Selection of Pavement Markings Using Multicriteria Decision Making

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A decision support system (DSS) that was developed to aid in the selection of pavement marking materials is described. The DSS is based on multicriteria decision making, a technique that enables a variety of considerations to be brought into the analysis. Through a series of interactions with a Connecticut Department of Transportation task force, the key criteria were identified and structured into a goals hierarchy. Safety, costs, and convenience are the major categories for the goals. The task force helped to establish an objective function that quantifies how each goal and subgoal contributes to the overall goal of selecting the best pavement marking. This objective function was incorporated into a computer-based model using off-the-shelf personal computer software.

Transportation agencies use numerous types of materials to mark pavements and curbs. These materials vary from relatively inexpensive water-borne paint to longer lasting, but more expensive, thermoplastic. Each of the materials has unique placement requirements, performance characteristics, and costs.

There are numerous criteria that must be considered when selecting a pavement marking material for a given application (i.e., a given stretch of roadway). These include safety, durability, ease of application, and cost. The literature on performance characteristics of such materials is extensive. The work by Dale (*1*), is just one example. However, very little attention has been given to the very significant question of what material is the most appropriate for use in a given application. Thus, the primary objective of the project described in this paper was to develop a decision support system (DSS) for the Connecticut Department of Transportation (ConnDOT) that could consider the relevant multiple criteria in a systematic way.

MULTICRITERIA DECISION MAKING

The specific analytical technique used in this paper—multicriteria decision making (MCDM)—is just one type of method that could be incorporated into a DSS. A survey of DSS applications between 1971 and 1988 is given by Eom and Lee (*2*), and a review of decision analytical software is given by Buede (*3*). Keeney and Raiffa (*4*) provide a comprehensive presentation of MCDM, including descriptions of numerous applications. Applications of DSSs in general and MCDM in particular to transportation are described in an interim report for NCHRP Project 20–29 (*5*).

The simplest kind of MCDM model uses an *objective function* based on the assignment of *weights* to measurement values associated with the various *criteria*. For example, consider a decision to be made on the purchase of a piece of machinery. Clearly, one of the criteria for the decision would be to minimize cost. Assume the only other criterion for the selection is to minimize noise. In general, there will be a trade-off between the criteria, and one desires to somehow mathematically weight their relative importance. Suppose weights of .7 and .3 have been assigned to cost and noise, respectively. To use these weights, it is necessary to first quantify the two criteria by choosing numerical measures for each of them. Suppose one of the alternatives under consideration costs $30,000 and produces 130 decibels when in operation. If the weights were applied directly to these measures, it is clear that adding the results would be meaningless. This problem can be solved by introducing the concept of "utility"—an indication of desirability that is measured on a scale ranging from 0 to 1. This concept is described more fully below. The two single-measure utilities that an alternative receives for the two criteria may then be multiplied by the associated weights, and the results added together to obtain an overall utility for the alternative. The alternative with the highest overall utility would be the most preferable. A slightly more complicated situation arises when one or more of the measures are not directly quantifiable, such as, for example, aesthetics. This situation arises in the pavement markings problem and is discussed more thoroughly below. However, the basic idea of weighting the various criteria remains essentially the same as in the simple example just described.

Perhaps the most challenging aspect of using MCDM is obtaining inputs to build the model from those persons most knowledgeable about the decision at hand.

MODEL DEVELOPMENT

The process of developing the pavement markings MCDM model was an iterative one. Initially, a meeting was held between the principal investigators and all ConnDOT task force members. This was followed by additional meetings between the principal investigators and individuals and subgroups from the task force. During these meetings, individuals were asked to identify goals that are relevant to the selection of pavement markings. Based on inputs from the individual and group meetings, a *goals hierarchy* was developed. At subsequent group meetings, the goals hierarchy was reviewed and revised by the task force, resulting in the goals hierarchy shown in Figure 1.

While refining the goals hierarchy, the task force concurrently identified measurement scales to be used for evaluating pavement marking alternatives. All goals at the lowest tier of the hierarchy must have measurements associated with them. The goals hierarchy shown in Figure 1 includes 12 measures (shown in ellipses). For each measure, a scale has been defined. Some of the scales use discrete

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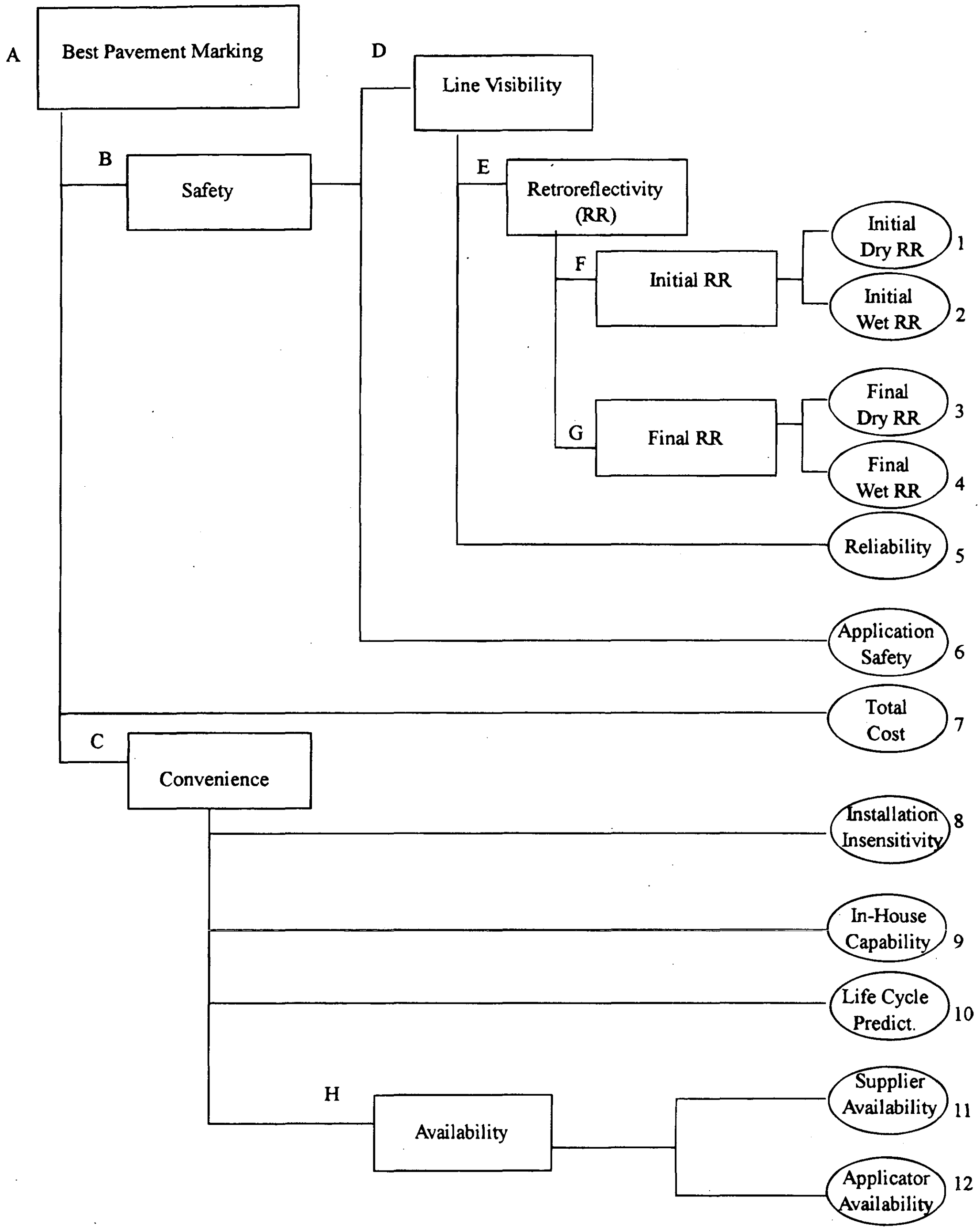

FIGURE 1 Goals hierarchy.

values ranging from 1 to 5 while others use continuous scales based on units such as dollars per meter per year. (The 12 measures in the pavement markings model are discussed later in this paper.)

As a final step in the development of the model, the task force established the weights and single-measure utility functions needed to quantify the model's objective function. With that completed, all of the inputs required for the computer-based model were defined. The model was built using the software package called Logical Decisions for Windows (Logical Decisions, Golden, Colo.).

To help demonstrate the model, an example problem defined by the task force will be used. In this problem, the *application* is lane striping of a six-lane, unilluminated, interstate highway with a 90 km/hr (55 mi/hr) speed limit, an annual average daily traffic (AADT) of 85,000, and a Class 1 surface 12 years old. The application is further defined by noting the existing markings are epoxy and that ConnDOT has full control over the time of application. Recall that an *alternative* is defined by the material and frequency of application. In the example problem, the alternatives under consideration are epoxy applied every year, epoxy applied every 2 years, and preformed plastic applied every 4 years. This example problem is the subject of analysis presented in a software users' guide by Anderson and Braun (*6*).

GOALS HIERARCHY

The goals hierarchy (shown in Figure 1) was developed through close cooperation between the principal investigators and the pavement markings task force. It represents a consensus regarding the criteria that are most important to consider when selecting pavement markings.

The goals at the higher levels of the hierarchy are general and have relatively straight-forward meanings. Sub-goals are more specific, until and at the lowest levels, very specific measurable attributes are defined. Measurement scales and mathematical functions that precisely define each measure and goal are presented later. For now, a more general discussion of the considerations that the various goals and measures are intended to capture is in order.

The safety goal is the more complex of the two goals at the second tier of the hierarchy. The two major components of safety relate to safety during application (Measure 6), and safety after the material has been applied, which is based on the line's visibility (Goal D). Application safety is related to the safety of the traveling public and of workers as pavement markings are being applied.

The other aspect of safety, line visibility (Goal D), is of major importance. This goal relates most directly to the practical function of pavement markings. Under Goal D, the hierarchy shows retroreflectivity (Goal E) and reliability (Measure 5). Broadly speaking, retroreflectivity relates to the visibility of the marking material, given that the material is still on the road. The reliability measure is intended to indicate the likelihood that the marking will remain on the road for the marking's specified life.

There may be a high degree of confidence that the marking will still be on the road at the end of its specified life, but this is only one aspect of the marking's durability. The other key aspect of durability is how visible the marking is at that time. Final retroreflectivity (Goal G) captures this aspect of durability. As mentioned earlier, a pavement marking *alternative* is defined by a marking type and a specified life span. For example, epoxy paint applied every year is a different alternative than epoxy paint applied every 2 years. In terms of the goals hierarchy, these two alternatives would achieve the same score for initial retroreflectivity (Goal F), but their final retroreflectivity measures would certainly be different (as would their costs).

For both initial and final retroreflectivity, dry-pavement and wet-pavement measures are both relevant. [The retroreflectivity measures (1 through 4) are discussed in more detail later in this paper.]

The next major branch of the hierarchy includes the cost measure. The reasons for including cost minimization as a major goal are obvious. Measure 7, total costs, is intended to capture all costs associated with a pavement marking alternative over a 10-year time horizon.

Other considerations that were mentioned by the task force relate to convenience and ease of planning and control. These considerations, which are included under Goal C in the hierarchy, are not as important as the cost and safety concerns, but they do play a role in selecting among pavement marking alternatives, especially when the alternatives are comparable in terms of costs and safety. The four components of the convenience goal are installation insensitivity, in-house capability, life-cycle predictability, and availability. Availability is further broken down into measures reflecting the number of suppliers of the pavement marking material and the number of applicators available to install it. (Each of these aspects of convenience is further discussed later.)

A more detailed discussion of the measures included in the goals hierarchy follows. A more detailed description of how the hierarchy relates to the model's mathematical objective function is provided later.

MEASURES

As far as the MCDM model is concerned, any given pavement marking alternative is completely described by the 12 measures shown at the lowest levels of the goal hierarchy in Figure 1. Given the central role that the measures play in the evaluation of alternatives, it is important that the alternatives be defined as clearly as possible. This section is devoted to a detailed discussion of the 12 measures and their associated measurement scales.

Measures 1 through 4—Retroreflectivity

Measures 1 and 3

Measures 1 and 3 are both dry-pavement retroreflectivities, measured in millicandles per square meter per lux. The advantages of these measures are that they are objective and the measurement scales are well defined. However, the disadvantages are that there may be difficulties associated with obtaining representative values of these measures for specific pavement marking alternatives. For example, it has been noted that the markings' performances can depend on the type of pavement to which it is applied. Procedures for establishing retroreflectivity values must be defined. Possibilities include using published data, taking measurements on a sample of Connecticut roads, or using some combination of sampling and published data.

Measures 2 and 4

Measures 2 and 4 represent pavement marking performance under moderate rainfall conditions. A scale ranging from 1 (barely visible) to 5 (excellent) was developed by ConnDOT for these measures because task force members knew of no standards or published data regarding retroreflectivity measurements under wet conditions. Should a standard technique for measuring wet-pavement retroreflectivities become available, the model can easily be changed to incorporate it into Measures 2 and 4. (This is discussed further in the Conclusion.)

Measure 5—Reliability

The reliability measure is quantified based on the five-point scale ranging from 1 ("ConnDOT has had experience with or strong reason to suspect premature failure.") to 5 ("There is strong evidence that the material has a high probability of lasting for its specified life."). A reliability measure needs to be established only once for any particular pavement marking alternative, and that value will then remain fixed unless new information about the alternative becomes available (e.g., based on additional experience with the material).

Measure 6—Safety

The measure for installation safety will also remain fixed for a given pavement marking alternative. In fact, it is simpler than the reliability measure in that it does not depend on the specified life span of the alternative (which might affect Measure 5).

For Measure 6, the pavement markings task force has proposed the measurement values shown in Table 1. These scores, which are based on ConnDOT's experience with marking types, correspond to specific explanations of different measurement values. **In these scales, higher scores are more desirable.** A discussion of how these ratings are converted to application safety and overall safety utility values through mathematical functions that consider the roadway characteristics of AADT and speed limit is given later in this paper.

The measure for installation safety is based on a five-point scale. As before, a value of 1 on the scale corresponds to the least desirable rating; that is, "Characterized by a combination of two or more constraints of long duration and/or unattached devices, and/or more than one normal lane occupied, and/or application time constraints." Conversely, a value of 5 corresponds to the most desirable rating; that is, "Characterized by short duration, no unattached devices, no more than one lane occupied, and no time constraints."

Measure 7—Costs

The total cost measure is more application-specific than some of the other measures. This cost measure is designed to incorporate all costs associated with the pavement markings that are expected to be incurred over a 10-year time horizon. The costs are broken down into several components, as shown in Table 2. The components are then combined to result in a cost measure that is in units of dollars per meter per year. As with all of the measures, it will be necessary to update the various cost components as new information becomes available.

Measures 8 through 12—Convenience

The five measures that relate to convenience are measured using ConnDOT-developed scales as described below. All of these measures are such that scores need to be defined only once for any particular pavement marking alternative; after that they only need to be updated if new information causes them to change. The task force has established the measurement values shown in Table 1 for two of the five convenience-related measures. It should not be difficult to establish similar tables for Measures 11 and 12.

Measure 8—Installation Insensitivity

This is measured on a five-point scale ranging from 1, "Characterized by being sensitive enough to substantially limit application to controlled conditions." to 5, "Characterized by being relatively insensitive."

Measure 9—In-House Capability

This is the simplest measure because it just requires a yes/no response to indicate whether ConnDOT has the capability to install the pavement marking material itself.

Measure 10—Life-Cycle Predictability

This is measured on a five-point scale ranging from 1, "Considered unpredictable due to past experience or a lack of experience," to 5, "Considered highly predictable."

TABLE 1 Values of Measures 6, 8, and 10 for Various Materials' Marking Types

Marking Type	Measure 6 Installation Safety	Measure 8 Installation Insensitivity	Measure 10 Life-Cycle Predictability
Paint:			
Solvent Based	5	5	5
Water Based	4	4	5
Epoxy	4	4	4
Acrylic	3	3	2
Preformed Plastic:			
Automatic Dispenser	3	1	3
Manual Installation	1	1	3
Thermoplastic:			
Extruded	4	4	2
Sprayed	4	4	2

TABLE 2 Breakdown of Costs (Measure 7) Based on a 10-Year Period

A.	Cost of Materials and Installation[a] for each Application.
B.	Expected Number of Applications in 10 Years.
C.	Maintenance Costs over 10 Years.[a]
D.	Cost of Each Eradication.[a]
E.	Expected Number of Eradications over 10 Years.
F.	Other Costs Incurred over 10 Years.[a]
Measure 7[b] = [(AxB) + C + (DxE) + F] / 10	

[a]$/m
[b]$/m/yr

Measures 11 and 12—Supplier and Applicator Availability

These are both measured on a five-point scale ranging from 1, "very limited," to 5 "plentiful."

Identification of Alternatives and Measure Values

As discussed above, much of the determination of measure values for a given alternative will be a simple matter of looking up measurement values in various tables. The development and updating of these tables, however, require that those most familiar with the pavement marking alternatives exercise careful judgment.

Another area where judgment is important is in the identification of alternatives. It should be noted that the system is set up to help decide among *viable* alternatives. When an alternative is unacceptable for any reason, the user should not enter measurement values for that alternative into the DSS.

Once the 12 measurement values have been entered into the DSS for each viable pavement marking alternative, the DSS can proceed with an analysis of the alternatives. How this analysis is performed is dictated by the form of the model's objective function.

OBJECTIVE FUNCTION

Measurement values for a particular alternative are transformed into an overall score for the alternative through the objective function. This transformation involves two major steps: (a) converting each measurement value into a single-measure utility value and (b) weighting single-measure utility values to obtain multimeasure utility values. (The conversion of measurement values into common units through the use of single-measure utility functions is discussed later in this paper.) For now, take as given that conversions of this type result in the following for each measure:

$$0 \leq SU_y(V_y) \leq 1 \tag{1}$$

where

V_y = the measurement value for the *y*th measure, and
$SU_y(V_y)$ = the single-measure utility value for the *y*th measure, given a measurement value of V_y. (This is abbreviated as SU_y throughout this paper.)

As discussed earlier, a particular pavement marking alternative will have a measurement value for each of the 12 measures included in the goals hierarchy. These will then be converted to utility values (SU_1 through SU_{12}) through single-measure utility functions, which need to be defined only once.

Multimeasure Utility Values

This next section focuses on how the single-measure utility values are combined to obtain multimeasure utility values. Multimeasure utility values are best explained by referring to the structure of the goals hierarchy. Consider, first of all, the goal of initial retroreflectivity (IRR), which is labeled Goal F in Figure 1. Given single-measure utility values for Measures 1 and 2 (dry IRR and wet IRR, respectively), the multimeasure utility associated with IRR is obtained as follows:

$$MU_F = W_1 SU_1 + W_2 SU_2 \tag{2}$$

where

MU_F = the multimeasure utility value associated with Goal F,
W_y = the weight given to the utility score for measure (or goal) *y*, and
$(W_1 + W_2) = 1$.

The weights W_1 and W_2 were established based on the task force's collective judgment regarding the relative importance of the dry-surface and wet-surface retroreflectivities. These weights remain fixed within the model.

A similar multimeasure utility function is established for Goal G (final-month retroreflectivity) as follows:

$$MU_G = W_3 SU_3 + W_4 SU_4 \tag{3}$$

where $W_3 + W_4 = 1$.

The utility scores for Goals F and G are then combined to obtain a utility score for Goal E as follows:

$$MU_E = W_F MU_F + W_G MU_G \tag{4}$$

where $W_F + W_G = 1$.

Note that Equations 2 and 3 could be substituted into Equation 4 to obtain Goal E's multimeasure utility in terms of a series of single-measure utility values and associated weights. This can be done for any goal to obtain its multimeasure utility function in terms of the measures that appear beneath it in the goals hierarchy.

The multimeasure utility function for Goal D, line visibility, is as follows:

$$MU_D = W_E MU_E + W_5 SU_5 \tag{5}$$

where $W_E + W_5 = 1$.

Measure 6, application safety, has a slightly different functional form, which is introduced as follows:

$$SU_6(\text{Adjusted}) = A_6 SU_6 \quad (6)$$

where A_6 is an "adjustment factor," defined as follows:

A_6 = (expected number of years between installations)/6.

This adjustment factor, which will have values ranging between 0 and 1, is introduced to account for the frequency of installation. Its effect is to make alternatives that require frequent reapplication appear less desirable.

Goal B, overall safety, which is another adjustment factor, is introduced as follows:

$$MU_B = A_S(W_D MU_D + W_6 SU_6) \quad (7)$$

where

$W_D + W_6 = 1$, and
$A_S = .5 \times$ (AADT of roadway/100,000) + $.5 \times$ (speed safety adjustment factor).

A_s, the "safety adjustment factor," is introduced to account for the traffic volume and speed limit of the roadway. This acknowledges that safety should be more heavily weighted when there are higher traffic volumes and/or higher speed limits. The Speed Safety Adjustment Factor (which has values ranging from 0 to 1) is defined as a function of roadway speed limit and is described later.

The branch of the hierarchy dealing with costs is relatively straightforward because cost utility functions are generally linear. Assuming a maximum cost of \$3.28/m/yr (\$1/ft/yr) for any pavement marking alternative, the following single-measure utility function is defined:

$$SU_7 = 3.28 - V_7 \quad (8)$$

[The cost measurement (V_7) is the only measurement in the hierarchy for which higher values are less desirable. Consequently, Equation 8 is such that lower costs result in higher utility values.]

The last major branch of the goals hierarchy is that under Goal C, convenience. The multimeasure utility function for convenience is as follows:

$$MU_C = W_8 SU_8 + W_9 SU_9 + W_{10} SU_{10} + W_H MU_H \quad (9)$$

where $W_8 + W_9 + W_{10} + W_{11} = 1$.

Note that the single-measure utility value for Measure 9, in-house capability, equals either 0 or 1. This corresponds to the yes/no nature of that measure.

Goal H, availability, requires further explanation. The two components of the availability goal combine as follows:

$$MU_H = SU_{11} \times SU_{12} \quad (10)$$

This multimeasure utility function is a multiplicative function of the two component single-measure utility functions. This functional form is appropriate because low scores on either supplier availability or applicator availability could result in inconvenience, even if the other measure is at a high level.

The only goal in the hierarchy for which a multimeasure utility function has yet to be defined is the overall goal of finding the best pavement marking alternative. The overall utility score for an alternative is calculated as follows:

$$MU_A = W_B MU_B + W_7 SUW_7 + W_C MU_C \quad (11)$$

where $W_B + W_7 + W_C = 1$.

Using Equations 2 through 10, Equation 11 could be expanded into a function of the measures (1 through 12), the roadway's AADT and speed limit, and the marking's expected time between applications.

WEIGHTS AND UTILITY FUNCTIONS

To complete the objective function discussed here, the weights (W_y) and the single-measure utility functions (SU_y) need to be defined.

Weights

Weights are used to quantify the way utilities associated with subgoals or measures are to be combined to form multimeasure utility values for goals. For example, Equation 2 states that the multimeasure utility value for initial retroreflectivity (Goal F) is obtained by adding (a) W_1 multiplied by the single-measure utility value associated with Measure 1 and (b) W_2 multiplied by the single-measure utility value associated with Measure 2. The weights W_1 and W_2 must sum to 1. Because both SU_1 and SU_2 have values between 0 and 1, MU_F will also range between 0 and 1. This will be true for all single-measure and multimeasure utility values.

The following seven sets of weights had to be defined for the model's objective function:

$$W_1 + W_2 = 1 \quad (12)$$

$$W_3 + W_4 = 1 \quad (13)$$

$$W_F + W_G = 1 \quad (14)$$

$$W_E + W_5 = 1 \quad (15)$$

$$W_D + W_6 = 1 \quad (16)$$

$$W_8 + W_9 + W_{10} + W_H = 1 \quad (17)$$

$$W_B + W_7 + W_C = 1 \quad (18)$$

Note that these equations correspond directly to the way that branches in the goals hierarchy merge together when moving from bottom to top. The only exception is the combination of Measures 11 and 12, which combine in a multiplicative rather than an additive manner, as shown in Equation 10.

The seven sets of weights needed for the model were established by the pavement markings task force.

Single-Measure Utility Functions

For each of the 12 measures shown in the goals hierarchy, a function had to be defined to convert measurement values into common units of utility. Utility is a measure of desirability. The utility scale for each measure has a range from 0 to 1, with 1 being the most preferred. Thus, a utility of 0 must always be assigned to the least preferred level of a measure and a utility of 1 to the most preferred level of a measure.

While the extreme values of all measures are known to have utilities of 0 and 1, the utility values corresponding to intermediate measurement values must be further defined. The correspondence between measurement values and utility values is described by a single-measure utility function.

Single-Measure Utility Functions for the Pavement Markings Problem

Single-measure utility functions had to be defined for each of the measures in the pavement markings model. There is, however, one measure for which a utility function was obvious. For Measure 9, in-house capability, a "yes" simply corresponds to a utility of 1, and a "no" results in a utility of 0. Utility functions for the other 11 measures are shown in Figures 2 through 7. Note that each of these functions is piecewise linear, and the line segment endpoints that define the functions are shown on the figures. These functions are all based on the inputs of the pavement markings task force.

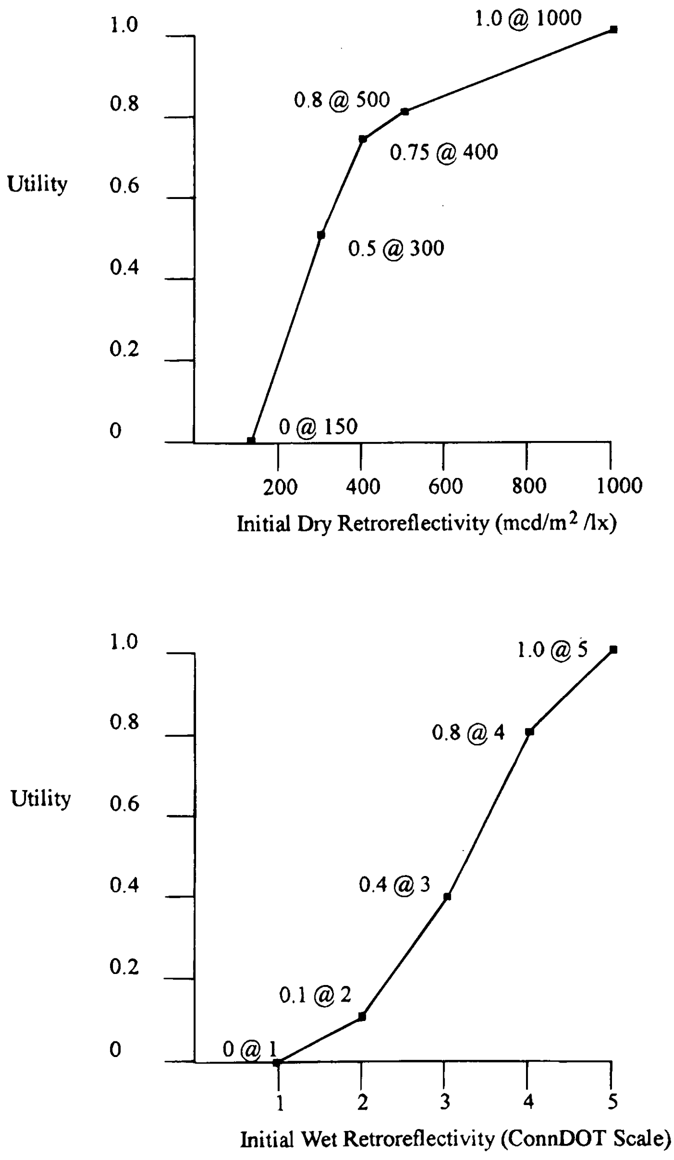

FIGURE 2 Single measure utility functions for initial retroreflectivity: (*top*) dry; (*bottom*) wet,

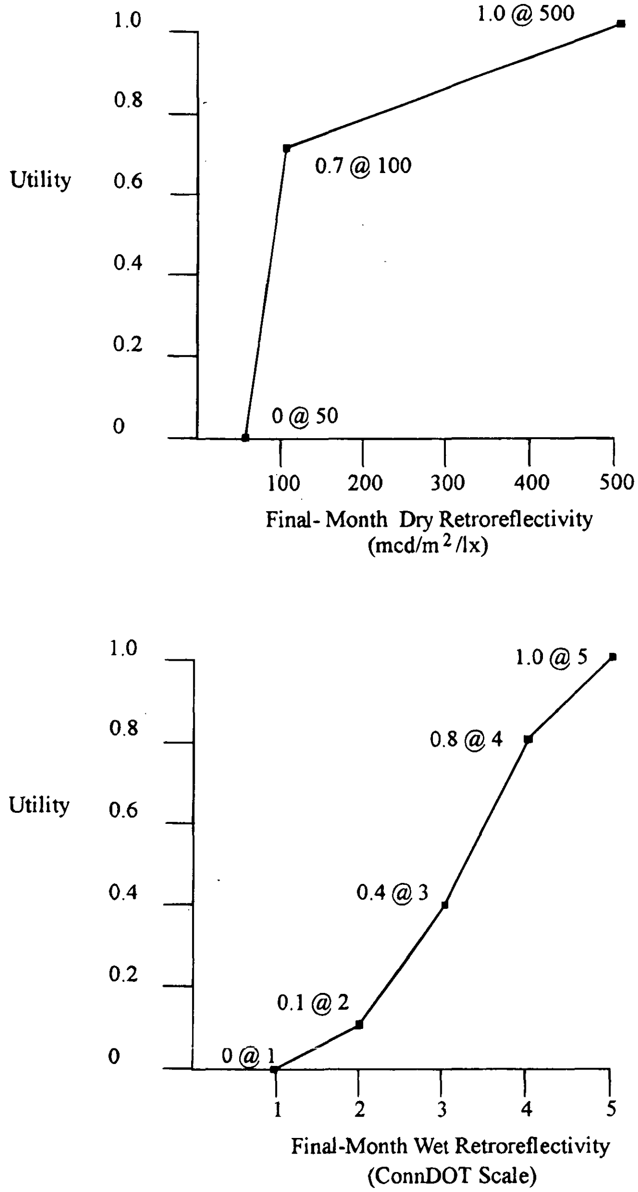

FIGURE 3 Single measure utility functions for final-month retroreflectivity: *(top)* dry; *(bottom)* wet.

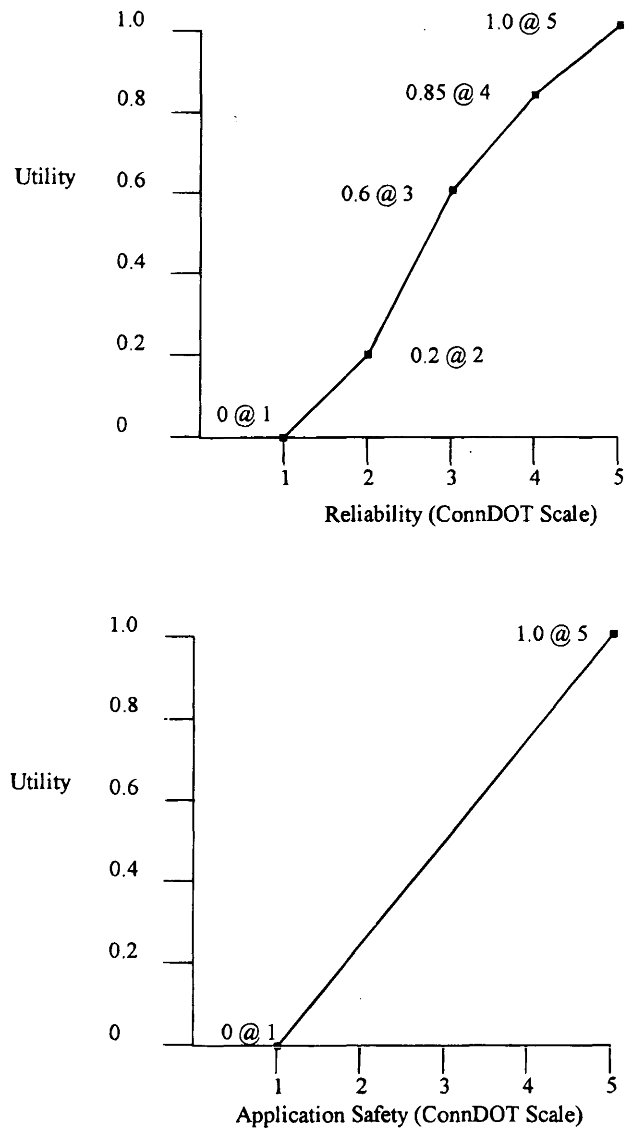

FIGURE 4 Single measure utility functions for *(top)* reliability; *(bottom)* application safety.

Speed Safety Adjustment Factor

Another mathematical relationship that had to be defined for the model is how the speed limit of a roadway relates to the speed safety adjustment factor, which is included in the multimeasure utility function for the safety goal (as shown in Equation 7). This relationship is shown at the bottom of Figure 7 (*b*). As with the utility functions, the function shown was defined by the pavement markings task force.

With the 12 functions and the 7 sets of weights defined, the model's specification is now complete. Pavement marking alternatives can be evaluated using the model, as long as 12 measurement values are available for each alternative.

SUMMARY AND CONCLUSIONS

This paper has presented the details of a multicriteria decision making model for choosing among pavement marking alternatives. The model development process has been outlined, the goals hierarchy has been presented and discussed, and the mathematical details of the model have been reported. The model has been entered into the software package called Logical Decisions for Windows, resulting in a PC-based decision support system that is ready for ConnDOT to use.

The model described in this paper and programmed into the DSS is changeable. By changing certain aspects of the base model, a knowledgeable user might be able to gain insight into a pavement

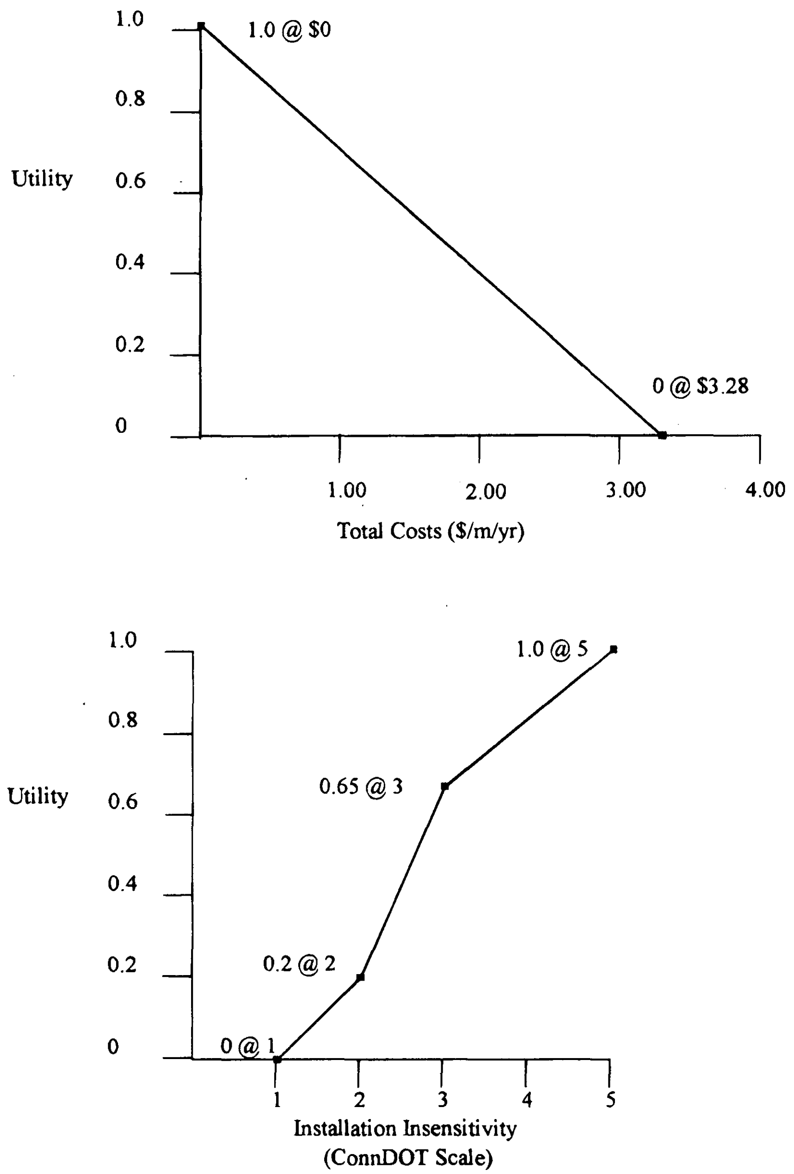

FIGURE 5 Single measure utility functions for (*top*) total costs; and (*bottom*) installation insensitivity.

marking selection problem that could not be obtained just by using the standard sensitivity analysis features provided by the software. Also, as new information and measurement techniques become available, it might be desirable to make permanent changes to the base model itself. For example, should standard techniques be established for measuring retroreflectivities under wet-pavement conditions, changes could be made to the scales and utility functions for Measures 2 and 4 within the model.

The process of developing the DSS has provided much insight into the pavement markings selection problem. By keeping the DSS's model up-to-date, the results of this project can be taken advantage of for years to come. ConnDOT has made a policy decision to begin using the DSS described in this paper for its next round of markings selection.

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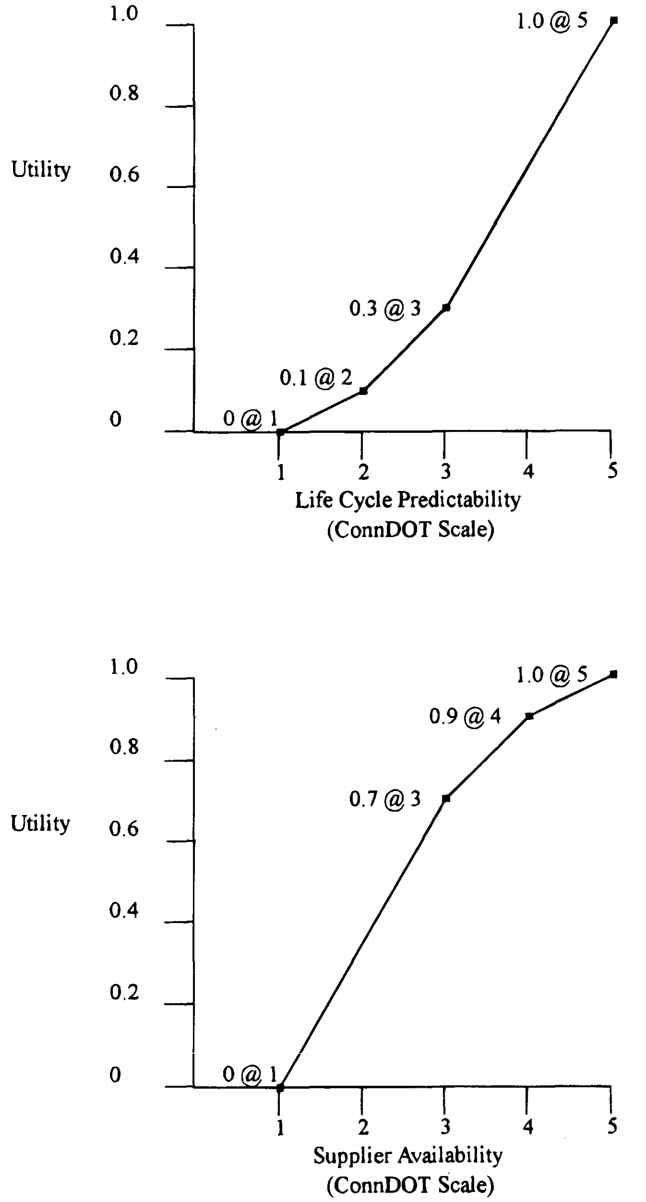

FIGURE 6 Single measure utility functions for (*top*) life-cycle predictability; and (*bottom*) supplier availability.

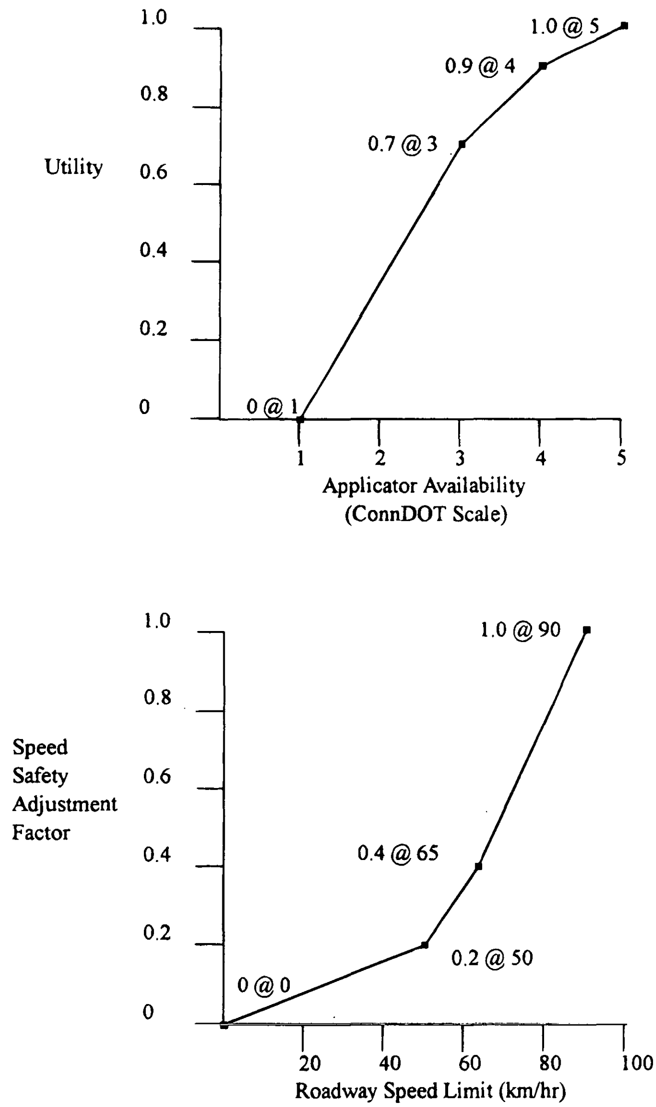

FIGURE 7 Single measure utility function for (*top*) applicator availability; and (*bottom*) speed safety adjustment factor.

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