Economic Analyses and Dynamic Programming in Resurfacing Project Selection

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The objective of this paper was to develop a dynamic-programming procedure by using economic analyses to assist in optimizing expenditures in pavement-resurfacing programs. Benefit relationships were determined from expected accident reduction, improved comfort, and savings in time, fuel, and maintenance. The only cost input to the program was the resurfacing cost of each project. Dynamic programming was adapted to the selection of projects for resurfacing in Kentucky. More than $8.4 million of additional user benefits would have been realized in 1976 if dynamic programming had been used in selecting projects. The benefit/cost ratio of sections selected for resurfacing by the current procedures was 3.21 compared with one of 4.22 if dynamic programming had been used.

Various management procedures and strategies may be employed to select and rank pavements for resurfacing. Subjective visual evaluations and objective measurements may be used alone or in combination. Sophisticated methods consider pavement roughness, skid resistance, traffic volume, and accidents in an economic analysis. Selection processes based on economic analyses have obvious advantages over other methods. Also, recourse to a computer is necessary for the analysis and ranking when more than a few projects and alternatives exist. A technique termed "dynamic programming" performs this task. The accuracy, however, depends on the accuracy of the benefit and cost values assigned to each element included in the analysis.

The Kentucky Department of Transportation first applied dynamic-programming techniques to the spot safety improvement program in 1974 (1). The application of dynamic-programming techniques to the resurfacing program was proposed as a way of optimizing expenditures. Since hundreds of candidate projects are recommended for resurfacing each year, it is difficult to select those that will yield the greatest benefit to the driving public. To apply dynamic programming or any other economic method to the resurfacing program, a reliable means of calculating benefits must be employed. This paper presents those procedures and criteria.

DYNAMIC-PROGRAMMING CONCEPT

The term "dynamic programming" was first used by Bellman to represent the mathematical theory of a multistage decision process (2). It is applied to allocate expenditures in a way that results in the maximum benefit. Three types of applications of dynamic programming are single-stage, multistage, and multistage that has a time factor. Single-stage programming is used to evaluate a single project that has several alternatives. Multistage programming involves selection of several projects that have several alternatives. Multistage dynamic programming that has a time factor is used when several projects and alternatives are considered and various time periods are involved. Multistage programming is currently being used in the safety improvement program in Kentucky. It was presumed to be also applicable to the resurfacing program.

Input to the model consists only of costs and benefits for a project and the useful life of the improvement. Costs are incurred by the highway agency, and benefits are gained by the road user (3). Costs associated with a project might include construction costs and annual maintenance costs. Benefits include savings of time and fuel, increased comfort (or ride quality), and accident reduction.

RESURFACING PROGRAM IN KENTUCKY

The Division of Maintenance is responsible for the statewide resurfacing program, which cost $12 million in 1977. The 12 highway districts select and rank resurfacing needs and submit a list of projects each year. A team composed of two engineers from the Division of Maintenance and one from the district reviews and evaluates the projects. The same two engineers from the Division of Maintenance evaluate sections throughout the state. According to a proposed form, maintenance sections are rated on a point system (maximum of 100 points) and are evaluated for service (15 points), condition (71 points), and safety (slipperiness) (14 points). A high point value indicates a need for resurfacing. Service evaluation is based on the annual average daily traffic (AADT) of the section. The maximum of 10 points is assigned to roads that have AADTs more than 10 501. An extra five points are added when traffic speeds are 22 m/s (50 mph) or more.

The subjective rating of pavement conditions (35 points) is based on raveling (spalling), cracking, patching, edge failure, base failure, out-of-section condition, and appearance. The proposed form would permit rating of severity as well as density (frequency) of the failure or deficiency. Rut depth from 9.5 to more than 22.2 mm (0.375-0.875 in) is assigned a maximum of 12 points. A roughness index (RI) is obtained by using the Kentucky method (4,5) or by correlation by using the Mays ride meter. Roughness ranges up to 24 points. If a roughness measurement cannot be obtained, ride quality is subjectively evaluated and rated as smooth (no points) to severely rough (22 points).

The safety rating is based on skid resistance. Pavements that have skid numbers (SNs) of 30 or less are assigned 14 points. The rating form used previously did not adequately weigh conditions that may warrant extreme measures when some important attribute was at an unacceptable level. The proposed form would require the addition of 100 points if the SN was 28 or less and the AADT was more than 1000. Similarly, 100 points would be added whenever the RI or rutting for a particular type of pavement and a given volume of traffic exceeded the values cited on the rating form. Resurfacing costs and district rankings are cited on each rating form.

PROCEDURE

Resurfacing costs and annual maintenance costs must be known, and benefits expected from accident reduction, improved comfort, and saving of time and fuel must be determined. Other inputs into the model include the probable life of the new surface, the interest rate, and unit costs of accidents, time, comfort, and fuel. These inputs can be easily changed from year to year as unit costs increase.

The effect of resurfacing on accident experience was found by analyzing the before-and-after accident data of approximately 3700 km (2300 miles) of road evaluated from 1973 through 1976. Correlations were also made between accident experience and pavement condition. This analysis was essential for projection of accident savings attributable to resurfacing.

An analysis was also made of the benefits to the road user from increased comfort. The cost of traveling over a newly resurfaced road was compared with that of traveling over a pavement in very poor condition. These costs were established from responses to questionnaires on which motorists indicated willingness to pay for travel on a new smooth pavement compared with travel on one in poor condition. The resulting costs per kilometer were converted to annual dollar benefits for highway sections, based on AADT and length.

Equations were also developed to compute benefits for time and fuel saving after resurfacing. Such information as pavement roughness, AADT, and vehicle speed were included in the analysis.

The resurfacing costs were those estimated by maintenance engineers for each section recommended for resurfacing. These costs were based on surface width, section length, type of surface, and many other factors. These costs represented present worth and were inputs into the dynamic-programming model.

A formula for annual maintenance costs was derived from annual maintenance costs for rural roads in Kentucky (6). Maintenance costs generally increase as a pavement ages. This was taken into account indirectly.

A present-worth factor was used to convert the annual maintenance cost and annual benefits to their present worth. For a given interest rate and number of years, a factor can be determined to convert a uniform series to its present worth (3).

Based on the costs and benefits computed for highway sections recommended for resurfacing in 1976, an appropriate computer program was prepared. An optimal priority listing of projects was derived. The projected benefits and costs of this optimal listing were compared with those of projects selected by using traditional methods.

SERVICE LIVES OF RESURFACING PROJECTS

Ideally, pavement overlays should be designed for a desired service life based on estimated traffic volumes. In this case, overlay types and thicknesses will vary by project and will influence resurfacing costs. The design period can be used as the estimated service life. To increase surface life, thicker, more durable surfaces should be used on roads that have heavy traffic volumes and heavy trucks. The overlay thicknesses for the resurfacing projects analyzed in this study were not based on structural designs but generally consisted of cost estimates for a standard 38.1-mm (1.5-in) surface course. The service lives of these overlays were estimated for various ranges of AADT. Service lives ranged from 7 years for AADTs of more than 8000 to 16 years for AADTs between 1001 and 4000. Lives of 12 years were estimated for sections that had AADTs of 400-1000 and 4001-8000. The actual designed service life can be used if known. The dynamic-programming model allows for input of the design life, which will then override the estimates above. In the past, standard 38.1-mm overlays have been customary. The program does allow for input of individual project design lives if this procedure is adopted in the future.

CALCULATION OF ROAD-USER SAVINGS

Before benefits can be computed for any highway improvements, some assumptions have to be made. If the condition of a pavement is known before it is resurfaced, the following questions must be answered before benefits can be computed:

1. How will the condition of the pavement change if no improvement is made to the pavement?
2. How will the condition of the pavement change if it is resurfaced?
3. What is the relationship between road-user costs and time as the overlay surface deteriorates over its useful life?
4. How can benefits be computed due to resurfacing for an overlay that has changing conditions throughout its life?

To answer these questions, two different types of assumptions were made to apply to the various types of road-user costs. The first is illustrated in Figure 1. Road-user costs are high at Cb after a pavement ages after time Ta. At time Tb, the pavement is resurfaced and the road-user costs immediately drop to level Ca. This reduction holds until time Tc, when road-user costs will increase either gradually or sharply. The second assumption applies to other types of road-user costs, which increase gradually after resurfacing until they reach a maximum level as shown in Figure 2. Point A represents the time shortly after a new pavement overlay. If no improvements are made to the surface, its condition will gradually worsen until it reaches point D. At this point, the pavement will not get much worse in terms of road-user costs; a road can only get so slick and rough and still be used. The road-user costs would then stay relatively constant at Cb until the road reaches point E in time. If the pavement is resurfaced at point B (road-user cost = Ca), the road-user costs would immediately drop to point G, which might be equated to no cost. The life of the new overlay will then be (Tb - Ta), or N. The road-user costs are then assumed to increase linearly over its life until they reach the peak value at point E. Another pavement overlay at point E would start the cycle once again.

If no improvements were made at point B, the road-user cost between times Ta and Tb could be represented by the area within the boundaries of BDEFG. This area gives the total road-user cost for time N. If the pavement is overlaid at time Ta, the saving in road-user costs is the shaded area represented by BDEG. By determining this area, the road-user saving or benefits can be found for the overlay life N.

The equation derived represents area BDEG. This area can be found by computing the area of the large rectangle (GHEF) and subtracting triangles 1 (GEF) and 2 (BHD). The final equation for BDEG total benefits (Bc) is as follows:

$$Bc = \left\{[(N)(Cb) - \tfrac{1}{2}(N)(Cb) - \tfrac{1}{2}(Cb - Ca)]\,[N - N(Ca/Cb)]\right\} Ff/N \qquad (1)$$

or

$$Bc = \left\{[(N)(Cb/2) - \tfrac{1}{2}(Cb - Ca)]\,[N - N(Ca/Cb)]\right\} Ff/N \qquad (2)$$

where Ff is a factor used to convert to present-worth benefits. The rest of the equation will give the average annual values of benefits for the project life, such as the following:

1. Average annual percentage of reduction in road-defect accidents due to resurfacing (accident benefit),
2. Average annual saving in comfort cost for the road user (cents per vehicle kilometer),
3. Average annual percentage of reduction in fuel cost, or
4. Average annual maintenance savings per vehicle kilometer.

Figure 1. First assumption of road-user costs versus time.

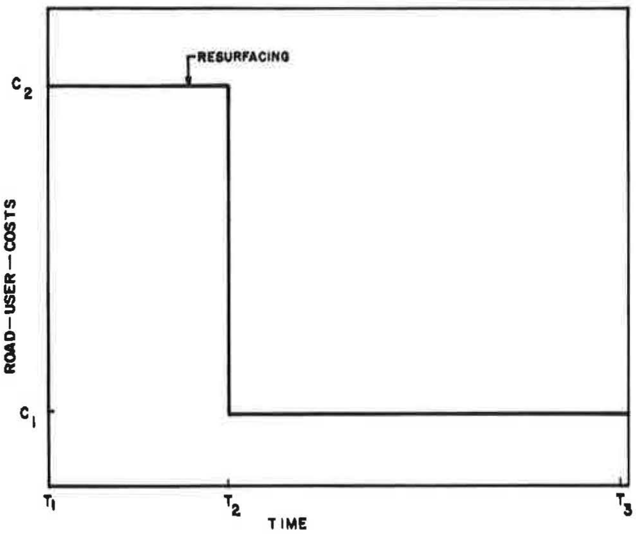
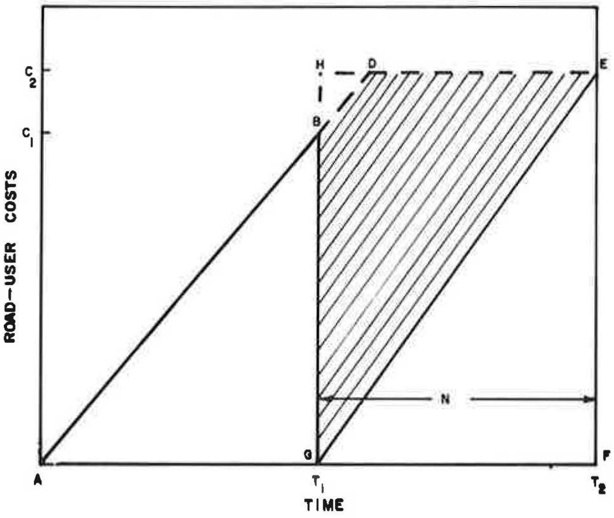


Figure 2. Second assumption of road-user costs versus time.



This assumption was used to estimate the present-worth benefits (road-user savings) in comfort costs, fuel costs, maintenance savings, and road-defect accidents. In all cases, road-user costs drop immediately after resurfacing. As time passes, the costs increase linearly until the maximum level is reached; then the road-user costs level off.

BENEFITS FROM RESURFACING

Increased Comfort

The value of comfort (or ride quality) to the road user has not been determined. In 1960, estimates of value for comfort were assumed by the American Association of State Highway Officials (AASHO) based on freedom of vehicle operation as follows (7):

1. Free operation, 0 cents/vehicle-km;
2. Normal operation, 0.3 cent/vehicle-km (0.5 cent/vehicle-mile); and
3. Restricted operation, 0.6 cent/vehicle-km (1 cent/vehicle-mile).

These unit costs are for operation of passenger cars in rural areas and for continuous movement on tangent or nearly tangent highways.

The benefit of any highway improvement that involves the comfort of a motorist may be approximated by observing the willingness of the motorist to pay for such benefits. One example of a superior highway facility may be Kentucky's toll roads (parkways). The average toll per kilometer (cars only) ranges from 0.9 to 1.5 cents (1.5-2.0 cents/vehicle-mile). The average cost for all toll roads is 1.2 cents/km (2.0 cents/vehicle-mile). The benefits to the motorist are greater on toll facilities when compared with the benefits from resurfacing other highway sections. A toll road offers not only a good riding pavement but also full access control, good alignment, improved safety, and reduced travel time. A reasonable benefit from a newly resurfaced road may be about half that of toll roads or around 0.6 cent/vehicle-km.

To gain a better understanding of the benefits derived from a newly resurfaced highway with respect to the improved comfort to the road user, a questionnaire was developed. The questionnaire asked what the motorist would be willing to pay to travel over a newly paved surface compared with a road in poor condition for a distance of 1.6-483 km (1-300 miles). The questionnaires were distributed to two groups. One group consisted of employees within the Kentucky Department of Transportation. There were 164 responses from this group. The other sample consisted of a selection from all licensed drivers. To obtain this sample, names and addresses of 1000 drivers were obtained from the driver's-license file. Letters not deliverable were sent to other drivers to assure a sample of 1000 drivers. Of the 1000 questionnaires sent, 203 were completed and returned. Although this is a response of only 20 percent, it was deemed an acceptable sample.

An average value per kilometer was calculated from each response. Responses from Kentucky Department of Transportation employees showed that the most common response (43 percent) was 0.6 cent/km. The median value and the mode were 0.6 cent/km. The average value was 0.8 cent/km (1.4 cents/mile). Results from the public at large were similar. Based on information available from other sources and the findings in this study, a benefit of 0.6 cent/km for increased comfort was chosen. This value corresponds to the benefit that would result from resurfacing a road in very poor condition.

The road-user cost of reduced comfort varies from 0 to 0.6 cent/vehicle-km, depending on the roughness of the pavement. The roughness may be expressed in terms of RI or present serviceability index (PSI). RI values normally range from about 300 for a smooth road to more than 1000 for a very rough road and correspond to a PSI from about 4.0 to about 1.5, respectively. The relationship between comfort costs and pavement roughness was assumed to be linear. As PSI decreases from 3.7 to 1.8, the comfort costs increase from 0 to 0.6 cent/vehicle-km. The comfort cost does not exceed 0.6 cent/vehicle-km. This value of the comfort cost in cents per vehicle kilometer before resurfacing corresponds to the value of Cb, which can be calculated as follows:

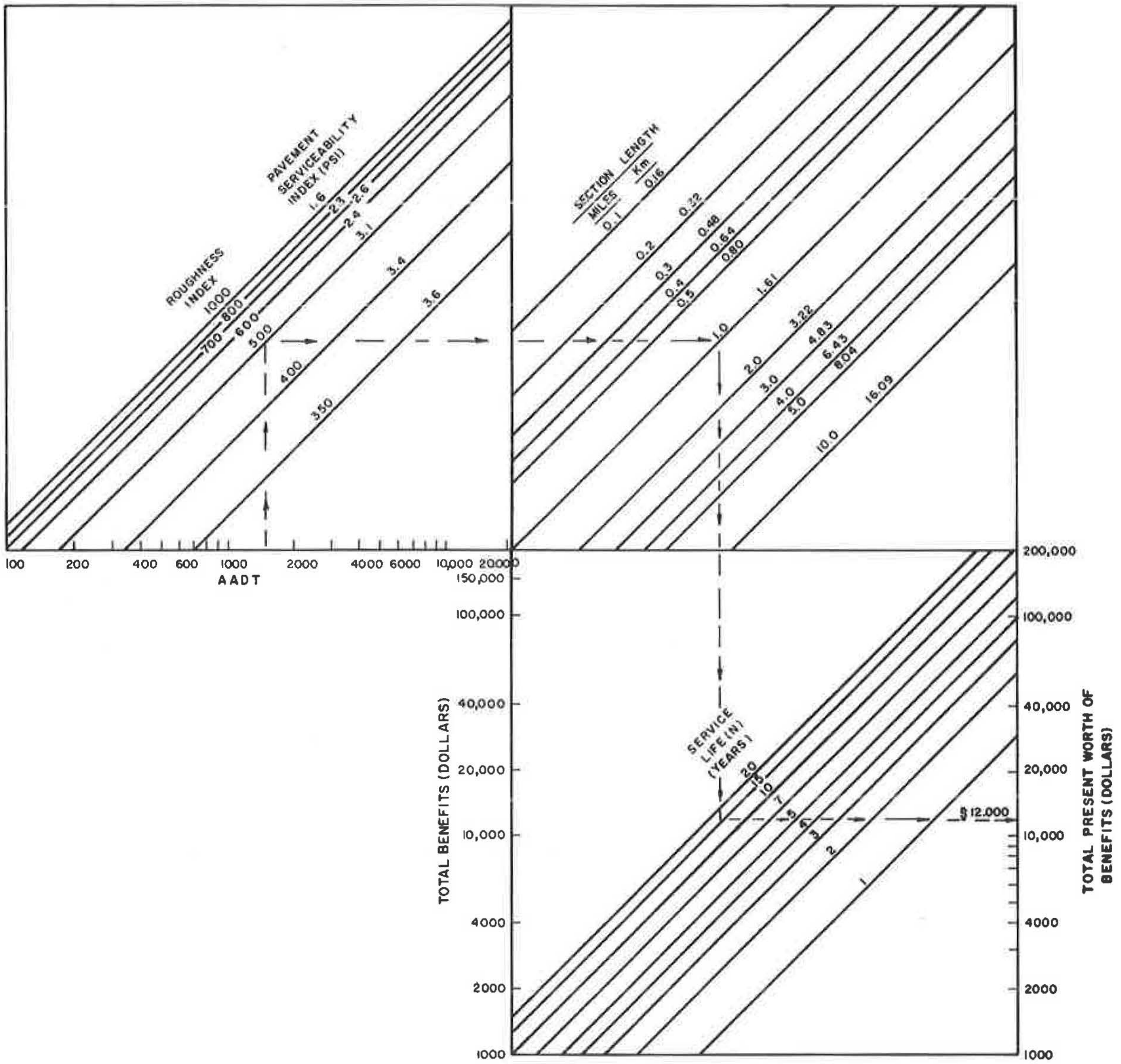
$$Cb = 0.0010(RI) - 0.31 \qquad (3)$$

By using the procedure described previously for computing lifetime benefits of a pavement overlay, the formula for comfort benefits is the following:

$$Bc = [(NCm/2 - \tfrac{1}{2})(Cm - Cb)(N - NCb/Cm)]\, Fc/N \qquad (4)$$

where Fc = (AADT)(365)(Ls)(PWF). Fc is a factor to convert to present-worth benefits. The rest of the

Figure 3. Nomograph for computing total comfort benefits due to resurfacing.



equation gives the average annual comfort cost (in dollars) per vehicle kilometer. The final equation then becomes the following:

$$Bc = [(NCm/2 - ½)(Cm - Cb)(N - NCb/Cm)(AADT)(365)(Ls)(PWF)]/N \quad (5)$$

where

Bc = present-worth benefit from driver comfort after resurfacing,
Cm = maximum possible comfort cost = $0.006,
Cb = comfort cost of pavement based on RI or PSI,
AADT = average annual daily traffic of the highway section,
Ls = section length (km),
PWF = present-worth factor, and
N = service life of the overlay (years).

To graphically determine the relationship among AADT, RI, section length, and comfort benefits, a nomograph was prepared (Figure 3). The nomograph gives approximate values, which will vary slightly from calculated values. To use the nomograph, enter the existing AADT on the highway section and draw a vertical line to the appropriate RI value. Proceed to the right to the section length and then down to the corresponding service life. Then read the total benefits at the right or left side of the page. (Similar nomographs were developed for the other savings, but they are not presented in this paper.)

Time Savings

Estimates of time savings by road users were determined on the basis of roughness of the pavement. Data used to develop this information were based partly on a 1972 report by McFarland in which vehicle speeds were associated with PSI (8). To further verify the effect of pavement roughness on vehicle speeds, vehicle speeds were observed before and after resurfacing a very rough section of road. Average speed after resurfacing was found to increase by about 4 m/s (8 mph). The pavement condition on the test section was assumed to be about as poor as will normally be encountered on a state-maintained road. The 4-m/s increase was used as the maximum when the expected speed increases after resurfacing roads that had an RI of more than 700 were estimated. The speed increase was related to RI and speed limit. No speed increases were assumed for a RI of less than 700. The maximum increase of 4 m/s occurs for speeds faster than 22.4 m/s (50 mph) and RIs of more than 950. Given the speed limit and RI, the computer program selects the approximate speed increase.

After the approximate speed increases expected after resurfacing a rough road had been determined, the formula for time savings for each vehicle was determined as follows:

$$St = Tb - Ta \tag{6}$$

where

St = time savings (h),
Tb = travel time before resurfacing (h), and
Ta = travel time after resurfacing (h).

Travel times are calculated from the following equations:

$$\begin{aligned} Tb &= L/Sb \\ Ta &= L/Sa = L/(Sd + Sa) \end{aligned} \tag{7}$$

where

L = section length (km),
Sb = vehicle speed before resurfacing (m/s),
Sa = vehicle speed after resurfacing (m/s) (assumed to be the posted speed limit), and
Sd = difference in speed due to resurfacing (m/s) (as determined by speed limit and RI).

The value of time was selected on the basis of a 1976 study by Agent (9). In that study, delay costs were found to be $4.87/vehicle-h.

The annual time saving after resurfacing a rough highway was computed based on the section length, traffic volume, cost per vehicle hour, and time savings per vehicle. The formula for annual benefit due to time savings (B) is as follows:

$$\begin{aligned} B = {} & (Tb - Ta\ \text{hr})(AADT\ \text{vehicles/day})\ (365\ \text{days/year}) \\ & \times (\$5.54/\text{vehicle-h}) \end{aligned} \tag{8}$$

or

$$B = 1777.55(Tb - Ta)(AADT) \tag{9}$$

Vehicle speeds were assumed not to be affected on roads that had an RI of less than 700. Rizenbergs, Burchett, and Davis have shown that the RI on many roads remains less than 700 for the life of the pavement and that the average RI was 430 just after resurfacing and increased linearly to only 510 after nearly nine years in service (4). Although the RI of some roads may never exceed 700 due to timely resurfacing, other sections may be resurfaced only once every 20 years or longer. Roads that exhibited an RI of less than 700 before resurfacing will not show a time-saving benefit as calculated by the formula, since Tb would equal Ta. By using the present-worth factor (PWF), the present-worth benefit from time savings (Bt) was found to be as follows:

$$Bt = PWF(1777.55)(Tb - Ta)(AADT) \tag{10}$$

The present-worth benefit from time savings due to resurfacing can be quite significant. For illustration, a graphical procedure was developed to easily determine the approximate present-worth benefits of time savings that will result due to resurfacing. The vehicle speed after resurfacing is assumed to be equal to the speed limit. The difference in vehicle speeds is determined by the model as a function of speed limit and RI. Subtracting this value from the speed limit gives vehicle speed before resurfacing.

Fuel Savings

Resurfacing a pavement affects fuel consumption in two ways. Consider a pavement that is very rough and on which vehicles are forced to travel at a reduced speed: Resurfacing this pavement will result in an increase in vehicle speeds and a corresponding increase in gasoline consumption of as much as 13 percent (10). However, rough pavements cause vehicles to bounce, and it takes energy to induce vehicle motion. Therefore, more fuel is required to maintain speed on a rough pavement than on a smooth pavement. A rough pavement may require the driver to brake to avoid very rough spots. Thereafter, the driver must accelerate to the desired speed of travel. This added acceleration increases fuel consumption. Assuming a traffic mixture of 80 percent cars, 10 percent pickups or vans, and 10 percent large trucks (six tires or more), the adjustment for increased fuel consumption may be 36 percent at 20.1 m/s (45 mph) on a level road (10). The net effect of resurfacing may be a 23 percent reduction in fuel consumption after adjustment for extra fuel (13 percent) needed to maintain up to a 4.5-m/s (10-mph) higher speed on the road after resurfacing. This maximum of a 23 percent reduction in fuel use was used for resurfacing a pavement in very poor condition (rough).

The linear relationship between RI and reduction in fuel costs was developed based on an analysis of that information. The percentage of reduction in fuel use (Fl) can be computed by the following equation:

$$Fl = 0.0365(RI) - 11.52 \tag{11}$$

As RI increases from 317 to 950 (bituminous pavements), the percentage of reduction in fuel costs increases linearly from 0 to 23 due to resurfacing. By applying the equation for converting to present-worth benefits from fuel savings due to resurfacing, the equation is as follows:

$$Bf = [(FmN/2 - \tfrac{1}{2})(Fm - Fb)(N - NFb/Fm)]\ Ff/N \tag{12}$$

where

Bf = present-worth benefits from fuel savings due to resurfacing a highway,
Fm = maximum percentage of reduction in fuel costs (23 percent) due to resurfacing, and
Fb = percentage of reduction in fuel costs based on RI before resurfacing.

Ff is a factor used to convert to present-worth dollars. The rest of the equation represents the average annual percentage of reduction in fuel savings due to resurfacing. The value of Ff must include the total traffic in vehicle kilometers that passes the section each year [(AADT)(Ls)(365)]. The fuel cost of these vehicle kilometers is found by assuming 65 cents/gal of gasoline and 5.1 km/L (12 miles/gal) for an average vehicle in Kentucky [national average of 5.0 km/L (11.85 miles/gal)]. The cost per gallon can be changed easily in the equation when it becomes out of date. The value of Ff is expressed as follows:

$$\begin{aligned} Ff = {} & (AADT\ \text{vehicles/day})(365\ \text{days/year})(Ls\ \text{km})(1/5.1\ \text{L/vehicle-km}) \\ & \times (0.17/\text{L}) \end{aligned} \tag{13}$$

$$Ff = 12.17[(AADT)(Ls)\text{dollars/year}] \quad (14)$$

By using the base equation and the present-worth factor for any service life N, the final equation becomes as follows:

$$Bf = \{[(FmN/2 - \tfrac{1}{2})(Fm - Fb)(Fb/Fm)](PWF)(12.12)(AADT)(Ls)\}/N \quad (15)$$

where Bf is the present-worth benefit from fuel savings due to resurfacing a highway.

Annual Maintenance Savings

Comparisons of maintenance costs were made for highway sections before and after resurfacing. A relationship between pavement age and maintenance cost per lane kilometer per year for bituminous pavements in Kentucky was given in a 1974 research report (6). Annual costs per lane kilometer increased to about $311 during the 15th and 16th years and then diminished sharply. Obviously, resurfacing began to supplant regular maintenance at that time. Costs from that analysis were obtained from average costs per lane kilometer per year for 13 years; Interstates and toll roads were excluded. For this analysis, only ordinary maintenance costs were considered. (Physical improvements such as extensive overlaying are not considered ordinary maintenance.) Here annual costs were inflated to 1976 dollars by using the cost index for highway maintenance and operation as given by the Federal Highway Administration (11). The peak annual cost after 15 years was found to be $560/lane-km ($900/lane-mile) based on 1976 costs. This cost corresponds to a highway section in very poor physical condition that requires considerable maintenance each year.

The determining factors used for estimating maintenance costs were the subjective rating of pavement condition and rutting cited on the rating form. The point values given there were converted to a percentage of the maximum points possible (100 points).

By using the rating of deficiency points for pavements considered in the 1976 resurfacing program, all pavements were found to have ratings between 10 and 60. Maintenance costs range from 0 to $560/lane-km/year for deficiency ratings of 10-60. Based on this curve and Figure 2, the formula for present-worth benefits was determined as follows:

$$Bm = \{(MmN/2 - \tfrac{1}{2})(Mm - Ma)[N - N(Ma/Mm)]\}\,Fm/N \quad (16)$$

where

Bm = present-worth benefits from maintenance savings due to resurfacing a highway section,
Mm = maximum annual maintenance cost per kilometer before resurfacing ($560),
Ma = annual maintenance cost per kilometer based on deficiency rating, and
Fm = factor for converting to present-worth benefits [(PWF)(Ls)].

The value for annual maintenance cost per kilometer can be computed as follows:

$$Ma = 11.2(\text{deficiency rating}) - 112 \quad (17)$$

where the deficiency rating varies from 10 (new pavement) to 60 (pavement in very poor condition). Thus the final equation becomes the following:

$$Bm = \{(MmN/2 - \tfrac{1}{2})(Mm - Ma)[N - N(Ma/Mm)](PWF)(Ls)\}/N \quad (18)$$

Accident Savings

One of the benefits from resurfacing a pavement is the reduction in accidents. To determine the benefits in accident reduction, a relationship between accidents and pavement condition must be known. Comparisons were made between the accident data and pavement condition for highway sections evaluated from 1973 through 1976. This involved 513 sections that had a total length of about 3700 km (2300 miles).

Two types of accidents were found to be affected by resurfacing. The first relationship was between the condition of the pavement and the number of road-defect accidents. Pavements that had excessive cracking, base and edge failures, raveling, patching, out-of-section conditions, and rutting were found to have the greatest reduction in road-defect accidents after resurfacing. This reduction in accidents was then converted to an equivalent of 15 percent reduction in total accidents. The relationship was developed between percentage of reduction in total accidents (Al) and deficiency points (Dt) as follows: $Al = 18 - 0.3(Dt)$. Deficiency points range from 10 to 60 for accident reductions of 0-15 percent, respectively.

The reduction in road-defect accidents was expected to be the greatest after resurfacing and to gradually diminish over the life of the overlay. The following general equation was used for computing present-worth benefits:

$$Brd = \{[(NAm/2 - \tfrac{1}{2})(Am - Ap)(N - NAp/NAm)](Ca)(An)(PWF)\}/N \quad (19)$$

where

Brd = present-worth benefits from reduction in road-defect accidents due to resurfacing,
An = annual number of accidents on the section,
Am = maximum percentage of reduction in accidents (15 percent),
Ap = percentage of reduction corresponding to a particular deficiency rating, and
Ca = cost of each accident ($4055).

The cost per accident was calculated by using the distribution of accident severities from police-reported accidents in Kentucky (1977). National Safety Council information on costs for each type of accident was applied to compute average cost per accident. Since virtually all proposed resurfacing sections are in rural areas (about 95 percent), only rural accidents were used to arrive at the costs of a representative accident. The average cost per accident was computed to be $4055.

Whereas resurfacing will cause a reduction in road-defect accidents, improved skid resistance of pavements will also reduce wet-pavement accidents. A relationship between accidents and pavement friction has been reported by Rizenbergs, Burchett, and Warren (12). The percentage of wet-weather accidents was found to be greatest on pavements that had low skid resistance. Percentages of wet-pavement accidents decreased as the SN increased to about 40. If a pavement had an SN less than 40 before resurfacing, the improved skid resistance after resurfacing would result in a reduction in wet-pavement accidents. The results of that study were used to compute the relationship between percentage of reduction in total accidents (Ar) and SN as follows: $Ar = 40 - SN$. In the range of SNs between 20 and 40, the reduction in wet-pavement accidents was about 50 percent, which corresponds to about 20 percent reduction in total accidents (12).

Class 1, type A bituminous concrete is the predominant mixture used in resurfacing, and the performance of this type of surface was used to determine when the skid resistance of an average pavement may reach an SN of 40 (after 3.7 million vehicle passes). The number of years wet-pavement accidents may remain reduced for various AADTs was found to be about five years for AADT of 400 or less, about seven years for AADT between 4001 and 8000, and three years for AADT more than 8000. A maximum of five years was selected in determining total accident reductions.

The general equation used for computing present-worth benefits was as follows:

$$Bww = (Ar)(An)(Ca)(PWF) \qquad (20)$$

where Bww is the present-worth benefits from reduction in wet-pavement accidents due to resurfacing and Ar is the percentage of reduction corresponding to a particular SN.

The accidents that may be reduced due to resurfacing consist primarily of road-defect and wet-pavement accidents. The procedure given here involves separate calculation of each component of accident benefits. After both benefit values are found, they are to be added to yield total present-worth accident savings.

Other Benefits

In addition to benefits from accident reduction, improved comfort, time savings, and fuel savings, there are other benefits associated with resurfacing of a highway. Examples of other such benefits include savings in vehicle maintenance costs, reduction in highway noise, and reductions in vehicle-related air pollution. These benefits are very difficult to quantify in terms of monetary benefits and thus were not included in the dynamic-programming model.

RESURFACING COSTS

Resurfacing costs are estimated annually for each road section recommended for resurfacing by the highway districts. The estimates are based on section length, highway width, number of lanes, type of proposed surface, and the availability and cost of materials and labor. In the 1976 resurfacing program, 1670 km (1037 miles) of road were considered; the total estimate was $29 615 000. The average statewide cost of resurfacing based on those estimates is $8825/lane-km ($14 200/lane-mile). This corresponds to an average cost of $17 600/km ($28 400/mile) for two lanes. The resurfacing costs used in the dynamic-programming model were the estimates given for each project.

DYNAMIC PROGRAMMING

Input

Input into the dynamic-programming model consists mostly of information and data available from the pavement-rating forms and includes location (district, county, route, and milepost), deficiency rating, RI, SN, AADT, speed limit, section length, and resurfacing cost. The total number of accidents during the previous year is an added input.

Other information needed for the program includes interest rate of money (assumed to be 8 percent in this study), average cost per accident ($4055 for rural roads in Kentucky for 1977), and number of locations being considered. Because the budget for resurfacing in each district is arrived at essentially on the basis of a formula described earlier, dynamic programming was applied to highway sections recommended for resurfacing by each district and the district's budget.

Output

A listing of benefits and costs and the benefit/cost ratios for each highway section are in the first part of the program output. A statewide listing of highway sections ordered by benefit/cost ratio is also contained in the program output. All benefits and costs and cumulative benefits and costs are cited there. This listing could be used to determine project priorities based entirely on the benefit/cost ratios. The final section of the program output contains listings of projects selected for each district based on allotment of funds for resurfacing in that district. The total cost and benefits and the benefit/cost ratios for the selected projects are also cited. All projects considered are listed, but only the costs and benefits of projects selected for resurfacing are shown.

PRESENT PROCEDURES COMPARED WITH DYNAMIC PROGRAMMING

A computer printout was also obtained that lists all 233 projects according to the benefit/cost ratio. The highest ratio was 20.10 and the lowest was 0.18. Information includes the location identification number (1-233), section length, project benefits, project cost, cumulative benefits, cumulative cost, cumulative benefit/cost ratio, and cumulative length. There were 251 km (156 miles) of road with benefit/cost ratios in excess of 4.0, and 1249 km (776 miles) of the 1520 km (944.9 miles) of road being considered had benefit/cost ratios more than 1.0. Cumulative costs for the 233 projects were $22.5 million, and cumulative benefits were more than $58 million. This corresponds to an overall benefit/cost ratio of 2.58.

The various benefits (savings) associated with resurfacing all projects were also detailed. When the projects were combined, 42 percent of the benefit ($24.5 million) resulted from fuel savings and 34 percent ($19.7 million) from comfort benefits. Other benefits include 15 percent ($8.6 million) for time savings, 6 percent ($3.3 million) for accident reduction, and 4 percent ($2.1 million) for maintenance savings. Of the 233 projects, only 42 had benefits from time savings (pavements with an RI of more than 700). All projects showed benefits due to improved comfort and maintenance savings; 53 sections showed no benefits from accident savings.

The results of selecting projects by dynamic programming for each district were compared with the results from procedures now used by the districts and the Division of Maintenance. The current procedure of selecting projects yielded total benefits that amounted to about $27.7 million compared with benefits of $36.1 million derived from projects selected by dynamic programming. The cost of the projects selected by dynamic programming was also slightly lower ($8.5 million compared with $8.6 million).

The benefit/cost ratio of projects selected for resurfacing in 1976 was 3.21 compared with 4.22 if the selection of projects had been made by dynamic programming on the basis of budget allocation to each district. Dynamic programming, therefore, would have yielded a 30.4 percent increase in benefits and would have reduced costs by 0.9 percent. The overall improvement in the benefit/cost ratio would have been 31.5 percent if dynamic programming had been applied.

Projects Selected on a Statewide Basis

If projects had been selected by benefit/cost ratio alone on a statewide basis by using funds allocated to the resurfacing program in 1976 ($8.6 million), the projects selected would have had an overall benefit/cost ratio of 4.52. This is somewhat higher than the ratio of 4.22 obtained by using dynamic programming based on budget allocations by district and is substantially higher than the 3.21 realized in 1976 by selecting projects according to established procedures. If the statewide budget of $8.6 million had been spent strictly according to the priority ranking based on the total deficiency ranking, the resultant benefit/cost ratio for all the projects would have been 3.29.

Comparison of Dynamic Programming with Benefit/Cost Method

Tests were made to compare the choice of projects selected for resurfacing by dynamic programming and by their benefit/cost ratios alone. A comparison by using one budget for the entire state ($8.6 million) was used. As stated earlier, an overall benefit/cost ratio of 4.52 was obtained by using a benefit/cost procedure (selection of projects based entirely on benefit/cost ratios). The results by using dynamic programming depended on the increment size used in the program. The amount of computer storage available becomes a problem if a small increment size is used. However, if the increment size is larger than some of the project costs, the efficiency of the program is decreased. Increment sizes of $50 000, $25 000, and $10 000 were used. This compares with an increment size of $1000, which was used for each individual district budget. For the $50 000 increment, a benefit/cost ratio of 4.43 was obtained. The benefit/cost ratio increased to 4.50 for the $25 000 increment size and 4.51 for the $10 000 increment size. This analysis showed that dynamic programming also yielded identical results compared with the benefit/cost method when an appropriate increment size was used.

SUMMARY AND CONCLUSIONS

The objective of this study was to develop an economic analysis and a dynamic-programming procedure that would assist in optimizing expenditures in the pavement-resurfacing program in Kentucky. Procedures were developed to compute benefits and costs of proposed projects and to determine which highway sections should be resurfaced under a given budget. A computer program was written to select an optimal list of projects for resurfacing based on road-user savings in accidents, travel time, comfort, maintenance costs, and fuel. Costs included in the model were resurfacing costs. Projects selected by the districts and projects selected by the Division of Maintenance for resurfacing in 1976 were evaluated by using the dynamic-programming model. An additional benefit of more than $8.4 million would have resulted from the use of the dynamic programming developed in this study. The benefit/cost ratio of sections selected for resurfacing by the current procedures was 3.21 compared with that of 4.22 if dynamic programming had been used. Projects selected by the Division of Maintenance had a much higher benefit/cost ratio (4.37) compared with projects selected by the districts (2.38). Projects selected on a statewide basis by dynamic programming or their benefit/cost ratio in 1976 would have resulted in a higher benefit/cost ratio (4.52) as compared with selections based on budget allocations to the districts (4.22). Selection of projects on a statewide basis and by using the total deficiency rating of pavements would have yielded a lower benefit/cost ratio (3.29). The economic analysis showed a very similar choice of projects when dynamic programming was used compared with selecting projects based solely on their benefit/cost ratio. The cost data included in this study should be updated before the program is used. The program is written so that the cost data can be easily changed.

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