A SYSTEMATIC PROCEDURE FOR THE DEVELOPMENT OF MAINTENANCE LEVELS OF SERVICE

Ram B. Kulkarni, Kamal Golabi, Fred N. Finn and Rubin Johnson, Woodward-Clyde Consultants

One of the basic requirements for the proper management of highway maintenance activities is the establishment of maintenance levels-of-service, i.e., at what levels or conditions should a maintenance activity be initiated. A systematic methodology was developed for determining the maintenance levels-of-service that would maximize the user benefits subject to the constraints of available resources. This paper describes a demonstration of the methodology for two maintenance problems in a state.

The necessary inputs for the methodology were obtained from the data base of information currently available to the state transportation department. The data base included information available in the literature, studies conducted within the department, information available from maintenance management systems, and experience and judgment of knowledgeable individuals within the department. Results of the analysis produced levels-of-service that were intuitively satisfactory. Sensitivity analyses were conducted to determine the impact of conditions such as budget cuts and changes in the relative weights of different considerations on the determination of optimum levels-of-service.

While the demonstration phase of the project was limited to two problems, the results indicate that the methodology can work and should be implementable by state agencies.

Maintenance levels-of-service are defined as threshold conditions at which maintenance is considered to be needed. As such, these levels-of-service will influence work scheduling requirements, resource allocations and work priorities. Selection of the maintenance levels-of-service is influenced by a number of considerations such as safety, comfort, protection of investment, environmental impact, and aesthetics.

At the present time there is no systematic, structured procedure for establishing maintenance levels-of-service or to adjust such levels when resources are constrained or increased. Woodward-Clyde Consultants has completed a study for the National Cooperative Highway Research Program (NCHRP) to develop a methodology for establishing levels-of-service based on well documented principles of decision analysis.

The purpose of this report is to describe the methodology by means of a demonstration of the procedures for two maintenance problems in the state of Louisiana.

In order to facilitate the description of the procedures the following terminology has been established.

1. Maintenance Element - a part of the highway system that requires maintenance (e.g., traveled-way, roadside, drainage, traffic services).
2. Maintenance Condition - a deficient condition of a maintenance element that needs to be repaired or corrected (e.g., cracking and rutting--for traveled-way; grass growth and litter and debris--for roadside).
3. Maintenance Activity - work required to repair or correct a maintenance condition (e.g., filling--for cracking; mowing--for grass growth).
4. Level-of-Service (quality standard) - threshold deficiency level of a maintenance condition that should trigger an appropriate maintenance activity (e.g., grass should be mowed when it is 12 inches high; a drainage ditch should be cleaned when 50 percent of its area is blocked).
5. Considerations - the factors used in evaluating the performance of maintenance elements (e.g., safety, riding comfort, economics, aesthetics).
6. Attribute - a numerical scale for measuring the effect on a given consideration (e.g., frequency of accidents--for safety; roughness--for riding comfort).

Approach

The methodology to select maintenance levels-of-service involves the following steps:

1. Structuring the problem.
2. Estimation of the effects of alternative maintenance levels-of-service on various considerations (e.g., safety, aesthetics).
3. Evaluation of the effects of alternative maintenance levels-of-service.

4. Determination of the optimum combination of maintenance levels-of-service.
5. Sensitivity analysis.
6. Recommendations.

A computer program ASOP (acronym for Algorithm for the Selection of Optimum Policy) has been written for implementation of all calculations required by the methodology.

Structuring the Problem

The following tasks are involved in structuring the problem:

1. Select maintenance elements (e.g., shoulders, pavement).
2. Select maintenance conditions (e.g., edge of traveled-way drop-off) for each maintenance element (e.g., shoulders).
3. Specify alternative levels-of-service for each maintenance condition.
4. Select considerations (e.g., safety) for each maintenance element (e.g., shoulders).
5. Select attributes (e.g., percentage of drivers who cannot recover) for various considerations (e.g., safety).
6. Identify the maintenance conditions (e.g., edge of traveled-way drop-off) which affect each attribute (e.g., percentage of drivers who cannot recover).

The implementation of the above tasks in Louisiana is described below.

Select Maintenance Elements

For the demonstration example, two maintenance elements--shoulders and roadside vegetation--were analyzed.

Select Maintenance Conditions for Each Maintenance Element

For shoulders, the edge of traveled-way drop-off is the maintenance condition of concern.

For roadside vegetation, the maintenance conditions of concern may include grass growth, weed growth, and brush and tree growth. The discussions with the Louisiana landscape specialist indicated that a combined mowing and herbicide spraying program is used for the maintenance of roadside vegetation.

Select Alternative Levels-of-Service for Each Maintenance Condition

The following procedure can be used to generate alternative levels-of-service. The department specialists for a given maintenance condition are asked to assume that there are no constraints of resources (dollars, manpower, etc.) for the particular maintenance condition under consideration. How would the specialists improve the level-of-service for that condition? Discussion of this question would provide a level-of-service which is generally higher than the current level-of-service used by the agency. Next, the specialists are told that there are moderate and severe budget cuts, successively for the maintenance condition. In order to accommodate the budget cuts, a reduced level-of-service would have to be adopted. How would the agency reduce the level-of-service in each case? Responses to this question would generate two levels-of-service which are generally lower than the current level-of-service. If it is meaningful in practice, some intermediate levels-of-service may also be considered.

At the conclusion of this step, a spectrum of alternative levels-of-service ranging from the highest (ideal) to the lowest (barely tolerable) are generated. Table 1 shows the alternative levels-of-service selected for edge of traveled-way drop-off and vegetation growth.

Table 1. Alternative levels-of-service for maintenance conditions of given maintenance elements.

Maintenance element	Maintenance conditions	Alternative levels-of-service
Shoulders	Edge of traveled-way drop-off	(1) Repair when drop-off is 1-inch. (2) Repair when drop-off is 2 inches. (3) Repair when drop-off is 3 inches. (4) Repair when drop-off is 4 inches. (5) Repair when drop-off is 5 inches.
Roadside Vegetation	Vegetation growth	(1) Mow 500,000 acres and spray 120,000 acres annually. (Mow full right-of-way before grass reaches 8 inches.)
		(2) Mow 300,000 acres and spray 120,000 acres annually. (Urban area: mow full width before grass reaches 8 inches. Rural area: mow 30 feet from edge of traveled surface after grass exceeds 12 inches.)
		(3) Mow 200,000 acres and spray 60,000 acres annually. (Urban area: mow full width after grass exceeds 18 inches. Rural area: mow one machine pass after the grass exceeds 18 inches.)
		(4) Mow 150,000 acres and spray 60,000 acres annually. (Mow for safety only.)

For edge of traveled-way drop-off, the alternative levels-of-service were specified in terms of the threshold amount of drop-off at which a shoulder should be repaired.

For roadside vegetation growth, the current maintenance practice in Louisiana consists of a combined mowing and herbicide spraying program. It was, therefore, appropriate to consider alternative levels-of-service in terms of increased or decreased amounts of mowing and spraying. Appropriate combinations of numbers of acres mowed and numbers of acres sprayed were selected in consultation with the department specialists to represent four alternative levels-of-service for controlling roadside vegetation. For a proper understanding and implementation of the levels-of-service in the field, it was also necessary to specify for each level-of-service the threshold height at which grass would be mowed and the width of mowing. Since urban and rural areas present different roadside environments, different provisions for these areas were made under each level-of-service.

Table 1 shows the alternative levels-of-service for roadside vegetation both in terms of (1) number of acres mowed and sprayed and (2) threshold height of grass and width of mowing for urban and rural areas.

Select Considerations for Each Maintenance Element

Considerations are the factors which affect highway users through the choice of maintenance levels-of-service for a given maintenance element. With regard to maintenance of shoulders, safety and preservation of investment appear to be the pertinent considerations. Aesthetics and environmental pollution are the appropriate considerations with regard to roadside vegetation maintenance. It should be noted that even though economics (maintenance cost) is an important consideration, it is viewed as a constraint on the system rather than as a user-related consideration.

Select Attributes for Various Considerations

An attribute is a numerical scale for measuring the effect of alternative maintenance levels-of-service on a given consideration. Table 2 lists the attributes of various considerations for each maintenance element.

Table 2. Considerations, attributes, and maintenance conditions affecting each attribute.

Maintenance element	Considerations	Attributes	Maintenance conditions affecting an attribute
Shoulders	Safety	Percentage of drivers who cannot recover	Edge of traveled-way drop-off
	Protection of investment	Percent change in pavement rehabilition cost	Edge of traveled-way drop-off
Roadside vegetation	Aesthetics	Index of pleasing appearance (4-point scale)	Vegetation growth
	Ecology	Index of environmental pollution (4-point scale)	Vegetation growth

Identify the Maintenance Conditions Which Affect Each Attribute

The maintenance conditions affecting each attribute are shown in Table 2.

Estimation of Effects of Alternative Maintenance Levels-of-Service on Various Considerations

The effect of alternative maintenance levels-of-service on a given consideration (e.g., safety) is estimated in terms of the attribute of the consideration (e.g., percentage of drivers who cannot recover). The effects were estimated in Louisiana by interviewing the department specialists for given attributes. To assist the specialists in the estimation, pertinent information and data available in the literature were reviewed with the specialists.

Because of limitations and applicability associated with information in the literature it was concluded that this source could not be used directly to establish the effects or impact of levels-of-service on pertinent considerations. Based on these conclusions, the specialists were asked to extrapolate the available information to the real-world situation, based on their experience and judgment.

Percentage of Drivers Who Cannot Recover

Assessment of the percentage of drivers who cannot recover for given amounts of edge of traveled-way drop-off was done in two steps:

1. What percentage of drivers will encounter the drop-off problem (i.e., accidentally drive over the edge of the traveled-way)?
2. Of the drivers who encounter the problem, what percentage would not be able to make a normal recovery?

Table 3 shows the results of the assessments. It is acknowledged that some of the estimates may be high. More time and background information would be necessary to improve on these estimates of the impact of various levels-of-service. The methodology, per se, would not be affected by any changes in these estimates.

Table 3. Effect of alternative levels-of-service of edge of traveled-way drop-off on percentage of drivers who cannot recover.

Threshold amount of edge of traveled-way drop-off	Percentage of drivers who drive over the edge of traveled-way	Percentage of drivers who cannot recover if they drive over the edge of traveled-way	Percentage of drivers who cannot recover
	(a)	(b)	(c = ab/100)
1"	15	0.01	0.0015
2"	14	0.5	0.07
3"	13	15	1.95
4"	12	55	6.60
5"	10	90	9.0

Percent Change in Pavement Rehabilitation Cost

High levels of allowable drop-off at the edge of the traveled-way may require extra preparation work on the edge of the pavement at the time an overlay is applied. No quantitative information was found in the literature to indicate the influence of edge of traveled-way drop-off on the change in pavement rehabilitation costs. Therefore, the specialists had to rely on their experience and judgment to estimate the amount of additional pavement work required prior to an overlay as a function of the amount of edge of traveled-way drop-off.

Table 4 shows the assessment of percent change in pavement rehabilitation cost for various amounts of edge of traveled-way drop-off.

Index of Pleasing Appearance

The alternative levels-of-service for roadside vegetation define a 4-point scale for the index of pleasing appearance. It is reasonable to assume that the levels-of-service incorporating higher amounts of mowing and spraying would enable the maintenance engineer to provide a more pleasing appearance to the roadside.

Table 4. Effect of alternative levels-of-service of edge of traveled-way drop-off on percent change in pavement rehabilitation cost.

Threshold amount of edge of traveled-way drop-off	Percent change in pavement rehabilitation cost
1"	0
2"	1
3"	5
4"	12
5"	15

Index of Environmental Pollution

The potential for environmental pollution is a function of the amount of herbicide spraying. The alternative levels-of-service for roadside vegetation, which specify the number of acres sprayed with herbicides, define a 4-point scale for the index of environmental pollution.

Evaluation of the Effects of Alternative Maintenance Levels-of-Service on Various Considerations (E.g., Safety, Aesthetics)

The objective of this step is to establish a preference (value) structure for evaluating the effects of alternative levels-of-service on various considerations, such as safety, aesthetics, etc. The effects on the considerations are measured in terms of the selected attributes. For example, for edge of traveled-way drop-off the effect of level-of-service on safety is measured in terms of the percentage of drivers who cannot recover.

The assessment of preferences involves two steps:

1. Assessing individual value functions of different attributes. The objective of this step is to determine how much better (or worse) one level of an attribute (e.g., percentage of drivers who cannot recover = 5) is relative to another (e.g., percentage of drivers who cannot recover = 10). This assessment is best done by those individuals in a state agency who are most knowledgeable with regard to a given attribute.
2. Assessing value tradeoffs between different attributes. If a decision problem involves multiple attributes and limited resources, it may not be possible to achieve the best levels of all the attributes. The decision maker, therefore, is required to think about how much he/she may be willing to sacrifice on one attribute (e.g., aesthetics) in order to improve another (e.g., change in rehabilitation cost). These value tradeoffs determine the relative weights of the attributes. The assessment of value tradeoffs should involve individuals who are responsible for setting and implementing maintenance levels-of-service.

The first step was completed during meetings with the department specialists with regard to edge of traveled-way drop-off and roadside vegetation control. The second step was completed during a group session which involved maintenance engineers from both headquarters and the district offices. The details of the specialists' meetings as well as the group session are provided below.

Assessing Different Drop-Off Attributes With Specialists

The objective of these meetings was to assess relative values of different levels of the attributes relevant to edge of traveled-way drop-off. The attributes were: percentage of drivers who cannot recover and percent change in pavement rehabilitation costs.

A general procedure used in assessing relative values of an attribute involves the following steps:

1. A range for an attribute is selected such that it would contain the highest and the lowest assessed levels of the attribute. For example, the attribute "percentage of drivers who cannot recover" had highest and lowest assessed levels of 9 and 0.0015, respectively (see Table 4). A range of 0 to 10 was, therefore, chosen for this attribute. Similarly, an appropriate range for "percent change in pavement rehabilitation cost" was 0 to 35.
2. The end-points of the range of an attribute are assigned arbitrary values, a common choice being 0 and 1. Then, a midvalue point on the range of the attribute is assessed. To illustrate this procedure, consider the attribute "percentage of drivers who cannot recover." We denote this attribute by θ_1 and its value function by $V_1(.)$. Values of 0 and 1 are assigned to the end-points of θ_1. Noting that lower levels of θ_1 are more desirable, we get

$$V_1(10) = 0 \text{ and } V_1(0) = 1.$$

Now, we want to assess a point, say θ_1^*, which has a value of 0.5; i.e., θ_1^* is the midvalue point on the range of θ_1.

To do this, different levels of θ_1 are successively proposed to the specialist. The specialist is asked to examine a given level of θ_1 and judge whether that level divides the total range of θ_1 into two parts, each having the same value. The analyst attempts to bracket the midvalue point by approaching it from both ends. For example, one can start with $\theta_1 = 1$. The specialist is asked: "Which is better--decreasing the percentage of drivers who cannot recover from 10 to 1 or decreasing it from 1 to 0?" Let us say the specialist indicates that decreasing the attribute from 10 to 1 is better. Next, $\theta_1 = 9$ is proposed. The question is asked: "Which is better--decreasing the percentage of drivers who cannot recover from 10 to 9 or decreasing it from 9 to 0?" The specialist may say that decreasing the attribute from 9 to 0 is better. By systematically varying the proposed levels of the attribute, one can zero in on the midvalue point, θ_1^*.

3. The end points and θ_1^* provide three points on the value function $V_1(.)$. Additional points may be assessed by dividing each of the two ranges, 0 to θ_1^* and θ_1^* to 10, into two equal value parts. A smooth curve can be drawn through the end points and the assessed intermediate points. A mathematical equation can be derived to best fit this curve. This equation represents the individual value function $V_1(.)$ for θ_1. The computer program ASOP automatically fits a quadratic value function, given the end points and the midvalue point for an attribute. The form of the function is

$$V_1(\theta_1) = a + b\theta_1 + c\theta_1^2.$$

Using the above procedure in Louisiana, the individual value functions for the following attributes were assessed:

θ_1 = percentage of drivers who cannot recover.
θ_2 = percent change in pavement rehabilitation cost.

Both the value functions were linear. This implies that a change in the same magnitude in the attribute anywhere in its range has the same value.

Assessing Different Roadside Vegetation Attributes With Specialists

The objective of these meetings was to assess the individual value functions for the following attributes:

θ_3 = index of pleasing appearance.
θ_4 = index of environmental pollution.

Both roadside vegetation attributes are represented on a 4-point discrete scale. Each point is associated with an alternative maintenance level-of-service (see Table 1). The procedure for assessing midvalue points discussed previously is not practical in the case of an attribute represented on a discrete scale with a limited number of points. The reason is that none of the points on the scale may provide a midvalue point. An alternative procedure, based on the concept of willingness to pay, was used.

To illustrate this procedure, consider the index of pleasing appearance. The participants were asked how much more they would be willing to pay in order to improve the index of pleasing appearance from its lowest level (number of acres mowed = 150,000; number of acres sprayed = 60,000) to each of the other levels. Following some discussion, the response of the participants was that they would be willing to pay 50 percent more to go to Level 3 and 200 percent more to go to Level 2. With regard to Level 1, the specialists did not see much benefit in moving from Level 2 to Level 1, and hence were willing to pay very little to go from Level 2 to Level 1. However, it was indicated that other individuals in the department, particularly those at the district level, might respond differently about going from Level 2 to Level 1. For this reason, it was decided to obtain group consensus on this question of how much one would be willing to pay to increase the maintenance level-of-service from Level 2 to Level 1. The group session, which is discussed in the next section, indicated that the group would be willing to pay about 8 percent more to go from Level 2 to Level 1.

The above assessments provided relative values of the four levels of the index of pleasing appearance (θ_3). Letting $V_3(i)$ denote the value of the i^{th} level, we get

$$V_3(3) = 1.5\ V_3(4)$$
$$V_3(2) = 3\ V_3(4)$$
$$V_3(1) = 3.08\ V_3(4).$$

If $V_3(4)$ is set to 1, the other relative values would be: $V_3(3) = 1.5$, $V_3(2) = 3$ and $V_3(1) = 3.08$. Since the end points of a value function were assumed to be 0 and 1, a linear transformation of the relative values was made by subtracting the minimum value (i.e., 1) and dividing by the range (i.e., 2.08).

Thus, the relative values are:

$$V_3(1) = 1;\ V_3(4) = 0$$
$$V_3(2) = \frac{3 - 1}{3.08 - 1} = 0.96$$

and

$$V_3(3) = \frac{1.5 - 1}{3.08 - 1} = 0.24$$

With regard to the index of environmental pollution (θ_4), the specialists were asked: "How much would it be worth to reduce the number of acres sprayed from the highest level (defined as 150,000) to each of the other two levels (120,000 and 60,000)?" Assuming the cost of the highest level to be 100 units, the response of the specialists was that, from the viewpoint of reducing pollution, it would be worth 15 and 30 units, respectively, to reduce the amount of spraying from the highest level to Levels 2 and 3. This yielded the following relative values of the levels of θ_4:

$$V_4(2) = 1.15\ V_4(1)$$
$$V_4(3) = 1.30\ V_4(1).$$

Since the fourth level (see Table 2) involves the same number of acres sprayed as the third level, it follows that $V_4(4) = V_4(3)$. By assigning the values of 0 and 1 to the end points of the scale, we get

$$V_4(1) = 0;\ V_4(2) = \frac{1.15 - 1}{1.30 - 1} = 0.5$$
$$V_4(3) = \frac{1.3 - 1}{1.3 - 1} = 1 = V_4(4).$$

The results of assessment of individual value functions are summarized in Table 5.

Table 5. Assessment of individual value functions of various attributes.

Attribute	Best level	Worst level	Midvalue point for a continuous attribute	Values of intermediate levels for a discrete attribute
1. Percentage of drivers who cannot recover	0	10	5	--
2. Percent increase in pavement rehabilitation cost	0	35	17.5	--
3. Index of pleasing appearance	1	4	--	Value of level 2 = 0.96 Value of level 3 = 0.24
4. Index of environmental pollution	4	1	--	Value of level 2 = 0.5 Value of level 3 = 1.0

Group Session for the Assessment of Value Trade-offs

The specifications of a value function over multiple attributes requires the assessment of trade-offs between competing attributes based on the value judgments of decision makers. In public policy decisions, a number of individuals may share the responsibility of deciding acceptable tradeoffs. It would, therefore, seem desirable that value judgments of decision makers be somehow "pooled" to obtain a "group consensus" that would be used in lieu of the opinion of any one individual. It is generally assumed that group consensus would have greater validity than individual value judgments in the assessment of tradeoffs. The technique used for trying to obtain group consensus values was the Delphi procedure.

The Delphi group sessions included eight individuals within the Louisiana Department of Transportation and Development who were involved in establishing current levels-of-service.

The sessions included a period of orientation during which pertinent background information was discussed. The procedures were explained and illustrative examples were acted out for the group.

Assessment Forms. Three assessment forms were used in the group sessions.

Form A: assessment of tradeoff between percentage of drivers who cannot recover and index of pleasing appearance.

Form B: assessment of tradeoff between percent change in pavement rehabilitation cost and index of pleasing appearance.

Form C: assessment of tradeoff between percentage of drivers who cannot recover and index of environmental pollution.

A blank copy of assessment Form A is shown in Figure 1.

Figure 1. Form A.

TRADEOFF ASSESSMENT USING DELPHI PROCEDURE
Form A

Date:____________
Iteration Number:____________

You have the choice between the following options:

	Percent of Drivers Who Will Encounter Drop-off and Not Recover	Index of Pleasing Appearance			
		Acres Mowed	Acres Sprayed	Urban	Rural
Option A	10	300,000	120,000	8"-Full width	12"-30' width
Option B	X	150,000	60,000	Mow only for safety	

At what level of X, would you be indifferent between the two options?

X = ____________

The results from the group sessions are summarized in Table 6.

Determination of the Optimum Combination of Maintenance Levels-of-Service

The objective of this step is to find the optimum combination of maintenance levels-of-service for all of the maintenance conditions included in the system. The criterion used for optimization is to maximize the overall value of highway user benefits subject to the constraints of available resources (dollars, person-days, etc.). The user benefits are specified in terms of the effects of levels-of-service on various considerations, such as safety, aesthetics, and protection of investment. The effects on these considerations are measured by the appropriate attributes, such as percentage of driver who cannot recover, index of pleasing appearance, and percent change in pavement rehabilitation cost.

Table 6. Consensus value tradeoffs between different pairs of attributes.

	Percentage of drivers who cannot recover		Index of pleasing appearancex	
Option A	10	Balancing Reward	1	Penalty
Option B	5.9		4	
	Percent increase in pavement rehabilitation cost		Index of pleasing appearance	
Option A	35		1	
Option B	15.4		4	
	Percentage of drivers who cannot recover		Index of environmental pollution	
Option A	10		4	
Option B	8.6		1	

Optimization Program

Mathematically the optimization problem is formulated as follows:

Let X_{ij} denote a binary variable such that

X_{ij} = 1 if the j^{th} alternative level-of-service (e.g., repair when edge of traveled-way drop-off is 2 inches) is selected for the i^{th} maintenance condition (e.g., edge of traveled-way drop-off).

= 0 if the j^{th} alternative level-of-service is not selected.

The objective of the analysis is to determine X_{ij} for all i and j to maximize $V(\theta_1, \theta_2, \ldots, \theta_n)$ subject to the following constraints:

$$\sum_i \sum_j C_{ij} X_{ij} \leq \text{available budget, } B$$

$$\sum_i \sum_j M_{ij} X_{ij} \leq \text{available person-days, } M$$

$$\sum_j X_{ij} = 1$$ (Only one of the alternative levels-of-service for each maintenance condition is to be selected.)

in which C_{ij} = cost of implementing the j^{th} level-of-service for the i^{th} maintenance condition, and

M_{ij} = person-days required for implementing the j^{th} level-of-service for the i^{th} maintenance condition.

A nonlinear integer programming algorithm has been developed to solve the above optimization problem. The algorithm has been coded in the computer program ASOP.

Estimation of Attribute Levels. The following estimation model is used in the program:

$$\theta = \sum_i \sum_j B_{ij}X_{ij}$$

in which θ = an attribute

X_{ij} = 1 if the j^{th} level-of-service for the i^{th} maintenance condition is selected.

= 0 if the j^{th} level-of-service is not selected.

B_{ij} = coefficient which estimates the incremental effect of X_{ij} on θ.

The first summation in the above equation is over all the maintenance conditions which affect θ, and the second summation is over all alternative levels-of-service for each of these maintenance conditions.

For the demonstration example in Louisiana, each attribute is affected by only one maintenance condition. Percentage of drivers who cannot recover (θ_1) and percent change in pavement rehabilitation cost (θ_2) are affected only by edge of traveled-way drop-off. Similarly, index of pleasing appearance (θ_3) and index of environmental pollution (θ_4) are affected only by roadside vegetation growth.

Program Output

The program output consists of the following parts:

Print Input Data. All input data are printed so that the accuracy of the data can be checked and information useful in evaluating the results is readily available.

Print Parameters of Value Function. The program computes the constants of the value function for each attribute in a quadratic form. These constants are printed.

The tradeoff information is used to calculate the scaling constants (relative weights) of different attributes. The scaling constants are also printed.

Print Estimation Coefficients. The estimation coefficients, B_{ij} are printed for each attribute.

Print Results of Base Case Analysis. The output describes the optimum solution, i.e., the level-of-service which should be adopted for each maintenance condition so as to maximize overall value (to highway users) while satisfying the resource constraints. The actual resources required to implement the optimum solution are displayed. The overall value of the optimum solution (on a scale of 0 to 1) is printed along with the contributions of the various attributes to the overall value.

Results of Base Case Analysis

Figure 2 shows the results of the base case analysis included in the program output. The optimum levels-of-service are:

1. Repair when edge of traveled-way drop-off is 1-inch.
2. Mow 300,000 acres and spray 120,000 acres. (This vegetation control program would allow mowing grass full width before it reaches 8 inches in urban areas and mowing grass 30 feet from the edge of the traveled surface after it exceeds 12 inches in rural areas.)

Figure 2. Results of the base case analysis.

Complete Enumeration

The selected policy is:

Edge of traveled-way drop-off	Repair when drop-off is 1-inch.
Vegetation growth	Mow 300,000 acres and spray 120,000 acres.

Costs of the Selected Policy

Materials (thousands of dollars)	Available - 5130, used - 5130
Thousands of Labor-Hours	Available - 644, used - 644
Equipment (thousands of dollars)	Available - 3380, used - 3377

Evaluation of the Attributes

Safety--percent of drivers who cannot recover	
Individual value - 1.000	Weighted value - .438
Percent change in rehabilitation costs	
Individual value - 1.000	Weighted value - .321
Pleasing appearance	
Individual value - 0.962	Weighted value - 0.173
Environmental pollution	
Individual value - .500	Weighted value - .031

THE VALUE OF THIS POLICY IS 0.96

The levels-of-service currently used in Louisiana for the two maintenance conditions are also the optimum levels-of-service selected by the program. This was to be expected because only a few variables had to be considered for the example, the analysis assumed the resources currently used for the two maintenance conditions, and the value judgments of those involved in setting the current levels-of-service were used. The strength of the methodology is that it will consistently select optimum levels-of-service when a large number of maintenance conditions were analyzed and when changes in the current maintenance budget become necessary. The overall value of the optimum solution is 0.96. The optimum levels-of-service provide the highest user benefits possible for the two maintenance conditions. No improvement in these levels-of-service would be possible even if higher amounts of resources were available. An examination of the contributions of the four attributes to the overall value reveals that the two attributes related to edge of traveled-way drop-off (percentage of drivers who cannot recover and percent change in rehabilitation cost) contribute 79 percent of the total value, while the remaining 21 percent of the total is contributed by the roadside vegetation attributes.

Sensitivity Analysis

The objective of this step is to assess the influence of changes in some of the major inputs and assumptions on the selection of the optimum combination of levels-of-service. The output of this analysis would identify the parameters to which the selection of optimum levels-of-service is very sensitive. The assessment of such parameters would obviously warrant more careful consideration.

The computer program ASOP has been designed to perform the following types of sensitivity analyses when requested by the user:

1. Effect of Changes in Available Resources. Available amounts of one or more resources may be changed and the effect on optimum levels-of-service may be examined.
2. Changes in Tradeoffs. The tradeoffs used in the base case analysis represent group consensus values obtained in the Delphi procedure. These tradeoffs yield the relative weights of various attributes. If significant differences of opinions were observed during the group session, different tradeoffs between attributes may be used in finding optimum levels-of-service. If the effect on optimum levels-of-service is significant, the differences in opinions are clearly critical and need to be resolved before levels-of-service can be selected.
3. Mandatory Inclusion of Specified Levels-of-Service. For certain important maintenance conditions, relatively high levels-of-service may be required; for example, the edge of traveled-way drop-off may be required to be less than 1-inch. The program can fix such levels-of-service and optimize on the remaining maintenance conditions.
4. Mandatory Exclusion of Specified Levels-of-Service. Certain levels-of-service may be considered to be impractical or infeasible. For example, with respect to edge of traveled-way drop-off, the lowest level-of-service (repair when drop-off is 5 inches) may be excluded from the analysis. The program will eliminate such a level-of-service from the search for the optimum solution.
5. Exclusion of Best Solution. This option would find the second best solution. If the value of this solution is nearly as good as that of the best solution, but the resources required for the second best solution are significantly lower than those required for the best solution, then the second best solution may be preferred.

In conducting the sensitivity analyses for the demonstration example in Louisiana, advantage can be taken of the fact that none of the attributes is simultaneously affected by both the maintenance conditions. Consequently, it is possible to determine the complete contribution of a given level-of-service of each maintenance condition to the overall value. The results are shown in Figure 2.

Recommendations

Recommendations are formulated after evaluating the results of the base case and the sensitivity analyses. The recommendations should include the following:

1. The optimum level-of-service for each maintenance condition in the system.
2. Resources which would be used in implementing the optimum levels-of-service.
3. Scenarios (e.g., budget cuts) which would require significant changes in the optimum levels-of-service.

Conclusions

The effort in Louisiana shows that it is feasible to use the methodology developed in this project to select levels-of-service for highway maintenance which would maximize user benefits subject to the constraints of available resources. The types of inputs required for the analysis can be obtained from the data base of information currently available to a state transportation department. The data base includes information available in the literature, studies conducted within the department, information available from maintenance management systems, and experience and judgment of knowledgeable individuals within the department.

The methodology requires the assessment of value judgments regarding tradeoffs between different considerations, such as safety, protection of investment, aesthetics, and environmental pollution. A Delphi procedure was used in Louisiana to obtain group consensus regarding tradeoffs from a number of individuals responsible for selecting levels-of-service both in the field and at headquarters. Certain improvements in the implementation of the Delphi procedure would seem desirable based on the experience in Louisiana. However, the types of assessment questions which need to be asked in the Delphi procedure are certainly practical and relevant to individuals involved in highway maintenance.

It would be desirable to provide certain types of objective data to the participants in the Delphi exercise in order to obtain more consistent and reliable value judgments. Examples of such data include statistics on accidents resulting from driving over the edge of traveled-way with various amounts of drop-off and surveys of user opinions regarding aesthetics of roadside vegetation under varying levels-of-service. These kinds of data are currently not available. The initial implementation of the methodology will identify the critical parameters on which objective data would be most useful. Limited studies to collect these data can be undertaken. The reliability of the results of the methodology would be expected to increase with the availability of additional data.

The computer program prepared for the use of the methodology facilitates the analysis significantly. The program is designed such that the assessed data can be directly input and all parameters (such as value coefficients, relative weights, and regression coefficients) are computed internally in the program. This relieves the user of the burden of making external calculations, which would require some theoretical background in decision analysis techniques.

The demonstration example in Louisiana involved only two maintenance conditions--namely, edge of traveled-way drop-off and roadside vegetation growth. The complete system of highway maintenance could involve 20 to 25 maintenance conditions of practical significance.

Acknowledgements

This study was conducted under the National Highway Research Program, Project 14-5. The opinions and findings expressed or implied in this paper are those of the authors. They are not necessarily those of the Transportation Research Board, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, nor the individual participating states.

The authors wish to acknowledge the efforts of the Louisiana Department of Transportation and Development for their assistance in the demonstration phase of the project. Special thanks are extended to Mr. Gerald Ray for his assistance.

The NCHRP Project Engineer was Mr. Ian Kingham and the authors wish to express their appreciation for his encouragement and advice during the project.

Mr. Ezio Alviti and Mr. Fereidoon Sioshansi assisted in various parts of the project and their efforts are hereby acknowledged.

References

1. Keeney, R.L. and H. Raiffa. Decisions with Multiple Objectives: Preferences and Value Trade-offs. John Wiley and Sons, New York, 1976.
2. Raiffa, H. Decision Analysis. Addison Wesley, Reading, Mass., 1968.