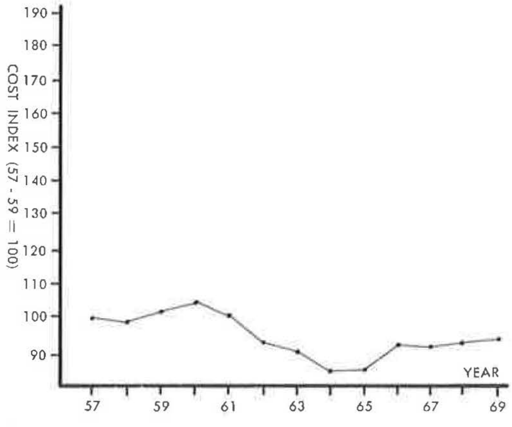


Figure 3. Materials cost index.

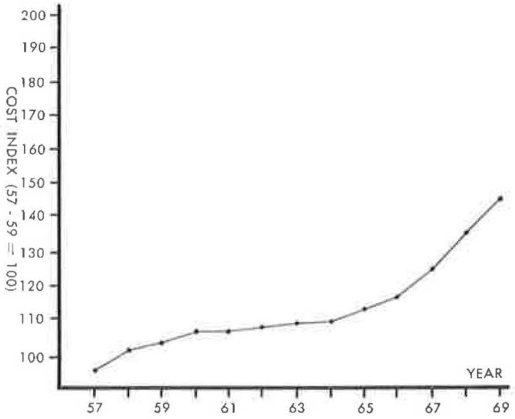


Figure 4. Composite cost index—labor, equipment, and materials.

There has been a substantial change in the overall composition of our state highway network between 1957 and 1969. Nondivided trunk highway mileage was reduced by over 600 centerline miles, whereas divided expressway and Interstate Systems, increased by 900 miles. In our analysis of maintenance costs during the 1957 to 1969 period, we were able to identify statistically a theoretical "fixed-cost" level for each type of highway system. Using the "fixed-cost" factors, it is possible to account for the extent of increase in total highway maintenance direct operational costs caused by changes in the highway systems mix.

Another important factor affecting the overall increase in highway maintenance direct operational costs is the result of expanding motor-vehicle registrations and highway travel. Higher traffic volumes affect both the upkeep of the physical elements of the highway and the extent to which operational services must be furnished. A further growing effect of high traffic volume is that it impedes the efficient performance of maintenance work.

A detailed analysis of substantial segments of our highway system, at varying traffic densities, provided a measure of the cost influence of increasing traffic in Minnesota. A positive correlation between traffic increases on our various highway systems and increasing maintenance costs is shown in Figure 5. Note that the costs are expressed in 1957-1959 dollars. The cost progression seems to be related to the difference between dual and single roadways with the trend for nondivided being somewhat steeper, which indicates that traffic increases have a more pronounced effect on the maintenance costs of nondivided highways.

Because it has been possible to quantify the effect of rising costs, changing systems mix, and increased traffic on maintenance costs, the value of unit-mile highway maintenance direct operational costs, as given in Table 1, can be statistically adjusted to indicate the cost level that would have resulted had these factors remained static. A plot of the adjusted index is shown in Figure 6 by the light dashed line superimposed over the original index. It can readily be seen that with these influences removed th cost index in 1969 drops from 223 to 132. If the impact of rising compensation and prices is excluded, changes in the systems mix and increased traffic leave a residual that we considered changes in the basic cost level.

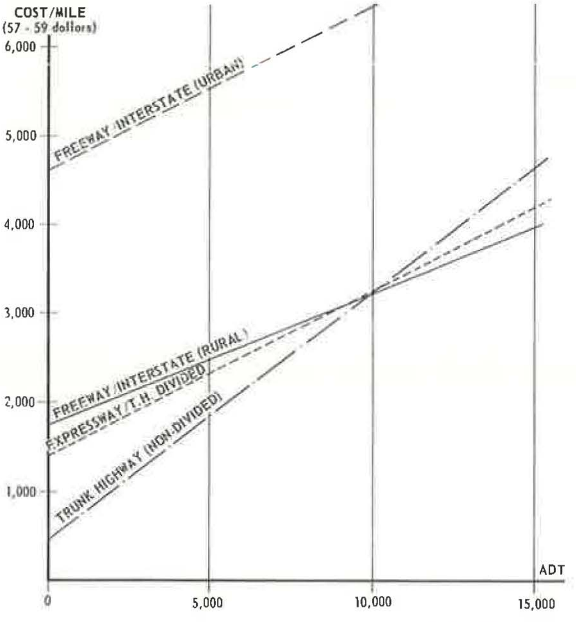


Figure 5. Relationship between maintenance costs and average daily traffic.

To establish clearly the change in the basic cost level, two further modifications were made in the adjusted unit-mile index of highway maintenance direct operational costs. First, the influence of cost changes caused by differing winter severity was negated, and, second, a representative trend line was mathematically established (shown by the bold dashed line in Fig. 6).

It should be noted that the resulting basic cost-level index for 1969 is 119. Therefore, when the influence of rising prices, changing systems mix, and increasing traffic is removed and winter severity is neutralized, the unit-mile highway maintenance direct operational costs increase modestly (only 19 percent between the base period and 1969). It was further noted that there was a negative trend during the 1967 to 1969 period that supported our subjective evaluation of the benefits achieved from an intensive maintenance wor

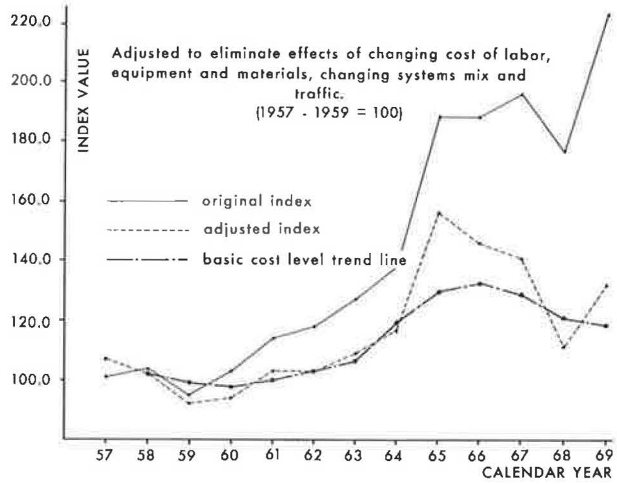


Figure 6. Adjusted index of unit-mile highway maintenance direct operational costs showing the basic cost level.

improvement program implemented during that period. From this analysis of past experience, we gained a better understanding of changes in the unit-mile cost index and developed impact formulas for cost projection.

The projection of highway maintenance direct operational costs required the development of a simulated unit-mile cost. This was a process of synthesis beginning with the actual base-period unit-mile cost level (Fig. 7). To the base-period unit-mile cost level, we added the cost of changes in the systems mix. Note that all costs are expressed in 1957-1959 dollars. These costs were developed on the basis of (a) "fixed-cost" ratios for each class of highway that were identified during the analysis of our past costs records and (b) projected mileage for each highway classification as denoted in the department's long-range highway systems plan.

Comprehensive estimates of future highway traffic volumes have been prepared as part of the process of projecting our highway construction needs. By using this information it was possible to identify anticipated traffic volumes for 1975 and 1986. By using the traffic volume forecasts and formulas developed during the study, anticipated maintenance cost increases due to greater traffic density were calculated and became part of the forecast.

Historical cost information used in this study reflects a period of time wherein pavement, shoulder, and structure maintenance requirements of the new Interstate and freeway systems were substantially below the level that will exist when the average pavement age is much greater. Until that time, unadjusted historical cost records will not provide a realistic basis for the projection of future cost levels for physical maintenance of the new Interstate and freeway systems. By using formulas concerning the relationship between age and maintenance requirements developed as part of a separate study and by analyzing cost data on completed sections of the

UNIT MILE COST* IN BASE PERIOD (BASED ON CENTERLINE MILES) + UNIT MILE COST* OF CHANGES IN SYSTEMS MIX BETWEEN BASE PERIOD AND TARGET YEARS

+ UNIT MILE COST* OF INCREASES IN TRAFFIC VOLUME BETWEEN BASE PERIOD AND TARGET YEARS + UNIT MILE COST* OF INCREASING AGE OF THE NEW INTERSTATE-FREEWAY SYSTEMS

+ UNIT MILE COST* OF CHANGE IN THE BASIC COST LEVEL BETWEEN BASE PERIOD AND TARGET YEARS = UNIT MILE HIGHWAY MAINTENANCE DIRECT OPERATIONAL COST, EXPRESSED IN 1957-1959 DOLLARS, FOR THE TARGET YEAR

*EXPRESSED IN 57-59 DOLLARS

Figure 7. Projection of highway maintenance direct operational costs (normal year).

Interstate System in Minnesota, it was possible to project the cost effect of this increase in Interstate and freeway age by 1975 and 1986, respectively. The relationship between the increasing average age of the Interstate and freeway system and the change in physical roadway maintenance costs is thus added to the forecast.

It is anticipated that changes in the scope and magnitude of the overall highway maintenance operation will result in a 3 percent annual growth in the basic cost level beginning in 1971. This represents an objective assessment of current trends and identified program needs. This rate of growth—expressed in unit-mile cost—is the final additive.

At this point we have simulated a unit-mile cost rate for highway maintenance direct operational costs, which is expressed in 1957-1959 dollars.

The next step (Fig. 8) represents the conversion of our formulated unit-mile highway maintenance direct operational cost figure from 1957-1959 dollars to target year dollars (for example, 1975 dollars). The factor necessary for this process was developed by projecting the indices of historical changes in compensation and prices shown previously. This projection was based on trends occurring during the 1957 to 1969 period. Information on future employee benefit proposals were formulated by labor and management, using the best available economic forecasts for the decade ahead. A projection was made of the annual anticipated labor compensation rates for each year from 1969 through 1975. The average annual change during this period was then used as a basis for projecting labor compensation rates from 1976 through 1986.

A similar in-depth analysis was made of equipment and material costs during the 1957 through 1969 period. As reported previously, these costs actually dropped below 1957-1959 levels for a substantial period and, in the case of materials, remained below these levels as of 1969. In both cases, however, a trend beginning in 1965 has been detected that would indicate that these costs have started to increase, although at a greatly reduced rate when compared to labor compensation costs. Although it cannot be expected that this trend will remain as moderate in the years ahead, it is anticipa that cost increases for equipment and materials will not reach the proportion that is expected in the labor market.

A composite index has been computed to reflect the combined influence of these three factors (labor, equipment, and materials). This composite index serves as a basis for determining the effect of rising compensation and prices on the maintenance program of the future. Using this projected index, the normal year unit-mile highway maintenance direct operational cost, expressed in target-year dollars, can be calculated. Further, with centerline mileage information available from the department's 20-year highway systems plan, total costs can also be formulated. We have projected normal-year costs, although anticipated plus and minus deviations resulting from aberrant winter severity have been developed.

By using the methodology just explained, it is possible to formulate normal-year total direct operational costs, in any given year, solely on the basis of information concerning changes in these influential factors.

Table 2 gives the Minnesota cost forecast for 1975 and 1986 along with formulated and actual cost for selected years between 1960 and 1969. Total direct operational costs are forecast at $53.5 million by 1975 and $106 million by 1986. These projections are based on normal winter conditions.

As noted in the preceding paragraph, direct operational costs have also been formulated for the period 1960 through 1969 by using the projection methodology. The deviation between formulated and actual cost in any given year during this period primarily represents the difference between actual winter conditions and theoretical normal conditions.

UNIT MILE HIGHWAY MAINTENANCE DIRECT OPERATIONAL COST, EXPRESSED IN 1957-1959 DOLLARS, FOR THE TARGET YEAR **X** LABOR, EQUIPMENT AND MATERIALS PROJECTED COST INDEX FOR TARGET YEARS

= UNIT MILE HIGHWAY MAINTENANCE DIRECT OPERATIONAL COST EXPRESSED IN TARGET YEAR DOLLARS **X** TOTAL CENTERLINE MILES BEING MAINTAINED IN TARGET YEARS

= FORMULATED NORMAL YEAR HIGHWAY MAINTENANCE DIRECT OPERATIONAL COSTS IN TARGET YEAR DOLLARS

Figure 8. Projection of highway maintenance direct operational costs (normal year).

TABLE 2

FORMULATED HIGHWAY MAINTENANCE DIRECT OPERATIONAL COSTS—1957 TO 1986 (Thousands of Dollars)

Item	1960	1962	1964	1966	1969	1975	1986
Cost[a] at 1957-1959 levels[b]	15.3	15.4	15.5	15.5	15.6	15.8	16.2
Increases[a] caused by changes in the basic cost level	0.0	0.4	2.9	5.2	3.0	5.5	11.0
Increases[a] caused by changing system mix	0.0	0.4	0.7	1.0	1.5	2.7	4.3
Increases[a] caused by changing traffic volume	0.1	0.6	0.8	1.2	1.8	4.8	8.4
Increases[a] caused by Interstate and freeway aging	0.0	0.0	0.0	0.0	0.0	0.2	0.8
Increases caused by rising labor compensation rates and higher prices	1.0	1.3	1.8	3.9	9.9	24.5	65.3
Total formulated normal year direct operational costs	16.4	18.1	21.7	26.8	31.8	53.5	106.0
Actual costs	15.7	18.1	21.4	29.2	34.7		

[a] Expressed in 1957-1959 dollars.

[b] The cost if all factors remained static except the number of centerline miles maintained.

Table 2 further provides a breakdown of formulated highway maintenance direct operational costs by the dominating factors that have influenced the increases noted between the 1957-1959 base period and 1969. The influence of these individual factors is also projected for 1975 and 1986.

The awesome fact about this forecast is that in the 6-year period immediately ahead (1970-1975), highway maintenance direct operational costs will increase by $5 million more than they did during the preceding 10 years. The anticipated increase between 1969 and 1986 will be 4½ times greater than the $16.5 million increase that occurred between the base period and 1969.

These projections do not include nonrecurring maintenance betterments, central office support services, and other functional costs. A second projection level, identified as the total functional cost of maintenance, includes the direct operational costs plus other maintenance-related expenditures of the department—e. g., centralized support services such as finance, personnel, and radio maintenance, the nonrecurring maintenance betterment program, and other costs of this nature. This adds an additional $8.5 million to the 1975 projection and $11.7 million to the 1986 figure.

The approach used in this study presents a reliable yardstick for determining within broad limits the extent of future resource requirements for highway maintenance. This approach is not intended as a substitute or replacement for more sophisticated techniques such as planning program budgets that will more accurately account for changing work loads, standards, levels of service, and productivity. A quantification of the projected magnitude of the highway maintenance problem, however, was considered a necessary first step in our effort to meet this challenge effectively. For the purpose intended, we believe that the approach used in this study provides a reasonable measure of future costs.

A note of caution is in order. It is not our intention that this forecast be used as a guide for the allocation of funds. The results obtained are useful for planning purposes only. The study identifies typical cost levels that might be reached by 1975 and 1986; it does not identify anticipated cash flow in any given year, either total or as a result of any specific cause. In this respect the actual dollar amounts are of less significance than the degree of change detected.

What is the value of this analysis of present and future maintenance costs?

1. It permits a more comprehensive assessment of total highway user tax revenue requirements in the future, thus allowing for systematic rather than panic solutions.

2. It helps government executives and administrators better understand the factors that influence and increase highway maintenance costs. Except for changes in the basic cost level, and to some extent changes in the system mix, the highway department can only respond to, not control, these factors.
3. It fosters new attitudes and appreciation for the increasing significance of the maintenance function.
4. It stimulates research efforts and commitment of resources thereto for the solution of the problem through new technology.
5. It provides criteria to measure the effect of policy and program changes relative to their influence on maintenance costs.
6. It generates greater top-management support for planning-program budgeting, work standards, methods improvement, and other efforts to reduce maintenance costs.

The complexity and magnitude of the highway maintenance problem is not widely appreciated outside the maintenance division. Only in recent years has maintenance management received the attention that it needs. Ineffective or nonexistent planning has been one of the more serious areas of neglect. We feel this study represents a positive step by the Minnesota Department of Highways to rectify this situation.

PLANNING AIRPORT SNOW AND ICE REMOVAL USING OPERATIONS RESEARCH TECHNIQUES

D. Tighe and D. B. Webber, Sorēs Inc., Montréal

ABRIDGMENT

•THE work described in this paper was carried out by a team of equipment engineers and operations research specialists. The analysis began in mid-1969 and was completed in December 1970.

The terms of reference for the study were established by the Federal Aviation Administration in 1967. Essentially, they called for an analytic approach that would "...describe and define in quantitative form, those factors which affect the design and

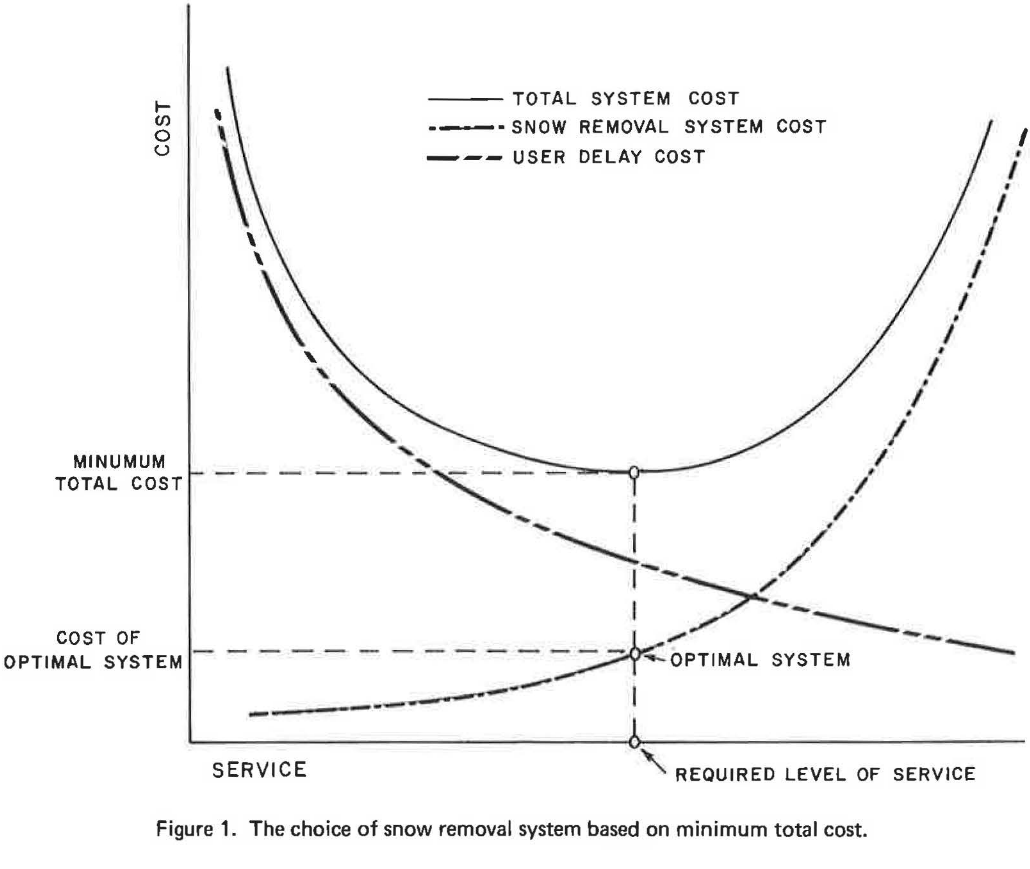


Figure 1. The choice of snow removal system based on minimum total cost.

Sponsored by Committee on Maintenance and Operations Costs and presented at the 50th Annual Meeting.

use of systems for removal of snow, ice, slush and standing water from civil airport surfaces. These descriptions and definitions should treat in detail removal system characteristics, specify critical or limiting factors of these systems, and the influence which the various physical operational and environmental factors have on system design. The systems should be applicable to all U.S. airports...."

The objective as stated is rather diffuse. Expressed more simply, the study attempted to answer two questions:

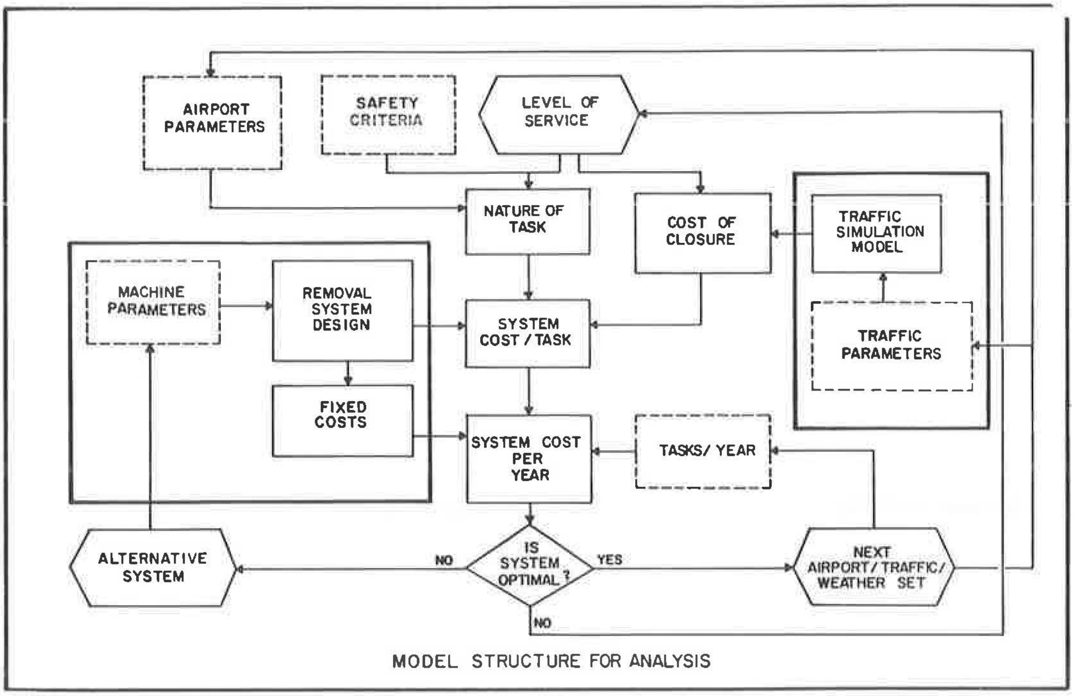
1. What level of service is an airport economically justified in giving to users?
2. What equipment and methods will give the best value for this money?

THE SNOW REMOVAL PROBLEM

It takes an investment in equipment and expenditures on labor and machine operation to make a runway safe during a snowstorm. Shortening the runway clearance interval will result in increasing costs of removal. The interruption of air traffic operations for clearance will result in user costs incurred through delays, diversions, and cancellations; however, these decrease as the interval shortens. Figure 1 shows the general variation in cost. It may be reasonably assumed that the optimum service level is that for which the total costs to airport and users is a minimum. The problem therefore is to choose the system that will ensure a minimum total cost for each airport type, level of traffic, and annual snowfall.

THE APPROACH

The objective of the general model was to calculate the total annual costs resulting from the use of snow removal systems of varying effectiveness—i.e., requiring vary-



Note:
1) Heavy lines enclose each model.
2) Dotted lines enclose inputs.
3) Other boxes show calculation.

Figure 2. An outline of the modeling approach to removal system planning.

ing intervals of time to accomplish a clearance operation (Fig. 2). This calculation in turn required (a) the design of alternative snow removal systems (Table 1) and (b) a traffic simulation model to allow evaluation of user costs resulting from different periods of runway closure (Fig. 3). By using the basic cost information provided by these submodels and taking into account the annual level of snowfall, the general model projected annual costs (Figs. 4 and 5).

To permit the use of meaningful generalizations about most real-life airport situations, a relatively large number of alternative combinations of airport, traffic, snow-

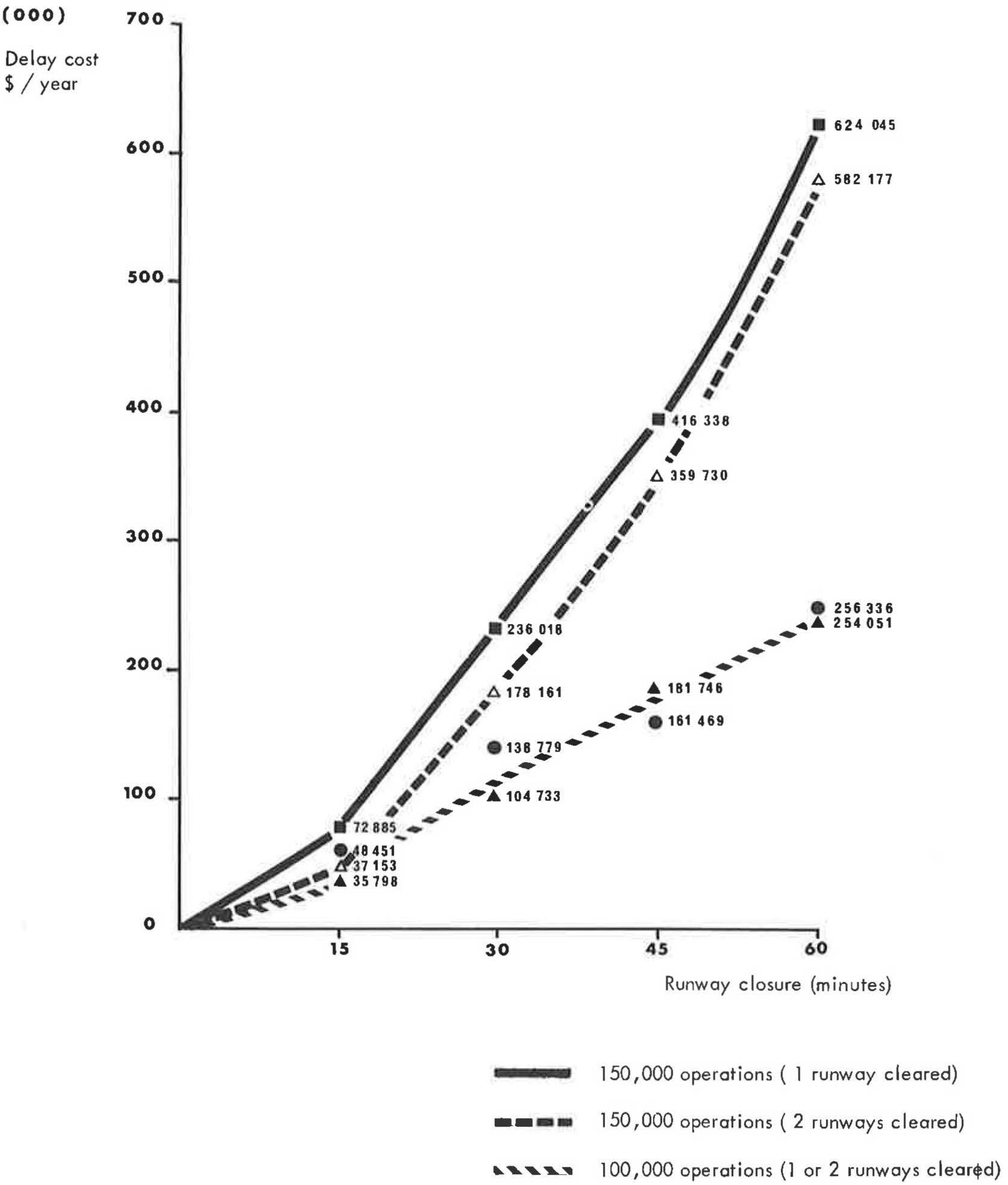


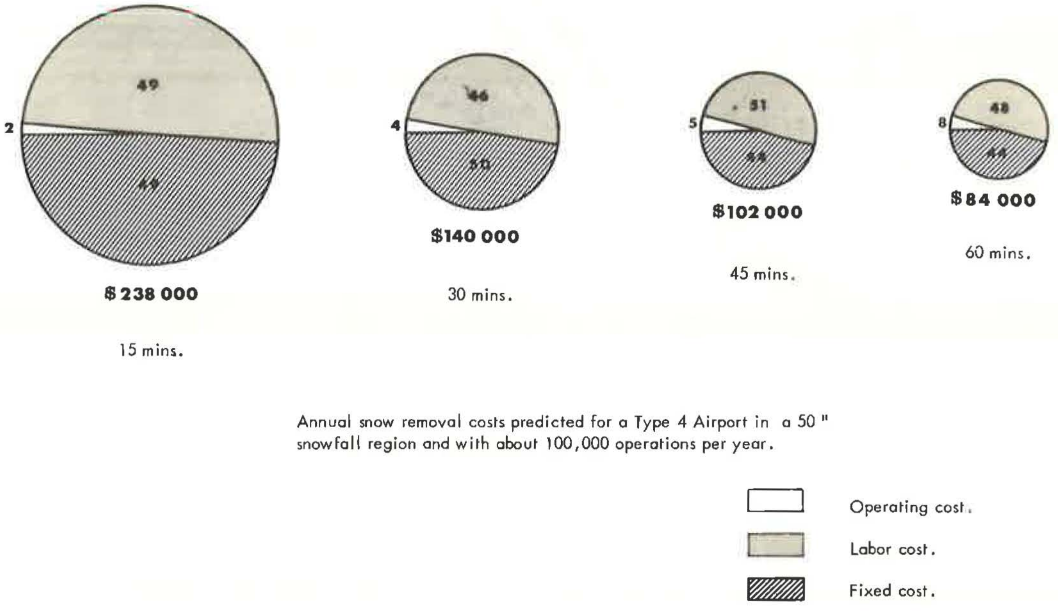
Figure 3. Annual delay costs incurred for different runway closure policies for snow removal on a type 4 airport.

TABLE 1

ALTERNATIVE EQUIPMENT PACKAGES FOR USE ON TYPE 4 AIRPORT

Clearance Time (Min)	No. of Units	Equipment Type	Capital Cost ($)	No. of Men
15	8	Sweeper	853,800	28
	10	4 × 2 plow		
	5	30-ft plow		
	3	High-speed blower		
	1	30-ft plow		
	1	Blower (small)		
30	4	Sweeper	497,500	15
	5	4 × 2 plow		
	4	30-ft plow		
	2	High-speed blower		
45	4	Sweeper	329,200	12
	4	4 X 2 plow		
	1	30-ft plow		
	1	High-speed blower		
	1	4 × 4 plow and wing		
	1	Blower (small)		
60	4	Sweeper	272,700	9
	3	4 × 2 plow		
	1	30-ft plow		
	1	High-speed blower		
75	2	Sweeper	231,500	6
	1	4 × 2 plow		
	2	30-ft plow		
	1	High-speed blower		

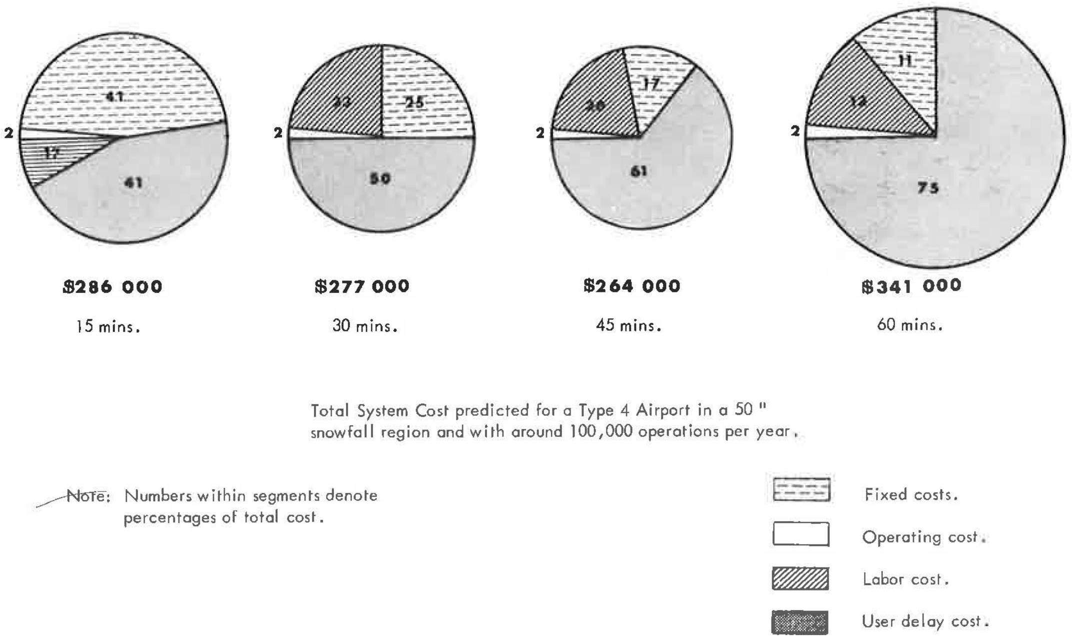
fall, and level-of-effectiveness were evaluated by using these models. Seven airport types were assumed. Levels of traffic ranged from 10,000 itinerant annual operations, of which 95 percent were assumed to be general aviation, to more than 400,000 with less than 10 percent general aviation content. Annual snowfall ranged from 25 to 125 in., and levels of effectiveness ranged from 15 min to 3 hours. Table 1 and Figures 3 through 5 provide an example of the process for one combination only.



Annual snow removal costs predicted for a Type 4 Airport in a 50 " snowfall region and with about 100,000 operations per year.

☐ Operating cost.
▨ Labor cost.
▨ Fixed cost.

Figure 4. Magnitude and allocation of removal system cost for varying runway clearance intervals.



Total System Cost predicted for a Type 4 Airport in a 50 " snowfall region and with around 100,000 operations per year.

Note: Numbers within segments denote percentages of total cost.

Figure 5. Magnitude and allocation of total cost for varying runway clearance intervals.

RESULTS OF THE STUDY

As stated previously, the study attempted to answer two questions. The first, regarding level of service, is answered by means of the diagram shown in Figure 6. By referring to this diagram the decision-maker is able to choose the service level appropriate for his airport layout, annual snowfall, and traffic intensity. The second question, concerning how this level can be achieved, is answered by reference to a diagram

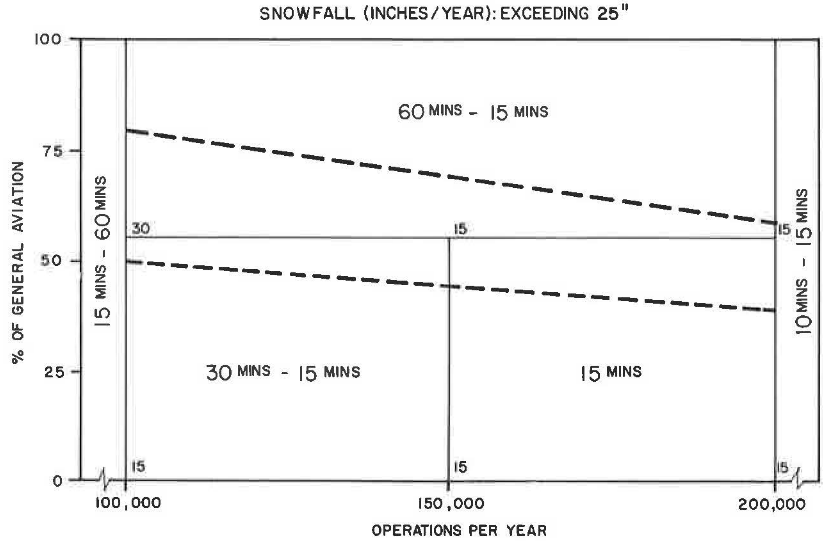


Figure 6. Runway clearance interval as a function of snowfall and traffic.

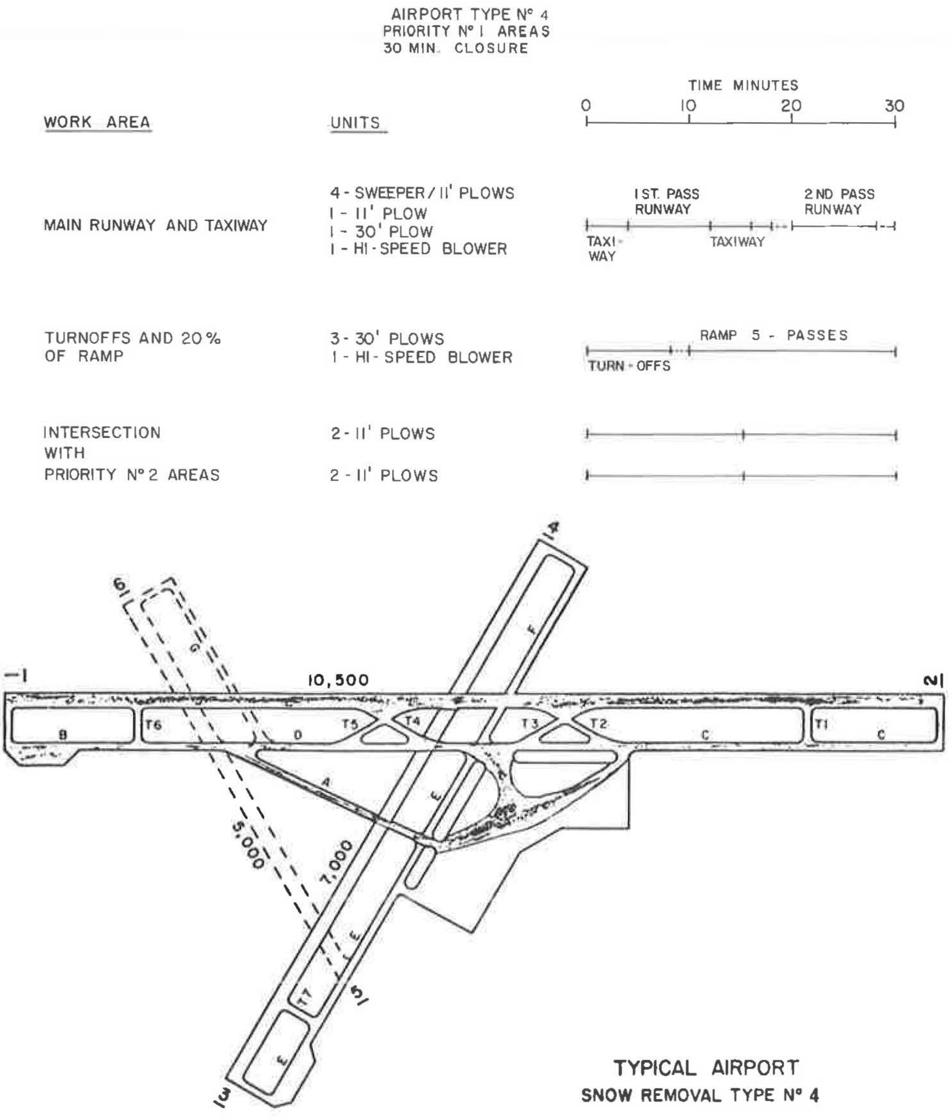


Figure 7. Equipment deployment for main clearance.

such as that shown in Figure 7, which is provided in conjunction with detailed equipment package and labor requirement specifications.

CONCLUSION

Although the study was concerned purely with airport snow removal, some parallels with the problem of snow clearance from roads or bridges may be inferred. Whether the problem area is an urban street network, a turnpike, or a bridge, the quality of snow or ice control must be based on consideration of benefits accruing to road users or the region as well as system cost. The approach to be taken, similar in its essentials, would probably comprise the following steps:

1. Derive clearance priorities for subareas or links within the road network;

2. Determine levels of service (speed of response and completeness of removal) for each link; and
3. Design removal systems, i.e., specification of types and numbers of machines, de-icing compounds, and men together with methods of deploying them for maximum effectiveness.

Where the snow and ice control task is carried out by subcontractors, the approach would generate (a) standard procedures for snow removal and ice control by subarea or link; (b) required equipment types, numbers, and manpower in each subarea; (c) required minimum performance for each subcontractor; and (d) a cost structure based on geographical area, required performance, and snowfall to allow a fair contract price to be set.

ACKNOWLEDGMENT

The study described in this paper was carried out jointly with Hovey and Associates Ltd., Ottawa, under contract with the Federal Aviation Administration System Research and Development Service. A final report containing study conclusions is available from the National Technical Information Service, Springfield, Virginia.

SOME USES OF THE STUDENT t AND CHI-SQUARE TESTS IN MAINTENANCE COST CALCULATIONS

Mathew J. Betz, Department of Civil Engineering, Arizona State University

•THIS PAPER discusses some of the uses of two statistical techniques on particular problems in highway maintenance cost evaluations. This is not intended as a thorough statistical presentation of the theory of the Student t and chi-square tests. This information can be obtained from any good statistical textbook. On the other hand, it is not meant to be an extensive compilation of example problems. It is hoped that it falls somewhere between the two, thus giving the engineer involved in highway maintenance cost calculations a general feeling for the statistical tests and a few examples that would allow him to use the statistical tests in cases that are common in highway engineering. The author has attempted to select problems that are common in this field and does not suggest that this paper covers all of the possible uses of these techniques.

Moreover, this paper should be taken as one of a series concerned with the application of statistics to highway maintenance costs. Thus, the paper will assume a knowledge of some elementary statistics. This includes a knowledge of statistical distributions, more specifically the normal distribution; a knowledge of the mean (the first moment about the origin) and other measures of central tendency; a knowledge of the variance (the second moment of the distribution about the mean) and the standard deviation; some basic concepts of probability; and the use of simple regression including tl concept of the coefficient of correlation.

CHARACTERISTICS OF HIGHWAY MAINTENANCE COSTS

Although expenditures for the maintenance and renewal of highways represent a substantial proportion of total highway expenditures, until quite recently relatively little attention had been given to the components of these costs and the analysis of their variability. It has only been in the past few years that scientific, comprehensive studies of highway maintenance have been undertaken, and the basic independent variables that affect highway maintenance have yet to be fully evaluated.

In general, highway maintenance operations and costs are difficult to analyze because of the large number of different physical operations involved, which range all the way from the patching and resurfacing of pavement surfaces to the cutting of grass and maintenance of rest areas. In addition, these operations are highly dispersed in time and place. This means that the majority of operations are relatively small in size and may be highly seasonal. Compounding the problem further is the fact that there are a large number of variables that may directly affect the various maintenance needs on a specific roadway. This in turn affects the cost. At least three major categories may be defined. The first category is the highway design characteristics, which include number of lanes, lane width, pavement design criteria, topography, etc. The second is the traffic characteristics, which include the average daily traffic volume, the percentage of trucks, the maximum wheel loads, etc. Last, there is the question of environmental characteristics. These could include temperature, precipitation (and a combination of these two), depth of frost, etc. All of these factors may affect the overall maintenance costs of the roadway. When the individual maintenance operations are evaluated separately, each of the independent variables has a different relative effect. In addition, many are closely interrelated.

Sponsored by Committee on Maintenance Costs and presented at the 48th Annual Meeting.

Although substantial highway maintenance data are now being accumulated, it is still very difficult to obtain much data where all of the parameters except the one of interest can be held constant. Thus, for most analyses the data sample size will be small. There are many cases where data that will measure the effect of only one parameter are not available.

The application of the Student t and chi-square tests is suitable in those cases where the sample size is relatively small. Therefore the use of these tests in determining statistical significance is a powerful tool in the analysis of specific maintenance parameters. They can be applied to maintenance costs of roads of different surface type, from different environmental areas, from different maintenance districts (this might indicate inefficient operation or necessary corrective measures in a particular district), or with different traffic characteristics.

USEFUL CONCEPTS

Before discussing the tests and numerical examples, it is useful to establish a few basic concepts and definitions that will be used later. The first of these is the difference between a population and a sample. A population is all of the possible items in the set under consideration. Thus, theoretically the population mean and the population variance could only be evaluated if a 100 percent count were made of all of the individuals within that population. In all highway and traffic engineering work this is a virtual impossibility because of economic restraints. Thus, in the real case the analyst must be satisfied with a sample. A sample is a selection of individual items out of the population. The reliability of the sample depends on the size of the sample. All engineers are at least intuitively aware of this in that they will put more reliance on figures based on several samples rather than on a figure based on only one observation. Thus, the parameters of the sample (the mean, variance, and other statistical values) tend to approach the corresponding parameters of the population as a sample size increases. In many cases where the sample is greater than 30 to 50 items the sample means are, for all practical purposes, equal to the population means. However, as previously indicated, very small samples may have to be used in the evaluation of highway maintenance costs.

Another useful fact that has application later in this paper is that the distribution of sample means taken from a population approaches a normal distribution no matter what the original population distribution function. For example, if a population were composed of 100 cards an equal number of which each have the numbers 0 to 9 printed on them, then the distribution of the population would be rectangular, i.e., each number would have $\frac{1}{10}$ of the total. If samples of two or more are selected from this population, it is clear that the mean of the samples would be the same as the mean of the population (in this case $4\frac{1}{2}$); however, sample means such as 0 or 9 would be quite unusual and values near the mean would be more common (Fig. 1). It can be shown that the distribution of these means is in fact a normal distribution. Furthermore, if the population function is skewed to one side or the other, the distribution of the means will also be skewed, but decidedly less so. Thus, a normal distribution can be used to compare sample means taken from a population.

The Student t and chi-square tests are used to determine whether there is a statistically significant difference between samples, between samples and populations, and between other statistical indices and some fixed value. This is accomplished by establishing a hypothesis and accepting or rejecting it. As explained in the following paragraphs, this is normally accomplished through consideration of the null hypothesis. This procedure assumes that the values are equal or from the same population and then attempts to reject this assumption. This paper will emphasize the rejection of a null hypothesis as the strongest statistical statement that can be made. The reason for this requires a knowledge of the types of errors that are inherent in the acceptance or rejection of a hypothesis.

There are two basic errors that are possible in rejecting or accepting a hypothesis. The first of these is called a type I error, which is the rejection of a hypothesis when it is true. This is associated with the alpha risk, where alpha is the probability that the error could occur. As with all statistical techniques, it is impossible to reject a

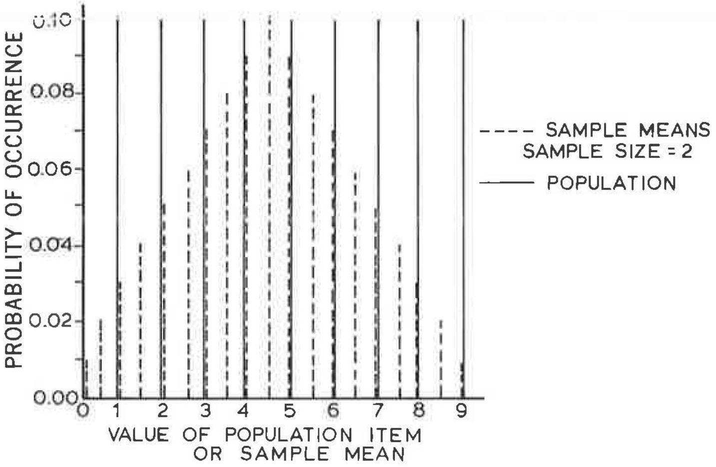


Figure 1. Distribution of a population and a mean therefrom.

hypothesis with 100 percent certainty. For example, if the acceptable alpha is equal to 0.05, the analyst is stating that he will reject the hypothesis realizing that 5 times out of 100 he will reject something that is in fact true.

The second error is the type II error, which is the acceptance of a hypothesis when it is not true. This is associated with the beta risk, where beta is the probability of this occurrence.

Thus, if one were to test whether a sample mean came from a particular population, the strongest position that could be taken would be to establish the null hypothesis (that they did in fact come from the same population) and then statistically reject this hypothesis. This involves only the selection and evaluation of the alpha risk because rejection of the hypothesis that they are the same involves only a type I error. If, on the basis of an acceptable alpha risk, one cannot indicate that the items under consideration are significantly different, then one is left with the possibility of accepting the hypothesis that they are the same. A consideration of the errors described previously would indicate that this is not as simple as the rejection of the hypothesis. The value of the beta risk must be considered. In other words, the probability of saying that they are the same when in fact they are not the same must be considered. Generally when one is attempting to reject the null hypothesis, one will select a relatively small alpha risk to ensure that his rejection will be true in the vast majority of cases. For example, an alpha of 0.05 to 0.10 is not uncommon. However, as the acceptable alpha risk is decreased in size, the beta risk increases for a sample of a given size. Although a null hypothesis may not be rejected at the 5 or 10 percent level, acceptance of the hypothesis may involve the acceptance of a substantial beta risk (often greater than 0.50) because the value of the beta risk can approach 1-α. Thus, acceptance of a hypothesis may not be desirable because of the danger of accepting something that is not fact.

THE STANDARDIZED NORMAL DISTRIBUTION

Any normal distribution can be transformed into what is referred to as the standardized normal distribution by using the following transformation:

$$Z_1 = \frac{X_1 - \mu_x}{\sigma}$$

where

Z_1 = a transformed value for the standardized normal curve,
X_1 = a value for the normal curve,

μ_x = population mean for normal curve, and
σ = standard deviation for normal curve.

Such a distribution will have a mean value of zero and a standard deviation around that mean equal to 1.0. All normal distributions can be transformed in this way. By using standardized tables for this transformed function, comparisons can be made that require the use of the area under part of the distribution function. Although not covered in this report, this procedure can be used to establish confidence limits about the mean of a population.

The standardized normal distribution is presented here because it may be used to solve a type of problem that occurs in the comparison of maintenance costs, which is similar in nature ot the problems that can be solved using the Student t test. The particular problem is the comparison of a sample mean to a population mean when the population standard deviation (σ) is known. The test statistic from the standardized normal distribution is formed by the calculation of the following quantity:

$$\frac{\overline{X} - \mu}{\sigma} (\sqrt{N})$$

where

$\overline{X}$ = sample mean,
μ = population mean,
σ = population standard deviation, and
N = sample size (number of observations).

Normally, in maintenance calculations one is concerned with both abnormally high and low figures, and thus the areas under both of the extreme tails of the distribution curve need to be considered. One can use a table of standard values and obtain the probability that the mean does in fact come from the population. Thus, if the value obtained from the table is 0.28, then 28 times out of 100 one could expect to get this value of sample mean or larger from the given population. If the probability is 0.05, then only 5 times out of 100 would this be expected. Such a low probability might lead the analyst to conclude that it did not in fact come from the population. As indicated previously, the normal technique would be to establish the null hypothesis and an acceptable alpha risk and to attempt to reject the null hypothesis. The following example indicates the use of this technique.

Suppose that data collected from a large number of locations indicate that the annual cost to maintain a 2-lane rural road is $1,200 per mile and that the standard deviation is 100. A sample of five maintenance sections is taken in an adjoining state that has a mean of $1,308 per mile per year and a standard deviation of 233. Is this sample mean significantly different from the mean of the first state (could they represent the same maintenance cost function)? An alpha risk of 0.05 or less can be accepted. Thus,

$$\frac{\overline{X} - \mu}{\sigma} (\sqrt{N}) = \frac{1{,}308 - 1{,}200}{100} \sqrt{5} = 2.40$$

From a standard table for a two-tail test, it is found that the probability that a sample mean of this value or larger could be obtained from this population is 0.016. Because this is less than the acceptable alpha risk, the null hypothesis can be rejected and we can state that the sample mean is significantly different from what would be expected from the population.

THE STUDENT t TEST

In many cases the standard deviation of the population is not known. The sample and its parameters are available. The hypothesis to be evaluated is whether this sample mean is significantly different from a population mean where the population standard deviation is not known. To accomplish this, an estimate of the value of the population standard deviation must be constructed from the standard deviation of the sample. The accuracy of this estimate is, naturally, a function of sample size. Therefore, a comparison using the standardized normal distribution as described previously might be misleading. The distribution used in this case is the Student t distribution. This is a distribution that is symmetrical around a mean, which has a value of 0 similar to the standardized normal. However, the distribution is a function of the degrees of freedom, which in turn is related to the sample size. The function approaches the standardized normal distribution as the degrees of freedom increase. At approximately 30 degrees of freedom the two functions are the same. At smaller values the Student t distribution is wider at the base than the standardized normal. The Student t distribution has several applications in the analysis of maintenance cost data.

As already indicated, the first of these is the comparison of a sample and population mean when the population standard deviation is not known. The statistic in this case is as follows:

$$t_{(N-1)} = \frac{(\overline{X} - \mu)\sqrt{N}}{S}$$

where

S = standard deviation of the sample = $\sqrt{\frac{\sum(X_i - \overline{X})^2}{N-1}}$

$t_{(N-1)}$ = Student t statistic with N - 1 degrees of freedom.

Again, the normal procedure is to establish the hypothesis that the two means are equal, to select an alpha risk, and then to attempt a rejection of the hypothesis. Standard tables of the value of the t statistic are available that present the statistic as a function of the level of significance and the number of degrees of freedom.

An example of the application of this technique may be illustrated using essentially the same data as in the previous example. In this case the population mean will still be considered as $1,200 per mile per year, but it will be assumed that the population standard deviation is unknown. The sample values will also remain the same. Because the sample size is 5, the t distribution has four degrees of freedom:

$$t_{(N-1)} = \frac{(\overline{X} - \mu)\sqrt{N}}{S} = \frac{(1{,}308 - 1{,}200)\sqrt{5}}{233} = 1.04$$

From the standard table of t values it is established that the probability of the sample mean coming from the population is greater than 0.35. Thus, the null hypothesis cannot be rejected, and the sample mean is not significantly different (at $\alpha = 0.05$) from what would be expected from the population. The statistic would have to exceed a value of 2.776 for there to be a significant difference at $\alpha = 0.05$.

Another application of the Student t distribution that is probably even more common to highway maintenance cost analysis is the determination of a significant difference between two samples means where their means and standard deviations are known but nothing is known about the population. In this case the t statistic to be used is the difference between the means divided by an estimate of the standard error of the difference between the two sample means. This may be written as follows:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sigma_{\overline{X}_1 - \overline{X}_2}}$$

where the hypothesis is that the samples come from populations with equal means and variances X_1, X_2 = sample means and $\sigma_{\overline{X}_1 - \overline{X}_2}$ = standard error of the difference between the two sample means.

Because small samples are involved the population means are unknown, and therefore an estimated standard error of the difference of the means must be calculated based on the sample deviations and the sample sizes. Thus, the statistic may be rewritten as follows:

$$t_{(N_1 - 1 + N_2 - 1)} = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{N_1S_1^2 + N_2S_2^2}{N_1 - 1 + N_2 - 1}}\ \sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$$

where

$t_{(N_1 - 1 + N_2 - 1)}$ = the t statistic with $N_1 - 1 + N_2 - 1$ degrees of freedom,
N_1, N_2 = sample sizes, and
S_1, S_2 = sample standard deviations.

In addition, the use of the foregoing formulation of the statistic assumes that the samples are independent. This would normally be the case for highway maintenance cost samples. The t distribution can also be used for nonindependent samples, and any statistics text will give the formulation of the t statistic in this case.

For example, assume that a highway maintenance cost sample was taken from another state with roads having characteristics similar to the previsously used sample. This second sample has a mean of $1,230 per mile per year and a standard deviation of 162. The sample size is five. (The sample sizes need not be equal.) The hypothesis is that the two sample means come from the same population. The α value is set at 0.05. Thus,

$$t_{(5 - 1 + 5 - 1)} = \frac{1{,}230 - 1{,}308}{\sqrt{\frac{5(162)^2 + 5(233)^2}{5 - 1 + 5 - 1}}\ \sqrt{\frac{1}{5} + \frac{1}{5}}}$$

$$= \frac{78}{\sqrt{50{,}188}\ \sqrt{0.40}} = \frac{78}{224(0.633)} = 0.55$$

Using a table of t values for 8 degrees of freedom, it is established that these could be expected to come from the same population more than 50 percent of the time. Thus, the null hypothesis cannot be rejected at $\alpha = 0.05$. The value of the statistic would need to exceed 2.262 in order to reject the null hypothesis at that alpha level.

The last application of the Student t test to be discussed here is somewhat different from the preceding. The t distribution can be used to evaluate if a correlation coefficient, r, in simple correlation is significantly different from zero. The question is often raised in correlation analysis as to the satisfactory value of the correlation coefficient. This is a most difficult question to answer and probably varies depending on the type of problem and sources of data. In many cases the correlation coefficient that would not be acceptable in measuring physical properties might be highly acceptable in measuring socioeconomic relationships. This is one case where the rejection of the null hypothesis may not be as meaningful to the analyst as the inability to reject the hypothesis. Again, the analyst must be cautioned that the inability to reject the hypothesis does not necessarily mean the acceptance of it. More specifically, then, the test can be used to reject the null hypothesis that the coefficient or correlation is equal to zero. If this is rejected, it still does not answer the question as to whether the correlation coefficient is acceptable in a given analysis. However, it would seem that if it cannot be rejected, i.e., if it cannot be said that the coefficient or correlation is different from zero, then this would cast considerable doubt on the meaningfulness of the relationship between the dependent and independent variables.

The Student t test can be used to test the difference from zero in simple correlation for linear or nonlinear relationships. In multiple correlation, a similar hypothesis test can be conducted using the F test, which is not discussed in this paper. The testing of partial correlation coefficients can be accomplished by the t test. In each case, the statistic is somewhat different. The only example included here is where simple linear regression is considered. In this case, the t statistic is as follows:

$$t_{(N-2)} = r\sqrt{\frac{(N-2)}{1-r^2}}$$

where

$t_{(N-2)}$ = the t statistic with N - 2 degrees of freedom,
r = simple correlation coefficient, and
N = number of points (observations) in correlation analysis.

Figure 2 shows a plot of maintenance effort as a function of average annual daily traffic. Also included is a plot of the trend line established by conventional correlation analysis. The value of the correlation coefficient for these data is 0.721. An observation of the trend line and data would indicate that no strong trend is evident. It is possible that a number of analysts, because of the r value, might accept this as a significant indication of relationship. Part of this may be due to a built-in bias on the part of the analyst in that he feels there should be a relationship. Thus, an evaluation of the significance of the correlation is of interest. The statistic is

$$t_{(7-2)} = 0.721\sqrt{\frac{(7-2)}{1-0.52}} = 2.34$$

To reject the hypothesis with an alpha value of 5 percent or less, the statistic would need to equal or exceed 2.571. Therefore, in this case, the analyst cannot state that this correlation is significantly different from zero. If a type I error were allowed 10 times out of 100, then it could be stated that the correlation coefficient is significantly different from zero for the standard tables to show that the statistic need only exceed 2.015.

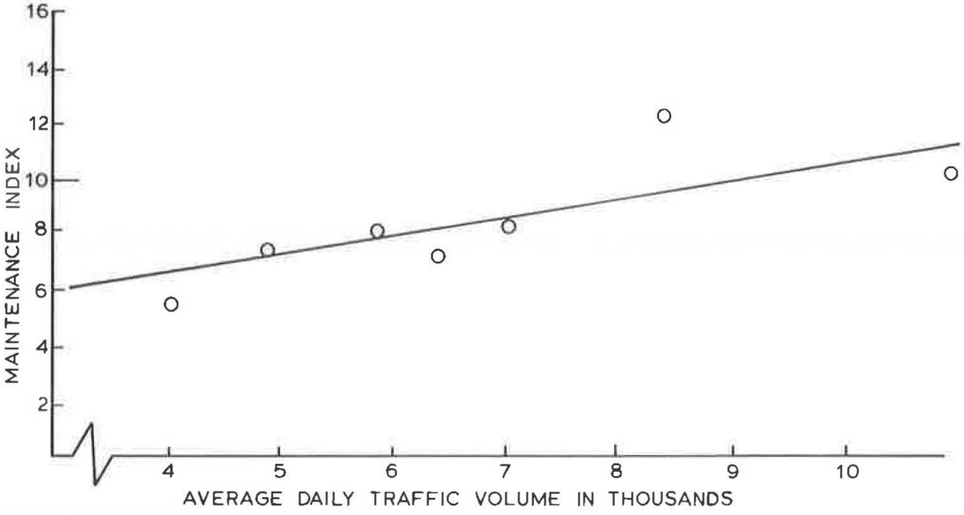


Figure 2. Maintenance effort versus traffic volume.

THE CHI-SQUARE DISTRIBUTION

The chi-square distribution is the function that would be obtained when values of sample variances are repeatedly drawn from a normal distribution. Naturally, this distribution function is related to sample size as was the Student t distribution. The chi-square statistic is normally proportional to the square of the difference from the sample value divided by the expected value. The distribution itself is skewed to the right at lower degree of freedom values. As the value of the degree of freedom increases, the function approaches symmetry around a mean that has a value of the number of degrees of freedom. Therefore, a chi-square distribution with 15 degrees of freedom is fairly symmetrical around the value 15.

Because the chi-square distribution represents the expected variation of sample variances taken from a population, it can be used in a manner similar to the standardized normal curve for evaluating the significant difference between a sample variance and a population variance when the population variance is known. The chi-square statistic in this case is as follows:

$$\chi^2 = \frac{(N - 1)S^2}{\sigma^2}$$

This type of problem is not common in the statistical analysis now generally used for maintenance cost data. It is more useful for the study of the range of errors that may be expected rather than the direct evaluation of significant differences between samples and populations. Therefore, no example is included.

However, the chi-square test can also be used where the expected frequency of occurrences may be developed through probability. This permits its use in an area that is much more meaningful to highway maintenance costs and to a much broader range of problems, including the evaluation of the performance of maintenance crews and equipment. The procedure is to establish the theoretical frequency of occurrences and then to establish the null hypothesis that the actual observed occurrences come from the same distribution. Again, an acceptable alpha risk will need to be established. The application of the technique and the details of calculation are probably best explained through the use of an example.

One may wish to compare several brands of equipment, each of which is supposedly designed for the same job and the same capacity. The index of equipment maintenance could be the number of hours of maintenance over a given time span. Model A needed 9 hours of maintenance whereas model B needed 23, model C needed 20, and model D needed 16. The null hypothesis is that this distribution could have come from a population where each had equal maintenance. The χ^2 statistic is

$$\chi^2_{(N-1)} = \sum \frac{(f - f_e)^2}{f_e}$$

where

$\chi^2_{(N-1)}$ = chi-square statistic for N - 1 degrees of freedom,
N = number of items (rows),
f = actual value, and
f_e = expected value (note: value should exceed five).

Table 1 gives the data for calculation of the statistic.

If the alpha risk were established at 0.05 or smaller, the χ^2 statistic would need to be 7.815 or larger to reject the null hypothesis. Therefore, the analyst cannot say that this distribution is significantly different from one where all units have equal maintenance requirements.

If one would accept an alpha of 0.10, standard tables would indicate that χ^2 need only exceed 6.251, for three degrees of freedom, to reject the null. Therefore, in one were willing to be wrong 1 in 10 times, one could say this distribution is significantly different

TABLE 1

STATISTIC DATA

Model	Actual Value f	Expected Value* f_e	$f - f_e$	$(f - f_e)^2$	$\frac{(f - f_e)^2}{f_e}$
A	9	17	-8	64	3.76
B	23	17	6	36	2.12
C	20	17	3	9	0.53
D	16	17	-1	1	0.06
Σ	68	68			6.47

*The expected number of hours of maintenance if all models required an equal amount.

TABLE 2

CALCULATION OF χ^2

Operation	f	f_e	$f - f_e$	$(f - f_e)^2$	$\frac{(f - f_e)^2}{f_e}$
Tire	70	54	16	256	4.74
Other minor	60	72	-12	144	2.00
Motor	25	36	-11	121	3.36
Other major	25	18	7	49	2.72
Σ	180	180			12.82

from a case where all units could be expected to have equal maintenance. Further analysis could indicate that the difference is due to model A. This would indicate that A is better than the others at some level of alpha.

In the preceding example, each item was assumed to be equivalent to the other and therefore to have an expected frequency equal to the others. This assumption is not necessary for the application of the chi-square test to this type of problem. The following example indicates the application of a case where this is not true.

Assume the following: When a given type of equipment needs maintenance, previous experience has shown that 30 percent of the time it is for tire or track repair, 40 percent for other light maintenance, 20 percent for motor removal and overhaul, and 10 percent for other major repair. In a particular job location, the frequencies have been 70, 60, 25, and 25, respectively. The null hypothesis is that these frequencies come from a population with the historical distribution. The calculation of χ^2 is given in Table 2.

The standard χ^2 table indicates a rejection of the null hypothesis with $\alpha = 0.05$ and 3 degrees of freedom when the statistic exceeds 7.815. Therefore, the null hypothesis can be rejected in this case. In fact, it can be rejected with an alpha of less than 0.01 (i.e., with a chance of error of less than 1 in 100). Thus, there is something unique about the job or location that may need investigation.

There are innumerable maintenance and maintenance cost problems that can be structured in the same way. For the analysis of maintenance costs, the use of chi-square is probably the most important of all the tests discussed in this paper.

CONCLUSIONS

This paper has tried to indicate briefly some applications of the chi-square and Student t tests to highway maintenance problems. It has discussed the establishment of hypotheses and the types of errors involved. Several examples of different types of highway maintenance problems have been presented. It is hoped that this paper will interest highway maintenance analysts in the use of these statistical techniques in the evaluation of their data.

ACKNOWLEDGMENTS

The author would like to thank Mr. Robert L. Lynch for his help during the preparation of this report and Dr. O. B. Moan for his review of the draft document.

REFERENCES

1. Betz, Mathew J. Highway Maintenance Costs—A Consideration for Developing Areas. Highway Research Record 94, pp. 1-27.
2. Bowker, Albert H., and Lieberman, Gerald J. Engineering Statistics, 7th Printing. Prentice Hall, Englewood Cliffs, N. J., 1965.
3. Byrd, L. G. Interstate Highway Maintenance Requirements. Meeting Preprint 594, ASCE National Meeting, San Diego, Calif., Feb. 1968, 9 pp.
4. Croxton, Frederick E., and Cowden, Dudley J. Applied General Statistics. Prentice Hall, New York, 1955.
5. Davis, D. W. Highway Maintenance. Proc. 2nd North Carolina Highway Conference, 1960, pp. 40-43.
6. Dixon, Wilfrid J., and Massey, Frank J. Jr. Introduction to Statistical Analysis. McGraw-Hill, 1957.
7. Greenshields, Bruce D., and Wyeda, Frank M. Statistics With Applications to Highway Traffic Analysis. Eno Foundation, Saugatuck, Conn., 1952.
8. Jorgensen, Roy, and Associates. Highway Maintenance Operations in Virginia. Virginia Maintenance Study, Jan. 1966.
9. Leonhard, William E. A Study of the Effect of Income on Trip Characteristics for Tucson, Arizona. Unpublished thesis, Arizona State University, June 1968.
10. Schwar, Johannes F., and Puy-Huarte, Jose. Statistical Methods in Traffic Engineering. Ohio State University, Engineering Experiment Station, Spec. Rept. 26, 1962.
11. Tallamy, Bertram D., Associates. Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index. NCHRP Rept. 42, 1967, 144 pp.

REGRESSION AND CORRELATION METHODS IN HIGHWAY MAINTENANCE OPERATIONS

Bertell C. Butler, Jr., Byrd, Tallamy, MacDonald, and Lewis

Regression-correlation analysis is explained with a minimum of theory, and its use is illustrated in a simple linear bivariate example. A regression relationship is established between highway maintenance expenditures and gasoline consumption. A coefficient of correlation is determined and tested for significance. Confidence limits are established for the regression curve. The application of regression-correlation for various highway maintenance functions is discussed, and the merits of the technique are emphasized.

•AS the mileage of modern divided controlled-access highways and the percentage of surface mileage increase to serve increasing traffic volumes, the highway maintenance engineer is faced with the need to provide additional service and a higher quality of maintenance. This need increases the demand for the highway maintenance dollar and makes it imperative that every technique available be exploited to reduce maintenance cost and improve the use of available resources.

The areas of highway maintenance that can be improved vary from operational procedures to long-range maintenance planning and budgeting. Within this spectrum there exists an infinite variety of cause-and-effect situations where a better understanding of the actual relationships could be used to improve the execution of the highway maintenance function.

This paper was prepared in an effort to encourage the use of the techniques of regression and correlation analysis, which are particularly suited to explaining and defining such relationships. Furthermore, the emphasis in this paper is on the application and use of the techniques rather than on their theoretical development.

Briefly, regression analysis is a mathematical technique used to create the most probable equation to define the relationship between variables. Correlation analysis is used to measure how well the equation actually explains the relationship. Regression equations can assume any number of forms—e. g., linear, cubic, parabolic—and can be used to establish the relationship among any number of variables. For simplicity, a linear bivariate situation will be used to illustrate the technique; that is, the relationship between two variables will be defined by a straight line determined by using a regression analysis.

To begin, consider the following situation. You have been charged with the task of determining the possibility of establishing a maintenance requirement formula based on traffic volume. Before devoting a lot of time to developing the necessary data, you decide to test for a relationship using data available in "Highway Statistics" (1). You find that available traffic volume data cannot be associated with maintenance expenditures. However, gasoline consumption on the highways, which can be directly related to vehicle miles, can be associated with total maintenance expenditures on all the roads in each state. Therefore, you decide to make a quick check of the relationship, if any, between gasoline consumption per mile and maintenance expenditures per mile. Using a table of 2-digit random numbers, you select 10 states to use as a sample. Gasoline consumption, maintenance expenditures, and total state mileage for the 10 sample states

---

Sponsored by Committee on Maintenance Costs and presented at the 48th Annual Meeting.

are obtained from the appropriate tables (1). Dividing both gasoline consumption and maintenance expenditures by mileage provides comparable information for each of the 10 sample states.

The objective is to determine if there is any relationship between gasoline consumption and maintenance cost. A good first step is to plot the values on graph paper, which provides a pictorial indication of the probable form, shape, and strength of any relationship that might exist. Conventionally, one variable is considered independent and is plotted on the horizontal axis; the other is dependent and is plotted on the vertical axis. For the example, gasoline consumption will be considered as independent and maintenance cost as dependent. The plot is shown in Figure 1; this type of plot is frequently referred to as a scatter diagram. Examination of the scatter diagram reveals a trend of increasing cost with increasing gasoline consumption, which confirms the original feeling that such a relationship might exist.

One way to establish the relationship between gasoline consumption and maintenance cost is to eyeball a curve through the points on the scatter diagram. This approach frequently produces a satisfactory measure of the relationship between the variables; however, it has several drawbacks. This approach can only be used for the two-variable situation. No two people are apt to draw the same curve, which raises questions concerning the objectivity of the curve or suggestions of prejudice on the part of the person fitting the data. Also, it is frequently desirable to measure how well the curve fits the data, which can only be determined subjectively for the eyeballed curve. Finally, the curve cannot be duplicated by others with the same data.

Regression analysis eliminates those drawbacks by formalizing the curve-fitting procedure. To see how the technique was developed, we begin by eyeballing a curve through the plotted points, as shown in Figure 2. The curve selected is a straight line, and it appears to fit the data as well as any other curve that might be drawn to define the relationship between gasoline consumption and maintenance cost. A straight-line model takes the general form $y = a + bx$ where b is the slope of the line and a is the y-intercept. For the example, x (the independent variable) is gasoline consumption in gallons and y (the dependent variable) is maintenance cost in dollars. The a and b values for the eyeballed curve are zero and 0.43, respectively, creating the equation $y = 0.43x$. Certainly this equation is one way of defining the relationship between x and y. However, it is not necessarily the best way because other curves might be drawn that would be closer in an overall sense to all of the points. This suggests that the first requirement in formalizing

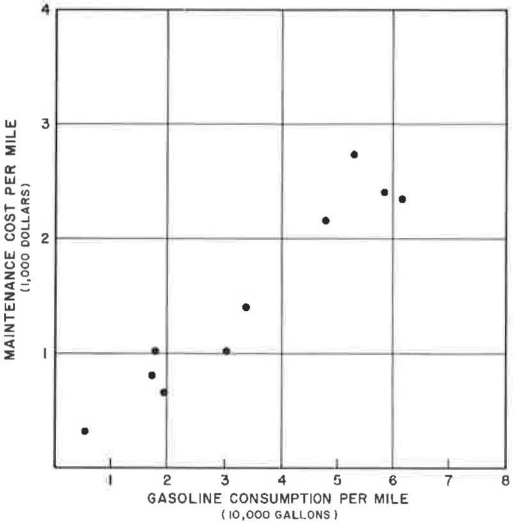


Figure 1. Scatter diagram.

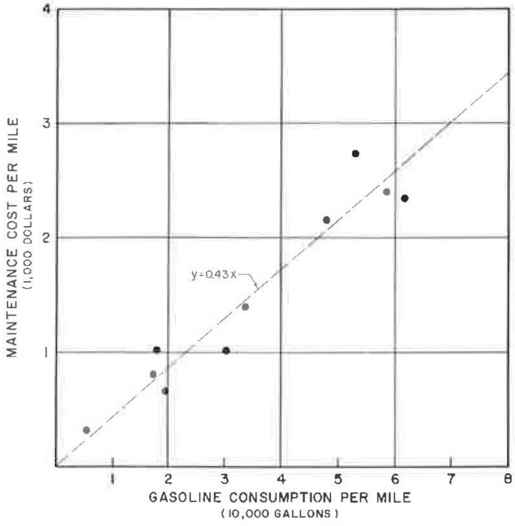


Figure 2. Eyeballed curve.

a technique to establish the best curve is to establish a method for evaluating the closeness of any curve drawn through the points. One such method is to measure the overall discrepancy between any curve and the plotted points. Then the curve that produces the minimum value for the sum of all discrepancies (vertical deviations) can be defined as the best. At first glance this would appear to be a fine solution. However, the discrepancies will have both positive and negative values. Consequently any number of curves, some producing very poor fits, could approach zero value. To eliminate the sign the deviations are squared. It can then be hypothesized that the best curve expressing the relationship between x and y is obtained when the sum of the squared deviations from the curve is minimized. As it turns out, this line is analogous to the arithmetic mean, commonly known as the average, which has the following important properties:

1. The sum of the deviations of a group of values from the mean value of the group equals zero.
2. The sum of the squares of the deviations of a group of values is a minimum when their origin is the group mean value.

In other words, the hypothesized curve will be the mean curve for the data. The procedure used to obtain the curve is known as the method of least squares, and it produces the line of best fit, also called the line of regression.

The regression line for the sample problem can be found by substituting the numeric values for the sum of the y's, x's, xy's and x^2's into the following two equations:

$$\Sigma y = na + b\Sigma x$$

$$\Sigma xy = a\Sigma x + b\Sigma x^2$$

These equations are referred to as the normal equations for bivariate linear regression and are derived using differential calculus theory, which states that the maximum or minimum value of a mathematical expression is always accompanied by a zero derivative at that point.

The total number of observations is represented by n and in the sample has the value of 10. To simplify the presentation of the numeric values needed to solve for the regression line, these values are given in Table 1.

Solving the equations for a and b produces the values

$$b = \frac{n\Sigma xy - \Sigma x \Sigma y}{x\Sigma x^2 - (\Sigma x)^2} = \frac{10(65.810) - (34.55)(14.87)}{10(153.785) - (34.55)(34.55)} = 0.419$$

$$a = \frac{\Sigma y}{n} - \frac{b\Sigma x}{n} = \frac{14.87}{10} - \frac{0.419(34.55)}{10} = 0.038$$

and therefore the resulting regression equation becomes

$$y = 0.038 + 0.419x$$

This regression curve has been plotted in Figure 3, where it is compared with the original eyeballed curve. The difference is nominal; however, it is important to remember that the regression curve can be duplicated by anyone possessing the same data, whereas the eyeballed curve cannot.

The curve that was just determined was the result of regressing y on x. Actually, x could have been regressed on y and a similar line calculated. However, it should be noted that the two curves will not be the same.

TABLE 1

SAMPLE OBSERVATION VALUES FOR REGRESSION ANALYSIS

x	y	xy	x^2	y^2
1.75	0.81	1.418	3.063	0.656
5.81	2.41	14.002	33.756	5.808
4.78	2.17	10.373	22.848	4.709
3.03	1.04	3.151	9.181	1.082
5.30	2.73	14.469	28.090	7.453
0.58	0.32	0.186	0.336	0.102
1.79	1.01	1.808	3.204	1.020
3.37	1.39	4.684	11.357	1.932
6.17	2.34	14.438	38.069	5.476
1.97	0.65	1.281	3.881	0.423
34.55	14.87	65.810	153.785	28.661

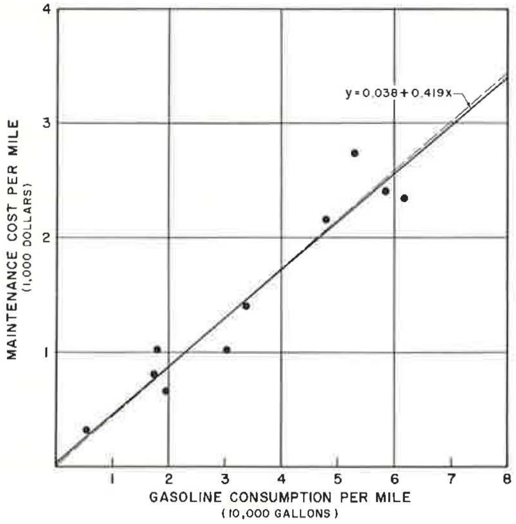


Figure 3. Regression curve compared with eyeballed curve.

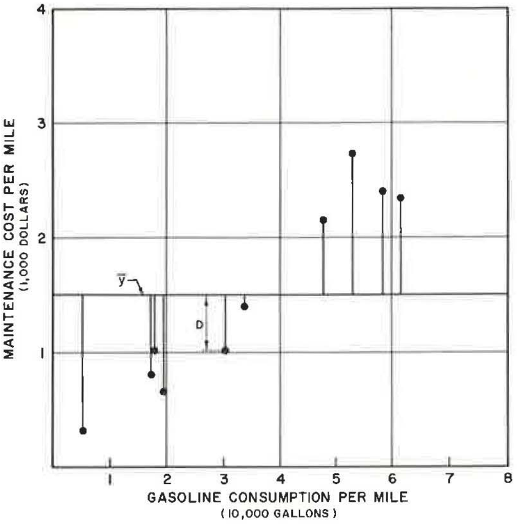


Figure 4. Deviations (D) in y about the y mean value ($\overline{y}$).

For two-variable situations a fairly good measure of how well the regression curve fits the data can be inferred by noting how closely the observations cluster about the regression curve on a scatter diagram. Again this is subjective, i.e., the observations are closely or widely spread. This is not very definitive, and certainly some sort of a quantitative measure would prove far more useful.

In Figure 4 a horizontal line has been drawn through the sample data to depict $\overline{y}$, the mean value for maintenance cost per mile. Further, it is known that, without additional information, $\overline{y}$ (mean) is the best single estimate of y for the given sample data. A series of vertical lines has been drawn between $\overline{y}$ and each y value. It is also known that the sum of the squares of these vertical deviations has a minimum value when their origin is the group mean value.

The regression curve was developed to provide the best estimate of y for any given x value. Therefore, the deviation of y about the regression curve should be considerably smaller than those about $\overline{y}$ if in fact there is any relationship between x and y. These deviations are shown in Figure 5 and are obviously smaller. In Figure 6 the portion of the vertical deviations about $\overline{y}$ that have been explained by the regression curve are illustrated. It can be shown that the sum of the squares of the deviations about $\overline{y}$ is equal to the sum of the deviations explained by the regression plus the sum of the squares of the deviations about the regression curve. This relationship provides the basis for defining the coefficient of correlation and can be mathematically expressed as

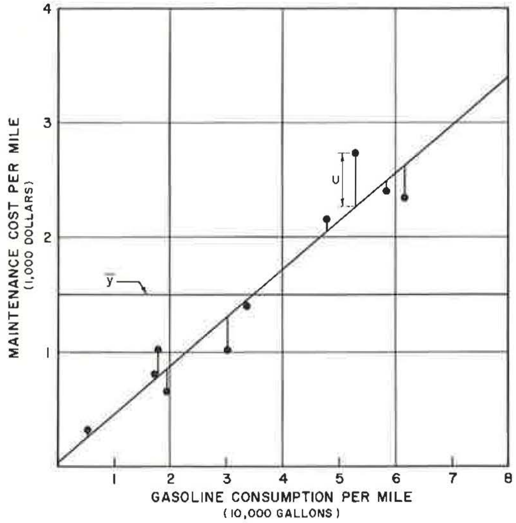


Figure 5. Deviations (U) in y about the regression curve.

$$\Sigma D^2 - \Sigma E^2 + \Sigma U^2$$

where

ΣD^2 = the sum of the squared y deviations and about the mean value,
ΣE^2 = the sum of the squared explained portions of the y deviations about the y mean value, and
ΣU^2 = the sum of the squared unexplained portions of the y deviation about the y mean value. (This is the same as the y deviations about the regression curve.)

Both sides of this expression are divided by ΣD^2 to produce

$$\frac{\Sigma E^2}{\Sigma D^2} + \frac{\Sigma U^2}{\Sigma D^2} = 1 \qquad (1)$$

When ΣE^2 equals ΣD^2 all of the variation about the y mean has been explained by the regression curve; therefore perfect correlation exists. This perfect correlation is defined as unity. From Eq. 1 it is clear that $\Sigma U^2/\Sigma D^2$ must be zero at this point. Conversely, when ΣU^2 equals ΣD^2 none of the variations about the y mean has been explained by the regression curve, and therefore the regression curve coincides with the horizontal line passing through the y mean value. Again, examining Eq. 1, it is equally clear that $\Sigma E^2/\Sigma D^2$ must be equal to zero at this point. The coefficient of linear correlation has been assigned the symbol r and is now defined by

$$r = \sqrt{\frac{\Sigma E^2}{\Sigma D^2}}$$

which is the square root of a portion of Eq. 1. The value of r cannot exceed unity and therefore r must fall between the values -1 and +1, representing perfect negative and positive correlation respectively. When r becomes zero no correlation exists, and the regression line coincides with the horizontal line passing through the y mean value. To compute r, the values given in Table 1 can be substituted into the working equation

$$r = \frac{n\Sigma xy - \Sigma x \Sigma y}{(\sqrt{n\Sigma x^2 - (\Sigma x)^2})\ (\sqrt{n\Sigma y^2 - (\Sigma y)^2})}$$

Substituting the appropriate values into the expression for the coefficient of correlation (r) produces a value 0.961. This value is quite close to 1 and therefore indicates that most of the deviations about the y mean value have been explained by the regression curve. The square of r (denoted r^2) is frequently a more convenient way to express the degree of the relationship and is known as the coefficient of determination. The advantage of using r^2 is that it expresses the direct portion of the variance in y about the y mean value that can be explained by a knowledge of x. The variance (V) is a measure of the variation in y about the y mean and is defined by

$$V = \Sigma D^2/n$$

For the example, it can be stated that 92 percent of the variance (V) has been explained by the regression curve relating x

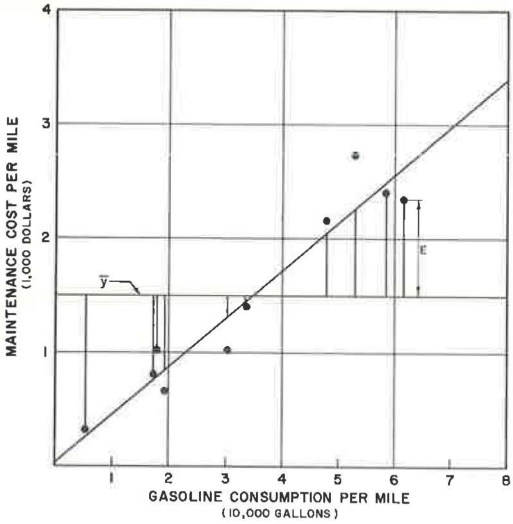


Figure 6. Deviations explained by regression (E) in y about the y mean value ($\bar{y}$).

and y. A regression analysis can also be made to develop the best fitting curve where a known relationship exists, but because of measurement errors the indicated relationship is erratic. This is referred to as fitting a functional relationship in contrast to the relationship illustrated. It should be noted that the coefficient of correlation has no meaning where a functional relationship is known to exist.

The regression curve, the coefficient of determination, and the coefficient of correlation are statistical descriptions of numerical data. Such descriptive measures are essential to any understanding of the processes that generate data. Therefore, in the example, the regression equation and the coefficient of correlation are suitable measures to describe the 10 sample observations. However, that is all they do. The more general application is to make statements concerning the general nature of things that can be inferred from the example analysis. In other words, what is the nature of the relationship between x and y for 50 states? Is the measure of correlation r meaningful or could it have occurred by pure chance? How accurately can the relationship predict unknown y values for given x values? The answers to these questions are found through using the techniques of statistical inference that are based on probability theory. A profusion of material exists covering this complex subject, and therefore to avoid obscuring the objectives in this paper no further attempt will be made to develop basic concepts. However, to understand some of the wider applications of a regression-correlation analysis, references will be made to various tests and techniques that are used in drawing conclusions from statistical data.

Consider the regression equation developed to fit the sample data. It relates x and y and does a pretty good job if the coefficient of the correlation value of 0.961 is at all significant. However, a sample of 10 is fairly small so it becomes necessary to determine if a coefficient of correlation having a value of 0.961 could have occurred by pure chance from a sample of 10. This question can be answered by using the test of significance. This procedure requires that one first assumes all 10 sample observations came from a source where no relationship exists between x and y. In this situation, the coefficient of correlation would equal zero. The properties of a population where the variations in x and y are completely random are well documented. Therefore it is possible to establish the probability of obtaining a coefficient of correlation having a value of 0.961 from such a source. Attempting to test the coefficient of correlation (r) often proves a bit cumbersome. Instead, the regression coefficient (b), which must equal zero when r is zero, is tested for the assumption that b is zero. A computed t-value is determined by dividing the regression coefficient (b) by the standard error of the regression coefficient. The standard error of the regression coefficient is defined as the square root of the sum of the squared deviations about the regression line divided by the sample size, i.e.,

$$S_e = \sqrt{\Sigma U^2/10}$$

The computed t-value can then be compared with a t distribution table value for any desired confidence level and appropriate degrees of freedom. For any test of the regression coefficient the appropriate degrees of freedom will be the sample number of observations (r) minus 2. For the example, with 10 observations this is 8 degrees of freedom. From Table 2 it may be seen that the t value at 0.99 confidence level is 3.355. This is the maximum t value that the computed t value would reach, 99 times out of 1,000 for 8 degrees of freedom if the regression coefficient (b) is zero. For the example, the regression coefficient (b) is 0.419 and the standard error of b is 0.042; therefore, the computed t value becomes

$$\frac{b}{S_e} = \frac{9.419}{0.042} = 9.881$$

TABLE 2

PERCENTILES OF THE t DISTRIBUTION

D.F.	t (0.70)	t (0.80)	t (0.90)	t (0.98)	t (0.99)
2	1.061	1.886	2.920	6.965	9.925
4	0.941	1.533	2.132	3.747	4.604
6	0.906	1.440	1.943	3.143	3.707
8	0.889	1.397	1.860	2.896	3.355
10	0.879	1.372	1.812	2.764	3.169
15	0.866	1.341	1.753	2.602	2.947
20	0.860	1.325	1.725	2.528	2.845
25	0.856	1.316	1.708	2.485	2.787
30	0.854	1.310	1.697	2.457	2.750
60	0.848	1.296	1.671	2.390	2.660

This is a large t value and the chances of getting such a value, if b were zero, are practically nil. Therefore, it should be concluded that the indicated correlation between gasoline consumption and maintenance cost cannot be rejected on the basis of available data.

A regression equation has been established as a meaningful measure of at least a mathematical relationship between maintenance cost and gasoline consumption. Now the question of predictions can be considered. This is usually the initial objective for making the regression-correlation analysis. In making the analysis, it was necessary to assume that both the x and y variables were normally distributed about their respective mean values. For the example problem, this assumption would indicate that the frequency with which deviations from the mean cost are expected, if plotted, would resemble the symmetrical bell-shaped normal distribution curve shown in Figure 7. The total area under this curve encompasses all conceivable values of a normally distributed group of data or 100 percent of the possible values. Also, any normally distributed data or group of observations can be completely defined by two measures, the mean and the standard deviation. The mean is defined as the sum of all values of the group divided by the number of values in the group,

$$\bar{y} = \Sigma y/n$$

The standard deviation is defined as the square root of the sum of the squared deviations from the mean value divided by the number of observations,

$$S = \sqrt{\frac{\Sigma(y - \bar{y})^2}{n}}$$

The S value can be used to define the limits of a constant portion of the total area under the normal distribution curve. Both the mean and standard deviation are shown in Figure 7. The mean is the point of symmetry, and the limits for one standard deviation encompass 67.6 percent of the total area under the normal curve.

For any normally distributed data these two measures always have the same interpretation. Therefore, given the mean and standard deviation of a group of observations, quality or confidence statements can be made concerning characteristics of the group. For example, given an aggregate stockpile with a mean single aggregate weight of 20 grams and a standard deviation of 2 grams, how uniform is the aggregate in the stockpile? If the aggregate weights are normally distributed, 67.6 percent of the aggregate in the pile will weigh between 18 and 22 grams. Two standard deviations will include about 95 percent of the area under the normal curve; therefore, 95 percent of the aggregate will fall within a 2-standard deviation measure of 4 grams, i.e., 95 percent of the aggregate weights will fall between 16 and 24 grams. Consider another question: Given a stockpile of aggregates having a mean of 20 and a standard deviation of 2, what will be the weight of a single aggregate selected at random from the pile? The best estimate will be 20 grams, but there is a very slight chance of getting exactly 20 grams. Rather, the aggregate can be expected to have a value that will fall between 16 and 24 grams 95

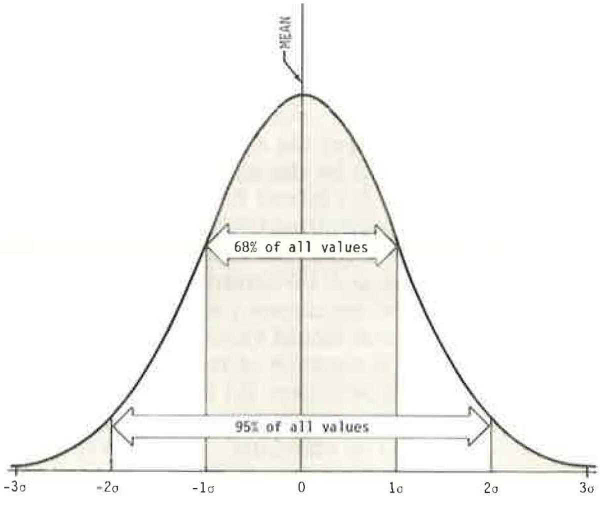


Figure 7. Normal distribution curve.

percent of the time. These are the 95 percent confidence limits for the best estimate of the weight of any single aggregate selected from the stockpile having a mean of 20 grams and a standard deviation of 2 grams.

A similar confidence statement can be made concerning the expected value of y for any given x in the sample regression relation. Recalling that the regression curve is analogous to the mean, and that the standard deviation is a measure of the variation in values about the mean, the analogous measure of variation about the regression curve is called the standard error of the estimate, which was defined earlier. For the sample, it can be stated that for any given value of x the value of y predicted by the regression equation will be between $y \pm S_e$ 67.7 percent of the time, or between $y \pm 2\ S_e$ 95 percent of the time.

In practice, this particular measure is not too useful because the sample is usually taken and analyzed to decide the nature of the population or universe from which the sample was obtained. The population or universe is defined as the complete source of information with common attributes or characteristics from which the sample was obtained. Therefore, the descriptive measures developed for the sample must be corrected to reflect inaccuracies attributed to the sampling process. These corrections are applied to the standard error of the estimate (S_e) and are a function of the sample size, the nature of the population, the type of prediction desired, and the confidence level sought. The resulting value establishes the confidence limits for a given prediction. Generally these confidence limits are placed around the entire regression curve. The limits will not parallel the regression curve because the analysis process places more weight on the values in the vicinity of the mean values for the variables.

Typical 95 percent limits are shown in Figures 8 and 9. The limits in Figure 8 reflect the accuracy of a mean value for y as predicted for various x values, whereas the limits in Figure 9 reflect the accuracy to be associated with a single projection of y for a given x.

To see how well the sample analysis explained the relationship between maintenance cost and gasoline consumption in the 50-state population, the population is shown plotted in Figure 10 and the sample regression curve is shown passing through the data. The 50-state population can also be considered a sample of some hypothetical infinite population or universe. In this hypothetical universe, inferences can be made concerning

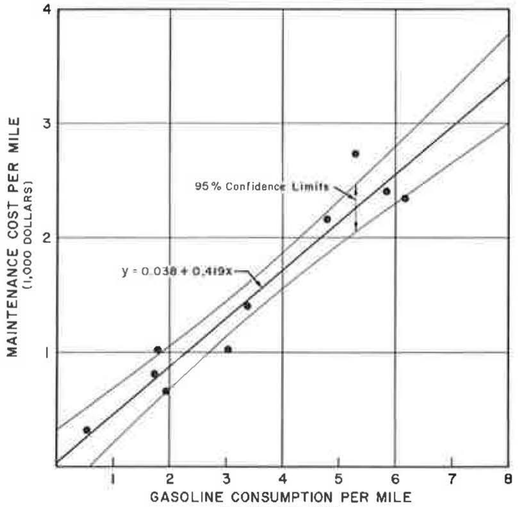


Figure 8. Regression curve with 95 percent confidence limits for an estimate of a mean y value.

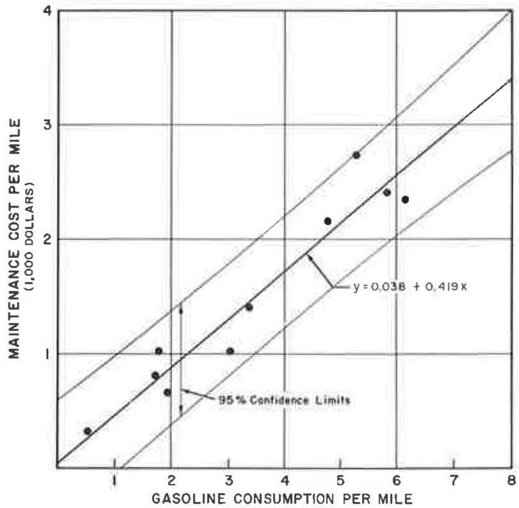


Figure 9. Regression curve with 95 percent confidence limits for an estimate of a single y value.

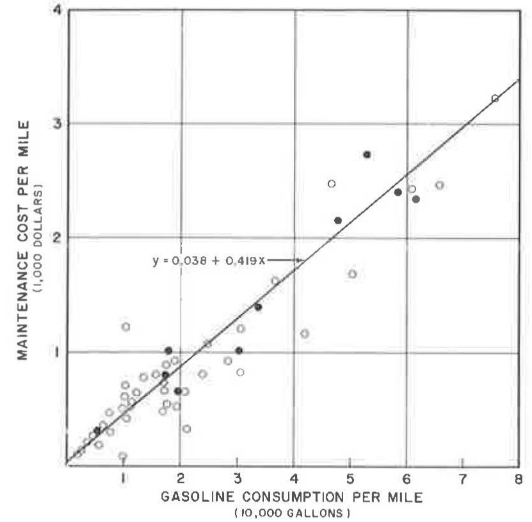


Figure 10. Scatter diagram of 50-state data.

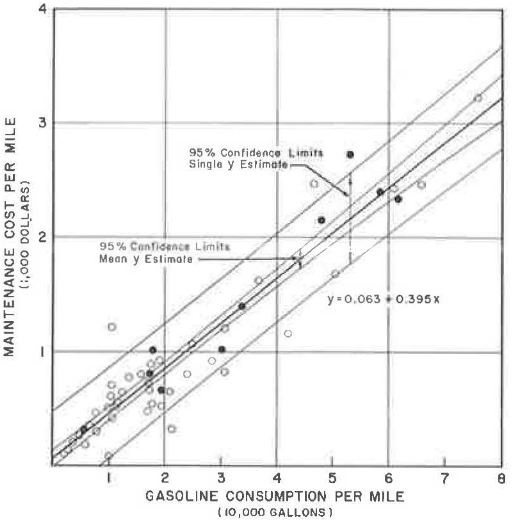


Figure 11. Regression curve and confidence limits for 50 states.

the true relationship between maintenance cost and gasoline consumption, i.e., the ultimate nature of things that cause the indicated mathematical relationship between maintenance cost and gasoline consumption. Therefore, a regression-correlation analysis can be made of the 50-state sample. The results are shown in Figure 11. It is not surprising that the results are similar to the 10-sample analysis, and, as one might intuitively have expected, the larger sample produced a better estimate of characteristic of the infinite population than the smaller sample.

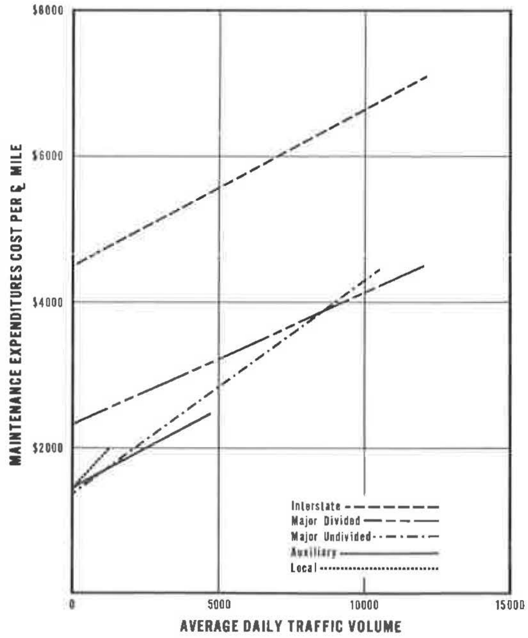


Figure 12. Ohio traffic and mileage influenced unit-cost index for highway maintenance.

An example of how the suggested relationship between maintenance cost and gasoline consumption (and therefore traffic volume) was applied practically is shown in Figure 12. These curves were developed using regression-correlation analysis and show how maintenance costs are expected to increase as traffic volume increases on five different classifications of state highways in Ohio.

Using traffic volume projects and the indicated relationships expressed by the curves, it was possible to predict the future maintenance requirements due to traffic volume increases on Ohio's state highways.

There are many other areas in highway maintenance where a regression-correlation analysis can be used to determine the relationship between variables or multiple combinations of variables. Some of these might include equipment age; equipment operating cost; equipment downtime; pavement age; maintenance requirements; pavement PSI; productivity; magnitude of workload; crew size; and environmental factors. Various combinations of these typical highway maintenance related items may warrant analysis.

Certain attributes of a highway facility may be a function of the subjective judgment of an observer. One such attribute was the present serviceability index (PSI) developed to evaluate pavement performance during the AASHO Road Test. In that instance, each member of a Pavement Serviceability Rating Panel made an independent subjective rating of the ability of 138 sections of pavement to service the highway user. Concurrently, AASHO Road Test field crews measured variations in the longitudinal and transverse profiles along with the amount of cracking and patching on the same 138 sections. The average subjective rating established by the panel was related to the latter objective measures using a multiple regression-correlation analysis. This resulted in a formula that could be used to compute a PSI for given measures of the profile, cracking, and patching for a pavement section. Looking to the future, it is quite possible that similar subjectively based objective measures of maintenance adequacy can be developed. This could be done by using regression-correlation techniques to establish measureable parameters that relate to subjective evaluations of maintenance adequacy; for example, the benefit of different levels of maintenance to the highway user. Highway user polls could be used to establish subjective values that could then be related to various objective measures of the facility. The established relationships would prove invaluable in developing a purely objective system to allocate maintenance resources to produce optimum values to the highway user. To illustrate this, consider the following 4-variable hypothetical problem.

A quantitative measure of mowing adequacy is desired for Interstate highways. A subjective rating of mowing adequacy on a sample of Interstate sections has been made by a panel of highway users. The problem is to establish if certain characteristics of the mowing areas for the sample sections can be related to the panel average rating.

Three measureable variables are selected to represent the characteristics of the mowed area. They are (a) average mowed grass height in inches, (b) the percentage of the grass area infested with obnoxious weeds, and (c) the percentage of the potential mowing area actually mowed. The quantitative measures for these 3 independent variables and the dependent variable subjective rating are given in Table 3. The linear model being fit using a multiple linear regression analysis is

$$Y = AX1 + BX2 + CX3 + D$$

When attempting to measure the association between more than 2 variables, it is nearly impossible to visualize any relationship. Therefore, the descriptive measures developed to describe the relationship for 2-variable examples become even more useful. A multiple-regression analysis is made to develop the best fitting curve, or more practically the best fitting equation to express the relationship between a number of variables.

TABLE 3

SAMPLE OBSERVATIONS FOR MOWING ADEQUACY

Variable			
x^1	x^2	x^3	y
4	25	90	80
6	10	80	90
7	20	95	80
5	30	60	65
6	20	90	80
7	50	100	50
10	40	75	45
5	15	100	90
4	0	70	100
11	15	95	70
8	40	100	55
4	5	100	95
7	15	50	75

The multiple-regression approach is similar to the 2-variable regression in that the deviations about a curve fitting the model are to be minimized. However, this approach involves fitting a 4-dimensional curve and cannot be undertaken easily by using manual methods. Manual methods are not necessary, however, because computer programs are readily available and provide a rapid solution to the problem.

Such a program was used to solve this problem. The resulting multiple-regression equation was

$$Y = 99.1 - 2.67X1 - 0.96X2 + 0.17X3$$

The multiple-correlation coefficient was 0.991 (r). A 2.8 t-value was obtained from Table 3 for 9 degrees of freedom at a 99 percent significance level. The following t-values were established for each of the regression coefficients:

$A = 2.67 \quad t = 6.5 > 3.25$
$B = 0.96 \quad t = 21.9 > 3.25$
$C = 0.17 \quad t = 3.6 > 3.25$

Therefore, with 99 percent confidence it can be stated that the model explains 98 percent (r^2) of the variation in the panel average subjective measures of mowing adequacy.

To summarize, regression-correlation analysis and related tests permit the establishment of the best solution in terms of fitting a model (equation) purporting to explain any group of observations. Further, the confidence that can be placed in the model and on the values it predicts can be delineated mathematically. Therefore, the techniques permit quantitative statements to be made about observed data that might otherwise be nothing more than an unrelated mass of numerical values. Also, inference can be made concerning the general nature or processes associated with the population from which the observed data were obtained.

In most instances considerable time, effort, and money are invested in securing data that are to be used to establish relationships. The nominal added time needed to perform regression-correlation analysis seems more than justified. In any case, far less effort is required to make an analysis than is needed to secure the data. Where large samples are involved and multiple-type analysis required, the computational aspects could become enormous. For these reasons, extensive use is made of computers.

Subjective or "seat of the pants" decision-making processes are continually being supplemented by the use of computers. Tremendous quantities of information can be handled and processed through highly sophisticated analytical techniques to produce meaningful indications to guide decision-making. Although these methods of analysis do not permit conclusions to be drawn without the risk of error, the principles of logic and probability associated with statistical methods produce correct answers more frequently than does guessing. This means that the risk of making the wrong inference is reduced, or, in a more positive vein, an improvement is made in the ability to choose the right or correct conclusions and therefore to make better decisions.

REFERENCES

1. U. S. Department of Transportation. Highway Statistics/1965. U. S. Govt. Printing Office, April 1967, Tables F2, MF-21, and M-1.
2. Ezekiel, M., and Fox, K. A. Methods of Correlation and Regression Analysis. John Wiley and Sons, New York, 1965.
3. Greenshields, B. D., and Weida, F. M. Statistics With Applications to Highway Traffic Analyses. Eno Foundation for Highway Traffic Control, Saugatuck, Conn., 1952.
4. Karmel, P. H. Applied Statistics for Economists, Second Edition. Isaac Pitman and Sons, London, 1963.
5. Lindgren, B. W., and McElrath, G. W. Introduction to Probability and Statistics. MacMillan, New York, 1959.
6. Natrella, M. G. Experimental Statistics. National Bureau of Standards Handbook 91, U. S. Department of Commerce, Aug. 1, 1963.
7. Volk, W. Applied Statistics for Engineers. McGraw-Hill, New York, 1958.
8. Williams, E. J. Regression Analysis. John Wiley and Sons, New York, 1959.

A SIMULTANEOUS EQUATION ECONOMETRIC MODEL OF WINTER MAINTENANCE COST CATEGORIES

William J. Dunlay, Jr., Department of Civil Engineering, University of California, Berkeley

Little is known about the quantitative influence of factors affecting winter maintenance expenditures. This report proposes a simultaneous equation stochastic model to explain or predict county expenditures for snow and ice control based on selected measures of a county's need for such specific operations as spreading chemicals and abrasives and plowing snow. Emphasis is on methodology, with specific findings cited only to illustrate the procedure. A procedure for applying the estimates produced by the model to evaluate county performance is recommended. It is suggested that counties can best be evaluated by a residual analysis in which they are grouped according to how their actual costs compared with those estimated by the model to determine whether counties in a particular group share any similar practices, policies, or deficiencies.

•IN RECENT years expenditures for snow and ice control by state highway departments have increased greatly, but research expenditures for studies of snow and ice control have remained relatively insignificant—0.25 to 0.50 percent of the total highway research expenditures in 1967 (9). Rising expenditures can be attributed to increased mileage of multilane highways, huge increases in vehicle miles of travel, greater public demand for bare pavement maintenance, and inflation. Reasons for the relative lag in winter maintenance research, however, are difficult to pin down.

Winter maintenance operations are initiated as the need for them, in the form of snow and ice on the roads, occurs. This need is often of an emergency nature and is difficult to predict, or even explain, with a degree of accuracy usable for planning purposes. The severity, duration, location, and time of hazardous snow and ice conditions are just a few of the unknowns that complicate winter maintenance operations and have probably discouraged research in this field. Yet, it is these same uncertainties that make further research necessary to develop better and more economical techniques for snow and ice control.

SCOPE AND PURPOSE

This paper is directed primarily to maintenance managers with some knowledge of statistical techniques. Two-stage least-squares estimation procedures are covered in detail, however, because they are not as widely known as standard regression methods.

The purpose of this paper is to propose a method by which expenditures for winter maintenance operations may be predicted and understood. Specific results are cited only to illustrate the proposed methodology, and findings are not critically examined because they are only preliminary.

The model described here is a system of simultaneous equations, each designed to explain the variation of specific categories of winter maintenance expenditures among the basic operating units of a state highway department. The basic operating unit is assumed in this paper to be a county office of the department. Typical categories of winter maintenance expenditures are given in Table 1.

Sponsored by Committee on Maintenance and Operations Costs.

TABLE 1

TYPICAL CATEGORIES OF WINTER MAINTENANCE EXPENDITURES

Index	Operation
y_1	Purchase and stocking of abrasives
y_2	Purchase and stocking of de-icing chemicals
y_3	Spreading of abrasives and chemicals
y_4	Plowing snow, slush, and ice
y_5	Snow fence installation

Testing and development of the model has thus far been accomplished using cross-section data from 66 counties for one winter season. Each equation has been constructed to explain the expenditure level for a particular operation using such influencing factors as (a) level of expenditures for other related operations, (b) temperature and frozen precipitation of a county, (c) state highway mileage and characteristics, (d) amount of traffic that must be accommodated, and (e) extent of the winter maintenance force operating within a county. The equations are of the general form

$$y_i = a + b_1 y_1 + \ldots + b_{i-1} y_{i-1} + b_{i+1} y_{i+1} + \ldots + b_n y_n + c_1 x_1 + \ldots + c_m x_m$$

where the y's are expenditures for such operations as given in Table 1, the x's are measured or observed characteristics of a county determined to have a predictable effect on y_i, and the coefficients (a, b's, and c's) are statistically estimated parameters that define the direction and significance of the relationships between y_i and the explanatory variables on the right-hand side of the equation. Variables not included in a particular equation can be considered to have a coefficient of zero.

For each equation one set of coefficients applies to all counties. Thus, it is the county-to-county variation that the model explains, and the coefficients must therefore be estimated using cross-section data. Procedures for using both time-series and cross-section data are available but are not widely understood. These procedures involve the added time-series problems of accounting for inflation and improved levels of service and nonuniform (among the counties) changes in these two items with time.

Endogenous variables are in units of dollars per mile of maintained highway within a county. These units were chosen because it is felt that such unit expenditures more accurately reflect differences in climate, extent of operation, and highway characteristics than do total expenditures.

OBJECTIVES

When constructing the equations one must select explanatory variables considered to have a predictable effect on each endogenous variable. The objective of this process, in addition to merely explaining the variation in existing expenditures, is to develop equations that reflect what a county's winter maintenance expenditures ought to be, based on characterics that seem inherently important in defining its true need for snow and ice control. Explanation of existing expenditures, however, is an important step in the development stage.

Once the equations have been fully developed they can be used for several purposes:

1. To apportion funds appropriated for winter maintenance among the counties according to their estimated needs for particular types of operation;
2. To predict the consequences of changes in policy on the different expenditure categories (e.g., what would be the effect of eliminating snow fences on plowing and spreading costs?); the consequences of such policy changes can thus be evaluated before they are implemented; and
3. To identify counties whose expenditures deviate significantly from those predicted by the model.

THEORY AND TERMINOLOGY

In single-equation multiple-regression analysis, variables are classified as either independent (explanatory) or dependent (to be explained). However, this classification is inadequate when considering a simultaneous system of the following form (which is the general form of all equations in this paper):

$$y_i = f_i\,(y_1, \ldots, y_{i-1}, y_{i+1}, \ldots, y_n;\, x_1, \ldots x_m) + e_i \qquad i = 1, \ldots, n \tag{1}$$

Note that a variable explained by one equation may itself be an explanatory variable in other equations. For example, expenditures for erecting snow fences are expected to both influence and be influenced by expenditures for snow removal. Variables of this type that are affected by and affect other explained variables are called endogenous variables.

Some variables have an effect on the expenditures to be explained but are not in turn affected by those expenditures. Such variables are not explained by the model; their values are determined by forces outside the model. Total annual snowfall, for example, affects certain winter maintenance expenditures but is obviously not affected by such expenditures. Variables having these characteristics are known as exogenous variables and are represented by the x's in Eq. 1. Descriptions of suggested exogenous and endogenous variables are contained in this paper.

To illustrate the theory and terminology of this section, the following two-equation model will be discussed:

$$y_1 = a_1y_2 + b_1x_1 + e_1$$

$$y_2 = a_2y_1 + b_2x_2 + e_2$$

Note that y_1 is explained by the first equation and used as an explanatory variable in the second. Thus, y_1 is an endogenous variable. The term dependent variable is used when referring to the expenditure variable explained by a particular equation.

To many readers the most striking difference between these equations and the more familiar multiple-regression equation is probably the inclusion of the y's as explanatory factors on the right-hand side of the equations. Although this complicates the process of obtaining unbiased estimators for the coefficients, it is very important to retain the y's as explanatory variables. Because the y's appear in more than one equation of the system, their interrelationships cannot be determined by examining any single equation, as in ordinary multiple-regression analysis; instead, a simultaneous analysis of all the equations of the system is necessary. These y's represent unit winter maintenance expenditures for such operations as plowing snow and erecting snow fences, which by their very nature must affect each other. For example, the erection of snow fences in appropriate locations will retard the formation of drifts, thus reducing the requirements for plowing. On the other hand, the areas subject to much drifting and therefore to the need for considerable snow removal will be the areas in which the expenditures for snow fences will be highest. The inclusion of the expenditure variables as explanatory factors reflects this type of mutual dependence.

The form and content (variables included) of each equation is called the structure of that equation, and the equations themselves are called structural equations. Construction of the model requires that hypotheses be made concerning the relationships between explanatory variables and various categories of winter maintenance costs. This is necessary in order to choose the variables that should most logically explain each cost category. These hypothetical relationships are represented by the content of the structural equations.

Estimating Procedures

The use of conventional least-squares procedures for estimating parameters of single multiple-regression equations of the form

$$y = a_1 + b_1x_1 + b_2x_2 + \ldots + b_n x_n + e$$

involves several assumptions concerning the disturbance or error terms, denoted by the symbol e in the preceding equation. It is assumed that this error term is a stochastic variable that represents the aggregate effects on the dependent variable of explanatory factors not included in an equation. The exogenous variables are assumed to be known without error. Variables not included are unknown, considered unimportant, or not quantifiable. It is further assumed in conventional least-squares estimation that the disturbance term is a random variable with an expected value of zero, a constant variance, and zero covariance with (stochastically independent of) each of the explanatory variables.

Consider the two-equation simultaneous system

$$y_1 = a_1y_2 + b_1x_1 + e_1 \tag{2}$$

$$y_2 = a_2y_1 + b_2x_2 + e_2 \tag{3}$$

If these equations are solved for y_1 and y_2, the solutions will be affected by both e_1 and e_2 in the manner shown in Eqs. 4 and 5. Thus, in Eq. 2, y_2 cannot be assumed independent of e_1; and similarly in Eq. 3, y_1 cannot be assumed independent of e_2. Under these conditions, it has been proved that the use of conventional least-squares techniques leads to biased estimates of the parameters of the system. However, a modification of these techniques known as two-stage least squares may be used to obtain unbiased estimates.

The first stage of the two-stage process is to solve the structural equations simultaneously to obtain an expression for each dependent variable with only exogenous variables as explanatory factors. Solving the preceding two-equation example simultaneously results in

$$\hat{y}_1 = \{b_1/[1 - (a_1a_2)]\}\, x_1 + \{a_1b_2/[1 - (a_1a_2)]\}\, x_2 + \{(e_1 + a_1e_2)/[1 - (a_1a_2)]\} \tag{4}$$

$$\hat{y}_2 = \{a_2b_1/[1 - (a_1a_2)]\}\, x_1 + \{b_2/[1 - (a_1a_2)]\}\, x_2 + \{(e_2 + a_2e_1)/[1 - (a_1a_2)]\} \tag{5}$$

This is called the reduced form of the model. Note that in the reduced form y_1 is a function of x_2 and x_1, whereas in structural Eqs. 2 and 3 it is a function of y_2 and x_1. This is the mechanism by which the effect of the endogenous variable (y_2) on y_1 is indirectly accounted for in the reduced form. That is, even though y_2 is not included in the reduced form equation for y_1, a linear function of the exogenous variable on which y_2 depends (x_2) is included.

The disturbance terms of the reduced form equations are linear functions of e_1 and e_2 and are therefore independent of the explanatory variables x_1 and x_2. Therefore, application of standard least-squares techniques results in unbiased estimators for the reduced form coefficient (the expressions in parentheses) and, thereby, unbiased estimates of the dependent variables $\hat{y}_1$ and $\hat{y}_2$.

In the second stage of the two-stage least-squares procedure, the estimates of the dependent variables are substituted for the actual values of the endogenous variables on the right-hand side of the structural equations as in the following:

$$y_1 = a_1\hat{y}_2 + b_1x_1 + v_1$$

$$y_2 = a_2\hat{y}_1 + b_2x_2 + v_2$$

A second regression is then performed on each of these equations to obtain unbiased estimators for the structural coefficients. Ordinary least-squares regression may now be used because the estimated endogenous variables are functions of only the exogenous variables and are therefore independent of the error terms.

Alternative Forms of the Model

Equation 1 illustrates the general form of the equations of this study. The f_i symbol of that equation represents the functional form of the i th structural equation. Three functional forms—linear, quadratic, and log-linear—have been considered.

In the linear form the equations are expressed as the weighted sum of a set of endogenous and exogenous variables raised to the first power:

$$y_i = a_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} b_{ij}y_j + \sum_{k=1}^{m} c_{ik}x_k + e_i \qquad i = 1, \ldots, n$$

The a_i's, b_i's, c_i's, and d_i's are the weights, or parameters, of the equations. The linear form is widely used because it is the simplest to specify and interpret. The sign of a coefficient (e.g., c_{ik}) represents completely the estimated direction of the relationship between x_k and y_i. The magnitude of the coefficient, along with the magnitude of the variable itself, is a measure of the sensitivity of y_i to changes in x_k, with other factors being held constant.

The quadratic form is similar to the linear form, except that the squares of the endogenous variables are included as additional explanatory factors. Quadratic equations have the form

$$y_i = a_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} b_{ij} y_j + \sum_{k=1}^{m} (c_{ik} x_k + d_{ik} x_k^2) + e_i \qquad i = 1, \ldots, n$$

In this form the change in the dependent variable (y_i) associated with a unit change in an exogenous variable (x_k), with other factors constant, is measured by the partial derivative of y_i with respect to x_k, which is $c_{ik} + 2d_{ik}x_k$. Thus the change in y_i resulting from a unit change in x_k is seen to be a function of x_k itself. Assuming that x_k is positive, the direction and strength of the relationship indicated by the sign and magnitude of this partial derivative depends on the magnitude of x_k and the signs and magnitudes of c_{ik} and c_{i2k}. To evaluate the average sign and strength of the predicted relationships, each partial derivative should be evaluated at the mean value of the associated exogenous variable.

The last functional form considered was the log-linear form. The equations in this form are expressed as the weighted sum of the logarithms of the explanatory variables,

$$\log y_i = \log a_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} b_{ij} \log y_j + \sum_{k=1}^{m} c_{ik} \log x_k + \log e_i \qquad i = 1, \ldots, n$$

Taking the antilog of both sides yields

$$y_i = a_i \prod_{\substack{j=1 \\ j \neq i}}^{n} y_j^{b_{ij}} \prod_{k=1}^{m} x_k^{c_{ik}} e_i$$

The coefficient of an explanatory variable in the log-linear form is equal to the ratio of the percentage of change in the dependent variable to the percentage of change in an explanatory variable. To verify this consider the two-variable example

$$\log y = \log a + b \log x$$

Taking the differential of both sides of this equation with respect to x, we get

$$dy/y = b\, dx/x$$

or

$$b = (dy/y)/(dx/x)$$

By interpreting the differentials as finite differences and by multiplying numerator and denominator by 100, we obtain

$$b = [\Delta y/y\ (100)]/[\Delta x/x\ (100)]$$

Thus, b is the percentage of change in y corresponding to a 1 percent change in x.

Although the log-linear form shows promise for application in this study, problems of interpreting the resulting residuals have delayed an accurate evaluation of this form; therefore, no further discussion of it is included in this paper.

VARIABLES OF THE MODEL

Endogenous Variables

The endogenous variables are winter maintenance expenditure categories such as those given in Table 1. The exact form of these variables depends on how maintenance costs are categorized for accounting purposes. If the expenditures are not broken down by individual functional operations, a model of this type is of little use because it is only these operations that can be related to conditions encountered in the field. As stated earlier, expenditures are in units of dollars per mile.

It is essential that the endogenous variables be mutually exclusive. For example, the cost of chemicals and abrasives must be excluded from spreading costs because there are separate endogenous variables for abrasive expenditures and chemical expenditures. Thus, only the labor and equipment costs associated with spreading are included in y_3. By the same requirement, endogenous variables for labor and equipment costs may not be included in the same model as the variables in Table 1. If equations for labor and equipment costs are desired, a separate model must be constructed.

Exogenous Variables

All characteristics of a county that could possibly affect some aspect of winter maintenance must be enumerated and their significance evaluated. These characteristics will at first be general in nature, such as highway characteristics, climate, traffic demand, and intensity of operations. It is then necessary to select or define some specific measure or index of each of the characteristics.

Examples of characteristics and associated specific measures that have been used in the background study of this paper are given in Table 2.

Data for calculating the highway, traffic, and operation indexes of Table 2 should be available from records kept by most highway departments (1, 2, 3, 4, 5). The climate variables can be determined from the climatic summaries of the U. S. Weather Bureau (11, 12, 13). Data for the suggested measure of highway ruggedness (x_2) can be compiled from 1:24,000 U. S. G. S. quadrangle maps or 1:250,000 Army Map Service maps.

Altitude may be an important determinant of winter maintenance requirements, but, because of the difficulty of obtaining a single index to represent the altitude of an entire county, this index has not yet been tested. The average elevation of a county's highways is suggested for initial consideration.

TABLE 2

EXOGENOUS VARIABLES

County Characteristic	Specific Measure or Index
1. Highway characteristics	
Multilane highways	x_1 = ratio of mileage of four or more lanes to total mileage
Ruggedness	x_2 = mean number of contour lines crossed per unit length of mapped road
2. Climate	
Coldness	x_3 = mean temperature, November through March
	x_4 = degree days below 32 F
Frozen precipitation	x_5 = total annual snowfall
	x_6 = annual number of days with ≥ 1 in. of snow on ground
3. Traffic demand	x_7 = population density, persons per square mile
	x_8 = motor-vehicle registration receipts in dollars per mile
4. Operation density	x_9 = number of trucks and graders per mile
	x_{10} = number of stockpiles per mile

TABLE 3

CORRELATION COEFFICIENT FOR THE ENDOGENOUS VARIABLES

y_1		y_2		y_3		y_4		y_5	
y_3	0.80	y_3	0.70	y_1	0.75	y_3	0.72	y_4	0.50
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
x_4	0.20	x_3	-0.22	x_1	0.25	x_8	0.21	x_9	0.21

CORRELATION ANALYSIS

To aid in the selection of specific explanatory variables to be included in each structural equation, the sample correlation coefficients between each endogenous variable and the other endogenous and exogenous variables of the model should be obtained and analyzed. The sample correlation coefficient is an estimate of the strength of the linear association between a pair of variables. Thus, the correlation coefficient may be close to zero when there is actually a strong but nonlinear relationship between two variables. The square of the correlation coefficient, known as the coefficient of determination, is a measure of the proportion of the variation in one variable that may be attributed to differences in another variable.

A significant correlation does not necessarily imply a causal relationship between two variables. Both may depend on some common third factor. Thus, a statistical relationship may exist between two variables even though to infer a causal relationship would be absurd.

To facilitate examination of the results of the analysis, the correlation coefficients between an endogenous variable and all other variables are tabulated, in descending order of significance, under that endogenous variable, as in Table 3.

Preliminary regression equations can also be constructed to determine the joint effect of various combinations of variables and to further analyze the significance of certain relationships. A step-wise least-squares procedure is suggested wherein those explanatory variables that do not have regression coefficients significantly different from zero (at some predetermined level of significance as measured by a t-value) are dropped from the equation one at a time, until only variables with significant coefficients remain.

To evaluate which of several alternative exogenous variables best relates a particular county characteristic to each endogenous variable, the correlation coefficients between a particular cost variable and the measures of that characteristic (e.g., climate) can be listed as in Table 4.

We see from Table 4 that x_3 serves as a better measure of "coldness" in explaining y_1 than does x_4. When constructing the equations, the measure of a characteristic that best relates to an endogenous variable as determined from Table 4 is the one used in the structural equation for that variable.

HYPOTHETICAL RELATIONSHIPS

To establish the structure of an equation, it is necessary to postulate the nature of the relationships between the dependent variable of that equation and the explanatory variables included. This involves making assumptions concerning the direction of the relationships and specifying how, on the basis of judgment and experience, each chosen characteristic is thought to affect the dependent variable in question, independent of any statistical correlations. The specific variables to represent the included characteristics are then selected on the basis of correlation and preliminary regression studies.

As an example of this process consider the equation for y_1, expenditures for abrasives, whose structure is given in Table 5.

TABLE 4

CORRELATION COEFFICIENTS OF CLIMATE INDEXES

Endogenous Variables	Exogenous Variables			
	x_3	x_4	x_5	x_6
y_1	-0.30	0.20	0.25	0.40
y_2	-0.25	0.30	0.45	0.40
y_3	-0.10	0.20	0.40	0.35
y_4	-0.40	0.30	0.60	0.50
y_5	-0.30	0.40	0.20	0.10

TABLE 5

VARIABLES IN THE EQUATION FOR y_1

Endogenous	Exogenous
y_2 = purchase of chemicals	x_1 = ratio of mileage of four or more lanes to total mileage
y_3 = spreading expenditures	x_2 = mean number of contour lines crossed per unit length of mapped highway
	x_3 = mean temperature, November through March
	x_6 = annual number of days with ≥1 in. of snow on the ground
	x_{10} = number of stockpiles per mile

Expenditures for purchasing chemicals (y_2) should affect abrasive expenditures because the same number of stockpiles is usually supplied and the same network of roads is treated from each stockpile. It is expected that this relationship will be negative because the greater the amount of chemicals used, the less should be the need for abrasives. The cost of purchasing abrasives is directly affected by spreading expenditures (y_3) because abrasive purchases are for the replenishment of stocks and spreading is the process by which stocks are depleted.

The exogenous measure of multilaning (x_1) is included because the larger the value of this variable is, the greater is the area of pavement per mile to be treated with abrasives. The index for highway ruggedness (x_2) reflects the fact that grades require more intense, immediate, and frequent treatment with anti-skid materials than level sections.

Climate is measured by mean temperature (x_3) and by the number of days with more than 1 in. of snow on the ground (x_6). Both meausres of climate are included because conditions that require abrasives are a function of both the amount of frozen precipitation experienced and the length of time that the snow or ice might be expected to linger on the pavement, which, in turn, is a function of coldness. Frozen precipitation and coldness are best correlated with y_1 by x_3 and x_6, respectively, as indicated in Table 4.

The number of stockpiles per mile (x_{10}) is the last exogenous factor. It seems reasonable to assume that counties with a greater number of stockpiles per mile will buy and stock more abrasives per mile. The structure of all other equations is established in a similar manner (14).

Because of the manner in which they are selected, the explanatory variables in an equation represent factors that are presumed to determine a particular winter maintenance expenditure. It may happen that a hypothesis is not supported by subsequent statistical analysis. An estimated coefficient may not be statistically significant, or it may have an algebraic sign opposite to that expected. This would indicate either a weakness in the equation structure or a true discrepancy between what has been assumed to be true and what actually occurs.

A weakness in structure often takes the form of an excessive interdependence among the explanatory variables, which causes one of two or more interrelated variables to have an unreasonable sign or coefficient. This condition, known as multicollinearity, can be tested by computing the correlation coefficients or by omitting the variable with a reasonable sign and coefficient in a subsequent analysis to see if the undesirable condition remains. When two or more explanatory variables are highly correlated it turns out that some linear function of these variables does the explaining that any one of them could have done alone. This function may be such that the estimated coefficients of the individual variables are considerably distorted.

EQUATION SOLUTIONS

After the equations are constructed they are estimated using the two-stage least-squares technique available in many computer library programs for statistical analysis (7). The resulting solutions must then be analyzed to determine if the hypothetical relationships have been confirmed.

The first step in the analysis of solutions is to determine which functional form, linear or quadratic, yields the best estimates of the actual expenditures. The following is an example of this comparison:

Dependent Variable	R^2	Linear Form, Sum of Squared Errors	R^2	Quadratic Form, Sum of Squared Errors
y_1	0.72	151,000	0.76	130,000

In the linear form 72 percent of the variation in y_1 is accounted for by differences in the explanatory variables whereas the quadratic form accounts for 76 percent, which implies that the sum of the squared differences between estimated and actual expenditures is less in the quadratic form. Because the primary objective of this study is not merely to explain existing expenditures, choosing the form that gives the best estimates is valid only if the structure of the equation is reasonable. All equations in the model must be compared to ensure that the best form for the model as a whole is selected.

In Table 6 the solution of the equation for y_1 is given in tabular form. The significance of the coefficients, as indicated by the t-ratios, should be considered first because if a variable's coefficient is not significantly different from zero that variable may just as well be omitted. Since, at 53 degrees of freedom, a t-value of 2.67 indicates significance at the 1 percent level, the hypothesis that a coefficient is equal to zero is rejected for all variables in Table 6 at the 1 percent level of significance.

Next consider the regression coefficients of the endogenous explanatory variables. The minus sign of the coefficient associated with y_2, expenditures for purchasing chemicals, indicates that the model has predicted a negative relationship between y_1 and y_2, which agrees with the hypothesis of the last section that the greater the expenditures for chemicals, the less the need for abrasives is. The positive coefficient of y_3, spreading costs, supports the hypothesis of a direct relationship between abrasive costs and spreading.

As described earlier, to obtain an estimate of the average direction of the relationship with each exogenous variable, the sign of the partial derivative with respect to the variable evaluated at its mean must be considered. These partials are shown in the last column of Table 6. In this example it turns out that three of the indicated directions are as hypothesized, and two (x_1, multilaning, and x_6, snowfall) are not. Further study of x_1 and x_6 is required to ascertain the reasons for the discrepancy in the signs of their partials.

ERROR ANALYSIS

A significant difference between the actual expenditure by a county for a particular operation and the corresponding estimate produced by the model may itself be revealing. If a county's expenditure is very much lower than that predicted by the model, one or more of the following causes may apply:

1. The county may perform the operation in a highly economical manner;
2. Greater emphasis may be placed by the county than by the state as a whole on related operations in treating a particular condition;
3. The extent of operation is not sufficient to provide an adequate level of service; and
4. Other explanatory variables not previously identified are required, in addition to or in place of existing variables, to make the structure more realistically reflect a county's true need for the operation.

TABLE 6

SOLUTION OF QUADRATIC EQUATION FOR y_1, UNIT EXPENDITURE FOR ABRASIVES

Explanatory Variable	Regression Coefficient	Student t-Ratio	Partial Derivative Evaluated at Mean of Variable
y_2	-0.08	106.7	
y_3	0.55	780.2	
x_1	262.18	55.2	-199.6
x_1^2	-6,124.77	148.6	
x_2	1.55	60.0	2.3
x_2^2	0.03	45.7	
x_3	-113.01	190.6	-11.5
x_3^2	1.62	171.3	
x_6	0.09	3.5	-1.1
x_6^2	-0.01	50.6	
x_{10}	4,697.00	245.2	2,911.7
x_{10}^2	-43,649.48	55.0	

Note: Degrees of freedom = 53
Explained variation = 76 percent.

Corresponding but opposite indications exist for large positive estimation errors.

The fourth possible cause must be resolved first because the other three are not valid unless the model reasonably represents the winter maintenance needs of a county. The third possibility must be evaluated outside the model because the model does not include any measure of the level of service provided. The model does, however, point to the possibility of a deficient level of service when actual expenditures are less than predicted.

To facilitate the evaluation of possibilities 2 and 4, bar graphs of the type shown in Figure 1 can be constructed. Percentage of error is used rather than the actual magnitude of the error to place all counties on a comparable scale. From Figure 1 it appears, because of the large errors of opposite sign, that county Y emphasizes some operations and deemphasizes others relative to the practices in the state as a whole. For example, expenditures for purchasing abrasives (y_1) are considerably greater than the model predicts, whereas chemical purchases (y_2) are less. County Z, on the other hand, has very small errors of opposite sign. In county X, the actual expenditures were all significantly greater than estimated by the model. The actual reasons for these differences must be ascertained outside the model.

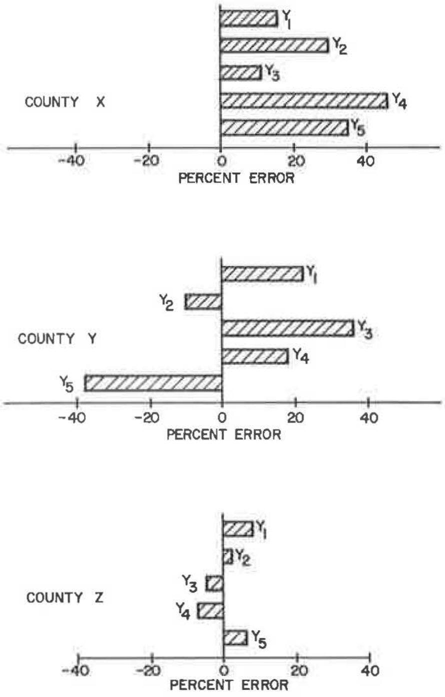


Figure 1. Percent errors in estimates of y's for three counties; percentage of error [(y_i = yi)/yi] 100.

Comparisons such as that of Figure 2 are recommended as an additional aid in identifying explanatory characteristics previously overlooked, or in evaluating the relative economy of each county's operation. Counties with higher rank (those in the top portion of Figure 2) may share some practice or policy that leads to relatively lower costs for the operation (purchasing abrasives in this example). Such practices can best be discovered by first grouping the counties according to how their cost compares with the model estimate and then examining counties in similiar groups. A ranking of this type also facilitates the identification of new characteristics whose values depend on the rank of a county, i.e., on the magnitude and sign of its estimation error. This can be accomplished by performing a contingency table or regression analysis to determine which new characteristics are most strongly related to the rank or residuals of the counties. Characteristics so identified are then converted to new or modified exogenous variables and included in subsequent solutions of the model. This type of feedback is essential to the development of the best structure for each equation.

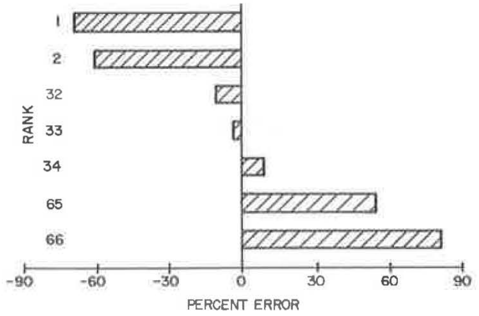


Figure 2. Percent errors in estimates of y_i for 7 of 66 counties ranked from largest negative to largest positive error.

CAUTIONS IN USING THE MODEL

It must be emphasized that the choice of variables and the types of functions to be fitted follow from one's familiarity with the maintenance operations involved. Intimate knowledge of the data is especially critical in a simultaneous equation model because a "wrong" variable in one equation may distort the coefficients of other equations. A "right" variable subject to large measurement errors may have similar consequences. Because explanatory variables are assumed in the analysis to be known without error, the precision with which each variable is measured may have important implications in applying the model.

The simultaneous equation method is appropriate in cases where the values of two or more variables are jointly dependent. The number of structural equations in a model must equal the number of endogenous variables, but if an individual equation contains only one endogenous variable, the dependent variable, that equation should be estimated separately as a single equation model using ordinary least-squares.

SUMMARY

This paper has described a model of simultaneous equations designed to predict county expenditures in Pennsylvania for certain basic winter maintenance operations. The flow chart shown in Figure 3 summarizes the procedures associated with this model.

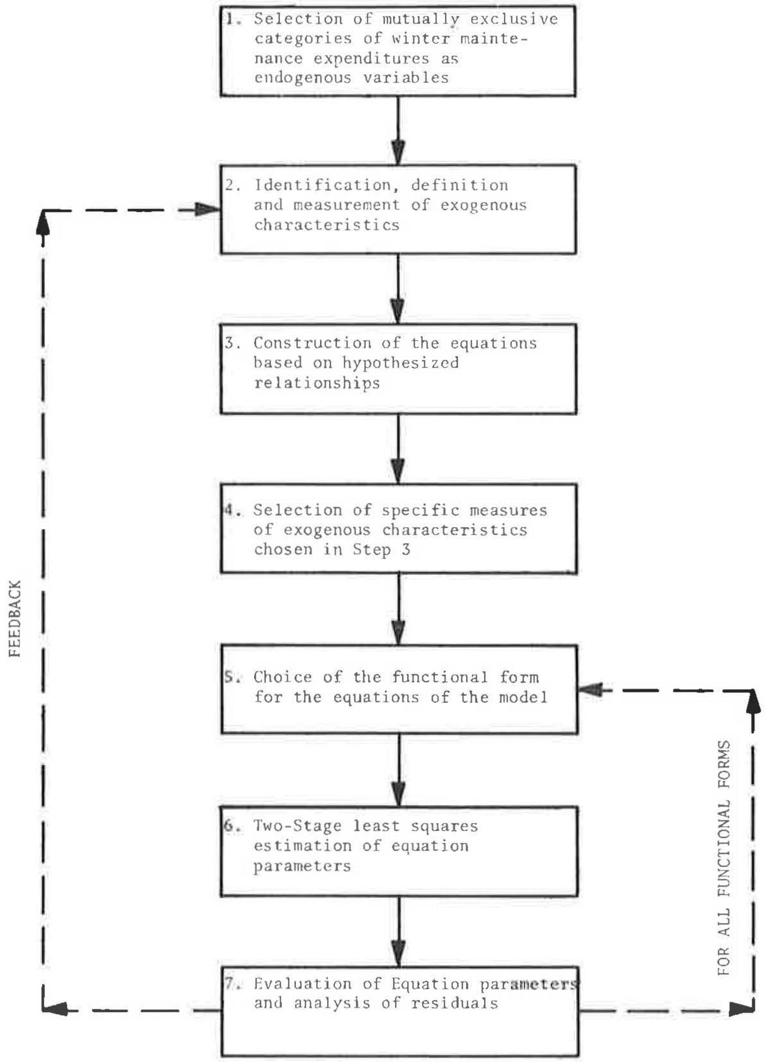


Figure 3. Summary of steps in model construction and evaluation.

The variables in each equation of the model were selected based on an examination of current practices and available data for describing characteristics of counties that affect their winter maintenance problems. A statistical analysis of the variables is used to measure the effect of certain county characteristics on expenditures for snow removal and ice control. Climate, traffic demand, highway width and grade, and operation intensity are the characteristics found to be most important in explaining expenditures.

Hypotheses concerning the nature of the relationships between expenditure categories and selected measures of the preceding characteristics serve as the basis for constructing the equations of the model. These hypothetical relationships are evaluated by examining the estimated parameters of the equations.

Finally, a procedure is recommended for applying the estimates produced by the model to evaluate county performance. It is suggested that counties can best be evaluated by grouping them according to how their actual costs compared with those estimated by the model and seeing if counties in a particular group share any practices or policies.

It is emphasized that only methodology is covered in this paper; details concerning specific variables and findings may be found elsewhere (14).

ACKNOWLEDGMENTS

This model was developed as part of a study of the cost-effectiveness of winter maintenance practices in Pennsylvania and was sponsored by the Pennsylvania Department of Highways and the Federal Highway Administration. The findings and conclusions are those of the author and not necessarily those of the sponsoring agencies. The author gratefully acknowledges the guidance of Owen H. Sauerlender in the development of the model. Appreciation is due other members of the staff of the Transportation and Traffic Safety Center for their invaluable assistance.

REFERENCES

1. Breakdown by Counties of Registration Receipts. Pennsylvania Department of Revenue, Harrisburg, 1968.
2. Correlation of Account Codes—Motor License and Highway Beautification Funds. Pennsylvania Department of Highways, Harrisburg, 1969.
3. Expenditure-Cost Report Number 511 by Organization Symbol, Allotment, and Object. Pennsylvania Department of Highways, Harrisburg, 1969.
4. Expenditure-Cost Report Number 561 by Organization Symbol, Allotment, and Function. Pennsylvania Department of Highways, Harrisburg, 1969.
5. Mileage by County of the State Highway System by Location in Townships, Boroughs, or Cities. Pennsylvania Department of Highways, Harrisburg, 1968.
6. Snow Removal and Ice Control. Highway Maintenance Manual. Pennsylvania Department of Highways, Harrisburg.
7. Halberg, M. C. Statistical Analysis of Systems of Simultaneous Linear Equations Using the Digital Computer. Pennsylvania State Univ., Agricultural Experiment Station, 1967.
8. Parman, W. J. A Pilot Study of Maintenance Costs of Idaho Highways. Univ. of Idaho, 1965.
9. Snow and Ice Control. Research Problem Statement No. 54, Highway Research Circular 62, March 1967, p. 48.
10. Twark, R. D. A Predictive Model of Economic Development at Non-Urban Interchange Sites on Pennsylvania Interstate Highways. Pennsylvania State Univ., 1967.
11. U.S. Weather Bureau. Climatic Summary of the United States—Supplement for 1931 through 1952—Pennsylvania. U.S. Govt. Printing Office.
12. U.S. Weather Bureau. Climatic Summary of the United States—Supplement for 1951 through 1960—Pennsylvania. U.S. Govt. Printing Office, 1964.
13. U.S. Weather Bureau. Climatological Data—Pennsylvania. U.S. Govt. Printing Office, Nov. 1968 through April 1969.
14. Dunlay, W. J. A Model of Simultaneous Stochastic Relations to Predict Winter Maintenance Costs in Pennsylvania. Pennsylvania State Univ., Pennsylvania Transportation and Traffic Safety Center, Report TTSC 6916, 1969.

HIGHWAY SHADE TREE MAINTENANCE

R. A. Bartlett, F. A. Bartlett Tree Expert Company

ABRIDGMENT

•HIGHWAYS that do not provide for the conservation and maintenance of trees help to make our country look like a concrete and asphalt wasteland. Yet, trees provide practical values beyond aesthetic considerations. They help eliminate highway hypnosis and driver tension, two major causes of accidents. Trees act as windbreaks for controlling hazardous crosswinds and snowdrifts. They also control soil erosion, preventing stream sedimentation and water pollution.

Although the benefits of trees along the highway are well recognized, federal and state governments have done little to maintain trees. Some states are investing as much as $500,000 a year for planting, but nothing for maintenance. This is being done in spite of a government-sponsored survey that conclusively shows that trees must be maintained if they are to survive the highway environment.

When instituting a planting and maintenance program, consideration must be given to the existing foliage as well as the types of trees to be planted.

Existing trees along new highways often have the soil compacted around the roots or the roots damaged during construction. Others will be killed by the polluted water running off the highway, or will suffer from lack of water due to the pitch of the roadway. When these conditions exist, the trees should be removed and new trees planted in places where survival is certain.

The following types of trees are able to endure highway conditions: Norway maple, sycamore, scarlet oak, honeylocust, eucalyptus, and eugenia. Evergreens are recommended in localities where they grow well. Shad bush, tung-oil, and tupelo have done well along both the east and west coasts.

After healthy, existing trees have been selected and new trees planted, an adequate maintenance program must be initiated if these trees are to endure and flourish. Regular feeding programs must be instituted to provide the trees with the nutrients they need to survive. Trees should be sprayed when infection or infestation occurs or is imminent. Pruning must be done regularly. Also, consideration must be given to the types of chemicals applied to roadways for snow and ice removal because toxic materials can damage and kill roadside trees.

RECOMMENDATIONS

A comprehensive highway tree census and continuing tree inventory should be initiated. The census should be conducted every 10 years to determine (a) the severity of tree ills and those problems of immediate concern; (b) the manpower and equipment necessary for an effective program; (c) the money required; and (d) the suitability of tree species planted or to be planted.

A master highway tree plan should be developed (a) to integrate economic, aesthetic, and ecological realities to form a practical program of landscape design and (b) to establish short-, intermediate-, and long-range goals that are flexible.

The following specifics should be considered: maintaining mulch, aerating the soil, feeding, watering, pruning, insect control, and tree removal.

Sponsored by Committee on Roadside Maintenance and presented at the 50th Annual Meeting.

THE USE OF ARTICULATED WHEEL LOADERS IN SNOW REMOVAL

Terence K. Young, Caterpillar Tractor Company

The fact that articulated wheel loaders are very efficient snow-removal machines and in many instances are better at clearing snow than trucks or graders will not surprise the many government officials who, as an emergency measure, have outfitted loaders with plows to clear unexpected snow from rural and urban areas. For example, a 4-wheel-drive, heavy-duty truck with plow must slow to approximately 10 mph in moderate and heavy snowfalls, whereas a wheel loader and plow can clear the road under the same conditions at 15 mph. The articulated wheel loader is also able to clear heavily drifted roads by lifting the plow and digging its way through the drift. The center-point steering of the articulated wheel loader makes it a very maneuverable machine that is almost impossible to get stuck because the rear wheels track in the path of the front wheels. Wheel loaders can be outfitted with highly specialized plows, buckets, and snow blowers to suit almost any job condition.

•SNOW removal and ice control represent a very sizable portion of government expenditures in the United States. Approximately $500 million is spent annually, of which $170 million is spent on equipment, $30 million on salt and chemicals, and $300 million on labor and operating costs. In spite of these major expenditures, government agencies responsible for snow removal have very little to show in the spring for the dollars spent during the winter months. Because no real capital improvements such as better roads or schools result from snow-removal expenditures, it is difficult to hold the public's attention and to justify adequate funding for personnel and equipment after the snow season is over. Snow removal, like refuse disposal, is a problem that everyone would like to forget, but when emergencies occur the public demands prompt and complete service. Often, because of inadequate budgets and lack of understanding on the part of the public, when emergencies do occur road maintenance personnel are forced to press non-snow equipment into service. The use of farm tractors or refuse collection vehicles with plows is a typical example. This, of course, is not the most efficient way to plow snow, but it can be a prudent compromise between the most efficient method of snow removal and getting the job done.

In many cases, government agencies have decided to purchase specialized snow-removal equipment; however, this often results in tying up excessive amounts of money in equipment that is used only a relatively few hours each year. This equipment does an acceptable job of snow removal, but it normally sits on a lot three-quarters of the year because of its limited and specialized abilities. Some of the large 4-wheel-drive trucks used for snow removal can have an owning and operating cost in excess of $30 per hour. Even though these specialized trucks could be used for road maintenance or sand and gravel hauling in the spring, summer, and fall, they normally are mothballed because of high operating and depreciation costs.

The individual charged with the responsibility of snow removal for a government agency, therefore, is faced with a dilemma. He can purchase specialized snow-removal equipment that is used only during winter storms or, on the other hand, he may choose

---

Sponsored by Committee on Snow and Ice Control and presented at the 50th Annual Meeting.

more versatile equipment that can be used throughout the year. The purpose of this paper is to suggest that standard wheel loaders equipped with snow-removal attachments are a logical solution to this problem.

Before discussing the relative advantages of the alternatives, a brief summary should be made of what basic snow-removal equipment and attachments are available to a government agency. Because of their high-speed capability, motor graders and 4-wheel-drive, heavy-duty trucks traditionally are the most widely used pieces of snow-removal equipment. More recently, articulated wheel-type front-end loaders are being used widely. These three pieces of equipment are generally equipped with the following basic attachments:

Trucks

1. Vee plow
2. One-way plow } with or without wing
3. Blower

Motor graders

1. Vee plow
2. One-way plow } with or without wing

Wheel loaders

1. Vee plow
2. One-way plow } with or without wing
3. Blower
4. Standard bucket
5. Side dump buckets

The majority of the thousands of snowplows being used in the United States and Canada are mounted on trucks. This is not difficult to understand because snow removal is considered essentially an emergency measure requiring fast action by highway departments. At present, only trucks offer high-speed (above 30 mph) capabilities. However, truck plowing is not all done at high speeds. Snowstorms accompanied by high winds frequently deposit the snow at such a rate that trucks are unable to keep the highways clear. As an accumulation of snow builds up, the trucks must slow down. At this point other types of equipment are often more suited to job conditions. Also, the high-speed capabilities of trucks can seldom be used to open up secondary roads or highways that have drifted shut during a storm. In situations of this kind, trucks are forced to ram their way into the drift until they lose their forward momentum. By repeating this action they are able to open up some drifted sections of road. However, if the drifts are deeper than the height of the snowplow, the trucks are rendered useless because the snow falling over and behind the plow makes it impossible for the truck to back up in preparation for another forward pass. Motor graders can have the same problem with drifted snow. Like trucks, they rely on the ramming effect of their forward motion to clear deeply drifted roads. Trucks used in this way often incur damage to the power train from the shock loads caused by the drifts.

The all-wheel-drive articulated wheel loader is a machine particularly suited to work of this type. In drifts too deep for the truck, the loader can raise its plow and clear the way. In making the opening pass through a deep drift a wheel loader equipped with a plow can move straight ahead with the plow raised. The operator is able to keep the plow in the upper portion of the drift by raising the lift arms and permitting the blade to throw the snow aside (Fig. 1). After knocking off the top part of the drift the loader can return and with one or more passes complete clearing the drift. Loaders working in this way can plow drifts as high as 15 to 16 ft as they actually shovel the drifts aside. Once a road has been opened, an articulated loader with a vee plow is very effective in widening because the machine has center-point steering. If banks are high they may be pushed back with the vee plow. A loader working at a 45-deg angle to the curb line can easily handle banks 6 ft or higher, pushing them back about 6 to 8 ft on each swing. With lower banks a wing can be used effectively with the vee plow (Fig. 2). Slightly crab-

Figure 1. Articulated wheel loader equipped with a reversible one-way plow.

Figure 2. Articulated wheel loader equipped with vee plow and wing.

walking the wheel loader by articulating the machine enables the operator to easily overcome any side drifting that might result from the winging operation.

One-way plows on articulated wheel loaders are also very effective road-widening tools, particularly after a road has been opened with a vee plow. An all-wheel-drive loader should maintain a 15-mph road speed to obtain proper rolling action of material across the moldboard and to cast the snow to the side. In clearing large areas such as parking lots, a wing can also be successfully used with a one-way plow. By placing the wing at ground level, a very wide swath can be cleared.

Snow blowers are high-production tools and can be used very effectively with wheel loaders. In this way the loader, which might otherwise be idle during the snow season, becomes a very valuable snow-removal tool; during the summer months only the blower, and not the prime mover, is idle. Blowers mounted on the lift arms of wheel loaders can load trucks (Fig. 3). For example, a 200-hp blower can load a 10-ton truck in about 30 sec. Blowers with 300 hp or more can be used to throw snow up to 200 ft to widen drifted highways or clear airport runways.

A right- or left-side dumping bucket can be a very high-production snow-removal tool. When locked into the 30-deg angle position, this type of a bucket is also an effective one-way plow. A side dump bucket coupled with the articulated steering of a wheel loader makes it possible to follow the curb line on a curve. This type of snow clearing is extremely difficult with trucks or motor graders. This side dump bucket can also be used to widen roads and push back banks. In addition, the operator can use it for loading salt, sand, or snow into hauling units. The side dump feature of this type of a bucket makes it an especially valuable tool in congested areas where minimum interference with traffic is essential (Fig. 4).

Figure 3. Snow blower mounted on the lift arms of an articulated wheel loader.

Figure 4. Wheel loader with side dump bucket, loading trucks.

An invaluable feature of wheel loaders is that most steer by pivoting about a center point. This gives a longer wheelbase and a shorter turning radius, which allows a loader to circle in less than twice its length. In this way a loader can negotiate narrow mountain roads and dead-end streets and work close to curbs in cramped quarters.

Loaders also are often able to operate at higher speeds than trucks in heavy or deep snow. Given a light snow, a truck can plow roads at a speed of 30 mph. Wheel loaders can almost match that by plowing light snow at 20 to 25 mph. More importantly, a wheel loader can clear heavy snow at a faster rate than trucks. In snow that slows trucks to 10 mph, a wheel loader can often operate at 15 mph or better. This superiority is the result of 4-wheel drive, power shifting, and low weight-to-horsepower ratio.

It is very difficult to get wheel loaders stuck because of their 4-wheel drive. Also, if the loader is center-articulated, the rear wheels will track the front wheels and ride only over compacted material. Articulation also allows the machine to duck-walk out of sticky situations. In addition, snow packed behind the blade can be released by raising the blade.

The following are some operational points to be considered in equipping wheel loaders:

1. A full match torque converter will increase the machine's performance in snowplowing;
2. Oversized tires and ballast will result in greater tractive effort and greater machine stability at high speeds;
3. Double chains with traction-type tires are of great value in icy conditions; and
4. If blowers are used, they should be carefully matched to the size of the loader.

In summary, careful selection of the basic machine and the correct attachments will give a government agency the best snow-removal tool. The wheel loaders discussed in this paper will not replace all other types of snow-removal equipment. For example, the truck-mounted plow is still generally the logical choice for high-speed plowing on expressways and major highways. For very heavy drifts, trucks equipped with large blowers may be a logical choice, but the possibility of using blowers on large wheel loaders should be considered. Motor graders also have their place in rural areas and for ice control. The articulated wheel loader equipped with vee plow, one-way plow, or side dump bucket is outstanding for opening and widening county and secondary roads, winging, and high-production snow-loading.

Anyone considering expanding or replacing his snow-removal fleet should keep in mind the versatility of the wheel loader—not only for snow clearing but also for year-round utility. Every agency involved in road maintenance can benefit from the year-round production capabilities of the wheel loader.

In any case, and whatever the final selection of equipment may be, it is essential that the job conditions and requirements be thoroughly analyzed and that machinery be properly matched to the job requirements.

RUBBER SNOWPLOW BLADES AND LIGHTWEIGHT SNOWPLOWS USED FOR THE PROTECTION OF RAISED LANE MARKERS

Donald R. Anderson, Washington Department of Highways

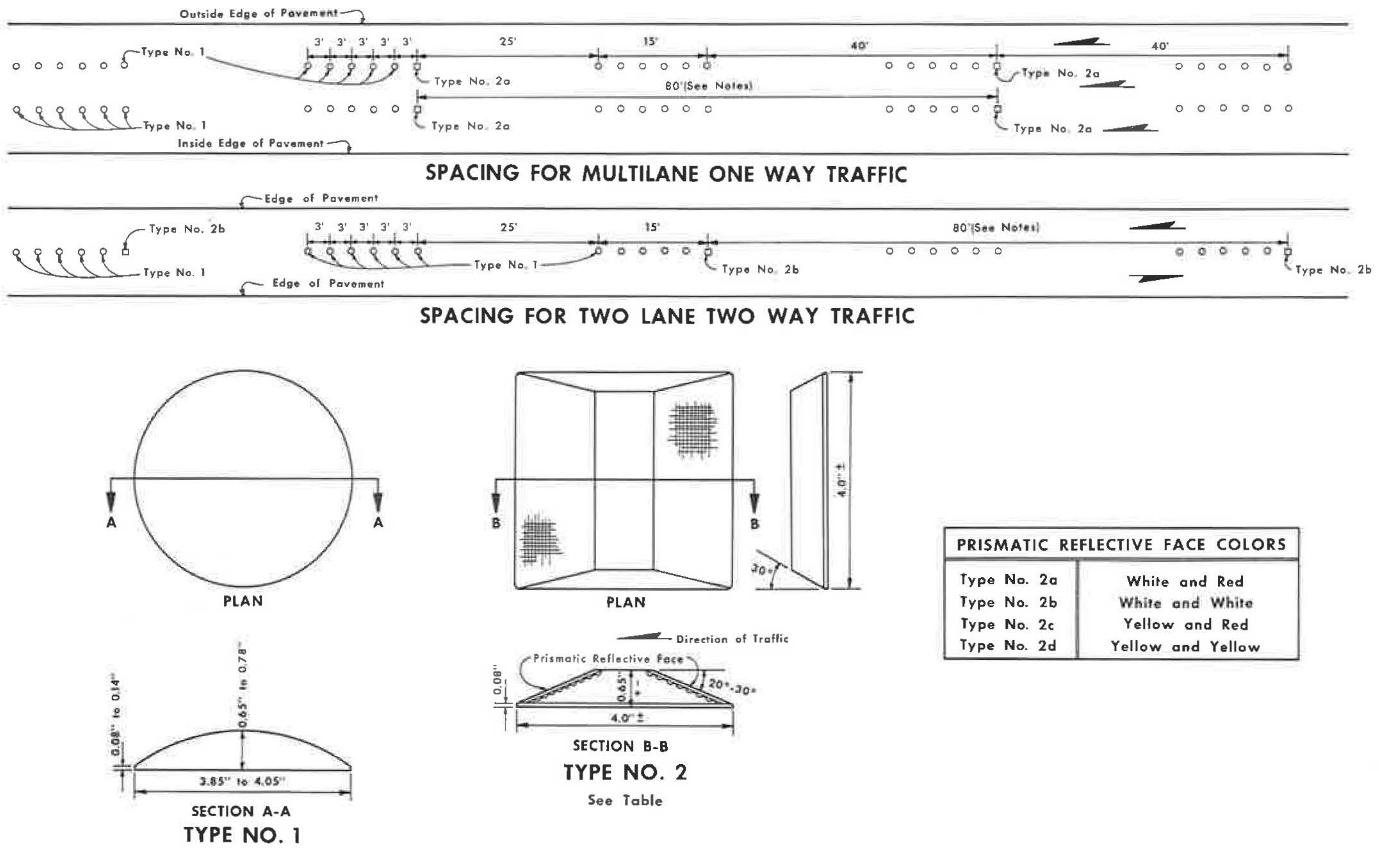
The Washington Department of Highways has adopted a policy of installing raised lane markers on all multilane freeways and interchange roadways in western Washington. Because the lane marker is expensive and easily damaged by standard snowplowing operations, a method had to be devised to plow snow and yet protect the raised markers. This paper reports the results of a 2-year study to expand the experience gained by earlier experiments with the rubber snowplow blade. The study was made to document the rubber blade's performance under typical winter road conditions and to evaluate the results of introducing the rubber snowplow blade and lightweight moldboard to the state's snowplow fleet. The lightweight snowplow was specifically designed for use with the rubber cutting edge. It eliminated one of the major causes of excessive wear, namely, the heavy weight of the standard moldboard. Before the lightweight plow was introduced, this problem had been partially overcome by installing a system of restrainer chains and turnbuckles to help support the standard plow's weight and reduce the down-pressure on the cutting edge. The rubber cutting edge was shown to be suitable for snowplowing except when temperatures are consistently below freezing and a slush or semithawing condition does not exist or could not be induced by chemicals. In spite of their higher initial cost, the rubber snowplow blades wear less per mile of plowing than medium steel plow blades and have shown a remarkable service life between blade changes.

•BARRIER or lane stripe effectiveness has been a matter of concern to highway engineers for some time. Until recently, a reflectorized pavement stripe has been the principal means used to delineate traffic lanes on multilane highways or to separate opposing lanes on two-lane roadways. The driver's inability to see readily the reflectorized painted traffic stripe during periods of rainfall or hours of darkness at normal speeds has long been recognized. It also has been established that wear or a moisture film covering the painted stripe on the pavement reduces the reflective ability of the small glass beads imbedded in the paint matrix (1).

It is the general policy of the Washington Department of Highways to paint the centerline or lane lines at least once every year and to paint the edge stripe every 2 years. Striping usually begins in the early spring and continues until inclement weather in the late fall or early winter stops the operation.

In the summer of 1961 research was started to develop a method of traffic line marking that would overcome the problems inherent in the use of painted stripes. Vendors of several types of pavement markings were invited to lay test sections of their product in a test area. These products included (a) hot-applied beaded thermoplastic material, (b) pre-formed, cold-applied, self-adhering plastic, (c) beaded thermoplastic dome-shaped markers, and (d) conventional, beaded white paint stripe.

Sponsored by Committee on Snow and Ice Control and presented at the 50th Annual Meeting.



PRISMATIC REFLECTIVE FACE COLORS	
Type No. 2a	White and Red
Type No. 2b	White and White
Type No. 2c	Yellow and Red
Type No. 2d	Yellow and Yellow

NOTES:

Throughout the length of horizontal curves with radii less than 5,000 feet, Type No. 2 markers shall be placed at 40 foot intervals. Each series of lane markers through the length of the curve will consist of one Type No. 2 marker and five Type No. 1 markers.

See the standard specifications and special provisions for further requirements.

Figure 1. Standard lane markers.

The first two materials were laid in 15-ft lengths at intervals of 25 ft. The stripe was 4 in. wide and approximately ⅛ in. thick.

The dome-shaped traffic markers were installed in a series of six markers spaced 3 ft apart for a total distance of 15 ft in a skip stripe pattern. They were cemented to the pavement by a two-component epoxy resin adhesive. The markers were 4 in. in diameter, flat on the bottom, rounded on the top, and protruded approximately ¾ in. above the pavement.

At the end of the first 30 months of the research project, the reflective value of the marker system became so obvious that the Highway Department adopted the raised traffic marker system for lane markings on all new construction of Interstate highways west of the Cascade Mountains. The raised traffic marker soon thereafter became a standard installation on all multilane highways west of the Cascade Mountains.

The Washington state standard for lane markers requires a set of six buttons placed 3 ft apart with 25 ft between sets. The first button in alternate sets, every 80 ft, is a prismatic reflective marker intended to enhance the night visibility of the system (Fig. 1).

In congested areas, the replacement of lane markers increases the maintenance man's exposure to the hazard of traffic. This problem can be alleviated somewhat by replacing the markers during the hours of lower traffic volumes.

Preliminary cost estimates of the system indicated that the cost of the marker system would be high initially, but when amortized over an expected 10-year period, it was estimated to be the same as the painted stripe system. The annual maintenance cost of the marker system, once installed, was said to be about one-quarter that of a painted stripe (1).

Because of the high cost of installation, it was obvious that measures had to be taken to protect the raised marker from possible damage during snowplowing operations. From 1962 until 1965, the maintenance division searched for possible methods of plowing snow without damaging the raised marker. The search proved to be discouraging because use of the raised marker had been very limited at the time, and the states that had used the markers had given them up because of snow removal problems. Our investigations revealed that a rubber bit had been used successfully in certain areas on small tractor-type units. Reports from England indicated that these units could plow snow without damage to the plow or to roadway appurtenances, such as curbs and manholes. Further investigations revealed that the rubber plow blade had been used in many municipalities on streets and airport runways.

In the spring of 1966, the Goodyear Rubber Company, through one of its local outlets, supplied the department with one hard-rubber snowplow blade. It measured 10 ft in length and was approximately 1½ in. thick and slightly over 10 in. wide (Fig. 2).

The blade was mounted on a standard Washington state snowplow in September, and a trial run was made over a short test section. Water was applied to the roadway ahead of the snowplow to lubricate the plow and to simulate a slush snow condition. The results of this test indicated that the rubber blade would pass over the plastic markers without damage to them and would squeegee the water (simulated slush) off the pavement surface. No appreciable wear of the rubber was noted after the short trial run (2).

The successful completion of the trial run provided the department with the needed incentive to order 24 blades for use during the following water in areas where the raised traffic markers had been installed. The blades were received late in January 1967. Consequently, they were not available for evaluation during the storms that occurred in late December 1966 and early January 1967.

Figure 2. Washington standard power reversible moldboard with rubber snowplow blade.

The rubber snowplow blade was used marginally in the winter of 1967. The Seattle Division was able to use a plow 13 hours in the vicinity of Bellingham and about 12 hours north of Seattle. The Tacoma Division used the plow for approximately 20 hours in the vicinity of North Fort Lewis and Tacoma. Because of this limited use, a definite comparison in the economy of rubber versus steel bits could not be made; however, it was shown that rubber blades could outwear the steel type. The limited use also substantiated the findings of the earlier experiment; i.e., rubber blades will do a satisfactory job of removing slushy snow from pavement surfaces and will ride over the raised traffic markers without damaging them. During this short period of time, it became apparent that it was important that the plow be adjusted properly to bear evenly upon the pavement surface in order to minimize the amount of wear and tear on the blade itself. One of the first approaches in solving the problem was to install side shoes on the standard plow to carry the weight of the plow and to equalize the pressure on the rubber blade. This approach was soon abandoned because the shoe damaged the raised button to the same degree as would a steel blade whenever the plow edge crossed the lane markers. To replace the shoe, a chain and turnbuckle assembly was installed between the truck and the standard plow to help carry the weight of the plow (Fig. 3). When properly adjusted, this system proved to be quite successful and is used with many of our standard plows today.

The idea of reducing the weight of the plow first developed in the fall of 1967. Our equipment personnel discussed the possibility of developing a lightweight plow with a local manufacturer, who had developed a prototype lightweight plow (Fig. 4). This design was modified to meet the requirements of the equipment engineer and one was ordered. It was received in early January 1968 for use in the Seattle area as part of this test.

PROCEDURES

Our maintenance division, like those in many other states, does not have a surplus of equipment for use for experimental purposes during a snowstorm. It taxes our forces just to keep all available equipment working during a storm. Consequently, we determined that all equipment used during the study would remain in general use and would operate in a normal manner. The only change to the normal routine would be that each operator would report his daily activities on a special form developed for the study. Automatic recording devices were developed and used in the final phases of the test to ease the reporting burden and to remove as much of the "human element" as possible. A Hobbs hour meter (Fig. 5) was used to record the blade contact hours and an Engler electric speedometer/odometer (Fig. 6) recorded the blade contact mileage. Each of these devices was activated only when the moldboard was in a down position and plowing.

Figure 3. Washington standard moldboard with chain and turnbuckle assembly.

Figure 4. End view of rubber snowplow blade attached to moldboard.

Figure 5. Hobbs hour meter mounting.

Figure 6. Engler electric speedometer/odometer.

These procedures resulted in a collection of empirical data that were more representative of what could be expected in the field than might be obtained from a laboratory approach to testing.

Because the main objective of the study was to determine the feasibility of using nondestructive type blades with lightweight moldboards, the data appeared to be decisive enough to justify practical conclusions.

One lightweight moldboard was available in the Seattle area for the study (Figs. 7, 8). Others used the regulation steel plow or steel plow coupled with a rubber-tipped snowplow. The regulation steel plow was used for comparative purposes.

Performance of each type of plow and blade was observed during actual operations under many different conditions that occurred during the storms of 1967 to 1969. Dim sions and weights were recorded after each storm to determine the rate of wear and t plow blade's resistance to damage under normal use.

PROJECT SCOPE

The project was designed to extend through a maximum of two winter seasons to ensure that enough plowing was done with a lightweight plow and rubber blade to obtain enough data to evaluate properly the moldboard and the nondestructive blade.

Three separate test sections were established for the study. Two of these sections were located north of Seattle and the third was established south of Olympia. Because

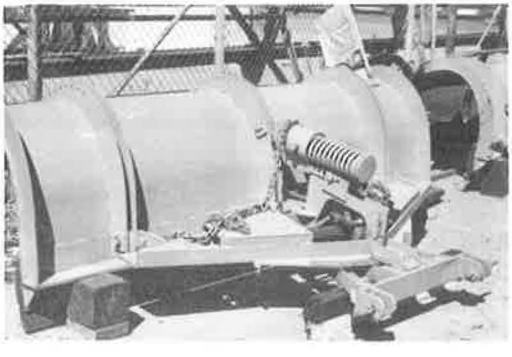


Figure 7. View of the 10-ft lightweight moldboard showing the spring shock absorber on circle. Plow exerts approximately 700 lb on cutting edge.

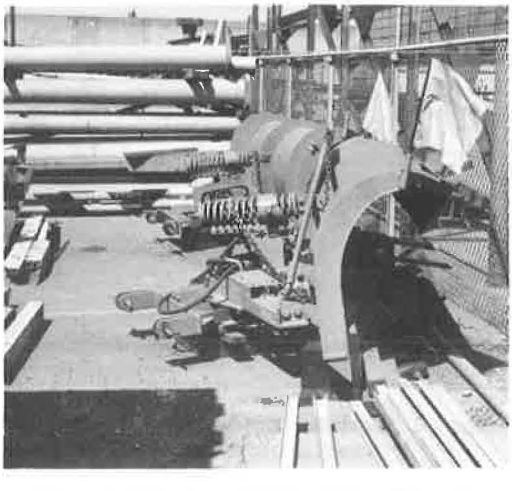


Figure 8. Side view of lightweight moldboard.

the test section established in the Olympia area involved different administrative and operational personnel, we felt that the data collected there could be used to validate results obtained in the Seattle area.

The test data in Table 1 recorded by Vehicle No. 6A5-4 are typical of the records received from all of the vehicles involved in the study. The rubber cutting edge used on Vehicle No. 6A5-4 weighed $85\frac{1}{2}$ lb when it was installed at the beginning of the season and 74 lb on January 31, 1969, at the end of the season. This weight loss represented an average loss in depth of $1\frac{5}{8}$ in. Data from the test vehicles are summarized in Tables 2 and 3.

PERFORMANCE OF STEEL CUTTING EDGE

For years, the department has used a medium steel cutting edge in its snowplowing operations. The medium-grade steel included 0.65 to 0.80 percent carbon, 0.20 to 0.40 percent manganese, and a maximum of 0.04 percent phosphorus and 0.05 percent sulfur.

Standard practice in most divisions on the west side of the Cascade Mountains, where a constant snow bottom is not normally encountered, is to change the cutting edge at least once every shift. Generally, the change is made between shifts so that the operator

TABLE 1

RECORD OF RUBBER SNOWPLOW BLADE TEST (VEHICLE NO. 6A5-4)

Date	Surface Condition	Total Plow Time (hours)	Total Plow Miles	General Performance
12/19/68	Slush	0.5	3	Bladed clean
12/21/68	Slush	2.0	34	Bladed clean
12/22/68	Slush	0.7	11	Bladed clean
12/31/68	Compact snow	3.5	50	Partially
12/31/68	Compact snow	4.5	87	Partially
1/1/69	Compact snow	3.5	53	Partially
1/2/69	Compact snow and slush	6.0	53	Bladed clean
1/2/69	Slush	3.0	38	Bladed clean
1/11/69	Slush	5.0	61	Clean
1/14/69	Slush	2.0	50	Clean
1/15/69	Slush	3.0	35	Clean
1/19/69	Slush	1.5	15	Clean
1/20/69	Fresh snow and compact	4.0	42	Partially
1/26/69	Fresh snow and compact	6.3	131	Partially
1/26/69	Fresn snow and compact	9.3	201	Partially
1/27/69	Fresh snow and compact	10.0	210	Partially
1/28/69	Fresh snow and compact	14.7	287	Partially
1/29/69	Fresh snow and compact	8.8	142	Partially
1/30/69	Snow and compact ice	8.7	146	Partially
1/31/69	Snow and slush	3.3	50	Partially
Total		100.3	1,699	

Notes: All plowing was on portland cement concrete pavement. Engler Electric Speedometer/Odometer was added 1/26/69 to record automatically the time and distance the plow was in contact with the roadway surface.

TABLE 2

RUBBER SNOWPLOW BLADE USE, WINTER SEASON, 1967-1968

Vehicle No.	Total Plow Time (hours)	Total Plow Miles	Total Blade Wear	General Performance
6A2-12	13.0	144	8 oz	Bladed clean to partially clean
6A2-25	12.5	135	6 oz	Bladed clean
6A5-2	15.4	194	8 oz	Bladed clean
6A3-46	3.8	76	Not available	Bladed clean
6A3-38	1.1	33	Not available	Bladed clean
6C2-56	36.5	455	1.35 lb	Worked well
6C2-56	29.0	884	2.70 lb	Worked well

TABLE 3

RUBBER SNOWPLOW BLADE USE, WINTER SEASON, 1968-1969

Vehicle No.	Total Plow Time (hours)	Total Plow Miles	Total Blade Wear	General Performance
6A5-4	100.3	1,699	11.5 lb	Clean to partially clean
6A3-38	175.3	3,118	19 lb[a]	Clean to partially clean (would not remove compact snow and ice)
6C2-56	51.3	1,189	Not available[b]	Clean to partially clean

[a] A 3-lb piece was torn and lost from the rubber bit.

[b] Weights were not available but measurements indicated a loss of 1⅛ in. at one end, ⅛ in. in the center, and ⅛ in. on the other end. The uneven wear was attributed to poor weight distribution of the plow.

TABLE 4

STEEL PLOW BLADE RECORD
(VEHICLE NO. 7C12-1, PLOW NO. 23C4-98)

Date	Hours	Miles	Remarks
12/18/68	2.5	81	New blade
12/22/68	3.0	63	
12/22/68	4.0	85	New blade
12/28/68	6.5	114	New blade
12/29/68	1.5	35	New blade
12/30/68	5.5	137.5	
12/31/68	13.0	95.0	
12/31/68	7.0	140.0	New blade
Total	43	750.5	

can be assured of an adequate depth of steel on the moldboard for cutting purposes during his shift. This practice often results in a waste of steel because frequently the cutting edge is not completely worn out. Because of the emergency nature of the work, these partially worn bits were considered expendable.

The final analysis of the data collected during the two winter seasons indicated that the formal data being collected were not as complete as expected; however, a partial record illustrates the fact that steel blades required constant changing (Table 4). This record indicates at least five new blades were requi during the time interval. These five blades logged only a total of 750.5 miles, or an average of 150.1 miles per blade. A longer life for steel blades is experienced in areas where a compact snow bottom is commonplace, as in certain areas in eastern Washington; however, where bare pavements are encountered, the medium steel blade will be completely worn away within a very few hours.

ANALYSIS OF WEAR AND COST DATA

No attempt was made to determine a parameter for measuring when a rubber blade was worn to failure and needed to be replaced. However, Table 5 indicates that at least 19 lb of wear on one side could be expected from an 85½-lb blade. An additional 19 lb could be expected to be available for wear if the blade were inverted and used until totally destroyed.

TABLE 5

RUBBER SNOWPLOW WEAR

Vehicle No.	Total Plow Miles	Total Blade Wear (lb)	Wear Ratio	Wear Cost ($)	Cost per Plow Mile ($)
		Winter Season, 1967-1968			
6A2-12	144	0.5	0.025	2.66	0.018
6A2-25	135	0.375	0.01875	1.99	0.015
6A5-2	194	0.5	0.025	2.66	0.014
6C2-56	455	1.35	0.0675	7.17	0.016
6C5-56	884	2.70	0.135	14.35	0.016
		Winter Season, 1968-1969			
6A5-4	1,699	11.5	0.575	61.10	0.036
6A3-38	3,118	19.0	0.95	100.95	0.032

For purposes of our analysis, we have assumed that an average rubber snowplow blade should lose 20 lb by wear before being discarded. Theoretically, over half of the blade's volume, or 43.75 lb, is available for plowing purposes. However, it is expected that many blades will tear or suffer irregular breakage that will reduce the actual amount of blade volume available for abrasive wear, and hence the lower conservative figure for expected weight loss is used.

To compare the cost per plow mile for rubber snowplow blades to medium steel, we made these additional assumptions:

1. Total cost of the rubber blade is chargeable after 20 lb of wear is experienced.
2. One hour of labor, Maintenance Man II class, at the weighted wage of $4.48 per hour (raised to $5.14 in fiscal year 1970) is required to change a snowplow blade.
3. A new medium steel cutting edge is required every 150 miles of plowing. It is recognized that additional mileage can be obtained during heavy snowstorms when plowing snow bottom. This is offset, however, by the fact that our practice to replace partially worn blades at the end of a shift reduces the amount of mileage obtained from a blade.

A cost per plow mile was calculated for each vehicle and rubber and steel blade tested as shown by the following example for Vehicle No. 6A2-12:

Given

1. Total plow miles = 144
2. Total blade wear = 0.5 lb
3. Average blade cost = $101.78

Then

$$\text{Wear ratio} = \frac{\text{Total Wear}}{\text{Maximum Wear Possible}} = \frac{0.5\text{ lb}}{20\text{ lb}} = 0.025$$

$$\text{Wear cost} = \text{Wear Ratio} \times (\text{Blade Cost} + \text{Cost of Installation})$$

$$= 0.025 \times (\$101.78 + \$4.48) = \$2.66$$

$$\text{Cost per plow mile} = \frac{\text{Wear Cost}}{\text{Miles Plowed}} = \frac{\$2.66}{144} = \$0.018/\text{mile}$$

Table 5 summarizes the results of these calculations.

Calculations for steel plow cost per mile as follows, using Vehicle No. 7C12-1 as an example:

1. Total plow miles = 750.5
2. Total blade wear = Total wear on 5 blades (The report began with a new blade and ended with the last blade completely worn.)
3. Average blade cost = $9.45
4. Wear Ratio = $\frac{5}{1.0}$ = 5.0
5. Wear cost = 5.00 × $9.45 = $47.25 plus cost to change 5 blades (Cost to change 5 blades = 5 × 1 man-hour × $4.48/hour = $22.40)

Therefore, total cost equals

$$\$47.25 + \$22.40 = \frac{\$69.65}{750.5} = \$0.093$$

(This cost does not take into account the rental of small tools or cost of materials that might be required to make the steel blade changes.)

From the calculations it can be seen that, in spite of the higher initial cost, the rubber snowplow blade is more economical than the medium steel blade in areas where bare pavement is encountered. The recent wage increase widens the difference of wear costs. These figures closely agree with other cost data developed in other areas.

RAISED TRAFFIC MARKER PROTECTION

The prime purpose of this study was to determine the effectiveness of the rubber snowplow blade in protecting the raised traffic marker. Although it is important to know that the rubber snowplow blade will outwear a medium steel blade and can effectively remove slushy or freshly fallen snow, it is probably more important to know that snow can be plowed from roadways with raised markers without damage to the markers.

To make this determination, we established a typical 1-mile control section within the limits of the two Seattle sections studied. The raised traffic markers were counted before the test began and periodic counts were taken thereafter. The markers were originally installed on the two sections by construction contracts in 1965.

To determine the number of markers missing since their initial installation, the raised traffic lane markers were counted shortly before the first snowfall in 1967. Counts were then made periodically during each winter before and after each snow period. Individual counts were made on sample sections in both the northbound and southbound lanes.

Test section 1, located immediately north of Seattle, is constructed of portland cement concrete and has three lanes in each direction. Data obtained from an analysis of the counts taken on the 1-mile sample section on the northbound and southbound lanes are given in Table 6. The higher losses in the 1968-1969 season were undoubtedly due to the severity of that winter. The Pacific Northwest suffered an extended winter season that year and snowfalls in the lower elevations were much greater than normal.

It should be further noted that part of the marker loss attributed to snow-removal equipment was possibly due to breakage caused by tire chains. We did not attempt to determine the number that were broken by chains because of the difficulties involved. We know that actual losses directly attributed to snow-removal equipment would be somewhat less than noted, but by considering all losses as caused by snow-removal equipment, we felt that we would be giving the rubber blades the most difficult test.

Test section 2, south of Everett, has two lanes in each direction and is constructed of asphalt concrete. A loss analysis of the counts taken on this section revealed the data given in Table 7.

A formal record of button loss was not kept in test section 3; however, the project supervisor in that district reported in his diary that counts before and after the snow season indicated that no loss due to snow removal was evident in the 1967-1968 season. Inspections in the 1968-1969 season found that an area on the south end of the district's

TABLE 6

TEST SECTION 1 DATA

Time or Cause of Loss	Northbound (percent)		Southbound (percent)	
	1967-1968	1968-1969	1967-1968	1968-1969
During the season	1.81	1.37	2.08	2.56
Attributed to snow-removal equipment	1.43	1.07	1.90	1.94
Caused by normal traffic	0.38	0.30	0.18	0.62

TABLE 7

TEST SECTION 2 DATA

Time or Cause of Loss	Northbound (percent)		Southbound (percent)	
	1967-1968	1968-1969	1967-1968	1968-1969
During the season	6.82	3.34	4.10	4.55
Attributed to snow-removal equipment	5.36	3.09	4.10	4.42
Caused by normal traffic	1.46	0.25	0	0.13

boundaries showed signs of some marker loss. This occurred, however, only in areas where steel plows from the adjoining district, which had no raised buttons, plowed snow while turning around to return their own district.

The initial count in 1967 indicated that only 158 markers were lost in the southbound lanes and 126 markers in the northbound lanes. This represented the loss since early 1965 when the traffic markers were first installed.

CONCLUSIONS

From our experience we have concluded that the rubber snowplow blade is an effective and economical tool to use during snowplowing operations, both for removing freshly fallen or slushy snows and for the protection of raised traffic markers or other raised appurtenances on the roadbed. The rubber snowplow blade is most effective when ambient temperatures are near or slightly above freezing. The use of calcium chloride or sodium chloride induces a slushy or thawing condition at a lower temperature range so that the rubber blade can be used more effectively.

Loss of raised traffic markers is not increased significantly when snow is removed with a rubber plow blade. Some of the minor amount of loss noted during the snow season can be attributed to damage from tire chains, studded tires, or other factors.

The rubber blade mounted on a lightweight moldboard is adequate for the job for which it was designed. The standard weight plow mounted with a rubber blade, properly supported, will also plow snow effectively without excessive wear of the blade. The weight on both types of plows must be evenly distributed and controlled to produce the most effective operation and to control blade wear.

A 2- to 2½-in. exposure of the rubber blade provides the best cutting edge. Less exposure slightly increases the blade's ability to cut compact snow but substantially increases the wear on the rubber blade. More exposure causes the blade to tend to roll under and slide over the snow instead of removing it. The blade can be inverted on the moldboard when one side wears out, thereby doubling the life of the blade.

Generally, snowplowing with a rubber blade, properly adjusted, is best done at speeds between 25 and 30 mph. Lower speeds are necessary if blade exposure is greater than the optimum because the blade tends to fold back and plow over the snow bottom instead of cutting at high speeds.

The State of Washington enjoyed an open winter during the 1969-1970 season, particularly in the lower elevations where the rubber snowplow blade is most generally used; consequently, that winter added nothing to our experience of the previous season. One district reported that not one blade was worn out during the season. Personnel from another district reported that after wrecking two steel plows on high monuments, they found that the rubber blades would ride over a monument, railroad crossing, broken pavement, and other obstructions. Most of the eastern Washington districts report limited use of the rubber blade with varying degrees of success, depending on the snow and temperature conditions at the time of plowing.

Our experience with the lightweight plow and rubber blade has convinced us that the combination is suitable for general use in western Washington and limited use in eastern Washington. We are planning to expand the use of the plow in all areas. As of May 1, 1970, we have added a total of 56 lightweight snowplows to our snowplowing fleet. We believe that more will be added once our personnel become acquainted with the new plow and accept the fact that it can do a good job in wet snows and yet is easier to carry and less hazardous to use than the older, heavier Washington standard reversible plow.

REFERENCES

1. Cody, L. W. Semi-Permanent Traffic Striping Research Project HR-78. Washington Department of Highways, May 1, 1967.
2. Stackhouse, J. L. Protection of Raised Traffic Markers in Connection With Snow and Ice Removal. Washington Department of Highways, 1967.
3. Rubber Snow Plow Blades and Lightweight Snow Plows Used for the Protection of Raised Traffic Markers. Washington State Highway Commission and U.S. Department of Transportation, Bureau of Public Roads. June 1969.