CONCLUSIONS

The main conclusion of the first few test series is that the RTM appears to be well suited to simulating the effects of heavy traffic loadings and climatic variations on full-scale pavement structures. As a result, a five-year research program jointly sponsored by the National Danish Road Laboratory and the Technical University of Denmark has been initiated. In this research program, nonconventional pavement structures and materials will be tested under varying climatic conditions simultaneously with more traditional structures. It is hoped that these tests will also contribute to the development of a predictive design procedure that will be superior to the deterministic procedures currently being used.

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Utility Decision Model for Pavement Recycling

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A decision model developed by using utility theory to evaluate various techniques for recycling of pavement materials is described. The model is quantified by using subjective opinions of experienced engineers who are familiar with pavement rehabilitation. Limited objective field data

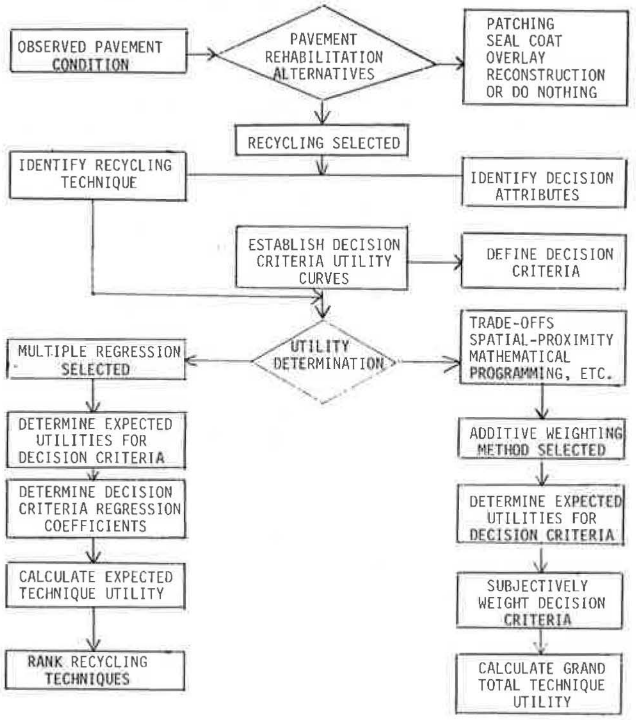
are also required. The analysis involves identification of various recycling techniques and decision criteria and development of utility data. The optimum recycling technique is determined based on the maximum expected utility associated with the technique. The decision model provides a systematic and rational means for evaluating all of the various criteria that should be considered in a decision on pavement recycling.

In the existing institutional framework, transportation officials make decisions on the recycling technique to be used in a given scheme of pavement rehabilitation. In almost all of the recycling projects that have been undertaken, cost and the availability of equipment have been the main factors in the choice of a recycling technique. Although these factors are extremely important, other factors or criteria also have an important influence on the decision to recycle. For instance, in recent years, highway engineers have become aware of energy and environmental considerations in their decisions. They would rather not consider techniques that use excessive energy or pollute the environment.

The decision to recycle pavement should therefore be based on a thorough analysis of possible recycling techniques by considering all of the various decision criteria and selecting the technique that would yield the greatest satisfaction to the decision maker. One way to achieve this is by using utility theory in the decision process.

Utility is a measure of individual preferences that can range from zero to one. The utility of any object or activity is the degree to which it or its consequences are perceived by the individual as satisfying his or her preferences in a given situation. The utility value need not be the same for two or more individuals or for a particular individual at all times or in all situations. Utility theory has been used successfully in the analysis of a variety of engineering problems. Examples include the study of the development of the Mexico City airport (1) and the determination of the optimum configuration for the supersonic transport (2).

Figure 1. Utility decision process in pavement recycling.



The utility approach can be used whenever a systematic analysis of possible alternatives requires the consideration of various decision criteria in the choice of an alternative. Such criteria include human values or preferences, uncertainty, and other judgmental elements as well as objective operational and technological considerations. Once recycling is selected as the pavement rehabilitation alternative, several possible recycling techniques are available. Utility theory can be applied to provide the information needed in making a rational decision on the choice of a recycling technique. The best technique for a particular scheme of pavement rehabilitation can be chosen on the basis of the relative power (or utility) of that technique to satisfy the decision maker.

This paper describes a decision model that uses utility theory to evaluate various techniques for pavement recycling and is based on material presented in detail elsewhere (3). A schematic diagram of the model is shown in Figure 1. The following basic components of the decision model are discussed:

1. Structuring the decision problem, which includes identification of the decision maker, definition of the decision problem, generation of recycling alternatives, and establishment of decision attributes and criteria;
2. Utility analysis, which includes establishment of utility functions and determination of decision-criteria utilities and technique utilities; and
3. Implementation of the decision model, which includes a discussion of the Use Estimates 1 (USEE1) computer program, data generation, and evaluation results.

STRUCTURING THE DECISION PROBLEM

The decision to use a particular recycling technique in a scheme of pavement rehabilitation is generally made by one or more state, federal, or local transportation officials. These officials can be identified here as the decision makers or simply the decision maker. The problem can be stated as follows: For a defined pavement condition and in view of various decision criteria or factors, what recycling technique(s) would yield the greatest satisfaction to the decision maker? The decision maker's first task in structuring the decision problem is to identify the various recycling techniques available.

Recycling Techniques

From a wide variety of recycling approaches, the Federal Highway Administration Demonstration Project 39 Technical Advisory Committee has identified three main categories of recycling (4):

1. Surface recycling involves reworking of the pavement surface to a depth of less than 25 mm (1 in) by heater-planer, heater-scarifier, and surface milling devices. This operation is a continuous single-pass, multistep process that may involve the use of new materials, including aggregate, modifiers, and/or mixtures. Several recycling techniques can be identified in this category based on the device used and whether or not additional aggregate and thin or thick overlay is used in the process.
2. In-place surface and base recycling involves in-place pulverization to a depth greater than about 25 mm (1 in) followed by reshaping and compaction. This operation can be performed with or without the addition of new binder or stabilizer. In-place recycling techniques can be identified based on (a) whether in the asphalt-concrete thickness of the existing pavement is less than 50 mm

(2 in) (thin asphalt concrete) or more (thick asphalt concrete) and (b) whether the in-place technique used is an equivalent method for minor or major structural improvement.

3. Central plant recycling involves the scarification of the pavement, removal of the pavement material from the roadway before or after pulverization, processing of material with or without the addition of a stabilizer or modifier, followed by laydown and compaction to the desired grade. Depending on the type of material recycled and the stabilizer used, this operation may involve the addition of heat (hot process) or no heat (cold process). Several techniques can be identified in this category based on whether heating is used and whether the technique is an equivalent method for a minor or major structural improvement.

Decision Attributes and Decision Criteria

In the decision to recycle a pavement in a particular condition, the broad objective is to be able to select the best technique or techniques that can provide optimum satisfaction to the decision maker. More specifically, the recycling technique that will be selected is the one that best meets a set of multiple objectives, such as

1. Minimize cost,
2. Maximize expected performance,
3. Minimize energy use,
4. Minimize environmental pollution and noise, and
5. Maximize safety.

This set of objectives can be considered the attributes of the recycling decision. But, because these attributes may be too general to be of practical use, subobjectives can be developed and associated with each attribute as a measure of effectiveness. These subobjectives can be considered the decision criteria. Their measurement can be quantitative or qualitative depending on the convenience or cost of measurement to the decision maker. A possible set of attributes, decision criteria, and measures of effectiveness for a pavement-recycling decision is given below (because the data used in the model developed in this study are in U.S. customary units, no SI equivalents are given):

Attribute	Decision Criterion	Measure of Effectiveness
Cost	Recycling cost	Dollars per square yard-inch
	Future maintenance cost	Dollars per lane mile per year
	Ride quality	Present serviceability index (PSI)
Expected performance	Expected distress	Distress deduct points
	Pavement life	Years
	Expected traffic	Relative traffic value
Energy	User energy savings	Btu per year
	Process energy	Btu per square yard-inch
Environment	Pollution	Qualitative rating
	Noise	Qualitative rating
Safety	Safety during recycling	Qualitative rating
	Safety performance	Qualitative rating

The qualitative rating scale for environmental and safety-related decision criteria is as follows: 1 = excellent, 2 = good, 3 = fair, 4 = poor, 5 = very poor, and 6 = unacceptable. Whereas the decision criteria specified under cost, expected performance, and energy attributes are measured quantitatively, those under environmental and safety attributes are rated qualitatively. Although this list of attributes and decision criteria is not intended to be complete, it illustrates the concept. Other possible attributes or decision criteria considered significant enough to influence the choice of a technique for pavement recycling can be identified by the decision maker.

UTILITY ANALYSIS

The decision-making process requires that value judgment be effectively exercised at the level of the individual decision criterion to provide an explicit quantitative relation between the magnitude of the decision criterion and the relative preference or utility derived by the decision maker. Such a relation, termed the utility function, can be used to determine the expected utility of each alternative.

Characteristics of Utility Functions

Utility functions possess some qualitative characteristics, and each characteristic implies a certain attitude of the decision maker with regard to his or her preference for consequences and lotteries. One of the characteristics of utility functions is monotonicity (5). This concept can be explained in terms of lotteries as follows: A standard reference lottery is preferred to a second standard lottery if and only if the first lottery's probability of receiving the most preferred prize is greater than that of the second (6). To illustrate this in a pavement context, a decision maker may assess performance in terms of ride quality x of the pavement. If $x_1 > x_2$, then the utility $u(x_1) > u(x_2)$. In this case, the utility function is said to be monotonically increasing.

If we now consider process energy as a decision criterion, use of more process energy does not yield a preferable prize in comparison with use of less process energy. So, if the process energy $x_1 > x_2$, then the utility $u(x_2) > u(x_1)$. In this case, the utility function is said to be monotonically decreasing. There are also situations in which the utility function is not monotonic.

Another characteristic of utility functions is risk aversion. This can be described by the various basic attitudes of decision makers toward risk. Consider a decision maker facing a lottery that yields a consequence x', or a less preferable consequence x'' with equal probability. The expected consequence $\bar{x}$ of this lottery is $\bar{x} = 0.5\,(x' + x'')$. Suppose the decision maker is asked to state a preference between receiving $\bar{x}$ for certain or the lottery. If the certain consequence $\bar{x}$ is preferred, the decision maker is actually saying that he or she prefers to avoid the risk associated with the lottery. A decision maker who has this type of attitude toward lotteries is "risk averse". From a mathematical derivation, it can be shown that a decision maker is averse to risk if and only if his or her utility function is concave in shape (5).

On the other hand, a decision maker who prefers any lottery to the expected consequence $\bar{x}$ is more than willing to accept the risks associated with the lottery and is said to be "risk prone". The utility function of a risk-prone decision maker is convex in shape.

Between the risk-averse and risk-prone cases is the "risk-neutral" case, in which the utility of the expected consequence equals the utility of the lottery and the utility function is linear.

In the determination of utility functions, a decision maker's utility function should not always be described as risk averse or risk prone for the entire length of the curve. In most decision situations, it is found that, up to a certain point in the utility function, the decision maker's preference is risk prone or risk averse and beyond that is risk averse or risk prone. So, instead of wholly convex or concave functions, we have functions that are part convex and part concave. This S-shaped function, which has a point of inflection where the preferences turn from prone to averse or averse to prone, can be used for determining utility functions in pavement recycling.

Assessment of Utility Functions for Decision Criteria

The assessment of utility functions can be considered as much an art as a science. Therefore, there are no set rules that invariably result in a utility function. In general, the assessment of utility functions requires conducting repeated interviews with carefully phrased questions that reveal, by determining levels of indifference, the actual shape of the functions. The approach suggested here involves several steps, including the following:

1. Determine whether or not the utility function for a decision criterion is monotonic. This might be done by asking questions such as, If an amount of the decision criterion x_k is greater than x_j, is x_k always preferable to x_j? If the answer to such a question is yes, it implies that the utility function for this decision criterion is monotonically increasing; if no, then the utility function should be monotonically decreasing.
2. Determine boundary limits for the utility function. Since utility is a measure of the relative preference of the decision maker on a scale from zero to one, the lower bound and upper bound can be set at a utility of zero and one, respectively. The values of zero and one can be assigned to the least desirable and most desirable magnitudes of the decision criterion.
3. Determine the expected consequence or magnitude of the decision criterion x for which the decision maker would feel like assigning a mean utility value $\bar{u}(x) = 0.5$.
4. Determine the expected consequence of the decision criterion for which the decision maker would assign a utility of 0.66 or 0.34 $[\bar{u}(x) \pm 0.16]$.
5. Determine which portion of the utility function is risk averse, risk neutral, or risk prone. This can be done by asking questions that reveal values of the decision criterion that would make the decision maker indifferent as to his or her satisfaction with using pavement recycling as a rehabilitation alternative. This helps fix inflection points on the utility function. Then the decision maker's preference can be tested before and beyond this value of decision criterion to determine his or her willingness to take risk.

In this approach, a five-point assessment procedure at utility values of 0, 0.34, 0.5, 0.66, and 1.0 can be made for the quantitatively measured decision criteria, and a three-point assessment at utility values of 0, 0.66 or 0.5, and 1.0 would suffice for the qualitatively rated decision criteria.

Determination of Decision-Criterion Utility

The utility functions determined from the foregoing discussion can be used to determine the utility of any decision criterion once a particular value of the criterion is known. But, in predicting the magnitude of each decision criterion, no one can predict with certainty the outcome at the time the decision is to be made. The uncertainty associated with estimates of outcomes is relatively rarely described in an explicit way; it is even more rarely included explicitly and quantitatively in the evaluation of outcomes. The riskiness associated with an alternative is usually handled subjectively or implicitly. However it is handled, uncertainty is present in recycling decisions.

The uncertainty concerning the estimates of a decision criterion (recycling cost, ride quality, pollution, etc.) can be explicitly and quantitatively represented by a probability density function. This representation ensures more confidence in the decisions made under uncertainty since the decision variables are described as a distribution of values instead of being treated as single values.

One of the most versatile probability density functions (pdfs) is the beta pdf, given by

$$f(x) = \Gamma(a + b)\, x^{a-1}\, (1 - x)^{b-1} / [\Gamma(a) \cdot \Gamma(b)] \qquad (1)$$

for $0 < x < 1$, $a > 0$, $b > 0$, and where $\Gamma(a)$ and $\Gamma(b)$ are gamma functions of a and b, which are distribution constants.

The beta pdf is a useful tool whenever a variable x is bounded at both upper and lower ends. Another advantage is the wide variety of shapes that can be obtained by varying a and b. The beta pdf is very convenient for determining the means and standard deviations of decision-criteria estimates. For optimistic or low (o), most probable (m), and pessimistic or high (p) estimates of the decision variable, the mean μ is given by

$$\mu = (0 + 4m + p)/6 \qquad (2)$$

and the standard deviation $\sigma = (p - o)/6$. The distribution parameters a and b are then given as

$$a = \mu \{[\mu(1 - \mu)/\sigma^2] - 1\} \qquad (3)$$

and

$$b = \{[\mu(1 - \mu)/\sigma^2] - 1\}\, (1 - \mu) \qquad (4)$$

These values of a and b are used to calculate the distribution function f(x) for any value of the decision criterion x.

The expected value of the decision-criterion utility is given by

$$U(x) = \int_{x\,\min}^{x\,\max} f(x)\, u(x)\, dx = \bar{u} \qquad (5)$$

and variance $\sigma(x)^2$ is given by

$$\sigma(x)^2 = \int_{x\,\min}^{x\,\max} f(x)\, u^2(x)\, dx - \bar{u}^2 \qquad (6)$$

where u(x) = utility function.

The decision-criteria utilities obtained are used in determining the recycling-technique utilities.

Determination of Recycling-Technique Utility

A variety of methods are available for determining utilities, including weighting, sequential elimination, mathematical programming, and spatial proximity methods. Each type has its own merits, but weighting methods have received the most attention and been most widely applied in the determination of utility. Of the various weighting methods available, simple additive weighting and linear regression have been chosen in this paper to weight the individual decision-criteria utilities in the process of determining the recycling-technique utility.

Additive Weighting

In additive weighting, the individual utilities for each decision criterion must be weighted and added together to give an overall utility for the recycling technique. This can be found from the relation

$$E(u)_i = \sum_{i=1}^{n} W_i \, U_i(x) \qquad (7)$$

where

$E(u)_i$ = overall or grand total value of utility for the technique i,
$U_i(x)$ = expected value of utility of the i th decision criterion, and
W_i = normalized weight of the i th decision criterion.

The weights of the decision criteria are normalized so that their sum is one; i.e.,

$$\sum_{i=1}^{n} W_i = 1 \qquad (8)$$

The overall variance of the technique $\sigma^2(u)$ is given by

$$\sigma^2(u) = \sum_{i=1}^{n} W_i \, \sigma_i^2(x) \qquad (9)$$

where $\sigma_i^2(x)$ is the variance of the utility of the i th decision criterion.

The additive weighting model assumes that even though there might be situations in which interaction among the various criteria is possible, the expected decision-criteria utilities are independent of each other.

Multiple Linear Regression

The general linear regression model is given by

$$y_i = a_0 + a_1 x_{i1} + a_2 x_{i2} + a_n x_{in} \qquad (10)$$

where

y_i = value of response (dependent) variable in the i th trial,
$a_0, a_1, a_2, \ldots, a_n$ = regression coefficients, and
$x_{i1}, x_{i2}, \ldots, x_{in}$ = known independent variables.

In some situations, the variables can be transformed, yet the model can be treated as a general linear regression model. One version of a transformed model is

$$\ln y_i = a_0 + a_1 \ln x_{i1} + a_2 \ln x_{i2} + \ldots a_n \ln x_{in} \qquad (11)$$

This model is equivalent to

$$y_i = e^{a0} x_{i1}^{a1} x_{i2}^{a2} \ldots x_{in}^{an} \qquad (12)$$

This transformed model can be called a log multiple regression model.

By using the decision-criteria utility values as independent variables, this regression model can be used to determine technique utilities from the relation

$$E(u)_i = e^{a0} U_{i1}^{a1} U_{i2}^{a2} \ldots U_{in}^{an} \qquad (13)$$

where $E(u)_i$ = expected utility for recycling technique i and U_{ij} = expected utility for the j th decision criterion for technique i.

The regression model assumes that, even though utility independence is a necessary condition in utility decisions, there can be some interaction among the various decision-criteria values. It therefore provides a means of transforming the decision-criteria utilities in order to use the concepts of utility independence.

IMPLEMENTATION OF DECISION MODEL

USEE1

The USEE1 computer program (3) uses the utility concepts discussed above to evaluate various recycling techniques for any defined pavement condition. Several decision criteria can be considered; for each criterion, the program input requires optimistic (low), most likely, and pessimistic (high) estimates, utility function data, weighting factors, and regression constants. The program fits a utility curve to the utility function data for each decision criterion and also fits a beta distribution curve to the three estimates. It then multiplies the two curves and integrates to come up with the expected decision-criteria utility U(x). It uses the weighting factors w_i to weight and sum the expected decision-criteria utilities to come up with a grand total technique utility E(u). The program also uses the regression constants ai with the expected decision-criteria utilities, assuming a log model to come up with expected technique utility E(u).

Data Generation

Since there are not many performance data available on pavement recycling, to implement the decision model, data generation in this study was geared toward subjective data and only limited objective field data. In this process, the subjective opinions of engineers who are familiar with pavement recycling were incorporated with objective data in the decision process. Assessment of utility thus implied that some procedure for extracting subjective data from individuals was necessary.

The procedure used in this study involved setting up a decision panel and getting the responses of individual decision makers to various questionnaires. The decision panel then met and, after they discussed their individual responses, a consensus value was taken for the decision analysis.

By this process, the utility data summary given in Table 1 was obtained. Questionnaires were also developed so as to obtain some useful information about the values of the decision criteria, the decision makers' implied preferences for the various recycling techniques under certain pavement conditions, and weighting factors for the decision criteria. Regression coefficients for the decision criteria were obtained by using a SELECT regression computer program (7).

Results of Evaluation

The USEE1 program was used to evaluate 24 recycling techniques for a pavement with moderate alligator cracking. The program output included utility functions for each decision criterion from the data given in Table 1, beta distribution plots for decision-criteria estimates, a weighting table, and a final output table.

Figures 2 and 3 show utility curves for the decision criteria of recycling cost and expected life. Figures 4 and 5 show distribution plots of decision-criteria estimates for recycling cost and expected life. The final

Table 1. Summary of decision criteria, utilities, and characteristics.

Attribute	Decision Criterion	Utilities	Values	Utility Characteristic[a]
Cost	Recycling cost ($\$/yd^2$-in)	1.0, 0.66, 0.50, 0.34, 0.0	0.10, 0.30, 0.60, 1.2, 2.0	Monotonically decreasing
	Maintenance cost [$/(lane mile/year)]	1.0, 0.66, 0.50, 0.34, 0.0	100, 250, 400, 1000, 3000	Monotonically decreasing
Expected performance	Ride quality (PSI)	0.0, 0.34, 0.50, 0.66, 1.0	1.2, 2.5, 3.5, 4.0, 4.8	Monotonically increasing
	Distress deduct points	1.0, 0.66, 0.50, 0.34, 0.0	0, 10, 20, 50, 100	Monotonically decreasing
	Life (years)	0, 0.34, 0.50, 0.66, 1.0	0, 3, 5, 7, 15	Monotonically increasing
	Relative traffic value	0, 0.34, 0.50, 0.66, 1.0	0.5, 0.70, 0.8, 1.0, 1.5	Monotonically increasing
Energy	User energy savings (Btu/year)	0, 0.50, 1.0	10^5, 10^9, 10^{11}	Monotonically increasing
	Process energy (Btu/yd^2-in)	1.0, 0.66, 0.50, 0.34, 0.0	200, 2000, 20 000, 25 000, 50 000	Monotonically decreasing
Environment	Pollution rating	1.0, 0.66, 0.0	1, 2, 6	Monotonically decreasing
	Noise rating	1.0, 0.66, 0.0	1, 2, 6	Monotonically decreasing
Safety	Safety during recycling rating	1.0, 0.66, 0.0	1, 2, 6	Monotonically decreasing
	Safety performance rating	1.0, 0.50, 0.0	1, 3, 6	Monotonically decreasing

[a] All S-shaped.

Figure 2. Results of recycling technique 24: recycling cost versus utility values.

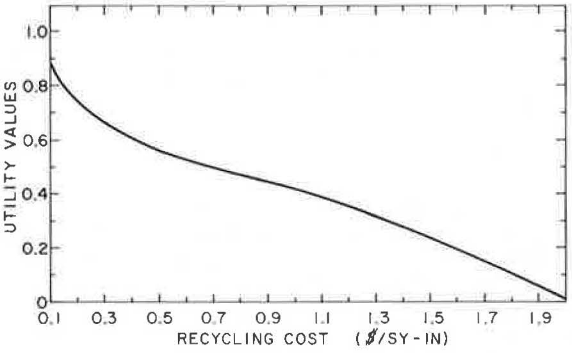


Figure 3. Results of recycling technique 24: expected life versus utility values.

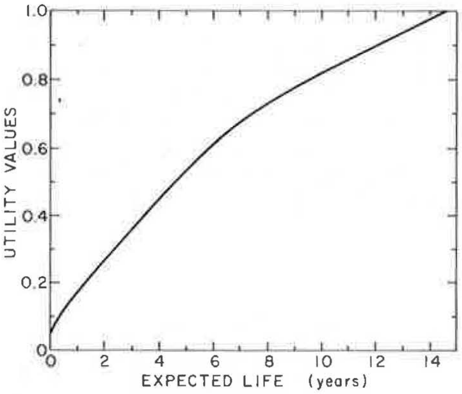


Figure 4. Results of recycling technique 24: recycling cost versus distribution frequency.

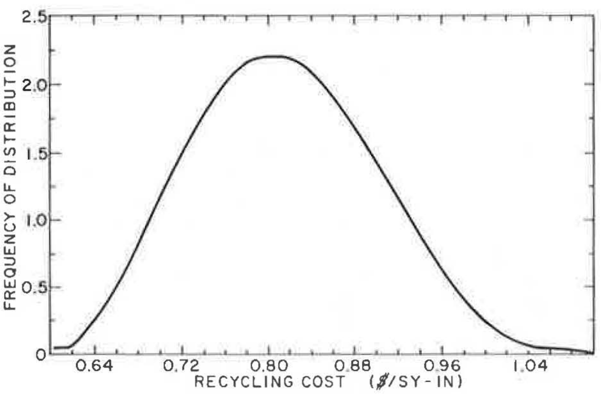
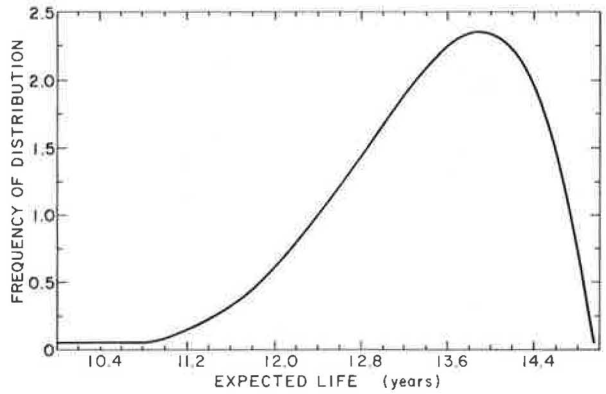


Figure 5. Results of recycling technique 24: expected life versus distribution frequency.



output table consists of displays of the three estimates, calculated means, standard deviations, expected decision-criteria utilities, variances, and weighted utilities and variances. At the bottom of the table is given grand total utility and variance for the additive weighting approach. Table 2 gives the final output for technique 24. The expected technique utility for the multiple regression approach is 0.928. Table 3 gives a summary of the utilities and rankings obtained from the analysis of the 24 recycling techniques by the decision panel set up for the model implementation.

The results indicated that, for these decision makers,

1. The possible range of technique utilities was smaller for the additive weighting model (0.429-0.716) than for the multiple regression model (0.095-0.928).
2. Techniques with low utilities in both models had considerably higher values in the additive weighting model than in the multiple regression model. On the other hand, utility values for the best techniques were considerably higher in the multiple regression approach than in the additive weighting approach.
3. Ranking of the techniques, although not exactly the same for both models, tended to result in good correlation for the two models. The techniques with low utilities were ranked low and those with high utilities were ranked high for both models.
4. Either model or both models can be satisfactorily used to select an optimum recycling technique for a pavement rehabilitation scheme.

Sensitivity analysis of the decision model also showed that

1. The utility values obtained for the recycling tech-

Table 2. Final output for recycling technique 24.

Decision Criterion	Estimate Low	Estimate Most Probable	Estimate High	Mean	Standard Deviation	Expected Decision Criterion Utility	Variance	Weighted Utility	Weighted Variance
Recycling cost	0.60	0.80	1.10	0.82	0.08	0.458	0.000 45	0.068	0.000 01
Maintenance cost	100.00	150.00	200.00	150.00	16.67	0.818	0.001 27	0.073	0.000 01
Ride quality	4.00	4.50	4.80	4.47	0.13	0.852	0.003 31	0.101	0.000 05
Distress	1.00	3.00	5.00	3.00	0.67	0.827	0.000 48	0.061	0.000 00
Expected life	10.00	14.00	15.00	13.50	0.83	0.945	0.000 99	0.126	0.000 02
Traffic	1.10	1.30	1.50	1.30	0.07	0.868	0.002 00	0.051	0.000 01
User energy savings	5^{9}	5^{10}	1^{11}	5.083^{10}	1.583^{10}	0.897	0.002 13	0.020	0.000 00
Process energy	20 000.00	23 000.00	25 000.00	22 833.00	833.33	0.390	0.000 47	0.012	0.000 00
Pollution	2.00	3.00	4.00	3.00	0.33	0.461	0.003 70	0.041	0.000 03
Noise	2.00	3.00	4.00	3.00	0.33	0.461	0.003 70	0.014	0.000 00
Safety during recycling	2.00	3.00	4.00	3.00	0.33	0.461	0.003 70	0.041	0.000 03
Safety performance	1.00	2.00	3.00	2.00	0.33	0.707	0.005 76	0.084	0.000 08
Weighted total								0.691	0.000 24
Grand total								0.691	0.000 24

Note: Data for central plant, hot process, major structural improvement with new binder, moderate alligator cracking.

Table 3. Summary of utilities and rankings obtained for 24 recycling techniques.

Technique	Additive Weighting Model Utility	Additive Weighting Model Ranking	Multiple Regression Model Utility	Multiple Regression Model Ranking
1	0.429	24	0.095	23
2	0.446	23	0.134	22
3	0.472	21	0.198	21
4	0.508	20	0.325	20
5	0.679	9	0.680	11
6	0.460	22	0.094	24
7	0.510	19	0.352	19
8	0.677	10	0.725	9
9	0.540	18	0.435	18
10	0.622	11	0.595	13
11	0.693	5	0.739	8
12	0.716	1	0.753	7
13	0.555	17	0.497	16
14	0.621	12	0.564	14
15	0.694	4	0.780	5
16	0.713	2	0.762	6
17	0.561	16	0.489	17
18	0.615	13	0.541	15
19	0.687	7	0.861	4
20	0.707	3	0.896	2
21	0.599	15	0.695	10
22	0.607	14	0.659	12
23	0.686	8	0.893	3
24	0.691	6	0.928	1

niques could change slightly but not significantly with an increase or decrease in one of the decision variables and this change could be higher for the additive weighting model than for the multiple regression model.

2. There can be considerable variation in the expected decision-criteria utilities because of changes in the values of the decision criteria. These changes could be more significant in the utilities of the qualitatively rated decision criteria than the quantitatively measured decision criteria.

3. Changes in the weighting factors or regression constants can result in differences in the utility values. However, this was found not to significantly affect the rankings of the recycling techniques in this study.

4. Because the uncertainties associated with the expected utility values can be small, this model could be used to compare recycling techniques without taking variances into consideration.

5. The expected performance of the pavement was considered to be the most sensitive attribute and ride quality the most important decision criterion in the decision panel's selection of an optimum technique. Cost was also important. Energy considerations were the least important. These results, however, are not absolute since they reflect only the preferences of the decision panel used.

CONCLUSIONS

This paper has demonstrated the applicability of utility theory to the decision-making process in selecting optimum recycling strategies for pavements. The model requires the identification of the various possible recycling techniques and the significant decision criteria that can affect the decision maker's choice of a technique. For each of these criteria, the decision process requires the determination of a utility function. It then considers the uncertainties associated with the estimates of decision-criteria values and determines expected decision-criteria utilities. Weighting factors and regression constants are used to weight the decision-criteria utilities, and the optimum recycling technique is defined based on the maximum expected utility associated with a technique.

Probably the major benefit derived from the application of utility theory to decisions on pavement recycling is that it provides a logical and consistent method for systematically evaluating all the various factors that should be considered before a recycling decision can be made.

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Seasonal and Short-Term Variations in Skid Resistance

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Preliminary results of a three-year program to investigate possible causes of seasonal and short-term variations in skid resistance are presented. The program was initiated in 1976 at the Pennsylvania State University to develop a method for predicting the lowest skid number a pavement is expected to attain during the year from a skid-resistance measurement made at any time during the year. Results of two years of testing indicate that skid-resistance variations of 15-30 SN_{40} occur at the changes of season from early to late fall and early to late spring. Higher numbers occur in the winter season. Skid numbers vary by about 25 percent between rainfall periods whether or not the surface is subject to significant traffic. Higher skid numbers are observed after heavy rainfall. Where traffic is low (average daily traffic < 1000), only minor macrotexture changes are noted from one season to another. On these pavements, therefore, microtexture changes are expected to cause the variations in skid resistance. Bituminous surfaces containing sandstone gravel aggregate are subject to small variations in skid resistance over time, whereas surfaces containing limestone and dolomite are subject to large variations. Temperature has been found to have insignificant effects on skid resistance.

Seasonal and short-term variations in skid-resistance measurements made according to the ASTM E 274 test method have been observed on Pennsylvania and other public highways (1, 2). These variations make it difficult to establish a maintenance management program in which skid resistance is an important factor. Day-to-day variations, apparently caused by rainfall patterns and local weather conditions, are superimposed on an annual cycle. At least in northern states, this annual cycle tends to be higher in winter through spring than in summer through fall. Frequent tests during the period from spring through fall reveal that the skid resistance of pavements may vary by as much as 25 percent during a single week.

To establish a means of interpreting skid-resistance data subject to seasonal and short-term variations, in 1976 the Pennsylvania Department of Transportation (PennDOT) initiated a three-year research program at the Pennsylvania Transportation Institute (PTI). The primary objective of the research is to investigate the possible causes of the variations and to develop a method for predicting the lowest skid number a pavement is expected to attain during the year from a skid-resistance measurement made at any time during the year. This paper summarizes the data and preliminary findings obtained during the first two years of the study.

TEST SITES

Six pavements on public roads in the State College, Pennsylvania, area were selected for the study according to the following criteria:

1. The pavements should be in a sufficiently small geographic area so that each could be tested within a short period of time by using the same skid tester.
2. As far as possible, the pavements should be subject to the same weather conditions.
3. The pavements should be at least three years old so that their surface characteristics would have stabilized.
4. The pavements should contain a variety of aggregates and mix designs and include at least one portland cement concrete pavement.
5. The pavements should have as wide a range of average daily traffic (ADT) as possible.

The selected pavements met all of these criteria. Their characteristics are summarized in Table 1.

During the 1976 test season, local weather conditions were monitored by rain gauges that were read at the time of skid tests. Since weather variations among the sites were small, the weather records provided by the Pennsylvania State University weather station were subsequently used as representative of the weather at all sites. Available daily weather data include the amount of rainfall, maximum and minimum temperatures, relative humidity, wind speed and direction, and cloud cover. In addition, the temperature of the pavement and the tire and ambient temperatures are measured at the time of skid testing.

Five test locations at each site are marked with a fluorescent orange square to assist the driver in conducting the daily skid tests at the same locations each day. A series of three nails have also been placed in the surface at each location so that pavement texture can be measured at the same spot each month.

At all locations, skid tests are made in the wheel tracks. At one site, skid tests are also made between the wheel tracks to verify whether skid-resistance variations occur where no significant tire traffic passes. Although skid resistance is expected to be higher between the wheel tracks, the behavior of short-term variations between the wheel tracks may provide further insight into the mechanisms involved.