# APPLYING MULTI-CRITERIA DECISION MAKING TO THE SELECTION OF PAVEMENT MARKINGS

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16. Abstract

This report describes a decision support system (DSS) that has been developed to aid in the selection of pavement marking materials. The DSS is based on multi-criteria 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 has been incorporated into a computer-based model using off-the-shelf personal computer software.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | LENGTH | | |
| in | inches | 25.4 | millimetres | mm |
| ft | feet | 0.305 | metres | m |
| yd | yards | 0.914 | metres | m |
| mi | miles | 1.61 | kilometres | km |
| | | AREA | | |
| $in^2$ | square inches | 645.2 | millimetres squared | $mm^2$ |
| $ft^2$ | square feet | 0.093 | metres squared | $m^2$ |
| $yd^2$ | square yards | 0.836 | metres squared | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | kilometres squared | $km^2$ |
| | | VOLUME | | |
| fl oz | fluid ounces | 29.57 | mililitres | mL |
| gal | gallons | 3.785 | Litres | L |
| $ft^3$ | cubic feet | 0.028 | metres cubed | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | metres cubed | $m^3$ |

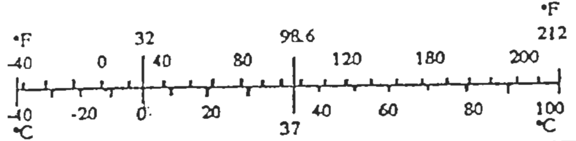
NOTE: Volumes greator than 1000 L shall be shown in $m^3$.

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | MASS | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | TEMPERATURE (exact) | | |
| °F | Fahrenheit temperature | 5(F-32)/9 | Celcius temperature | °C |

*SI is the symbol for the International System of Measurement

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | LENGTH | | |
| mm | millimetres | 0.039 | inches | in |
| m | metres | 3.28 | feet | ft |
| m | metres | 1.09 | yards | yd |
| km | kilometres | 0.621 | miles | mi |
| | | AREA | | |
| $mm^2$ | millimetres squared | 0.0016 | square inches | $in^2$ |
| $m^2$ | metres squared | 10.764 | square feet | $ft^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | kilometres squared | 0.386 | square miles | $mi^2$ |
| | | VOLUME | | |
| mL | millilitres | 0.034 | fluid ounces | fl oz |
| L | litres | 0.264 | gallons | gal |
| $m^3$ | metres cubed | 35.315 | cubic feet | $ft^3$ |
| $m^3$ | metres cubed | 1.308 | cubic yards | $yd^3$ |
| | | MASS | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.205 | pounds | lb |
| Mg | megagrams | 1.102 | short tons (2000 lb) | T |
| | | TEMPERATURE (exact) | | |
| °C | Celcius temperature | 1.8C + 32 | Fahrenheit temperature | °F |



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# SYMBOLS AND DEFINITIONS

**Alternatives** are objects to be ranked (i.e., different pavement markings and their expected life spans).

**Measures** are quantitative variables that describe alternatives.

**Goals** are containers that hold measures and other goals. Goals are not quantified directly. An alternative's performance on the measures underneath a goal are used to infer its performance on the goal itself. Goals and measures are organized into a **goals hierarchy**, which has a structure resembling that of an organization chart.

**$V_y$** is the measurement value associated with the yth measure.

**Single-measure Utility Function** is a mathematical function that converts a measurement value into a **utility**, which is a common unit of measure used across all measures and goals. Utility scores always range from zero to one, with one being most desirable.

**$SU_y(V_y)$** is the single-measure utility function value for the yth measure, given a measurement value of $V_y$. This is abbreviated as $SU_y$.

**Multi-measure Utility Function** is a mathematical function that combines measures to obtain an overall utility value for a goal.

**$MU_Z$** is the multi-measure utility function value for goal Z.

**$W_y$** is the weight given to the utility of goal or measure y.

**DSS** is an abbreviation for decision support system.

**MCDM** is an abbreviation for multi-criteria decision making.

# I. INTRODUCTION

## Background

Currently, ConnDOT employs various chemical marking systems to provide route guidance and safety information to motorists. These systems vary from reflectorized painted lines to thermoplastic and epoxy systems. Recently, new types of plastics have made inroads into the pavement markings market. Each of these systems has unique placement and performance requirements and characteristics, with significantly different costs.

There are numerous criteria that must be considered when selecting a pavement marking alternative for a given application (i.e., a given stretch of roadway). These include safety, durability, ease of application, as well as costs. The primary objective of the project described in this report has been to develop a decision support system (DSS) that will consider the relevant multiple criteria in a systematic way.

For the purposes of this project, a useful definition of a DSS is as follows:

> A decision support system is a computer-based, interactive system that is designed to assist decision makers, rather than replacing them.

The pavement markings DSS is not a system that makes decisions on its own. Human judgement is still required because there are always considerations that cannot be adequately incorporated into a computer-based model.

To clarify the way in which the pavement markings DSS is intended to be used, the following policy statement is proposed:

### Draft Policy on Highway Pavement Markings

To insure the safety and proper guidance of the motoring public, the Department shall utilize pavement markings on state highways. The selection of pavement marking materials for any given application will be based on consideration of all relevant factors, with safety and cost-effectiveness being primary concerns.

The Pavement Markings Decision Support System provides a computer-based model that incorporates multiple criteria relevant to the selection of pavement markings. This system shall be used to assist decision makers in selecting marking materials for specific applications.

Again, it should be emphasized that the system is intended to assist decision makers, not to replace them. For the DSS to be used to its full advantage, the underlying multi-criteria decision making (MCDM) model should be well-understood by the user of the DSS. Fortunately, MCDM concepts are not complex. As far as mathematics is concerned, MCDM requires only a knowledge of basic algebra. Keeney and Raiffa (1993) provide a comprehensive presentation of MCDM, including descriptions of numerous applications.

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 simple model with two criteria -- cost-effectiveness and safety, with each criterion being measured on a scale ranging from zero to one. Assume that these scales are in units of "utility," which is a measure of desirability. To complete the specification of this simple model, weights associated with the two criteria need to be defined. For example, cost-effectiveness could be given a weight of 0.3, and safety a weight of 0.7. The two single-measure utilities that an alternative receives for the two criteria are multiplied by the associated weights, and the results are 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 measurements are made using scales that do not translate to utility in a linear manner, as discussed later in this report. However, the basic idea of weighting the various criteria remains essentially the same for other applications (such as the pavement marking problem) that are richer than the simple example described above.

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. The next subsection summarizes the interactions that have occurred to obtain inputs needed for the development of the pavement markings selection model.

### Outline of Model Development Process

The process of developing the pavement markings MCDM model has been an iterative one. Initially, in January of 1994, a meeting was held between the principal investigators (PIs) and all ConnDOT task force members. This was followed in February by subsequent meetings between the PIs 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. Further refinements continued to be made to the hierarchy through September of 1994, resulting in the current goals hierarchy shown in Appendix A.

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 Appendix A includes twelve measures, and for each of these a scale has been defined. Some of the scales use discrete values ranging from one to five, while others use continuous scales based on units such as $/foot/year. The twelve measures in the pavement markings model are discussed further in Section III of this report.

As one of the final steps 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 a software package called "Logical Decisions for Windows" (Logical Decisions, Golden, Colorado).

The first version of the completed model was documented in a draft final report that was circulated amongst ConnDOT personnel in August of 1994. Appendix C describes how the model was refined in response to ConnDOT comments regarding the earlier version of the model.

To help demonstrate the model, an example problem defined by the task force has been used. This example problem, which is shown in Table 1, is the subject of analysis presented in a software Users Guide (Anderson and Braun 1994) that has been prepared for this project as a separate document. The Users Guide provides details regarding how to input data and analyze alternatives using the p.c.-based software that has been used to program the model described in this report.

Table 1. Example problem defined by the task force

Application:

line striping / lane line
interstate highway, 55 m.p.h.
3 lanes in each direction
ADT = 85,000
class 1 surface, 12 years old
unilluminated
existing markings = epoxy
ConnDOT has full control over time of application

Alternatives

epoxy every 1 year
epoxy every 2 years
preformed plastic every 4 years

Scope and Organization of the Report

This working report describes the MCDM model that has been developed and incorporated into the pavement markings DSS. Sections II and III describe the goals hierarchy and the measures, respectively, in further detail. Section IV then discusses the form of the objective function, which specifies the way in which quantitative measures combine to result in an overall "score" for a pavement marking alternative. Section V presents details regarding weights and single-measure utility functions that are part of the mathematical model. Section VI concludes the report by providing some thoughts regarding the use of the DSS.

## II. THE GOALS HIERARCHY

The goals hierarchy shown in Appendix A has been developed through close cooperation between the principal investigators and the pavement markings task force, as discussed earlier. The goals hierarchy 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 straightforward meanings. As one moves down the hierarchy, sub-goals get more specific until, at the lowest levels, very specific measurable attributes are defined. In Sections III, IV and V, measurement scales and mathematical functions that precisely define each measure and goal are presented. This section provides a more general discussion of the considerations that the various goals and measures are intended to capture.

The safety goal is the most complex of the three 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 incorporates considerations related to the safety of the travelling 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. Note that 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 two years (as indicated in Table 1). 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 further detail in Section IV.

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 ten-year time horizon. Since task force members have indicated that the availability of alternative funding sources can affect the selection of marking materials, it may make sense to run the model multiple times using costs based on different funding scenarios. The components of total cost are further detailed in the next section. For discussion purposes here, let us take for granted that measure 7 captures all relevant costs.

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 amongst 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 in Section III.

This section has provided a general discussion of the goals hierarchy shown in Appendix A. A more detailed description of how the hierarchy relates to the model's mathematical objective function is provided in Section IV. But before this objective function can be described, a more detailed discussion of the twelve measures included in the goals hierarchy is in order.

## III. MEASURES

As far as the MCDM model is concerned, any given pavement marking alternative is completely described by the twelve measures shown at the lowest levels of the goal hierarchy in Appendix A. The higher-level goals are essentially just functions of some or all of the twelve measurement values (and, in some cases, the ADT and speed limit of the roadway and expected time between applications). Given the central role that the measures play in the evaluation of alternatives, it is important that they be spelled out as clearly as possible. This section is devoted to a detailed discussion of the twelve measures and their associated measurement scales.

Appendix B presents a "Pavement Marking Evaluation Checklist," which has been designed to be used as a tool for documenting measurement values for each pavement marking alternative. Once this form has been filled in for a particular pavement marking alternative, it will be a simple matter to enter the information into the DSS so that the alternative can be compared against others (each of which would have their own filled-in form).

The first section of the checklist shown in Appendix B requests information about the roadway to be marked. The speed limit and ADT are needed for "adjustment factors" that are incorporated into the objective function (as discussed in Section IV). The pavement type is important to know because retroreflectivity readings for a pavement marking could be a function of pavement type. Note that the data describing the application (i.e. stretch of roadway) is going to be the same on all checklists for the pavement marking alternatives being considered for that application.

The next section of the checklist asks for a description of the pavement marking alternative. It is important for the expected number of years between applications to be specified because the model has been set up to treat different life-spans as different alternatives, even if the marking type is exactly the same. The life-span is also considered when establishing values for the cost measure.

### Measures 1 through 4 -- Retroreflectivity

Measures 1 and 3 are both dry-pavement retroreflectivities, measured in millicandles per square meter per lux. They have advantages in that they are objective and the measurement scales are well-defined. However, there are disadvantages in 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. Within ConnDOT, plans are currently underway to evaluate pavement marking materials placed on Connecticut highways during the summer of 1994. This field study will continue until the materials have served their useful lives. The data resulting from this study is likely to be useful for defining retroreflectivity measurement values for pavement marking alternatives.

Measures 2 and 4 represent pavement marking performance under moderate rainfall conditions. A scale has been 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 section of this report.

Measure 5 -- Reliability

The reliability measure is quantified based on the five-point scale shown in Appendix B. A reliability measure only needs to be established 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).

Measures 6 -- Application Safety

The measure for application 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 below.

| Marking Type | Measure 6 Application Safety |
|---|---|
| **Paint** - Solvent Based | 5 |
| - Water Based w/o Lead | 4 |
| - Epoxy | 4 |
| - Acrylic | 3 |
| **Preformed Plastic:** | |
| - Automatic Dispenser | 3 |
| - Manual Installation | 1 |
| **Thermoplastic:** | |
| - Extruded | 4 |
| - Sprayed | 4 |

These scores, which are based on ConnDOT's experience with the marking types, correspond to the explanations of the different measurement values shown in Appendix B. **Note that, in these scales, higher scores are more desirable.** Section IV includes a discussion of how these ratings are converted to application safety utility values through a mathematical function that considers time interval between installations. To fill out the checklist in Appendix B for measure 6, one can simply look up the measurement value for the given marking type in a table such as that shown above.

Measure 7 -- Total 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 ten-year time horizon. The costs are broken down into several components, as shown in Appendix B. The components are then combined to result in a cost measure that is in units of dollars per linear foot per year. As with all of the measures, it will be necessary to update the various cost components as new information becomes available. As mentioned in the previous section, alternative funding sources may affect the various cost components, depending on how the DSS users consider them.

Measures 8 through 12 -- Convenience

The five measures that relate to convenience are measured using the ConnDOT-developed scales shown in Appendix B. Measure 9, in-house capability, is the simplest because it just requires a yes/no response to indicate whether or not ConnDOT has the capability of installing the pavement marking material themselves. Each of the other four convenience-related measures uses a five-point scale. As with all other measures except costs, higher scores on the convenience measures are more desirable. The details of the five-point scale for each of the four measures (8, 10, 11 and 12) are spelled out in Appendix B. All of these measures are such that scores only need to be defined 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 below for two of the five convenience-related measures. It should not be difficult to establish similar tables for measures 11 and 12.

| Marking Type | Measure 8 Installation Insensitivity | Measure 10 Life-cycle Predictability |
|---|---|---|
| **Paint** - Solvent Based | 5 | 5 |
| - Water Based w/o Lead | 4 | 5 |
| - Epoxy | 4 | 4 |
| - Acrylic | 3 | 2 |
| **Preformed Plastic:** | | |
| - Automatic Dispenser | 1 | 3 |
| - Manual Installation | 1 | 3 |
| **Thermoplastic:** | | |
| - Extruded | 4 | 2 |
| - Sprayed | 4 | 2 |

As discussed above, much of filling out the checklist shown in Appendix B 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, requires that careful judgement be exercised by those most familiar with the pavement marking alternatives.

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

Once twelve measurement values have been entered into the DSS for each viable pavement marking alternative, then the DSS can proceed with an analysis of the alternatives. The way that this analysis is performed is dictated by the form of the model's objective function, which is described in the next section.

## IV. THE 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: 1) converting each measurement value into a single-measure utility value; and 2) weighting single-measure utility values to obtain multi-measure utility values.

The conversion of measurement values into common units through the use of single-measure utility functions is discussed later on. For now, let us take as given that conversions of this type result in the following for each measure:

$$0 \leq SU_y(V_y) \leq 1$$

where: $V_y$ is the measurement value for the yth measure; and $SU_y(V_y)$ is the single-measure utility value for the yth measure, given a measurement value of $V_y$. (This is abbreviated as $SU_y$ throughout this report.)

As discussed in Section III, a particular pavement marking alternative will have a measurement value for each of the twelve 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 only need to be defined once. Discussion of how the single-measure utility functions are defined is postponed until Section V. For now, we will focus on how the single-measure utility values are combined to obtain multi-measure utility values.

Multi-measure 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 labelled goal F in Appendix A. Given single-measure utility values for measures 1 and 2 (dry IRR and wet IRR, respectively), the multi-measure utility associated with IRR is obtained as follows:

$$MU_F = W_1SU_1 + W_2SU_2 \tag{1}$$

where: $MU_F$ is the multi-measure utility value associated with goal F; $W_y$ is the weight given to the utility score for measure (or goal) y; and $(W_1 + W_2) = 1$.

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

A similar multi-measure utility function is established for goal G (final-month retroreflectivity), as follows:

$$MU_G = W_3SU_3 + W_4SU_4 \tag{2}$$

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:

$$MU_E = W_FMU_F + W_GMU_G \tag{3}$$

where: $W_F + W_G = 1$.

Note that equations (1) and (2) could be substituted into (3) to obtain goal E's multi-measure utility in terms of a series of single-measure utility values and associated weights. This can be done for any goal to obtain its multi-measure utility function in terms of the measures that appear beneath it in the goals hierarchy.

Continuing up the hierarchy to goal D, line visibility, its multi-measure utility function is as follows:

$$MU_D = W_EMU_E + W_5SU_5 \tag{4}$$

where: $W_E + W_5 = 1$.

Moving over in the hierarchy to measure 6, application safety, we introduce a slightly different functional form, as follows:

$$SU_6(\text{adjusted}) = A_6SU_6 \tag{5}$$

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

$$A_6 = \text{(expected number of years between installations) / 6.}$$

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

Moving up the hierarchy to goal B, overall safety, another adjustment factor is introduced, as follows:

$$MU_B = A_S[W_D MU_D + W_6 SU_6(\text{adjusted})] \qquad (6)$$

where: $W_D + W_6 = 1$; and

$$A_S = .5 \times (\text{ADT of roadway} / 100{,}000) + .5 \times (\text{Speed Safety Adjustment Factor}).$$

$A_S$, the "safety adjustment factor" is introduced to account for the traffic density 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 zero to one) is defined as a function of roadway speed limit in Section V.

The branch of the hierarchy dealing with costs is relatively straightforward because cost utility functions are generally linear. Assuming a maximum cost of \$ 1.00/lin.ft./yr. for any pavement marking alternative, the following single-measure utility function is defined:

$$SU_7 = 1 - V_7 \qquad (7)$$

**The cost measurement, $V_7$, is the only measurement in the hierarchy for which higher values are less desirable.** Consequently, equation (7) 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 multi-measure utility function for convenience is as follows:

$$MU_C = W_8 SU_8 + W_9 SU_9 + W_{10} SU_{10} + W_H MU_H \qquad (8)$$

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

Note that the single-measure utility value for measure 9, in-house capability, is equal to either zero or one. 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:

$$MU_H = SU_{11} \times SU_{12} \quad (9)$$

This multi-measure 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 multi-measure 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:

$$MU_A = W_B MU_B + W_7 SU_7 + W_C MU_C \quad (10)$$

where: $W_B + W_7 + W_C = 1$.

Using equations (1) - (9), equation (10) could be expanded into a function of the measures (1 through 12), the roadway's ADT and speed limit, and the marking's expected time between applications. Therefore, it is only the information elicited by the checklist included as Appendix B that needs to be specified for each individual pavement marking alternative, as discussed in Section III.

The focus of this report will now turn to the details of the weights and single-measure utility functions referred to above.

## V. WEIGHTS AND UTILITY FUNCTIONS

To complete the objective function discussed in the previous section, the weights ($W_y$) and the single-measure utility functions ($SU_y$) need to be defined. These are discussed individually below.

### Weights

Weights are used to quantify the way that utilities associated with subgoals or measures are to be combined to form multi-measure utility values for goals. For example, equation (1) states that the multi-measure utility value for initial retroreflectivity (goal F) is obtained by taking $W_1$ times the single-measure utility value associated with measure 1 plus $W_2$ times the single-measure utility value associated with measure 2. The weights $W_1$ and $W_2$ must sum to one. Since $SU_1$ and $SU_2$ each have values between zero and one, $MU_F$ will also range between zero and one. This will be true for all single-measure and multi-measure utility values.

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

$$W_1 + W_2 = 1$$

$$W_3 + W_4 = 1$$

$$W_F + W_G = 1$$

$$W_E + W_5 = 1$$

$$W_D + W_6 = 1$$

$$W_8 + W_9 + W_{10} + W_H = 1$$

$$W_B + W_7 + W_C = 1.$$

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 (9).

The seven sets of weights needed for the model were established by the pavement markings task force. The weights are shown in Table 2.

Table 2. Weights established by the task force.

$W_1$ = .44 $W_2$ = .56

$W_3$ = .44 $W_4$ = .56

$W_F$ = .41 $W_G$ = .59

$W_E$ = .60 $W_5$ = .40

$W_D$ = .66 $W_6$ = .34

$W_8$ = .31 $W_9$ = .18 $W_{10}$ = .24 $W_H$ = .27

$W_B$ = .41 $W_7$ = .40 $W_C$ = .19

To obtain the "overall weight" of a given measure at the lowest level of the hierarchy, the weights for all goals above the measure are multiplied together. This results in the overall weights shown in Table 3.

Table 3. Overall weights for the twelve measures.

Measure 1. Initial Dry RR.--.41x.66x.60x.41x.44 = .029

Measure 2. Initial Wet RR.--.41x.66x.60x.41x.56 = .037

Measure 3. Final Dry RR. --.41x.66x.60x.59x.44 = .042

Measure 4. Final Wet RR. --.41x.66x.60x.59x.56 = .054

Measure 5. Reliability. -- .41x.66x.40 = .108

Measure 6. Application Safety. -- .41x.34 = .139

Measure 7. Total Costs. -- .400

Measure 8. Installation Insensitivity --.19x.31 = .059

Measure 9. In-house Capability. -- .10x.18 = .034

Measure 10. Life Cycle Predictability --.19x.24 = .046

Measure 11. Supplier Availability
.19x.27 = .051*
Measure 12. Applicator Availability

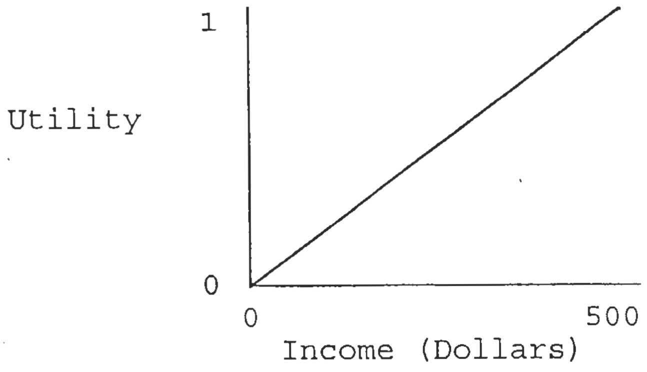
* this weight is shared by measures 11 and 12 through a multiplicative interaction.

## Single-Measure Utility Functions

For each of the twelve 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 zero to one, with one being the most preferred. Thus, we always assign a utility of zero to the least preferred level of a measure and a utility of one for the most preferred level of a measure.

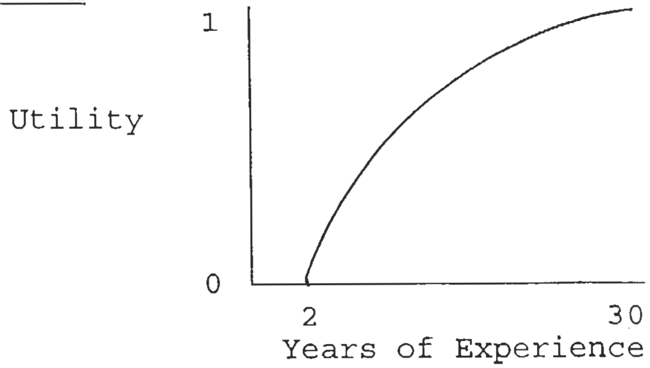
While we know that the extreme values of all measures have utilities of zero and one, the utility values corresponding to intermediate measurement values must be further defined. The correspondence between measurement values and utility values is described by a single-measure utility function. For discussion purposes, let us consider four general shapes of utility curves: 1) straight line; 2) concave down; 3) concave up; and 4) s-curve.

Straight Line



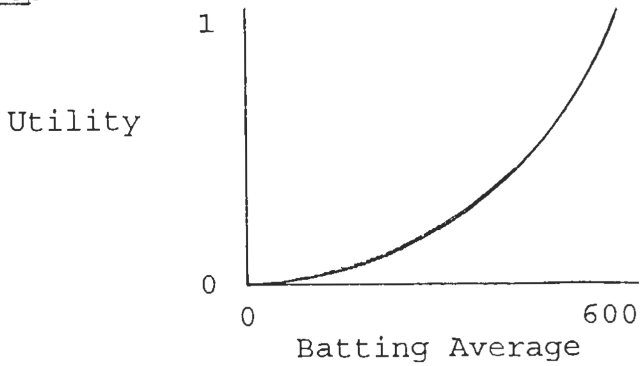
With a straight line utility curve, conversion is very easy since it assumes that equal increments of utility are associated with all levels of the measured value. This type of curve would be appropriate, for instance, if the measured values were in dollars.

Concave Down



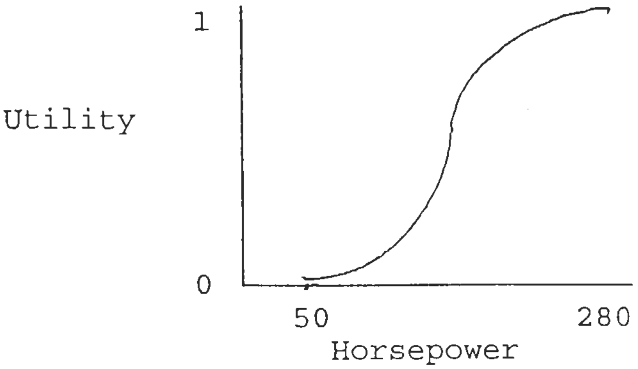
In the concave down utility curve, increments of utility at lower levels of the measured value are greater than those at higher levels. This type of curve might be appropriate for, say, evaluating years of experience when hiring a new employee.

Concave Up



In the concave up utility curve, increments of utility at higher levels of the measured value are greater than those at lower levels. This type of curve might be appropriate for, say, evaluating the performance of an athlete. Increases in utility associated with a barely competent amateur might be relatively small compared to increases approaching the "superstar" category.

<u>S-Shaped</u>



The S-shaped curve consists of a combination of concave up and concave down curves. In essence, such a curve reflects two sets of relationships. For example, suppose the measured value is the horsepower of an automobile. The concave up range might indicate increasing increments of utility as the horsepower rises from that just barely acceptable to power the vehicle, to a range where performance becomes quite important. This is followed by the concave down branch wherein increments of utility decrease as a range of power that cannot realistically be used is reached.

While the discussion above has been in terms of hypothetical examples, we must define such functions for each of the measures in the pavement markings model. There is, however, one measure for which a utility function does not need to be further defined. For measure 9, in-house capability, a "yes" simply corresponds to a utility of one and a "no" results in a utility of zero. Utility functions for the other eleven measures are shown in Figures 1 - 11. Note that each of these functions is piece-wise linear, and the line segment endpoints that define the functions are shown on the figures. These functions are based on the inputs of the pavement markings task force.

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 multi-measure utility function for the safety goal (as shown in equation 6). This relationship is shown in Figure 12. As with the utility functions, the function shown in Figure 12 was defined by the pavement markings task force.

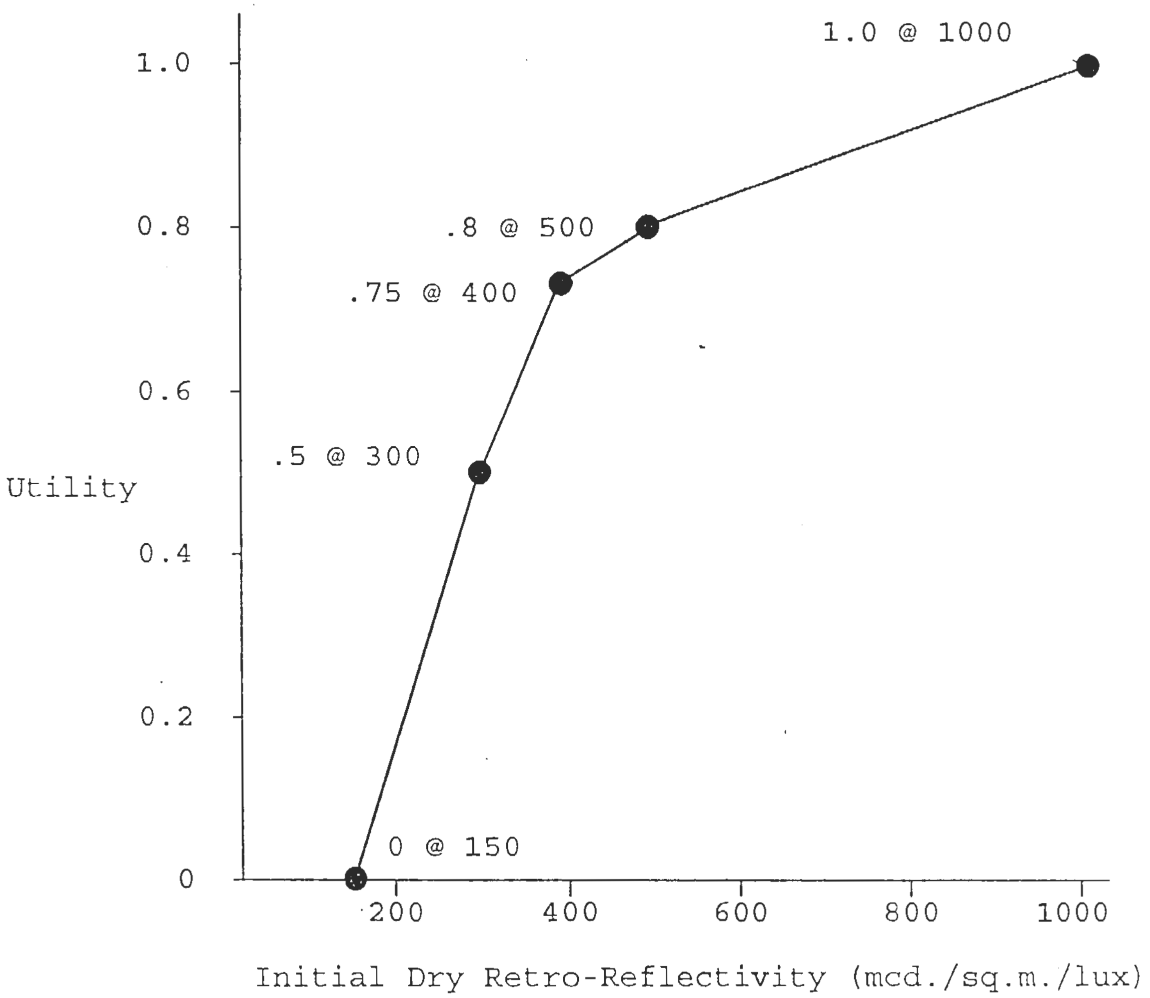


Figure 1. Single-measure utility function for Initial Dry Retroreflectivity (measure 1).

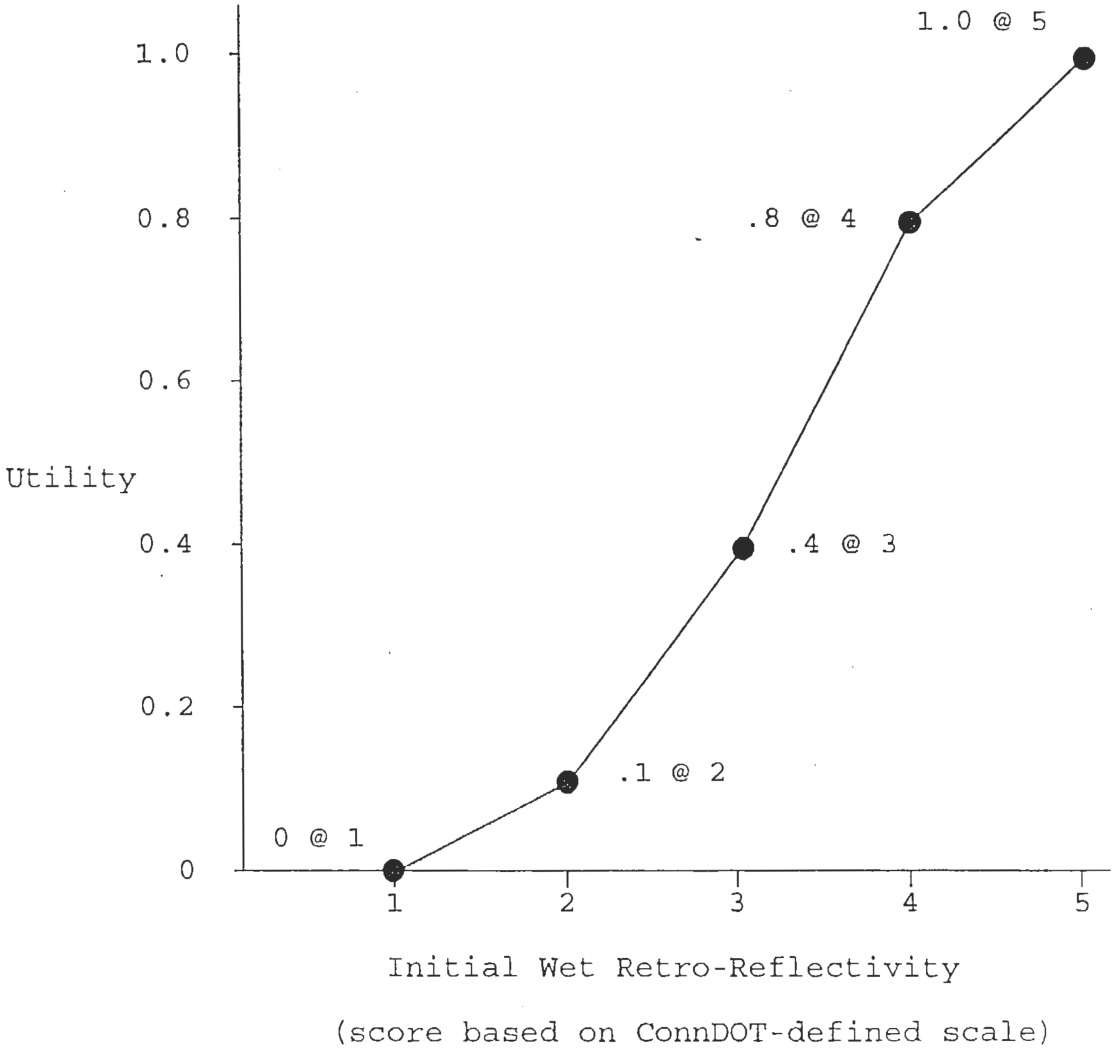


Figure 2. Single-measure utility function for Initial Wet Retroreflectivity (measure 2).

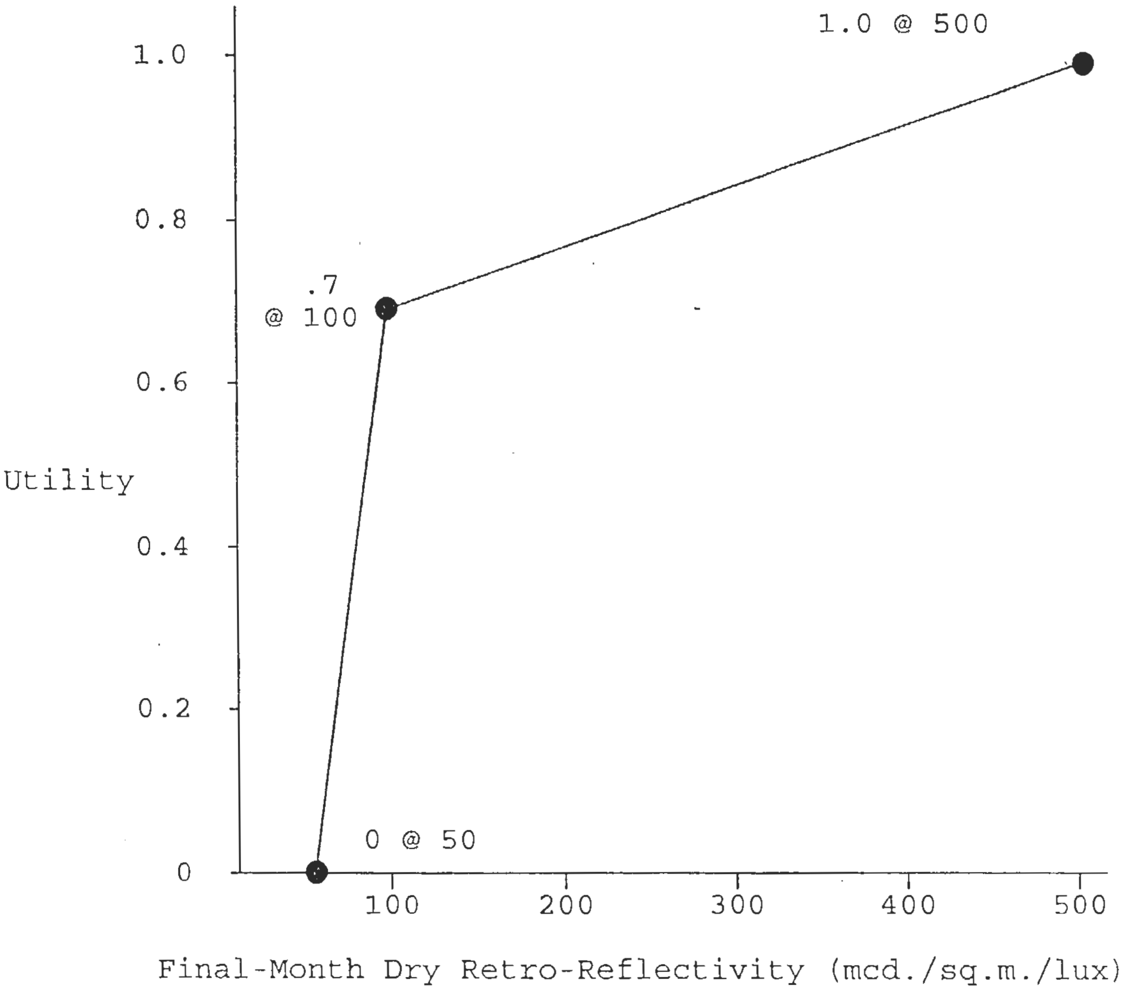


Figure 3. Single-measure utility function for Final-Month Dry Retroreflectivity (measure 3).

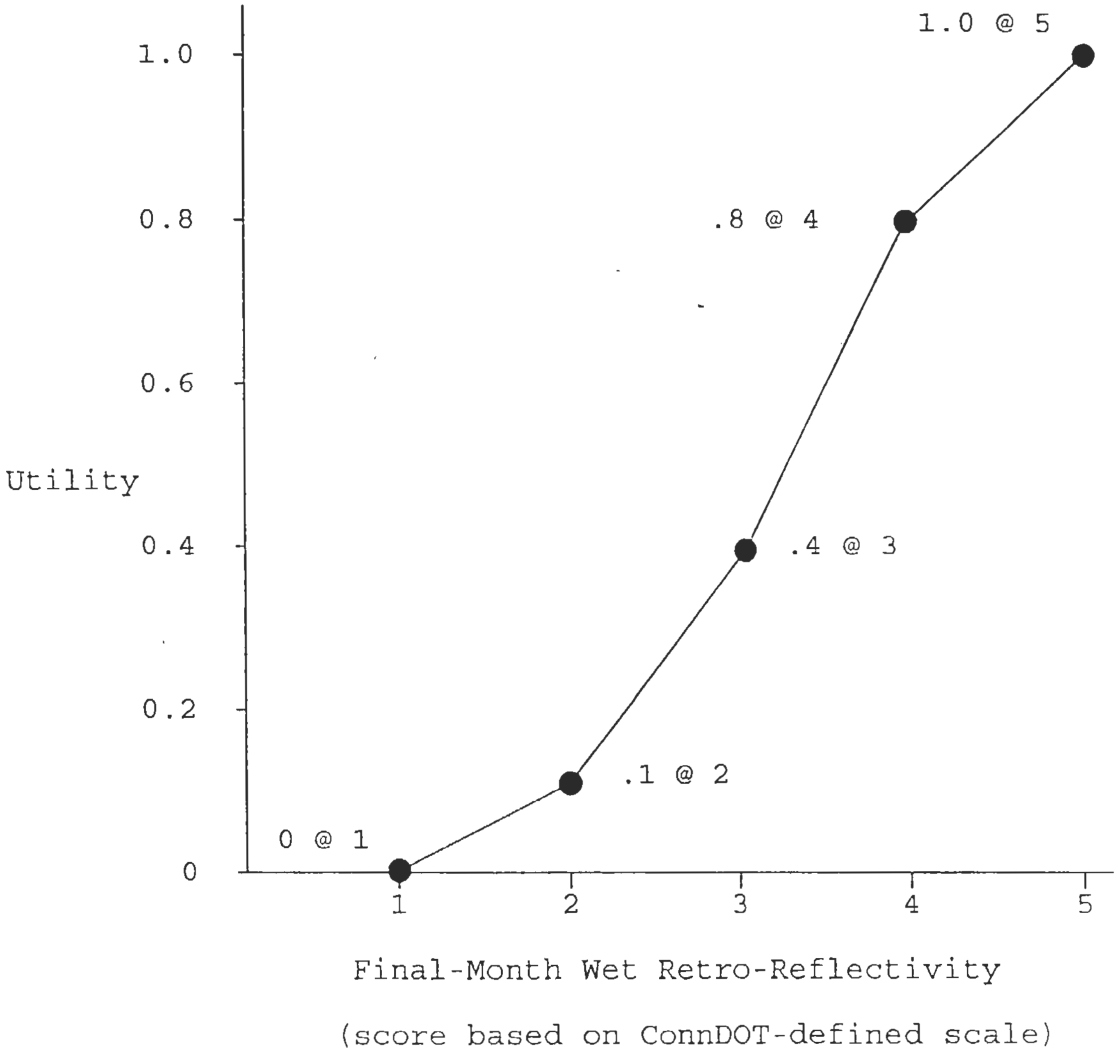


Figure 4. Single-measure utility function for Final-Month Wet Retroreflectivity (measure 4).

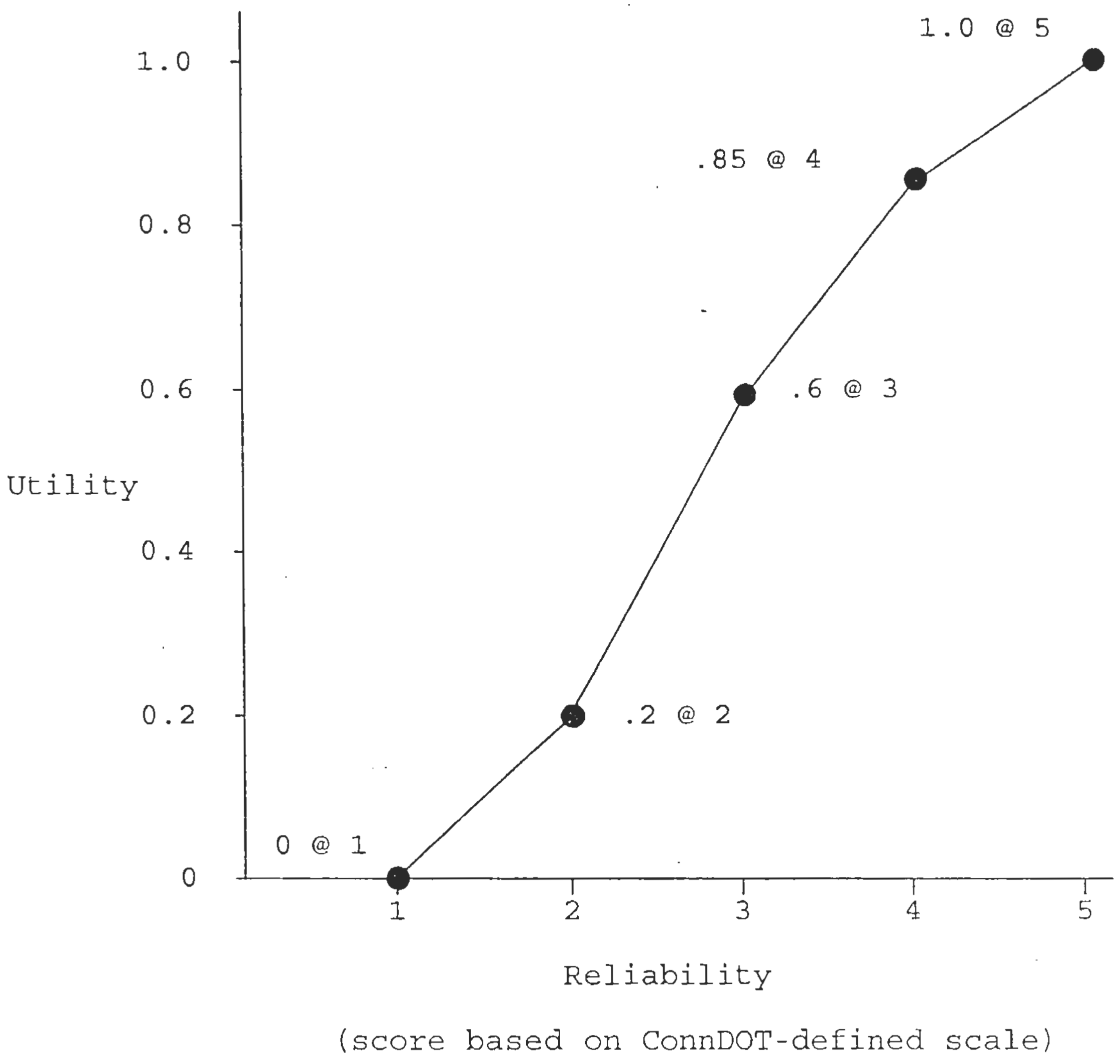


Figure 5. Single-measure utility function for Reliability (measure 5).

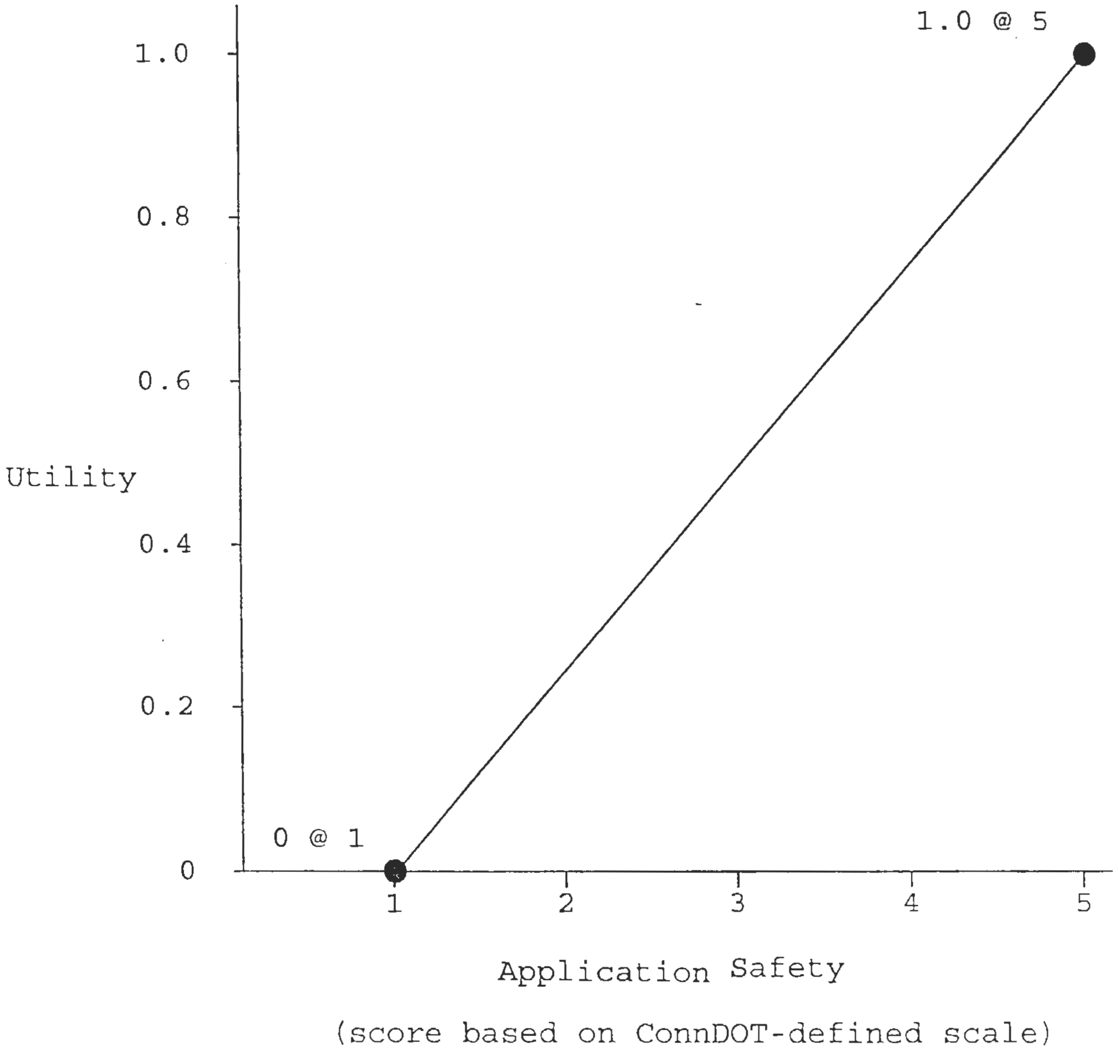


Figure 6. Single-measure utility function for Application Safety (measure 6).

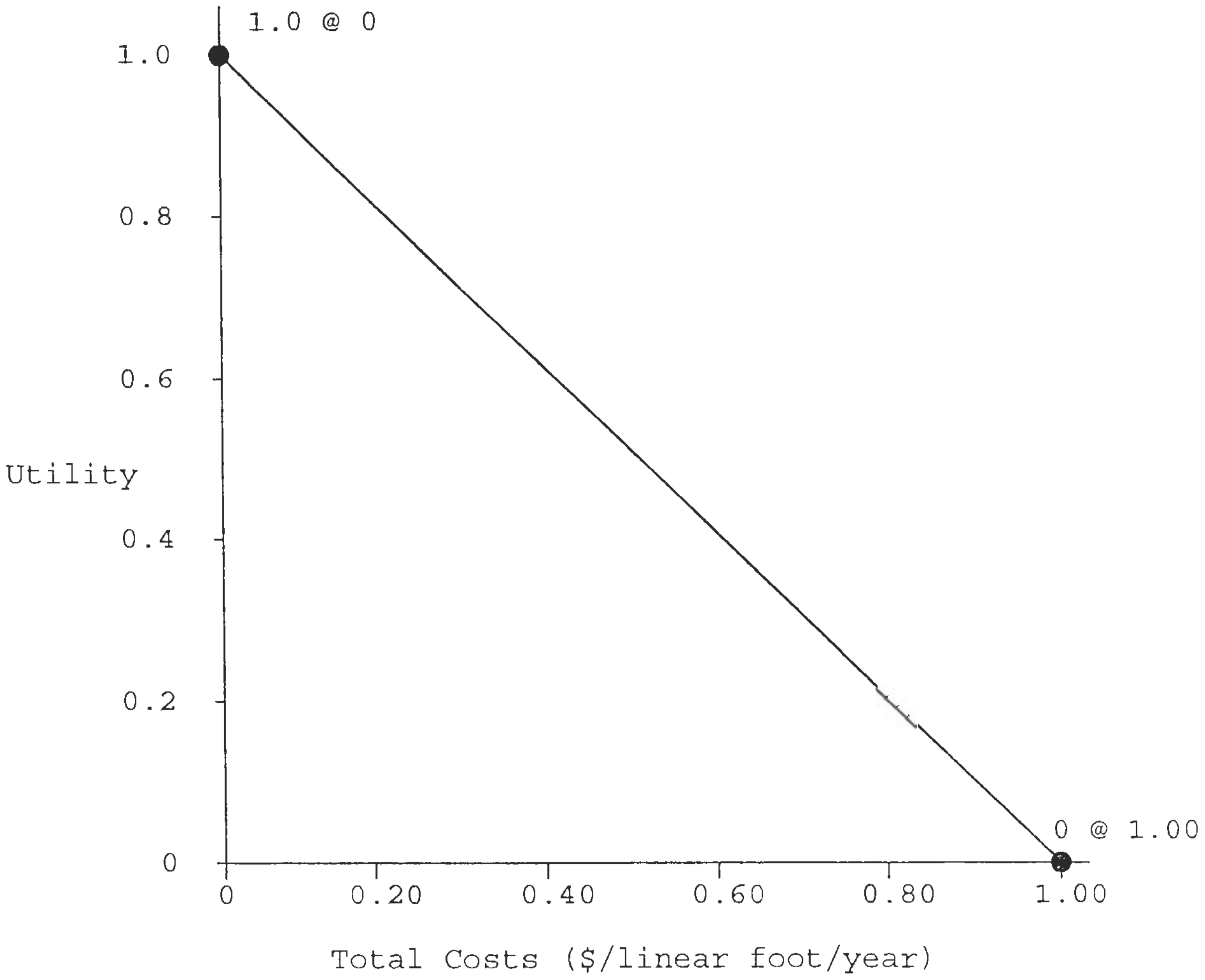


Figure 7. Single-measure utility function for Total Costs (measure 7).

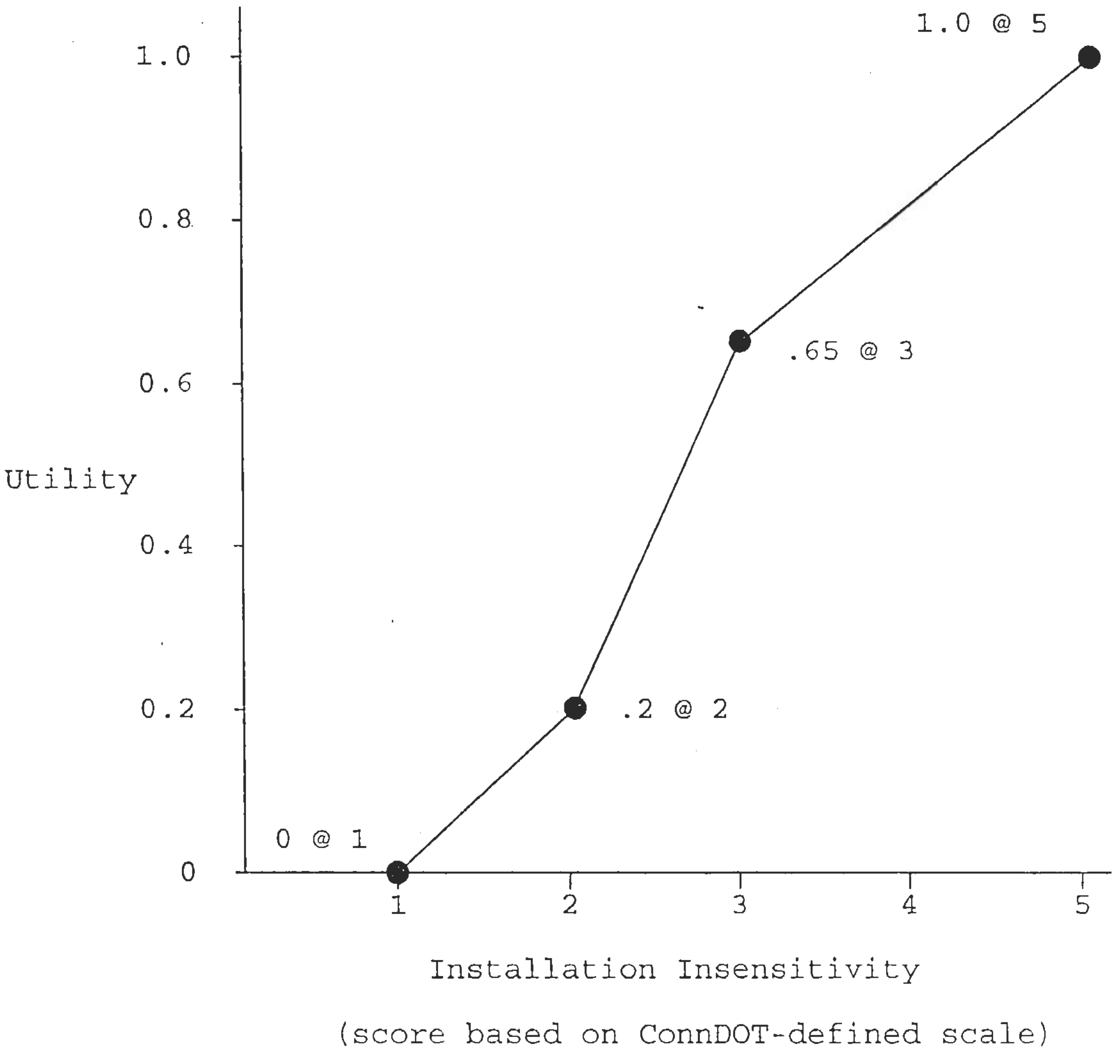


Figure 8. Single-measure utility function for Installation Insensitivity (measure 8).

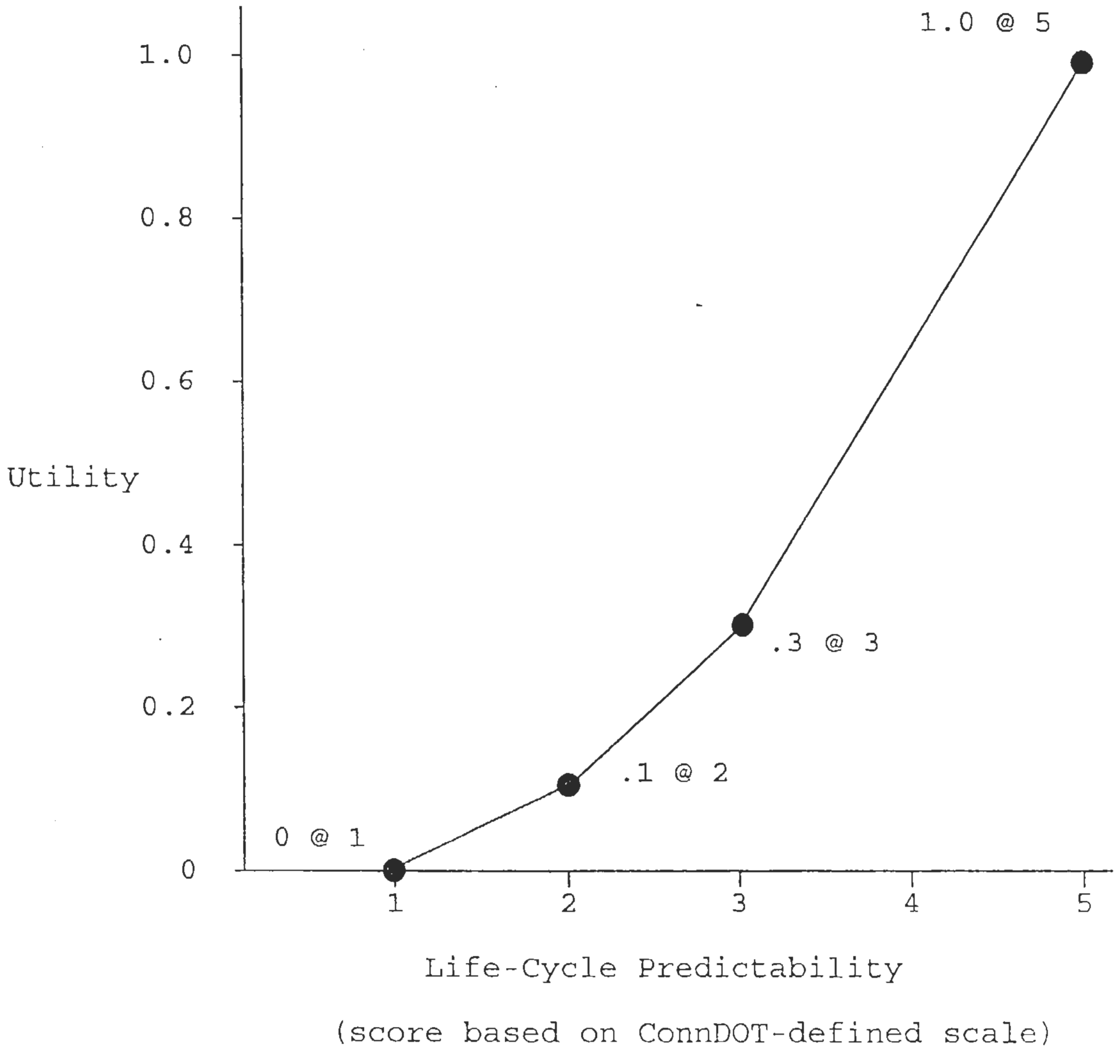


Figure 9. Single-measure utility function for Life-Cycle Predictability (measure 10).

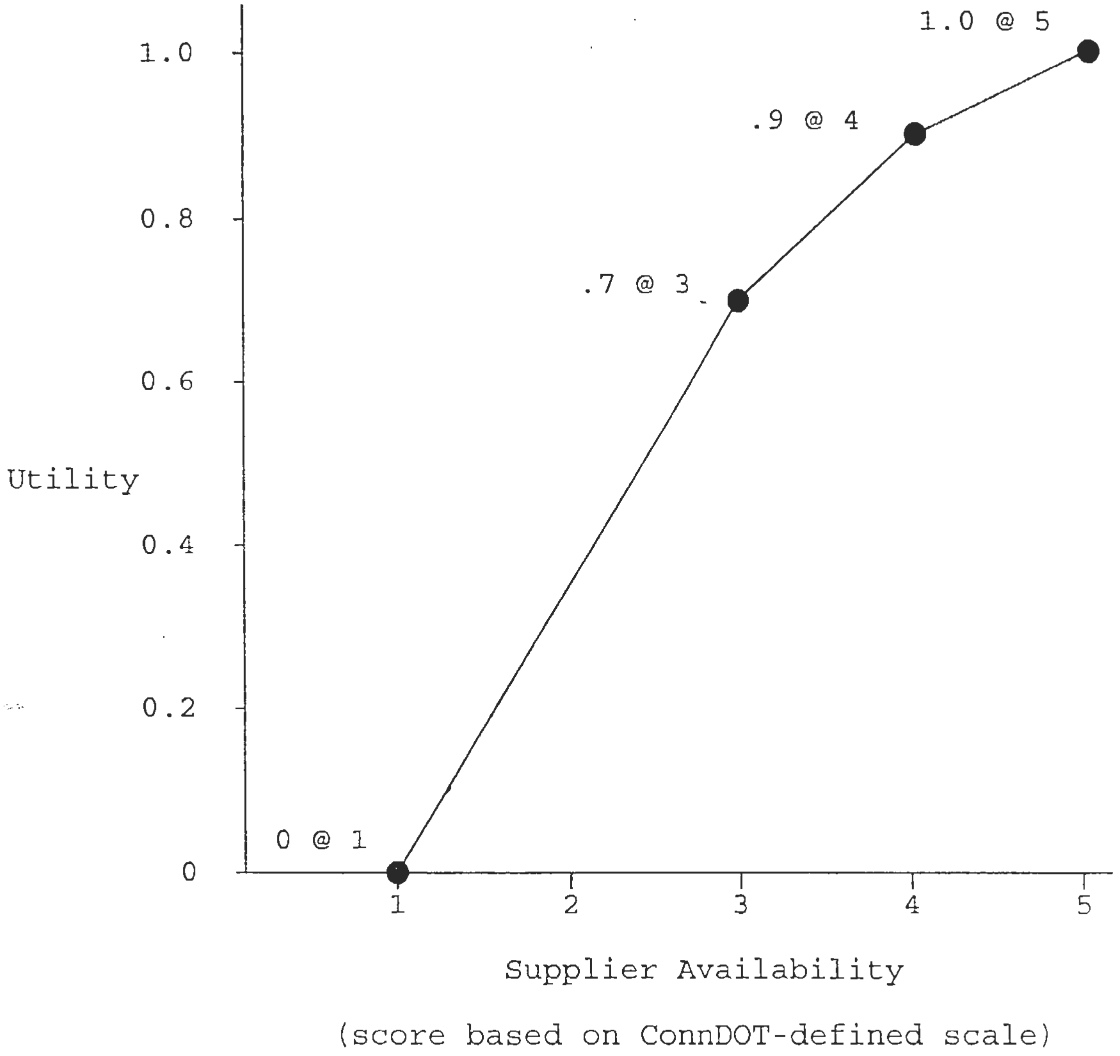


Figure 10. Single-measure utility function for Supplier Availability (measure 11).

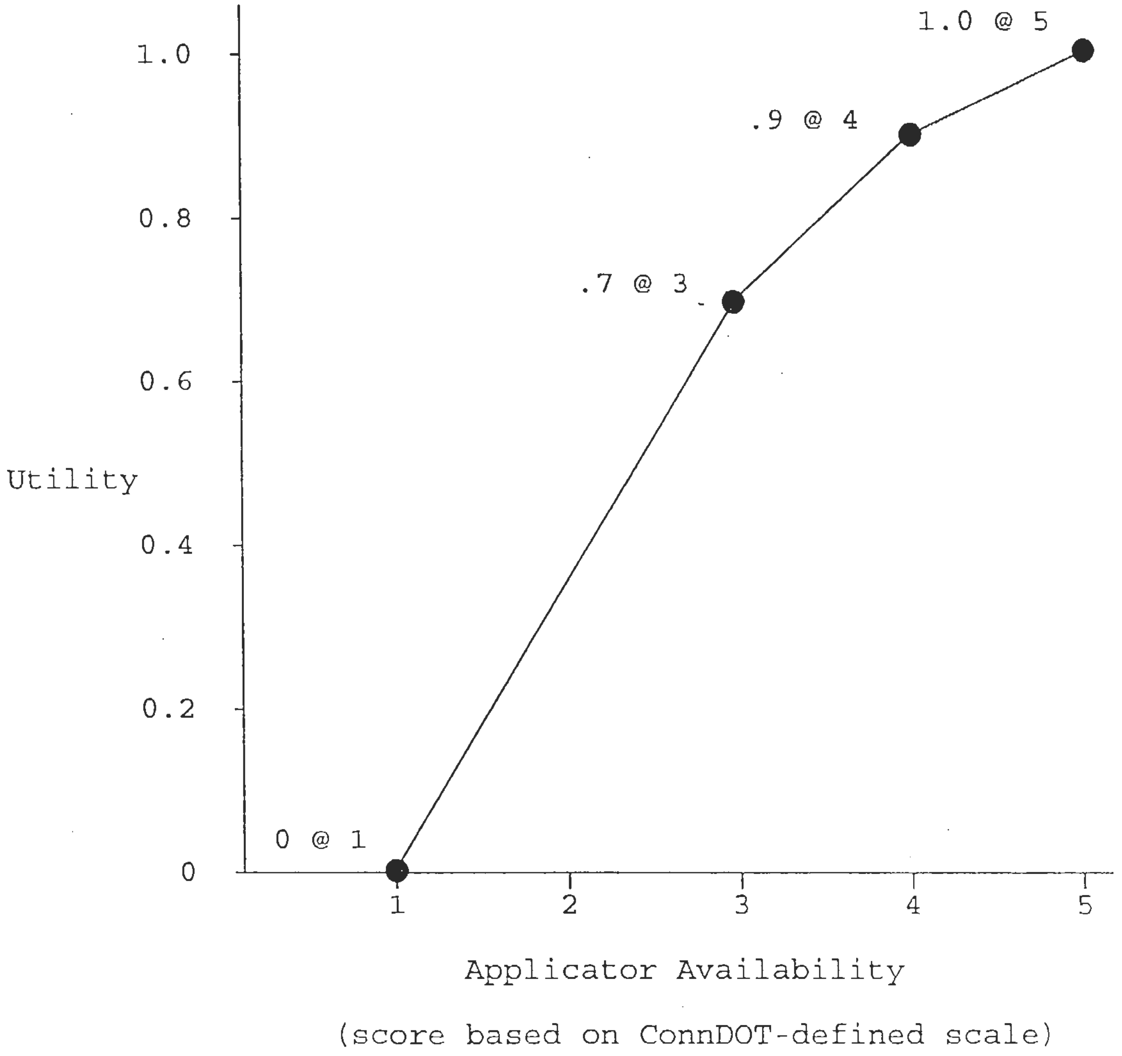


Figure 11. Single-measure utility function for Applicator Availability (measure 12).

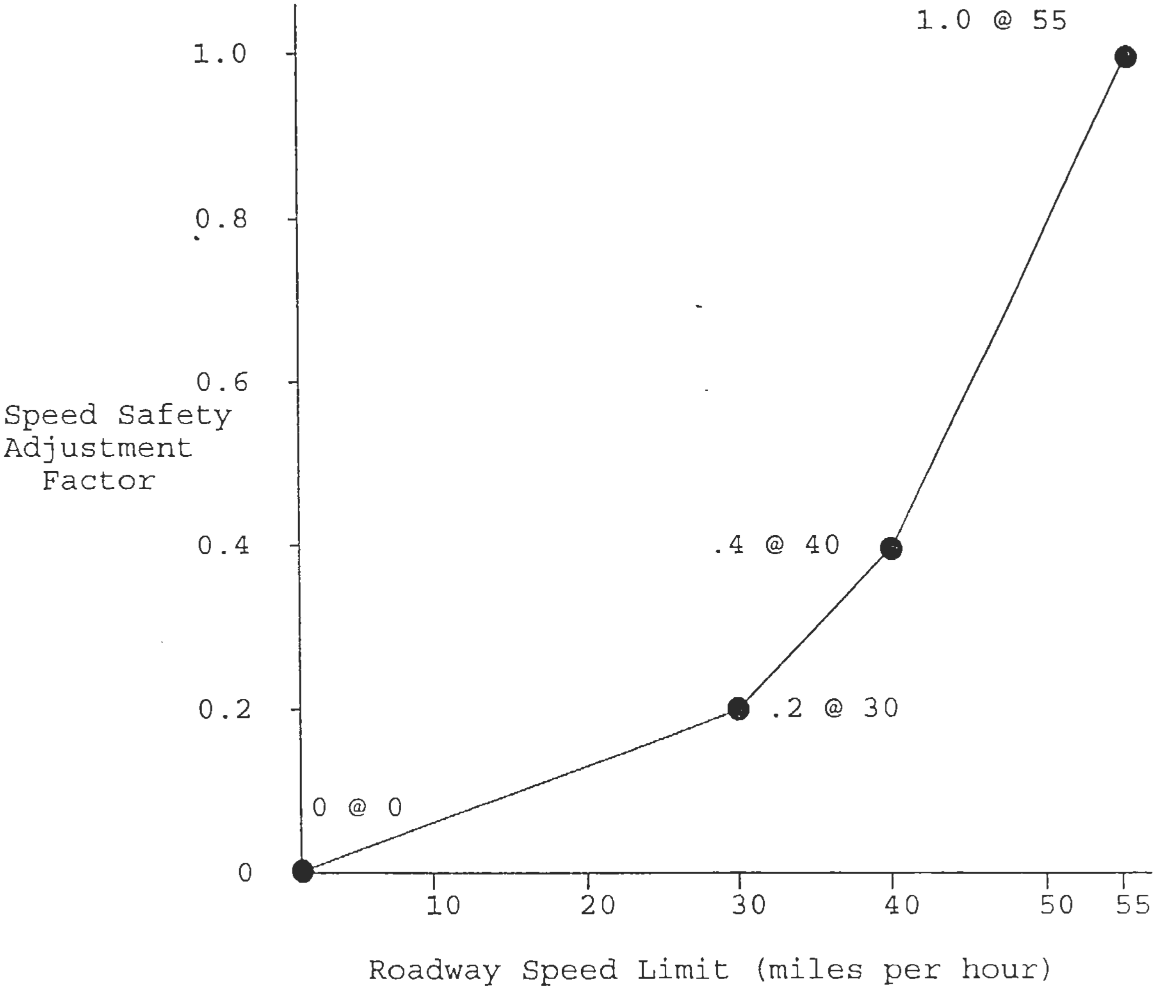


Figure 12. Speed Safety Adjustment Factor as a function of roadway speed limit.

With the twelve functions and the seven sets of weights defined, the model's specification is now complete. At this point, pavement marking alternatives can be evaluated using the model, as long as the information on the checklist in Appendix B is available for each alternative.

## VI. CONCLUSION

This report has presented the details of a multi-criteria decision making model for choosing amongst pavement marking alternatives. The model development process was outlined, the goals hierarchy was presented and discussed, and the mathematical details of the model were reported. The model has been entered into a software package called "Logical Decisions for Windows" (Logical Decisions, Golden, Colorado), resulting in a p.c.-based decision support system that is ready for ConnDOT to use.

A users guide for the DSS has been prepared as a separate document. This users guide shows how to input alternatives' measurement values into the system, and how to use the various features of the software to rank alternatives and perform various kinds of sensitivity analyses. The menu-driven software is very user-friendly, and one does not need to have a thorough understanding of the underlying model to be able to use it. However, familiarity with the model will enable a more complete understanding of the results provided by the DSS.

The model described in this report and programmed into the DSS is not unchangeable. The software enables the user to change all aspects of the model, including the goals hierarchy, weights and utility functions. The users guide written for this project does not describe how to make the changes -- it just addresses the use of the system with the model remaining as described in this report. However, the software manual provided by Logical Decisions describes how to make changes to all aspects of the model.

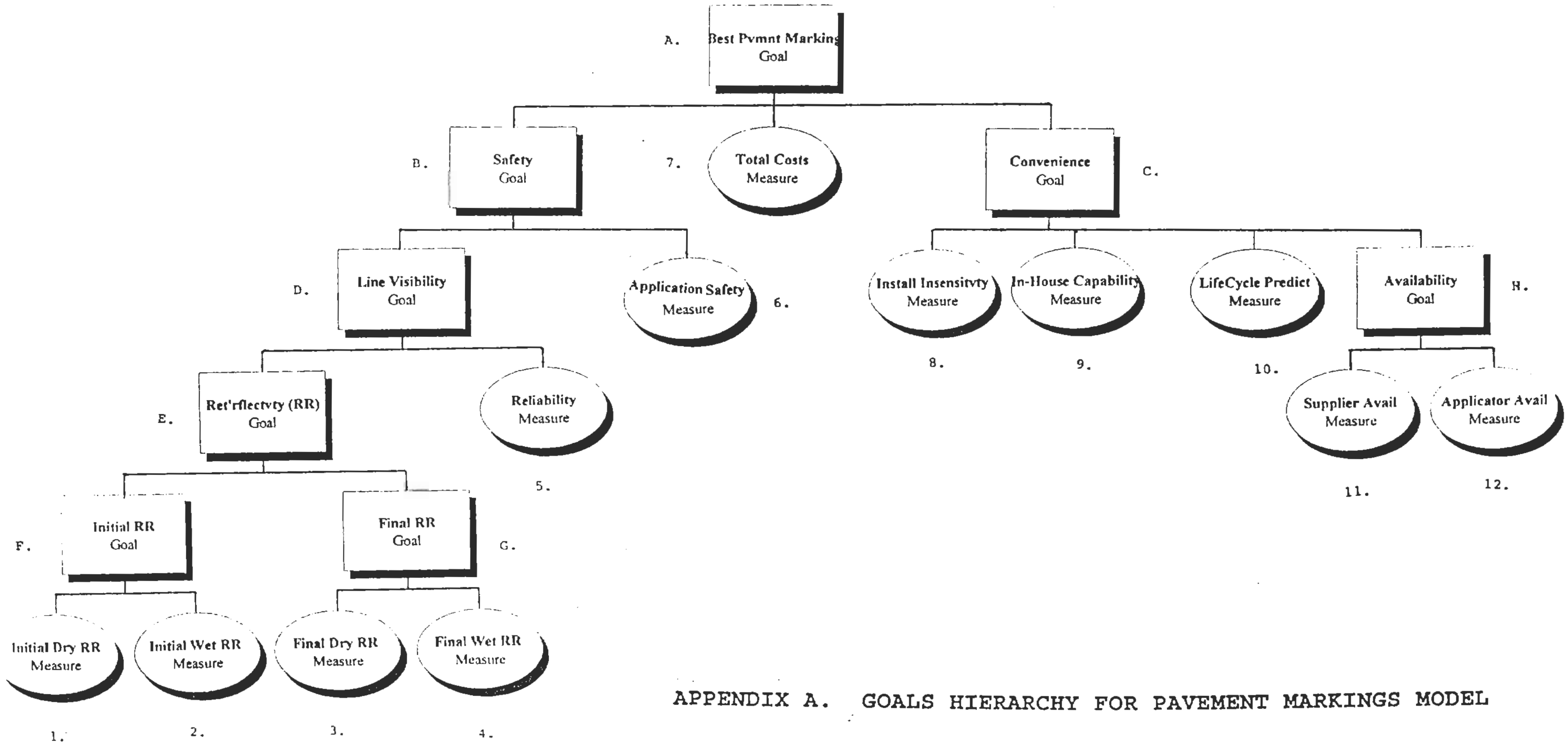
Although the current model is based on the inputs of the pavement markings task force, it should not be considered unchangeable. By changing certain aspects of the base model, a knowledgeable user might be able to gain insight into a pavement marking selection problem that could not be obtained just 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. A person who is familiar with the contents of this report and who knows how to use the Logical Decisions software should be able to implement changes to the model without much difficulty. Appendix C describes how the model was changed in response to suggestions that emerged based on reviews of an earlier version of 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.

## REFERENCES CITED

Anderson, R.A. and Braun, S.M. Users Guide for Applying Multi-Criteria Decision Making to the Selection of Pavement Markings, Transportation Institute, University of Connecticut, Storrs, 1994.

Keeney, R.L. and Raiffa, H. Decisions with Multiple Objectives, Cambridge University Press, Cambridge, 1993.



APPENDIX A. GOALS HIERARCHY FOR PAVEMENT MARKINGS MODEL

## APPENDIX B. PAVEMENT MARKING EVALUATION CHECKLIST

Description of Application
(i.e., the stretch of roadway to be marked)

Roadway label and location: ________________________________

Speed limit: __________ ADT: ____________

Pavement type: ____________________

Description of Pavement Marking Alternative

marking type: ____________________
(e.g. epoxy)

expected number of years
between applications: __________________

Measurement Values for Pavement Marking Alternative

**Measure 1.** Initial dry-pavement retroreflectivity (based on when the marking is initially applied).

____________________ mcd./sq.m./lux

**Measure 2.** Initial wet-pavement retroreflectivity.

Under moderate rainfall conditions, the retroreflectivity of the newly-applied pavement marking is:

Circle one:

1) Barely visible.
2) Below average.
3) Average.
4) Above average.
5) Excellent.

**Measure 3.** Final-month dry-pavement retroreflectivity (based on the final month of the marking's specified life-span).

__________________ mcd./sq.m./lux

**Measure 4.** Final-month wet-pavement retroreflectivity.

Under moderate rainfall conditions, the retroreflectivity of the pavement marking during the final month of its specified life-span is:

Circle one:

1) Barely visible.
2) Below average.
3) Average.
4) Above average.
5) Excellent.

**Measure 5.** Reliability. Circle one:

1) ConnDOT has had experience with or strong reason to suspect premature failure.
2) ConnDOT has some reason to suspect that there could be premature failure.
3) There is little reason to suspect premature failure.
4) Evidence suggests that the material has a high probability of lasting for its specified life.
5) There is strong evidence that the material has a high probability of lasting for its specified life.

**Measure 6.** Application safety. Circle one.

1) 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.
2) One major constraint, either long road duration or unattached devices.
3) One or more moderate constraints.
4) Two or fewer minor constraints of duration, devices, lanes occupied or time constraints.
5) Characterized by short duration, no unattached devices, no more than one lane occupied, and no time constraints.

Total costs (based on a ten-year time horizon and considering the funding available for this application)

A. cost of materials and installation ($/lin.ft.) for each application: ______ A.

B. expected number of applications in 10 years: _____ B.

C. maintenance costs over 10 years ($/lin.ft.): ______ C.

D. cost of each eradication ($/lin.ft.): ________ D.

E. expected number of eradications over 10 years: ____ E.

F. other costs incurred over 10 yrs. ($/lin.ft.): _____ F.

**Measure 7.** = [(AxB) + C + (DxE) + F] / 10 = ___________ ($/lin.ft./year)

**Measure 8.** Installation insensitivity. Circle one:

1) characterized by being sensitive enough to substantially limit application to controlled conditions.
2) characterized by being sensitive to the extent that significant caution must be exercised prior to the application.
3) average sensitivity when compared with other materials and only ordinary care need be exercised prior to application.
4) slightly sensitive with minor caution required prior to application.
5) characterized by being relatively insensitive.

**Measure 9.** In-house capability. Can ConnDOT apply this type of pavement marking? Circle one:

0) No    1) Yes

**Measure 10.** Life-Cycle Predictability. Circle one:

1) considered unpredictable due to past experience or a lack of experience.
2) considered to have a wide range of life-cycle predictability and/or not presently adequately familiar.
3) considered to have a range to the extent that we are not yet comfortable with the life-cycle's prediction. Based on limited and/or inconclusive experience, unable to rank otherwise.
4) considered to be predictable but with a few divergent experiences.
5) considered highly predictable.

**Measure 11.** Number of suppliers of the pavement marking material. Circle one:

1) very limited
2) somewhat limited
3) average
4) more than average
5) plentiful

**Measure 12.** Number of applicators of the pavement marking material. Circle one:

1) very limited
2) somewhat limited
3) average
4) more than average
5) plentiful

## APPENDIX C. AN EXAMPLE OF MODEL REFINEMENT

This appendix describes how the pavement markings model was changed from an earlier version to the version that is described in the main body of this report. The changes described here were made in response to comments from ConnDOT personnel who had examined the earlier version of the model. The purpose of outlining these changes is to emphasize the fact that the model is not unchangeable. Hopefully, further refinements to the model based on future inputs from users will continue to occur over time.

Figure C.1 shows the goals hierarchy for the earlier version of the pavement markings model. Compared with the later version of the hierarchy, which is shown in Appendix A, this earlier version includes one extra measure -- i.e. eradication safety (measure 7). This measure was removed from the model because ConnDOT personnel felt that, although eradication safety is an important issue, eradication occurs in such a small amount relative to installation that it does not make sense to include it in the model. They felt that it was more appropriate for eradication to be considered outside of the model by the decision-maker who was using the decision support system.

Another characteristic of the earlier version of the model that was subsequently changed is its range on the total cost measure. Figure C.2 shows the old single-measure utility function for total costs, which ranges from 0 to $10.00 per linear foot per year. Upon reexamination, it was decided that the model did not need to allow for such a wide range of cost values. With the range narrowed to that shown in Figure 7, differences in costs between pavement marking alternatives ended up translating into more significant differences in overall utility than they had previously.

Another range adjustment was made for the expected number of years between installation, which enters into the model through the adjustment factor $A_6$ that is included in equation 5. The earlier version of the model allowed intervals of up to ten years, whereas the updated version used the more realistic maximum interval length of six years. As with the cost function, the effect of this change is to increase the impact of differences in measurement values on differences in utility scores.

The three changes to the model described above were easily implemented using the Logical Decisions software. Along with the changes to the computer-based model, it is also important for all documentation to be updated. This documentation includes the checklist shown in Appendix B and the Users Guide by Anderson and Braun (1994). Because future refinements of the model are likely to take place, it is recommended that ConnDOT establish procedures to ensure that the documentation is kept up-to-date. As long as such procedures are in place and users are knowledgeable about the features of the Logical Decisions software, the implementation of further refinements to the model should present no serious difficulties.

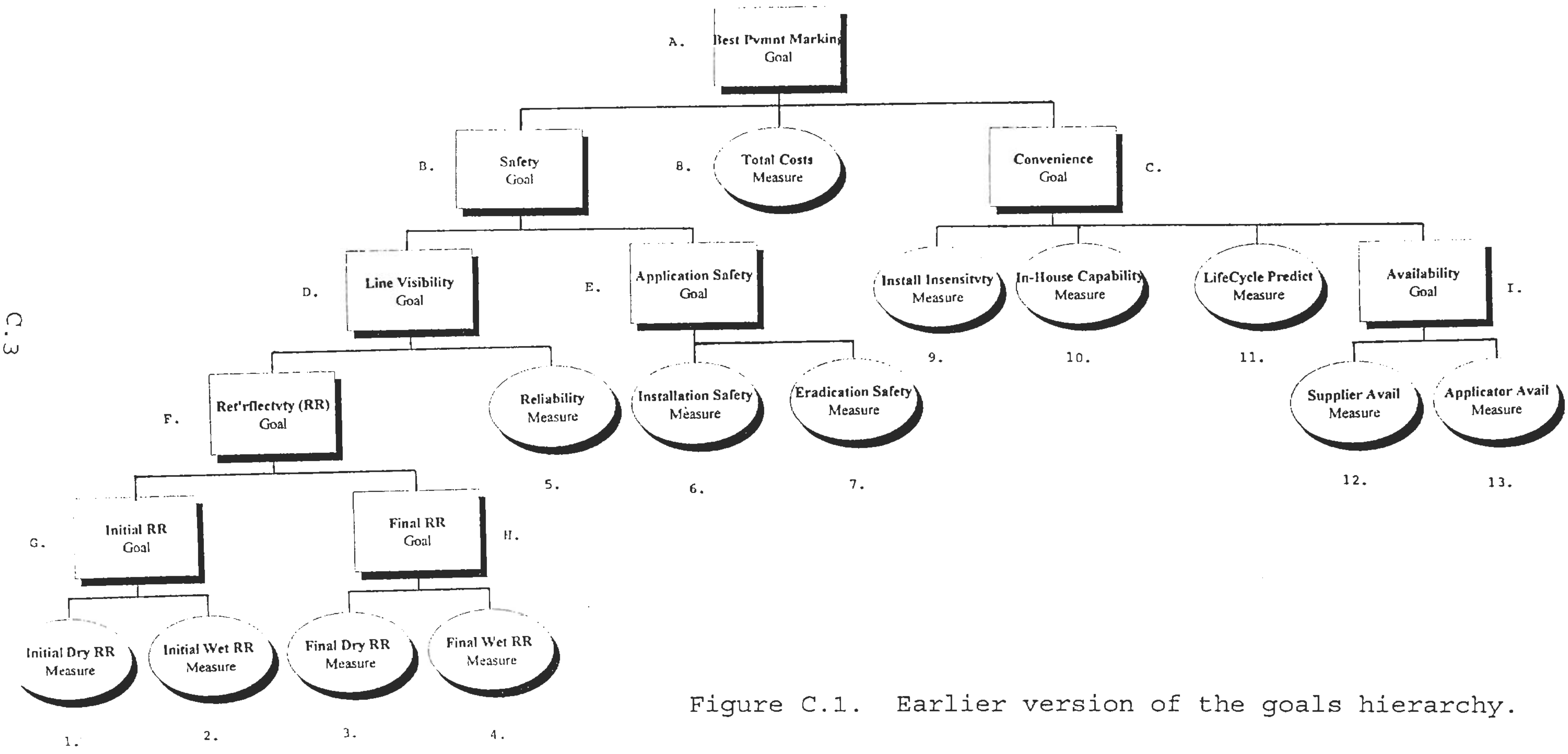


Figure C.1. Earlier version of the goals hierarchy.

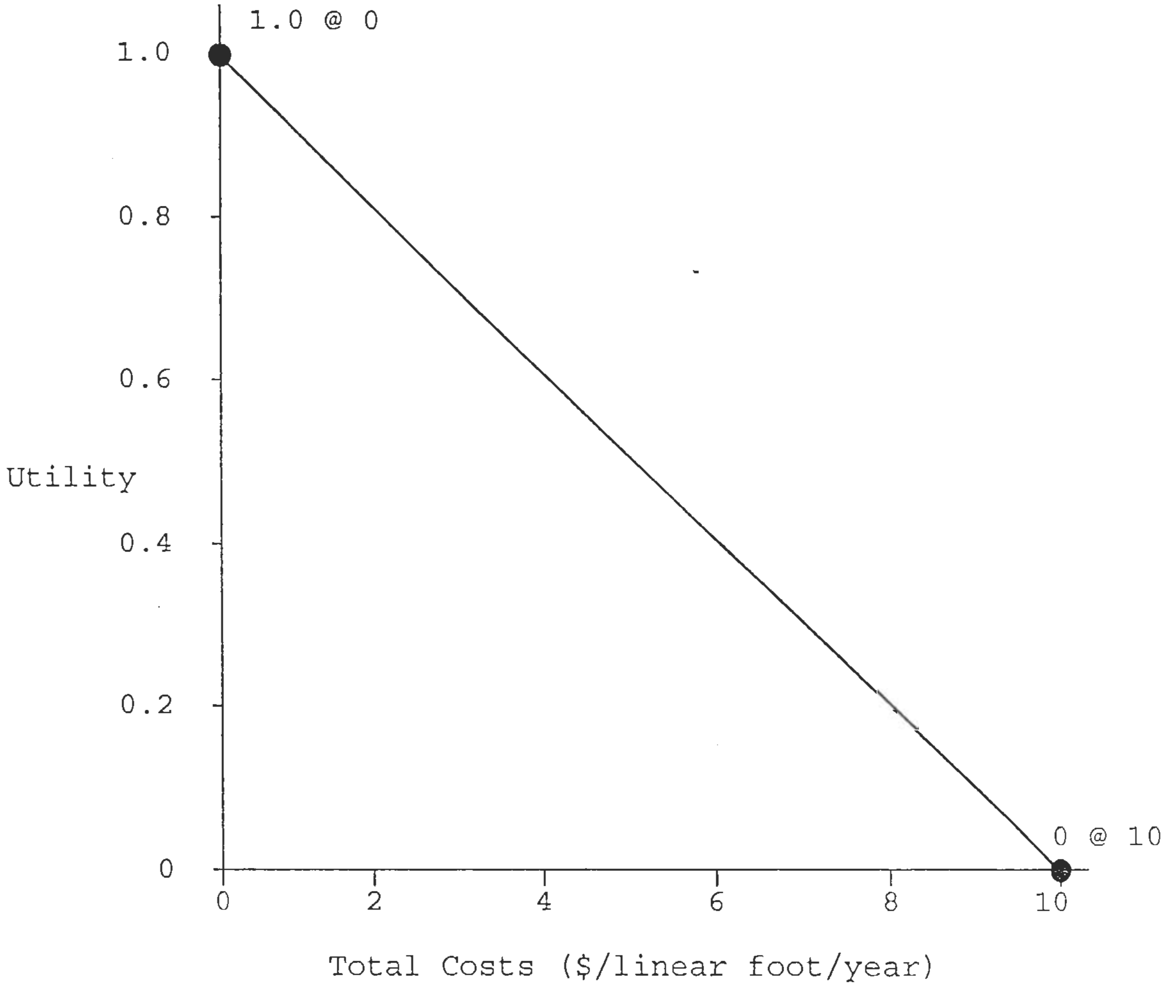


Figure C.2 Earlier version of single-measure utility function for Total Costs (measure 7).