Evaluating the Applicability of Analytical Decision Support Tools for the Connecticut Department of Transportation

Final Report

August 1994

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16. Abstract

In response to an area of need expressed by ConnDOT's Commissioner, this project has endeavored to identify decision support tools that would have a high probability of being useful within ConnDOT. The project began with a broad-based review of decision support systems, and then focused on one category of these systems -- that dealing with alternative evaluation and decision analysis. Multi-criteria decision making (MCDM) and decision and risk analysis (D&RA) are the two techniques within that category that appear to be most appropriate for ConnDOT. In addition to summarizing the findings regarding the various decision support techniques, this report includes a description of five stages of interactions between the principal investigators and ConnDOT personnel. These interactions have had a strong effect on the direction the project has taken. As of the writing of this report, work continues on a follow-on project involving the application of MCDM to the problem of choosing amongst pavement marking alternatives. The follow-on project also calls for identification of other potential applications of MCDM and D&RA within ConnDOT.

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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

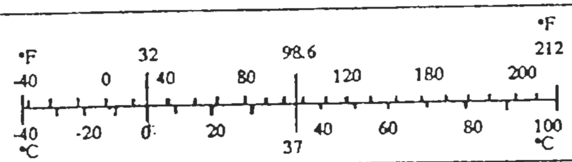
NOTE: Volumes greator than 1000 L shall be shown in m^3.

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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DM -- decision maker.

D&RA -- decision and risk analysis.

DSS -- decision support system.

MCDM -- multi-criteria decision making.

PIs -- principal investigators.

I. INTRODUCTION

On August 28, 1992, a meeting was held between the University of Connecticut's President Hartley and other University officials and ConnDOT's Commissioner Frankel, Deputy Commissioner Sullivan, and other ConnDOT Administrators. The past, present, and future of the Cooperative Research Program, celebrating its 30th Anniversary, was the primary topic. At that meeting, four areas of need were presented by Commissioner Frankel and Deputy Commissioner Sullivan for consideration by researchers at the University.

One of these needs, identified by Commissioner Frankel, dealt with the decision-making environment for managers within the Department. In the face of resource limits and conflicting demands, major decisions are made between "competing" transportation modes; "competing" projects within each mode; and alternatives within projects and operational areas. The Commissioner had observed that a variety of decision-support tools were used in the private sector by managers working in complex environments. While decision-support techniques have resulted in significant benefits for many organizations, it was unknown whether any would be appropriate for use within ConnDOT. Subsequent to this meeting, the principal investigators developed the proposal for this project, which was designed to address the area of need indicated above.

The approach taken at the beginning of this project was to start with no preconceptions regarding the types of decision support tools that would be most appropriate for addressing ConnDOT's needs. Specific techniques would be looked at in-depth only after a wide variety of tools were investigated. It was believed that this approach would be the best way of ensuring that entire categories of potentially attractive tools would not be overlooked.

After a survey of decision support tools was performed, the techniques that appeared to be most appropriate for addressing ConnDOT's needs could be focussed upon. To ensure that a proper focus was being established, a high degree of interaction between the principal investigators and ConnDOT personnel has occurred over the course of the project. This interaction has been an investment of time and effort that has hopefully resulted in an increased probability of successful adoption of the decision support tools identified as most appropriate for ConnDOT.

The report is organized based on the way that work was performed on the project. Section II presents a broad-based review of decision support systems literature. Section III then provides an in-depth discussion of the two techniques that were identified as most appropriate for addressing ConnDOT's needs. These two techniques are: 1) multi-criteria decision making; and 2) decision and risk analysis. Section IV describes the interactions that have occurred between the principal investigators and ConnDOT personnel as part of this project. These interactions are reported because they have had a strong impact on the way the project has progressed. Section V concludes the report with a summary of what has been accomplished and how it has affected the direction being taken on a follow-on project. The proposal for the follow-on project is included as Appendix B. Appendix A summarizes material that was presented by the principal investigators at a ConnDOT all-managers' meeting in November, 1993.

II. REVIEW OF LITERATURE

As stated in the introduction, this project began with a broad-based review of decision support systems literature. Before focusing on a particular set of tools to recommend for use within ConnDOT, the principal investigators believed it was important to learn as much as possible about all of the types of tools available. Although it is not possible to present a comprehensive review of all decision support systems (DSSs) within this report, this section does provide a categorization of DSSs and discusses examples of tools within each category. More detailed discussions of multi-criteria decision making and decision and risk analysis are provided in Section III.

Overview of Decision Support Systems

For the purposes of this presentation, let us define a DSS as follows:

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

The development and use of DSSs have increased substantially in recent years. In a survey of DSS applications, Eom and Lee (1990) identified over 200 applications of DSSs reported in the literature between 1971 and 1988. Of those, 41% appeared between 1981 and 1985; and 31% between 1986 and 1988. Review of the literature that has appeared since 1988 confirms an upward trend in the development and use of DSSs.

While there are many different kinds of DSSs, the three basic components shown in Figure 1 are common across all types. These components are: 1) a data base, which stores information used by the DSS; 2) an engine, which manipulates the data in predefined ways to obtain usable results; and 3) a human interface, which is used to solicit inputs and present outputs to the user(s). Of the three components, the engine is the one that defines most of the character of the DSS.

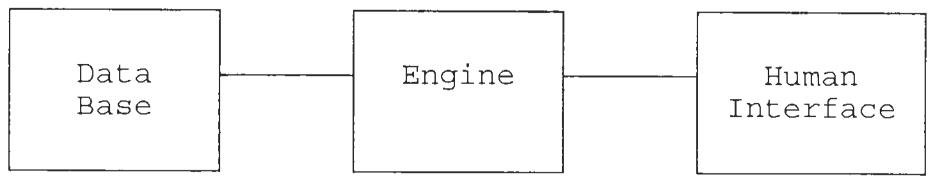

Figure 1. Basic components of a decision support system.

Over the years, various researchers have developed alternative classification schemes for decision support systems. For example, Sainfort et al. (1990) defined categories based on the point in the decision-making process at which the tool is applied. Their divisions included: problem structuring aids, evaluation aids, and implementation aids. Another approach to categorizing decision support tools is to focus on the different situations in which they might be used, particularly with regard to the complexity of the problem and the level of sophistication of the engine. Five categories that can be considered from this viewpoint are: 1) data management; 2) alternative generation; 3) alternative evaluation and decision analysis; 4) management science / operations research modeling; and 5) artificial intelligence. This is the classification scheme that is used to structure the remainder of this section.

Data Management

Decision aids suited to data management include those techniques that organize data in a way that provides the decision-maker (DM) with a better perspective from which to evaluate the information. Types of tools commonly used for this purpose are statistical methods such as bar charts, histograms, scatterplots, variability measures, regression analysis, etc. Decision-makers have relied on the assistance of statistics for centuries. However, with the huge increase in the amount of information realized since the development of computing technology, such tools have become essential for organizing data so that assimilation of the information by the DM is possible. Database management systems are also tools that, at least in part, serve in this capacity. These types of decision tools do not directly suggest solutions to the DM, but they enable him to be better informed when he makes a decision. An example of this kind of DSS is the "PM Planner" software developed and used by ConnDOT Maintenance.

Techniques that provide a means for data collection for use in future decisions can also be classified as data management tools. Management techniques used to monitor progress of projects or programs provide information that can be used as the basis for decisions regarding future, related projects or programs. Such methods also provide a basis for decision-making in the context of the project underway.

Data management tools and techniques are helpful, if not necessary in decision-making scenarios involving a significant amount of data, or where data collection and monitoring are relied upon for future decisions. But the fact that these types of aids do not directly suggest a solution to the DM implies that these techniques may not be well suited for all types of decision problems. In many situations, the presentation of and/or the evaluation of alternative solutions are important parts of what the DM is looking for from the DSS.

Alternative Generation

Alternative generation techniques are more sophisticated and require more DM involvement than the data management techniques. The generation of ideas and potential solutions is obviously a more complicated function than the organization and presentation of data.

The process of alternative generation can take many forms. It can involve many people or only one person. The number of potential alternatives can be limited or quite large. Regardless of the case, the generation of alternatives plays a crucial role in defining the caliber of the final decision. Past studies (Cosier 1978, Cosier 1980, and Mitroff et al. 1979) have shown that different approaches to alternative generation have different effects on both the quality of the alternatives generated and on the number of alternatives generated. It is for this reason that many DMs look toward DSSs as a means of generating good sets of alternatives.

One of the most prominent types of available decision tools that focuses on alternative generation is the group decision support system (GDSS). The GDSS is a computer-based system aimed at providing a medium through which a group can interact on an equal level to aid in the group decision-making process. GDSSs come in varying forms that provide varying levels of support. One feature that nearly all GDSSs have in common is an alternative-generating module. In most cases the alternative generation technique supported by GDSS is brainstorming. The advantage offered by the computer is that all participants are offered an equal opportunity to provide input. The freedom allowed by this approach leads to more and higher quality alternatives (Lewis and Keleman 1990).

Other decision support systems, focusing on one DM, offer slightly different techniques that attempt to trigger idea generation on the part of the DM. Most of these techniques are included as a separate module within commercially available decision support software.

Manual aids have also been used and studied in the past. Two such tools are the Dialectical Inquiry System (DIS) and the Devil's Advocate (DA) technique. The DIS approach is based on examining the assumptions underlying a potential solution to a problem, negating the assumptions, and developing a counterproposal based on the negated assumptions. With the DA approach, the assumptions are examined as with DIS, but a critique of the assumptions is developed as opposed to a counterproposal based on the negated assumptions. Various studies of the two techniques (Cosier 1978, Cosier 1980, Mitroff et al. 1979, and Schwenk 1984) have identified advantages of both in terms of the quality of alternatives and decisions, and in terms of the DMs satisfaction with the decision-making process.

Alternative generation is necessary in those situations when the options available to the DM(s) are ill-defined, or even unknown. Loosely defined problems that offer the DM a high degree of flexibility are well suited to such techniques as brainstorming, so that as many potential solutions as possible can be evaluated. In situations where the potential solutions are well-defined, such decision aids are not necessary, and the emphasis changes to an evaluation of the known alternatives.

Alternative Evaluation and Decision Analysis

In the context of many decisions, the DM is aware of the options available to him or her, but may have difficulty in objectively evaluating them. DSSs for alternative evaluation and decision analysis use techniques designed to assist the DM in choosing amongst available options. Several different techniques are available for doing this, but all perform the following basis function: evaluation of alternatives based on the attributes of each option or the potential outcomes that go along with each alternative.

Within this category of DSSs, the following three techniques are most popular:

1) cost/benefit analysis -- standard financial analysis that typically determines the net present value of an alternative based on dollar values of associated costs and benefits over a specified time horizon;

2) multi-criteria decision making (MCDM) -- similar to cost/benefit analysis, except that multiple criteria are

identified and used to develop a utility function that serves as the basis for evaluating alternatives; and
3) decision and risk analysis (D&RA) -- similar to MCDM in that utility functions are developed, but D&RA is more general because it explicitly incorporates uncertainties and allows for multiple, sequential decision options.

In Section III, MCDM and D&RA are discussed in further detail. They are the techniques that have been identified as being most relevant to this project. Cost/benefit analysis is a very important tool, but its use is so common that a detailed explanation of it is not appropriate for this report. Because the DSS category of alternative evaluation and decision analysis is elaborated upon in Section III, it will not be further discussed in this section.

Management Science / Operations Research (MS/OR) Models

In their survey article, Eom and Lee (1990) identified MS/OR models as the most popular type of engine component for decision support systems. Sixty percent of the articles they reviewed employed MS/OR models. However, because it focused on published reports, their review may not represent the types of DSSs used in practice. For example, the less sophisticated DSSs that perform straightforward data management are unlikely to appear in journal articles. Nevertheless, the prevalence of MS/OR models in the Eom and Lee survey is a good indication of the importance of this category of DSSs.

MS/OR modeling techniques tend to be more complex than methods used for alternative evaluation and decision analysis. Because these mathematical models are very structured, they tend to have a high developmental cost, and they are less easily transferred to situations other than those for which they were developed.

A well-known example of a MS/OR modeling technique is linear programming (LP). Linear programming techniques are frequently applied to decision problems involving optimal resource allocation. LP modeling involves the development of linear functions defining relationships amongst variables in the form of constraints. The problem is then solved so that a solution is obtained which is optimal with respect to a specified linear objective function.

Kroeber and LaForge (1980) suggest several types of problems well-suited to linear programming methods: problems where ingredients must be blended; make or buy problems; investment selection problems; transportation problems involving several supply points and distribution channels; and worker assignment problems. Linear programming has found several uses in transportation planning, including use within various decision support systems for pavement management (e.g., Davis and Van Dine 1991).

The maintenance facility location model developed by Campbell and Davis (1994) is based on a mixed-integer programming (MIP) model. MIP is similar to linear programming, except that some of the decision variables must take on integer values. Network programming and transportation programming are other variations of linear programming. Non-linear programming is also related, except that it allows for more general functional forms than does LP.

Dynamic programming is a quantitative method that accounts for time intervals in a decision-making process. Trueman (1978) describes four concepts of dynamic programming:

"*Stage* - each point in the problem where a decision must be made.

"*State* - information describing the problem at each stage, generally in the form of specific values of state variables.

"*Policy* - a decision-making rule which, at each stage, permits a feasible sequence of decisions.

"*Optimal policy* - a policy which optimizes the value of a criterion, objective, or return function."

According to Andriole (1989), dynamic programming methods are well-suited to problems dealing with production planning, resource allocation, and equipment reliability and replacement. Other problems involving multi-stage or time-phased decisions are also likely to be well-suited to a dynamic programming approach.

MS/OR models are sometimes classified based on whether they use deterministic information or stochastic information. For modeling situations where uncertainty is important to include, the following tools have been widely used: queuing analysis; Markov processes; and Monte-Carlo simulation. Books such as Anderson, Sweeney and Williams (1994) cover these MS/OR techniques along with an array of deterministic modeling techniques such as LP.

While MS/OR models have been and will continue to be the basis for very useful decision aids for organizations such as ConnDOT, their situation-specific nature and relatively high level of sophistication make it difficult to recommend them for broad-based adoption within the Department. It is more appropriate for them to be considered for use on specific problems, such as the maintenance facility location problem addressed by Campbell and Davis (1994). Consequently, MS/OR models are not emphasized in the remainder of this report, even though they are an area of great interest to both of this project's principal investigators.

Artificial Intelligence

Probably the most sophisticated DSSs available today are those that utilize artificial intelligence (AI) engines. AI is a relatively new field aimed at developing computer systems that use the knowledge provided by experts and generated by the computer to work through a problem, using the information in a human-like thought process.

AI systems are not limited to those that aid in the decision-making process. In fact, their applications are quite widespread, ranging from robotic vision systems to expert systems. Expert systems (ES) are likely the form of AI that is most directly applicable to decision support. An expert system uses a "knowledge base" provided by experts so that their expertise can be easily accessed by others. One well-known example of such expert systems are medical condition diagnostic tools. Provided with information regarding a patient's condition and specific test results, the ES will diagnose the likely cause(s) of the patient's condition.

Use of AI in decision-making is a new and exciting area. This excitement, however, may lead some to see AI as a decision-making panacea, which it is not. AI can be an expensive and complex technique to use when developing a decision-making aid. Until further developments are made in this field, applications should be very carefully evaluated before substantial investments are made. Further discussion of AI can be found in books such as Mirzai (1990) and Harmon and King (1985).

III. TOOLS FOR ALTERNATIVE EVALUATION AND DECISION ANALYSIS

This section of the report provides a more detailed discussion of the category of DSSs that was identified as most appropriate for further investigation. Within this category, the two techniques that are of greatest interest are: 1) multi-criteria decision making (MCDM); and 2) decision and risk analysis (D&RA). These techniques are covered individually in this section.

Multi-Criteria Decision Making (MCDM)

MCDM methods involve four major steps: (1) define the evaluative criteria upon which the selection of alternative(s) will be based, (2) specify the relative importance of the criteria, (3) assign measurement values for each alternative corresponding to each of the criteria, and (4) select the most appropriate alternative.

With the aid of computers, the number of alternatives that can be evaluated, or the number of criteria upon which the evaluation is based, is virtually unlimited. Examples of applications of MCDM will be provided, but first the basic steps of the MCDM process are discussed.

Once the alternatives to be considered as part of the decision-making process are generated, criteria for evaluating the alternatives must be developed. The criteria are developed by the decision maker(s) and are required as inputs to the DSS.

After criteria are defined, the decision makers have the opportunity to specify the relative importance of each criterion with respect to the others. A simple, commonly-used approach for this is the assignment of weights to the different criteria. More sophisticated MCDM tools allow for the development of more complex utility functions that define the relative importance of the criteria. The process of specifying the relative importance of the criteria is dependent on the specific MCDM analytical approach employed.

Before the alternatives can be evaluated, each alternative must be assigned a measurement value associated with each criterion. As with the development of utility functions, the details of assigning measurement values for alternatives are dependent upon the specific MCDM analytical approach in use.

Based on the utility function and the measurement values provided by the user(s), the alternatives are then evaluated. The result is, in most cases, the identification of one alternative that is "best", based on the inputs of the DM(s). Sensitivity analysis can then be performed to see how robust the decision is in the face of changes to the utility function.

One approach to MCDM is that of "goal programming." Goal programming involves identification of required or desired achievement levels for specific goals or criteria. The goals are prioritized (similar to establishing the relative importance of criteria, as discussed above), and a decision rule based on minimization of deviations from the specified achievement levels is implemented.

Another MCDM approach that has been widely used is the analytic hierarchy process (AHP). Developed by Saaty (1980), AHP has been the subject of much praise and criticism (see Dyer 1990). AHP is similar to other MCDM in that it involves the identification of evaluative criteria and the assignment of values to the criteria for each alternative. The major difference lies in the way that the relative importance of the criteria is established. A hierarchical structure of criteria and sub-criteria is developed and used as the basis for defining the overall utility function.

MCDM techniques are in widespread use in a variety of applications, nearly all of which use some form of DSS. An assortment of inexpensive MCDM software is readily available and adaptable to many different decision-making scenarios. Several surveys and evaluations of this type of software have been performed in the recent past. Three of these are discussed briefly below.

Buede (1992) performed a thorough evaluation of 32 DSS packages separated into five categories. Buede's categorization separates what we have defined as MCDM methods into two categories: value matrix packages and multi-attribute utility analysis (MAUA). Value matrix packages assist the user in creating a matrix of options and criteria for the purpose of developing a weighted score for each of the options. The MAUA packages take a similar approach, but also provide a means for the hierarchical structuring of the evaluative criteria. The purpose of Buede's study was to identify those features of the available software that are most useful in a decision support software package. The software features discussed not only relate to the performance of the software, but also to the user friendliness of the packages. Also included are brief description of the software packages, including prices (which range from $40 to $1500) and the hardware requirements of the packages (all PC-based).

A more recent survey by Buede (1993) is not an evaluation, but instead reports information that was provided by software producers. That summary covers both MCDM software and software for decision and risk analysis, which is discussed in the second part of this section.

Hodge et al. (1992) presents yet a third survey of low cost (under $600) decision support software, focusing only on those packages that support multi-attribute decision analysis (a form of MCDM). Their compilation reports summary information concerning 24 packages, but does not provide evaluative insight or judgement.

Many of the software packages discussed in the evaluations and surveys mentioned above have been used successfully in a variety of decision-making scenarios. Several examples are included in the book by Keeney and Raiffa (1993). In many instances, the use of a $500 MCDM software package can provide such an improvement in the decision-making process that the cost of the package itself becomes irrelevant.

Barnhart (1993) reported on how Boeing used an MCDM-based DSS for the selection of a supercomputer. In the initial stages of the decision-making process, Boeing established the criteria upon which the systems would be evaluated. This process consisted of a brainstorming session to identify all criteria for the decision. The list of criteria was then pared down to the key criteria and subcriteria, and the criteria were weighted according to their importance in the evaluation of alternatives. Information upon which to evaluate each alternative was then gathered from potential vendors. This information was used, via the software package *Criterium*, to rank each of the potential vendors based on five main criteria: price, performance, user needs, operational needs and management issues. Initially, the top six alternatives appeared to be very comparable. However, once the required information was entered into the software package, the best computer was quickly identified. As stated by Barnhart (1993), the decision support software:

"* reduced the risk of the decision to buy a multi-million dollar computer.
* allowed the evaluation team to present its decision with confidence.
* documented the results so that anyone can examine how and why the decision was made.
* facilitated group decision-making."

In a similar application, Intel used an MCDM-based DSS called *Decision Pad* for the selection of suppliers, as reported by Evans-Correia (1991). The use of a DSS has allowed Intel to go beyond the simple number crunching analysis provided by purchasing software and spreadsheet programs to enable them to include more evaluative criteria in their selection process and to obtain a fair comparison of vendors. The software allows specification of multiple criteria and weighting of criteria in order of importance. It also simplifies the monthly reevaluation of suppliers and potential suppliers.

While most published reports expound upon the virtues of MCDM techniques, these techniques do have some disadvantages. Perhaps the most significant is that they do not allow for sequential decision-making over time. Also, MCDM techniques do not provide a means for explicitly accounting for uncertainty in outcomes. This disadvantage can be overcome to a degree, however, via the use of sensitivity analysis, which is available in most commercially-available packages.

Decision and Risk Analysis (D&RA)

D&RA tools are more complete than MCDM techniques in that the likelihoods of specific outcomes are included in the analysis. D&RA techniques use probability trees and influence diagrams as tools to assess the probability of occurrences affecting a decision. The probability of specific outcomes is assessed based on the probability of events occurring that must precede the specific outcomes. For example, the probability of receiving four inches of snowfall is dependent on the probability of precipitation and the probability of temperatures being below freezing. To maintain the manageability of probability trees, it is necessary that the number of possibilities be limited to only those that are realistically probable. Development of an influence diagram is based on forecasting a chain of events, and then assessing the likelihood of each event given the likelihoods of the other events. These considerations are also reflected in decision trees, which are discussed in greater detail below.

Decision trees are the most popular tool used for D&RA. In developing a decision tree, the DM must provide an evaluation of key uncertain events (and potential outcomes), and a valuation of each potential outcome. The decision tree provides both a graphical and a quantitative representation of the decision problem.

Decision trees are frequently used as tools in strategic decision making. An example of a decision tree is provided in Figure 2. Different decision options are represented by branches of the tree. Depending on the option chosen, another decision may be required, or an uncertain event may be encountered. In either case, the tree branches out further. Following a series of chance events and/or decisions, a final outcome is reached resulting in a "payoff", or value assigned to that outcome. The decision tree can then be analyzed to determine the expected value of the original decision options. In Figure 2, this analysis suggests that the most appropriate course of action is to allow for the possibility of alternate fuels when the new transit facility is constructed.

ILLUSTRATION OF DECISION AND RISK ANALYSIS:

Hypothetical Problem: Allowing for Alternate Fuels in the Construction of a New Transit Facility

Assumptions:

-- project costs without allowing for alternate fuels: $ 2.0 million

-- project costs with allowing for alternate fuels: $ 3.0 million

-- cost to upgrade a facility to allow for alternate fuels: $ 2.0 million

-- probability that alternative fuels will be used in the near future: 60 %

Note: costs and probabilities have been fabricated solely for illustration purposes.

DECISION TREE FOR HYPOTHETICAL EXAMPLE:

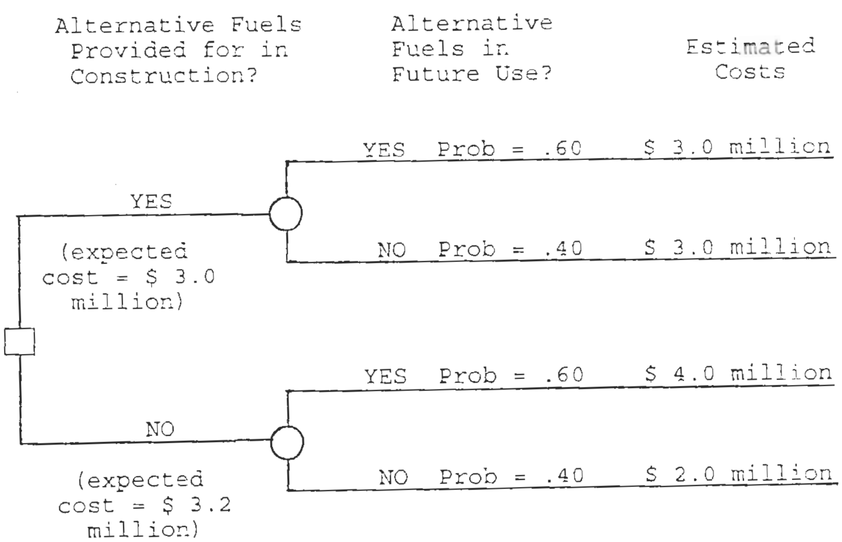

Figure 2. Example of a decision tree based on a hypothetical problem.

D&RA offers many of the same benefits as MCDM because multiple criteria can be incorporated into the analysis. Unlike MCDM, however, the probability of future outcomes is explicitly incorporated into the decision-making model and D&RA has the capability of accounting for decisions that are sequential over time. Accordingly, D&RA can be considered the more complete of the two methods discussed in this section.

Although it is more complete than MCDM, D&RA is not without its disadvantages. For example, it is important that decision makers be familiar with how to construct a decision tree. Although decision tree construction aids are available in many commercial software packages (see review by Buede 1993), the software cannot construct the tree for the decision maker. To accurately construct a decision tree, detailed knowledge of the decision(s) to be made and the potential outcomes is necessary. Without a thorough understanding of the process, construction of an appropriate tree can be difficult. Even with guidance from computer-based systems, a general understanding of decision trees is essential to ensuring the accuracy of the model.

Although some degree of user sophistication is needed, the knowledge requirements are not so great as to present a serious obstacle to the use of D&RA. In a special issue of the journal Interfaces that focused on D&RA, Kirkwood (1992) indicates that the use of this technique is quite wide-spread. He also discusses recent theoretical developments in the area that have been incorporated into decision support software. Based on the successful use of D&RA tools reported by organizations such as DuPont (Krumm and Rolle 1992); General Motors (Kusnic and Owen 1992); and several electric utility companies (Balson, Welsh and Wilson 1992), it is clear that D&RA techniques are well-established and valuable tools for supporting decision makers in a variety of organizations.

The in-depth review of D&RA and MCDM described in this section and the broad-based review of literature described in Section II together represent only the first part of the work performed for this project. The second part of the project involved communicating findings with ConnDOT and receiving their input regarding the types of tools that would be most useful to them. The interactions involved in this second part of the project are described in the next section.

IV. INTERACTIONS WITH CONNDOT

After completing the literature review and deciding upon a tentative set of decision support tools to focus on, the principal investigators (PIs) obtained feedback and further input from ConnDOT. Interactions between the PIs and ConnDOT occurred in five stages involving the following ConnDOT personnel:

Stage 1) Research Management;
Stage 2) Executive Management;
Stage 3) All ConnDOT Managers;
Stage 4) Personnel with potential applications; and
Stage 5) A Task Group focused on the pavement markings application.

At the first stage of interactions between the PIs and ConnDOT, the PIs presented a summary of the literature review, with emphasis on the MCDM and D&RA material. This stage occurred during September, 1993. The primary objectives at this stage of interaction were: 1) to determine whether it was appropriate for the project to focus on alternative evaluation and decision analysis methods; and 2) to identify who else within ConnDOT the PIs should be interacting with for the remainder of the project.

At a meeting between the PIs and ConnDOT's Director and Assistant Director of Research and Materials, the various types of decision support systems were discussed. The discussion started with an overview of decision support systems, including the five varieties discussed in Section II. The discussion then turned to further explanation of tools for alternative evaluation and decision analysis.

Multi-Criteria Decision Making (MCDM) was illustrated using two examples, one from the British Columbia Power Authority (Keeney and McDaniels 1992) and one from the University of Connecticut (Office of the Provost 1993). Both of these examples use MCDM techniques to help with strategic decision making at the highest levels of the organizations. As these examples were being discussed, it was suggested that an illustration that would have more meaning to ConnDOT personnel would be useful when the technique was presented to others within the Department. A ConnDOT study addressing the selection of alternative fuels for transit buses was mentioned, and a copy of the report resulting from that study was subsequently given to the PIs. As discussed later on, the problem of selecting alternative fuels was used thereafter as a basis for illustrating the MCDM technique.

The other technique discussed in depth with ConnDOT Research Management was Decision and Risk Analysis (D&RA). This technique was illustrated by describing how the DuPont corporation has used D&RA for various kinds of decisions, including the selection of a strategy for new product introduction (see Krumm and Rolle 1992). Decision trees and influence diagrams -- two tools of D&RA -- were illustrated using simple examples. Again, it was suggested by ConnDOT that the PIs develop an example that would be more meaningful to others within the Department. The problem of whether or not to allow for alternate fuels when constructing a new transit facility was suggested. Subsequently, a hypothetical example based on this problem served as an effective illustration of the D&RA technique (refer back to Figure 2).

Besides MCDM and D&RA, group decision-making methods were also discussed. These methods work in conjunction with MCDM and D&RA to ensure that inputs are obtained from all stakeholders, and to help build consensus and commitment to decisions. Group decision-making methods include participatory techniques such as: brainstorming, the Delphi method, and what Kusnic and Owen (1992) call the "unifying vision process." ConnDOT Research Management agreed that methods such as this were important to use for decisions involving multiple stakeholders, and they indicated that personnel within ConnDOT had received training in such a technique called the "total quality effort" (TQE). In fact, this participatory technique had been used during the aforementioned alternative fuels study.

Besides discussing alternative evaluation and decision analysis techniques with ConnDOT Research Management, the PIs also proposed possibilities for application areas within ConnDOT. At this stage, the proposed application areas related to the management systems required under the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). Shown below is an excerpt from an article written by a strategic planner for the Texas DOT.

> Prioritizing complex alternatives such as congestion mitigation strategies may require multicriteria/multiobjective methods for some of the new management systems.
> (Hagquist, 1993, p. 20).

The PIs believed that MCDM and D&RA had high potential for use both within and across the various management systems required under ISTEA. ConnDOT Research Management confirmed that ISTEA was a key concern within the Department.

At the conclusion of the first stage of interactions between the PIs and ConnDOT, agreement had to be reached regarding how to proceed with further interactions. It was decided that the PIs would deliver a revised version of their presentation to a group of ConnDOT Executives, who would then help to decide how to proceed further.

The second stage of interactions between the PIs and ConnDOT began when the PIs prepared a presentation packet for review by ConnDOT Executive Management. This packet was a pared-down and refined version of what the PIs had discussed with ConnDOT Research Management. In October of 1993, the PIs met with a group from ConnDOT that included two Deputy Commissioners and the Director of Research and Materials. At this meeting, there was general agreement that the next step should be a presentation by the PIs at a ConnDOT all-managers' meeting.

Stage three of the interactions between the PIs and ConnDOT occurred at the all-managers' meeting held at ConnDOT headquarters in Newington, Connecticut in November of 1993. In front of the entire group of managers, the PIs delivered a presentation based on the material shown in Appendix A. Again, this presentation was along the same lines as what was discussed with ConnDOT Research Management and Executive Management. However, for the all-managers' meeting the presentation was designed to be delivered within a twenty-minute block of time. As indicated on the last page of Appendix A, the PIs sought input from ConnDOT management regarding the appropriateness of the techniques and possible areas of application. During the meeting's break, several managers visited the PIs at a graphical display area that the PIs had set up in the building's lobby. During these visits, MCDM and D&RA techniques were discussed in further depth, and ideas for possible applications were identified. One of the possible application areas for MCDM that emerged was that of evaluating alternative pavement markings. Arrangements were made to follow-up on the ideas generated at the all-managers' meeting, and this concluded the third stage of interactions between the PIs and ConnDOT.

The fourth stage of interactions occurred during December of 1993. This stage included further discussion of possible application areas and identification of a decision problem to use as an initial application. Of the two techniques (MCDM and D&RA), MCDM is conceptually simpler and more easily adopted, which contributed to it being preferred as the technique to be used for the first application. Discussions at this stage of the project revealed that weighted scoring, which is a simple form of MCDM, was already being used within ConnDOT as the basis for a "Project Development Rating System." Further development of this system was considered as a possibility for the first application of an MCDM-based DSS, but the problem of choosing amongst pavement marking alternatives eventually emerged as the preferred initial application. The decision to apply MCDM to the pavement markings selection problem marked the conclusion of stage four of the interactions between the PIs and ConnDOT.

Stage five began with the formation of a pavement marking task group composed of ConnDOT personnel from the following areas: Traffic, Research and Materials, Construction, Highway Operations, and Design. The function of this task group has been to work with the PIs to accomplish tasks A through J of the work plan shown in the project proposal included as Appendix B of this report. This work, which is part of a follow-on project stemming from the project described in this report, will be concluded during the summer of 1994. A description of the interactions between the PIs and ConnDOT during this stage will be included in a separate report describing the pavement markings application.

This concludes the discussion of the interactions that have occurred between the PIs and ConnDOT. These interactions have had a strong effect on the path that the original project followed and on the direction that the follow-on project has taken. Further interactions will be essential for the successful completion of Tasks K and L of the follow-on project (see Appendix B), which involve identification and follow-through on other applications of MCDM and/or D&RA within ConnDOT.

V. CONCLUSION

This project was initiated with the primary goal of identifying decision support tools that would have a high probability of being useful within ConnDOT. Based on the progress that has been made on this project and the progress to date on the follow-on project, it appears as though this goal has been accomplished. Ultimately, however, the success of this project will be judged by the extent to which alternative evaluation and decision analysis tools are being used within ConnDOT several years from now.

This report has been structured according to how work proceeded on the original project. Initially, a broad-based review of the literature on decision support systems was performed. This review was summarized in Section II. Then, attention was focused on two tools for alternative evaluation and decision analysis. Section III discussed these tools (multi-criteria decision making and decision and risk analysis) in depth.

Section IV described five stages of interactions that have occurred between the principal investigators and ConnDOT personnel. At each stage, the focus of the project has been further clarified until, finally, at stage five, work on a specific application was initiated.

Work on the pavement markings application is still in progress. Multi-criteria decision making software has been purchased, a goals hierarchy has been developed, and progress has been made on establishing a utility function. As the work progresses, the principal investigators and the ConnDOT personnel involved continue to learn more about MCDM and the kinds of interactions that are necessary to build a useable computer-based decision support system.

The follow-on project described in Appendix B includes, as tasks K and L, the identification of other potential applications for alternative evaluation and decision analysis tools within ConnDOT. Considering the nature of the follow-on project, it is clear that the original project described in this report actually represents a first step towards meeting the need that was communicated by Commissioner Frankel in the summer of 1992.

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APPENDIX A. MATERIAL PRESENTED AT CONNDOT MANAGERS' MEETING

Slide 1

EVALUATING THE APPLICABILITY OF ANALYTICAL

DECISION SUPPORT TOOLS FOR ConnDOT

Joint Highway Research Project # 93-2

Principal Investigators:

Dr. Gerard Campbell, UConn School of Business
Dr. Christian Davis, Uconn School of Engineering

Slide 2

OBJECTIVES OF THIS PRESENTATION

1) Inform ConnDOT management about the project.

2) Illustrate two specific decision support techniques:

   i) Multi-Criteria Decision Making;

   ii) Decision and Risk Analysis.

3) Request your input regarding applicability.

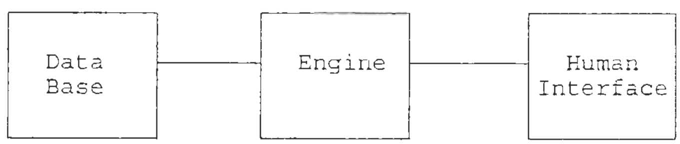
Slide 3

INITIAL PROJECT FOCUS:

Broad-Based Review of Decision Support Systems

<u>Decision Support System</u>: a computer-based, interactive system that supports decision makers, rather than replacing them.

BASIC COMPONENTS OF A DECISION SUPPORT SYSTEM:



Slide 4

FIVE VARIETIES OF THE "ENGINE" COMPONENT:

1) Data Management

2) Alternative Generation

3) Alternative Evaluation / Decision Analysis

4) Management Science / Operations Research Models

5) Artificial Intelligence / Expert Systems

CURRENT PROJECT FOCUS:

Alternative Evaluation / Decision Analysis

Slide 5

TOOLS FOR ALTERNATIVE EVALUATION / DECISION ANALYSIS:

1) Cost / Benefit Analysis

2) Multi-Criteria Decision Making

3) Decision and Risk Analysis

COMMON CHARACTERISTICS:

-- relatively simple to learn

-- applicable to a wide range of problems

-- help to improve communication and facilitate informed debate

-- serve as vehicles for consensus-building

-- supported by inexpensive, P.C.- based software

-- widely used in private and public organizations

Slide 6

ILLUSTRATION OF MULTI-CRITERIA DECISION MAKING:

Hypothetical Problem: Alternate Fuel Selection

Criteria:	Costs	Safety	Pollution	
Weights:	.50	.30	.20	
Alternatives				Total Score
Methanol:	3	1	1	2.0
Natural Gas:	2	2	1	1.8
Solar:	1	3	3	2.0

scores based on each criterion

Note: scores and weights have been fabricated solely for illustration purposes.

Slide 7

ILLUSTRATION OF DECISION AND RISK ANALYSIS:

Hypothetical Problem: Allowing for Alternate Fuels in the Construction of a New Transit Facility

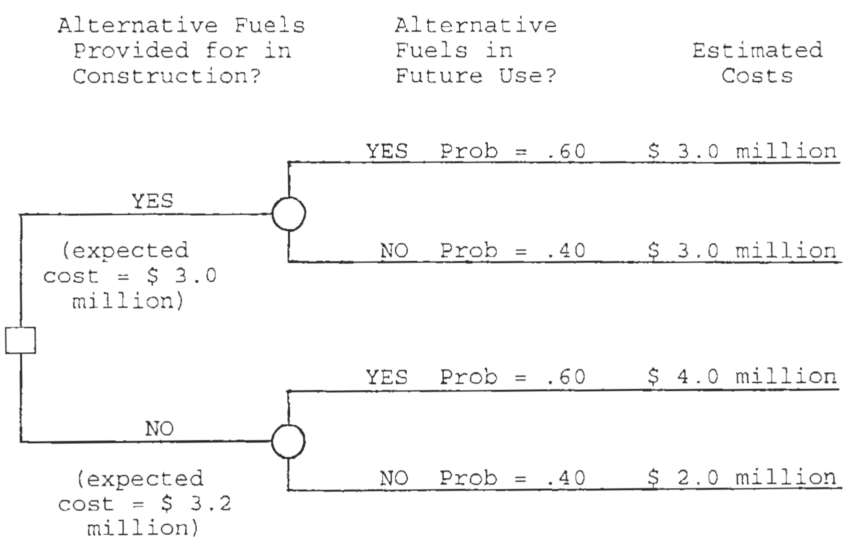
Assumptions:

- -- project costs without allowing for alternate fuels: $ 2.0 million
- -- project costs with allowing for alternate fuels: $ 3.0 million
- -- cost to upgrade a facility to allow for alternate fuels: $ 2.0 million
- -- probability that alternative fuels will be used in the near future: 60 %

Note: costs and probabilities have been fabricated solely for illustration purposes.

Slide 8

DECISION TREE FOR HYPOTHETICAL EXAMPLE:



Slide 9

POSSIBLE APPLICATION ENVIRONMENT FOR
ALTERNATIVE EVALUATION / DECISION ANALYSIS:

Six Management Systems Required under ISTEA

-- Pavement Management

-- Bridge Management

-- Safety Management

-- Congestion Management

-- Intermodal Management

-- Public Transportation Management

Within systems: multiple criteria, uncertainties, and sequential decisions exist within each system.

Across systems: by analyzing trade-offs that encompass different performance measures, multi-criteria analysis can help to integrate the six systems.

Slide 10

BENEFITS REPORTED BY USERS:

-- improved communication within the organization

-- increased attention to new and different approaches

-- change is facilitated

-- seen as clear and logical approach to making choices

-- helps to clarify issues amongst stakeholders

-- facilitates informed debate

-- helps to handle unavoidable value trade-offs

Slide 11

REQUIREMENTS FOR SUCCESSFUL IMPLEMENTATION:

-- Top management's support

-- Introductory training for all users

-- In-depth training for "internal experts"

-- Purchase of P.C. - based software

-- Adoption by individual managers for specific projects

Slide 12

FROM ConnDOT, WE WOULD LIKE TO KNOW:

1) Which techniques(s) should we pursue?

a) Multi-Criteria Decision Making
b) Decision and Risk Analysis
c) both
d) None of the above

2) In what areas and on what specific projects might these techniques be useful?

TO OFFER YOUR INPUT:

-- See us during the meeting's break

-- Call us at the phone numbers listed on your handout.

APPENDIX B. PROPOSAL FOR FOLLOW-ON PROJECT

Joint Highway Research Program Project Proposal

IMPLEMENTING DECISION SUPPORT TECHNIQUES
FOR THE SELECTION OF PAVEMENT MARKINGS AND OTHER APPLICATIONS

Continuing Project No. 93-2

Principal Investigators:

Gerard M. Campbell
Christian F. Davis

December 1993

1. 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, plastics have made inroads into the pavement marking market. Each of these systems have unique placement and performance requirements and characteristics, with significantly different costs.

Given the diverse highway system in this state, there is a need to develop and implement policies which treat the use of various marking materials in an optimal and cost-effective manner. An ongoing study in our Cooperative Research Program at the University of Connecticut presents a technical basis to develop needed policies or guidelines for the use of various pavement marking materials.

In the above-mentioned ongoing study, the principal investigators have identified Multi-Criteria Decision Making (MCDM) and Decision and Risk Analysis (D&RA) as two decision support techniques that have good potential for use within ConnDOT. Both of these techniques have been successfully applied in many organizations to support a wide range of decisions involving the evaluation of alternatives. There is interest in using these techniques on specific applications within ConnDOT, especially with respect to the use of MCDM for evaluating pavement marking alternatives. However, there is little expertise within the organization regarding these techniques and associated commercially-available software packages.

Benefits of Multi-Criteria Decision Making and Decision and Risk Analysis that have been reported by users include the following:

- -- they improve communication;
- -- they clarify issues for stakeholders;
- -- they facilitate informed debate;
- -- they help to build consensus;
- -- they increase attention to new approaches;
- -- they provide defensible approaches to decision making.

The techniques are especially useful when there are other relevant criteria besides costs, which is certainly the case for the problem of selecting pavement markings. For that application, safety, durability, ease of application, and reflectivity are the types of additional criteria that must be considered when choosing amongst available pavement marking alternatives such as paints, epoxies and plastics.

Because the potential for the decision support techniques to be used within ConnDOT is very good, it is important for initial applications to be done carefully. Initial successes will increase the likelihood that the above-mentioned benefits can be achieved on a large scale within ConnDOT.

2. Objectives

The primary objective of this project is to support the use of Multi-Criteria Decision Making for the development of guidelines for the application of various types of pavement marking materials on Connecticut highways. A secondary objective is to explore other potential applications of Multi-Criteria Decision Making and Decision and Risk Analysis within ConnDOT.

3. Work Plan

In recognizing the importance of pavement markings, a Task Group has been designated by the Deputy Commissioner of the Bureau of Engineering and Highway Operations (see Attachment 1). This Task Group represents a significant cross section of affected DOT offices. It will function to provide practical guidance to the researchers in terms of DOT operations and requirements.

The principal investigators will provide support for the introduction of Multi-Criteria Decision Making within ConnDOT. Their support will be greatest during the first application, which will involve the use of MCDM for evaluating pavement marking alternatives. For this application, the principal investigators will be heavily involved in the process of identifying objectives and building an objective function for use in evaluating alternatives. The P.I.s will also identify and procure appropriate software and transfer it to ConnDOT for them to use in evaluating pavement marking alternatives.

After MCDM has been applied to the problem of selecting pavement markings, other applications for MCDM will be pursued. The focus of the project will turn from a specific application to more wide-spread dissemination of the MCDM technique. By the end of this part of the project, the usefulness to ConnDOT of Multi-Criteria Decision Making should be well-established. It is not expected that Decision and Risk Analysis will be applied in this part of the project, but the principal investigators will assist in identifying potential applications for that technique if there is sufficient interest. Support for the application of D&RA might be provided in the future if the project is continued beyond what is outlined in this proposal.

Specific work tasks are outlined below:

Task A -- Conduct a group meeting for all stakeholders to discuss the application of MCDM to the evaluation of pavement markings.

Task B -- Work individually with stakeholders to identify sets of objectives to be used for evaluating pavement markings.

Task C -- Combine sets of stakeholders' objectives into a single set, and review this set with stakeholders at a second pavement markings group meeting. At the meeting, discuss the need to identify measurable attributes for all objectives.

Task D -- Work individually with stakeholders to identify measurable attributes and begin to develop an objective function (e.g. weights) to be used for evaluating pavement markings.

Task E -- Discuss the objective function at a third pavement markings group meeting.

Task F -- Outline the information needed for each type of pavement marking so that the evaluation can be completed.

Task G -- Write report describing the pavement markings application.

Task H -- Select and procure two copies of Multi-Criteria Decision Making software.

Task I -- Learn to use the MCDM software and set it up for the pavement markings application.

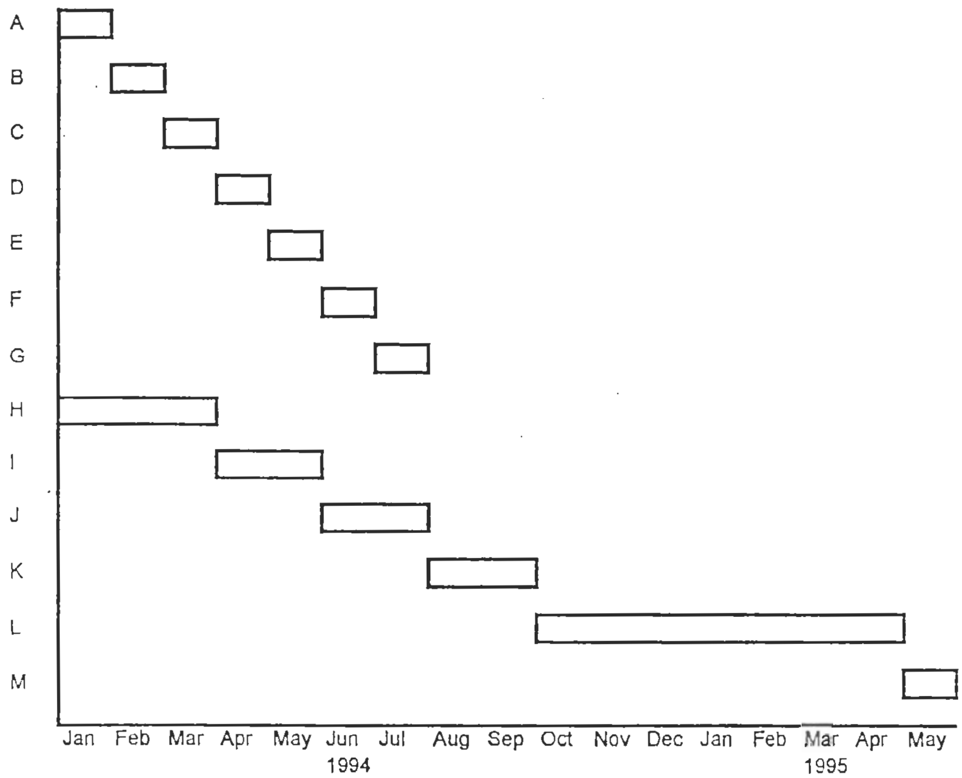
Task J -- Deliver one copy of the MCDM software to appropriate ConnDOT personnel, and demonstrate its use for the pavement markings application. Provide support as they learn to use the software themselves.

Task K -- Identify other potential applications of Multi-Criteria Decision Making and/or Decision and Risk Analysis within ConnDOT.

Task L -- For attractive applications of MCDM identified in step K, provide assistance in selecting software, identifying stakeholders, etc.

Task M -- Write Final Report, which will include the report from step G as one of its sections.

4. Work Schedule



Attachment 1

PAVEMENT MARKINGS
TASK GROUP FOR UCONN WORK

Project JH 93-2

Walter Coughlin - Chairman - Traffic
James Simo - Research
Rolland Mayo - Materials Testing
Paul Breen - Construction
John Micali - Highway Operations
William Seory - Design
Vincent Avino - Traffic