Application of Multi-Criteria Decision Making and Risk Analysis to Congestion Management

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16. Abstract

This paper describes how two operations research decision making tools, Multicriteria Decision Making (MCDM) and Risk Analysis (RA), were applied within a congestion management system for selecting among corridor improvement options. These two tools were used in conjunction with transportation system modeling techniques. Each corridor improvement option is defined to have certain consequences with respect to the decision maker's goals. The measures of the consequences are estimated or forecast by the UMTA four-step modeling process and by traffic simulations using NETSIM. Air quality measures are estimated using MOBILE5a. Uncertainty in the future operating environment is also included in the procedure. The procedure is demonstrated through a simple hypothetical application in which two alternatives are compared. The example shows that the concepts involved are relatively easy to learn and use. Off-the-shelf software, which is available to implement these tools, provides useful sensitivity analysis features which are discussed as part of this paper.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

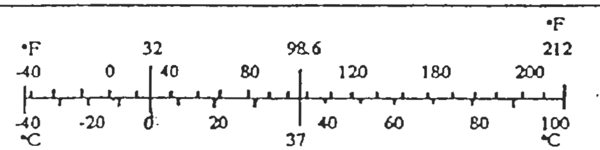
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.093	metres squared	m²
yd²	square yards	0.836	metres squared	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	kilometres squared	km²
	VOLUME			
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft³	cubic feet	0.028	metres cubed	m³
yd³	cubic yards	0.765	metres cubed	m³
	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

NOTE: Volumes greator than 1000 L shall be shown in m³.

*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			
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
ha	hectares	2.47	acres	ac
km²	kilometres squared	0.386	square miles	mi²
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
	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

CMS -- congestion management system.

DM -- decision maker.

ISTEA -- Intermodal Surface Transportation Efficiency Act

RA -- risk analysis.

MCDM -- multi-criteria decision making.

I. INTRODUCTION

The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) mandated that each state develop and implement management systems for highway pavements, bridges, safety, congestion, public transportation and intermodal analysis. The research described herein deals specifically with congestion management. It involved a cooperative effort among researchers of the Connecticut Transportation Institute, the Connecticut Department of Transportation (ConnDOT), and the Capitol Region Council of Governments (CRCOG).

As more fully described below, two techniques of operations research, which are widely used in the private sector, were adapted and integrated for application to congestion management. The techniques, multi-criteria decision making (MCDM) and risk analysis (RA), are frequently used within a decision support system framework that is intended to promote orderly and expedient decision making.

Besides improved decision-making, benefits of decision support systems include:

- improved communication
- clarification of issues for stakeholders
- facilitation of informed debate
- assistance in building consensus
- identification of new approaches
- provision of defensible approaches to decision making
- assistance in handling unavoidable value trade-offs

The last item listed above is especially significant if the Congestion Management System (CMS) is to be integrated with one or more of the other management systems. Integration of these systems will necessitate an approach that incorporates the relevant multiple criteria that span across the six systems. Because MCDM can explicitly consider multiple criteria, its application within a congestion management system can facilitate that system's integration with the other systems.

It cannot be over-emphasized, however, that the techniques are intended to *assist* the decision maker, not *replace* him. Accordingly, informed involvement of all stakeholders is critical at all stages of the process. Conceptually, the potential benefits of application of MCDM and RA to any of the management systems are rather obvious; the unique contribution of the present research is the manner in which the two techniques are linked together and supported by other modelling (e.g. traffic and air quality).

An additional observation is in order at this point. Although the recently enacted National Highway System (NHS) legislation has made the management systems optional, the need for the systematic approach remains. The Federal Highway

Administration has determined that because of the planning regulation requirements, the CMS is still mandatory for TMAs. Indeed, much of what would be required for project level congestion management is required of a major investment study (MIS). Moreover, in a letter to the Federal Highway Administration, Richard Martinez of ConnDOT notes that "...as substantial effort has gone into developing a CMS, including extensive coordination with MPOs, this Department will continue to produce this document. Additionally, the MPOs have found it to be useful, and they have endorsed its continuation." According to a recent article in "Congestion Management News", most states have similar views *(1)*.

Following a review of the literature in the next section, this report describes the methodology in detail. The cooperative effort between the principal investigators and ConnDOT and CRCOG in building the model is given after that, followed by a simple numerical example and conclusions.

II. LITERATURE REVIEW

Efforts to manage congestion pre-date ISTEA. For example, Nash *(2)* describes California legislation of 1989 and 1990 allocating funds for congestion management. Similarly, Kurtz *(3)* reviews efforts in Los Angeles County in the late '90s. Activity in other states since the passage of ISTEA is described by Mcleod *(4)* (Florida), the Texas Department of Transportation *(5)*, the North Carolina Department of Transportation *(6)*, Arnold *(7)* and O'Brien and Jacobson *(8)*. The need for CMSs as well as a discussion of their general features is described by numerous authors, such as Hoeft *(9)*, Lindley *(10)*, Orski *(11)*, Arnott and Small *(12)*, Flynn *(13)*, and Fleet *(14)*. The use of geographic information systems (GIS) as a tool for implementing management systems in general is described by Johnson and Demetsky *(15)*. A major "pooled fund" study to use GIS technology as a system integrator is currently underway. As noted in the Charter for that study, "...(Its) mission is to build an information framework for comprehensive transportation planning which integrates management systems and planning activities to support effective decision making."*(16)*

A description of CMS and discussion of performance measures and strategy evaluation is given in the text of a three day training course by the Federal Highway Administration (FHWA) *(17)*. The FHWA also published a *Technical Report* *(18)* giving case studies for several states and discussing performance measures. Performance measures are also described by Levinson et al. *(19)*. The proposed guidelines for the development of CMSs in Connecticut are given in a 1994 paper *(20)*.

The application of MCDM to transportation projects has been reported by a number of investigators. Won *(21)*, applied three different MCDM methods; concordance analysis , goals achievement matrix, and compromise solution, to auto restraint in Seoul. Giuliano *(22)* used a slightly modified concordance analysis to investigate nineteen transportation alternatives for the Santa Ana transportation corridor in Orange County, California, a source of prolonged peak hour congestion. Bielli *(23)* makes a case for the use of DSSs in dealing with the complexity of urban traffic systems with a large number of conflicting goals. Gomes *(24)* describes a MCDM technique that is easily understood by transportation decision makers and is particularly well suited for situations that require the participation of the public in the process. Kulkarni and his associates *(25)* used a formal decision analysis technique to evaluate alternative alignments for a proposed project wherein the main differences between the alternatives were the environmental and socio-economic impacts of each. The linking of MCDM and DRA is described in a simplified example by Ossenbruggen *(26)*, who introduces the element of uncertainty in the design of a flood protection system. The element of uncertainty associated with transportation decisions is discussed by, among others, Khisty *(27)* and Lewis *(28)*.

III. METHODOLOGY

Multicriteria Decision Making

As the name implies, MCDM involves choosing from among several alternative solutions to a problem based on a tradeoff between multiple criteria or goals. For example, consider the design of an intersection. Further, assume that the design *alternatives* under consideration are (a) left turn bay and (a) no left-turn bay. Depending on the design chosen, a *consequence* will result. For the simple example, we might express a consequence in terms of construction cost, operating cost, air pollution, fuel consumption, and traffic accidents. Presumably, we would choose a design that would minimize each of the five components of the consequence. Unfortunately, in all likelihood, no such design would exist and we would need to make tradeoffs. The basic tool for displaying the tradeoffs is a *goals hierarchy*. The goals hierarchy for the intersection design is shown in Figure 1. Note that the overall goal is to select the "best design" and that several of the goals have been grouped. This grouping allows the goals to be more easily weighted. Also note that the original five components are represented by ellipses. We will refer to these as *measures* and to the higher level entities (rectangles) as *goals*.

The numbers shown next to the goals and measures in Figure 1 correspond to a set of weights which have been assigned. The set of weights chosen will be unique to each individual decision maker and must sum to unity across a given level of the hierarchy. If values were shown for each of the measures, it would be apparent that multiplying the measure values by weights would be meaningless. To overcome this difficulty, the concept of *utility* is introduced. The disparate measures are converted into common units, termed *utiles,* which vary from zero (least preferred) to one (most preferred). The determination of the appropriate conversion functions is often one of the major tasks in the MCDM process.

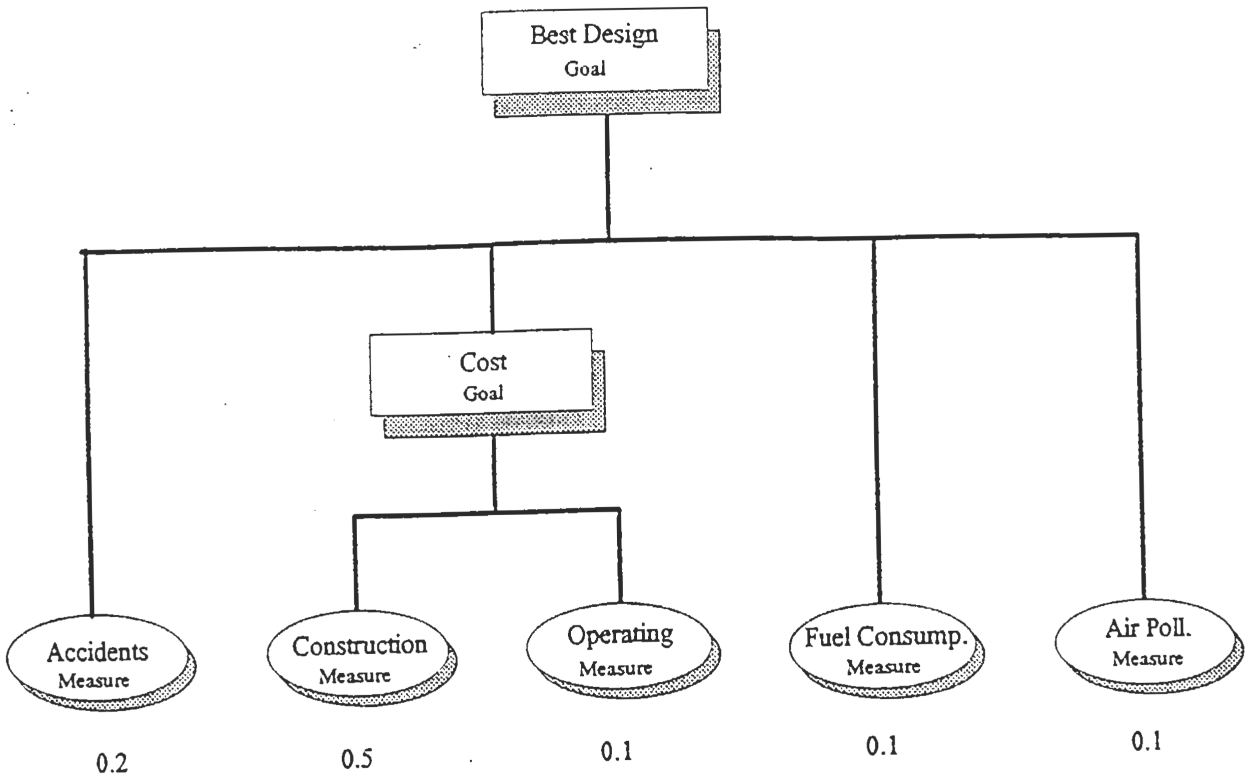

Figure 1. Goals hierarchy for intersection design.

Having established the appropriate utility functions, weights, and measurement values, the process of evaluating the alternatives is straightforward. Each of the alternatives is evaluated by calculating its overall utility. The alternative having the highest utility is then the "best". While, as noted above, the technique is not intended to replace the experience and judgement of the decision maker, it can be a powerful tool when used to support the decision making process.

Risk Analysis

One of the shortcomings of standard MCDM techniques is that they cannot explicitly handle the uncertainties and sequential decision making that RA methods can handle. However, there is no reason why MCDM methods cannot be used in conjunction with RA tools like decision trees and influence diagrams. This type of approach is likely to be appropriate for transportation system planning in general and congestion management in particular because key future events (such as the availability of federal funding and regulations, and predictions made by the transportation modeling process) have a significant degree of uncertainty, and major decisions are likely to depend on the outcomes of these events. For models to be useful in practice, such dependencies must be explicitly incorporated into the analysis.

The basic tool of RA is the *decision tree*, shown schematically in Figure 2. The decision-maker (DM) must chose between alternatives a and a'. Depending on the alternative selected, a "consequence ", **C** or **C'** is reached. The DM would select the alternative leading to the most preferred consequence. In general, the consequence would be represented by a vector of attributes, i. e.,

$$C \leftrightarrow [x_1, x_2, \ldots x_i, \ldots x_n] = X \qquad (1)$$

where the x_i are in disparate units of measurement. In our simple intersection example, the x_i are the five measures. As noted earlier, the disparate measure values must be converted into utiles so that the weighting can be made. The incorporation of chance events into the decision tree is illustrated in the next section.

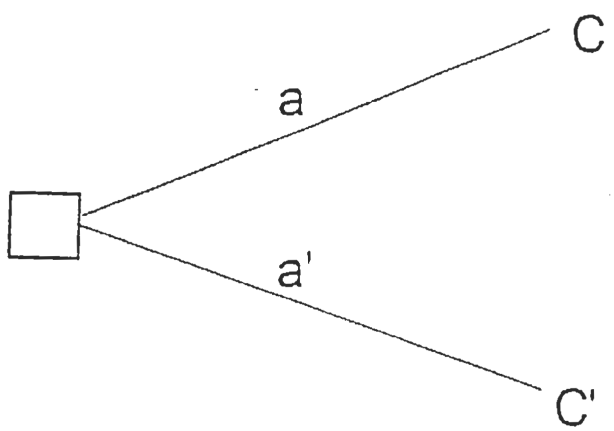

Figure 2. Simple decision tree.

MCDM and RA Combined

Figure 3 shows, conceptually, how MCDM and RA can be coupled. Note that each end of a branch of the decision tree represents the *state of nature* arising from the indicated sequence of decisions and chance occurrences along the branch. In the tree shown, the top entry is the utility of having made decision A and then experiencing outcome 1 of chance event 1 followed by outcome 1 of chance event 2. Knowing the state of nature, an overall utility can be obtained using the techniques described earlier. The *expected* overall utility of each alternative is obtained by working backwards through the tree, weighting the overall utilities by the various probabilities.

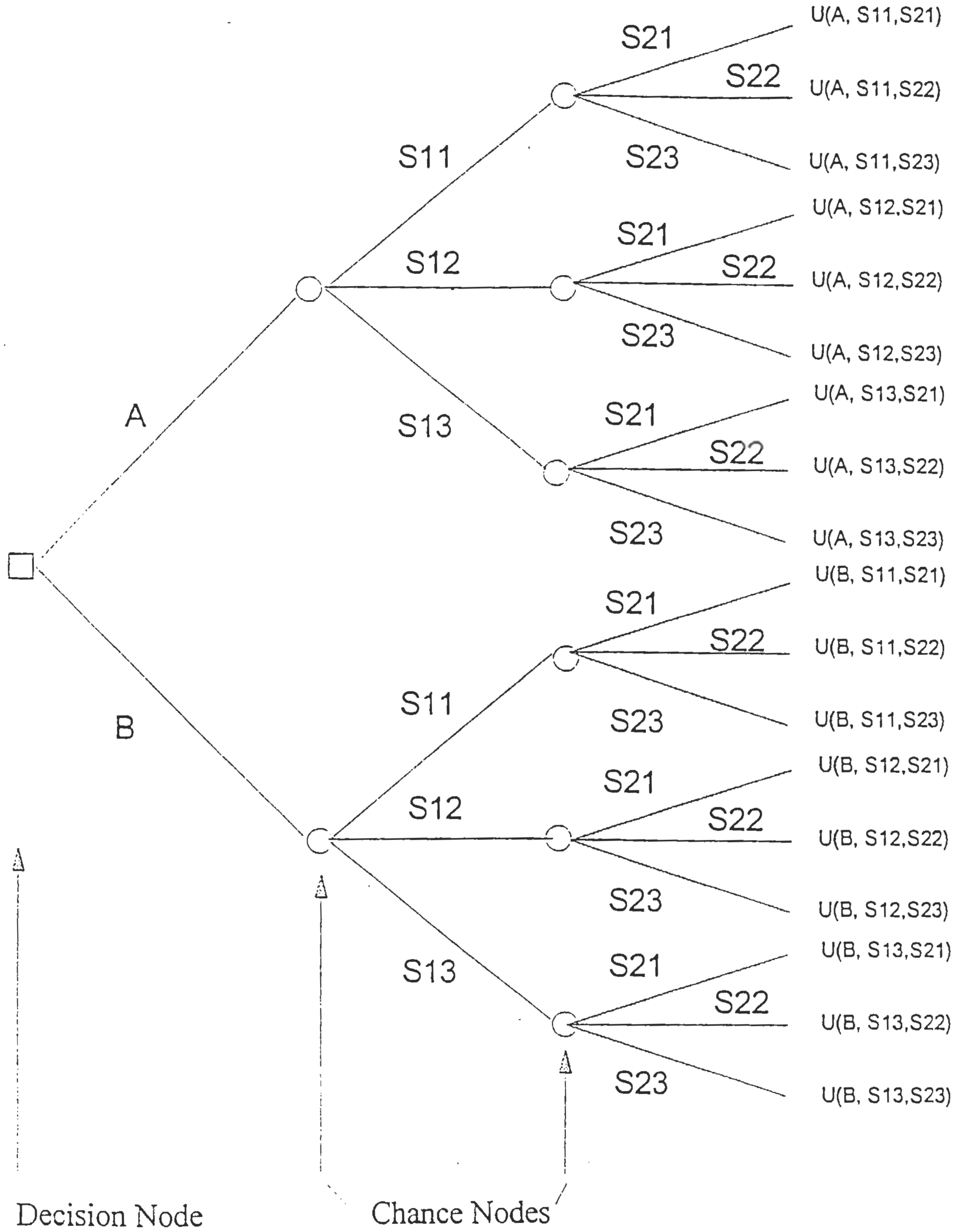

Figure 3. Coupling of MCDM and RA.

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 occurred to obtain inputs needed for the development of the congestion management model.

IV. MODEL BUILDING

The Cooperative Effort

In response to ISTEA, ConnDOT proposed the following two-tiered approach for a congestion management system:

Tier 1: a statewide system of annual reporting and monitoring;

Tier 2: 15 separate regional systems for the purposes of evaluating and implementing congestion reduction strategies.

Under this proposed approach, tier 2 is the joint responsibility of ConnDOT and each MPO (Metropolitan Planning Organization). The present project explored the applicability of MCDM and RA techniques to congestion management decisions with an eye towards incorporating the techniques as part of the second tier of ConnDOT's proposed system.

The specific objectives of this project were as follows:

A) To build an integrated MCDM and RA model that could be useful for supporting congestion management decisions.

B) To adopt one or more of these models to assist in decision-making for a specific congestion management application within one of the state's MPOs.

C) To present the results of the application described above to other MPOs as a way of encouraging additional use of D&RA techniques for other congestion management applications.

Throughout the project, the research team worked closely with personnel from the ConnDOT Bureau of Policy and Planning and CRCOG. Following a literature review of the state-of-the-practice of congestion management, the team reviewed alternatives, evaluation criteria, and performance measures that have been identified as being relevant to congestion management.

The Integrated Models

The linking of models and the flow of information for the overall process are shown in Figure 4. Note that two models have been added - a traffic simulation model (NETSIM) and an air quality model (MOBILE5a). These models are required to transform network characteristics and origin/destination tables for the various *alternative/scenario combinations* into measurement values required as input to the MCDM model. Additional measurement values, not related to traffic modelling, are input directly. In the term *alternative/scenario combination, alternative* refers to a particular congestion management strategy, e.g. increased transit, and is the choice of the decision maker. The term *scenario* refers to a state of nature defined by specified outcomes of all chance events.

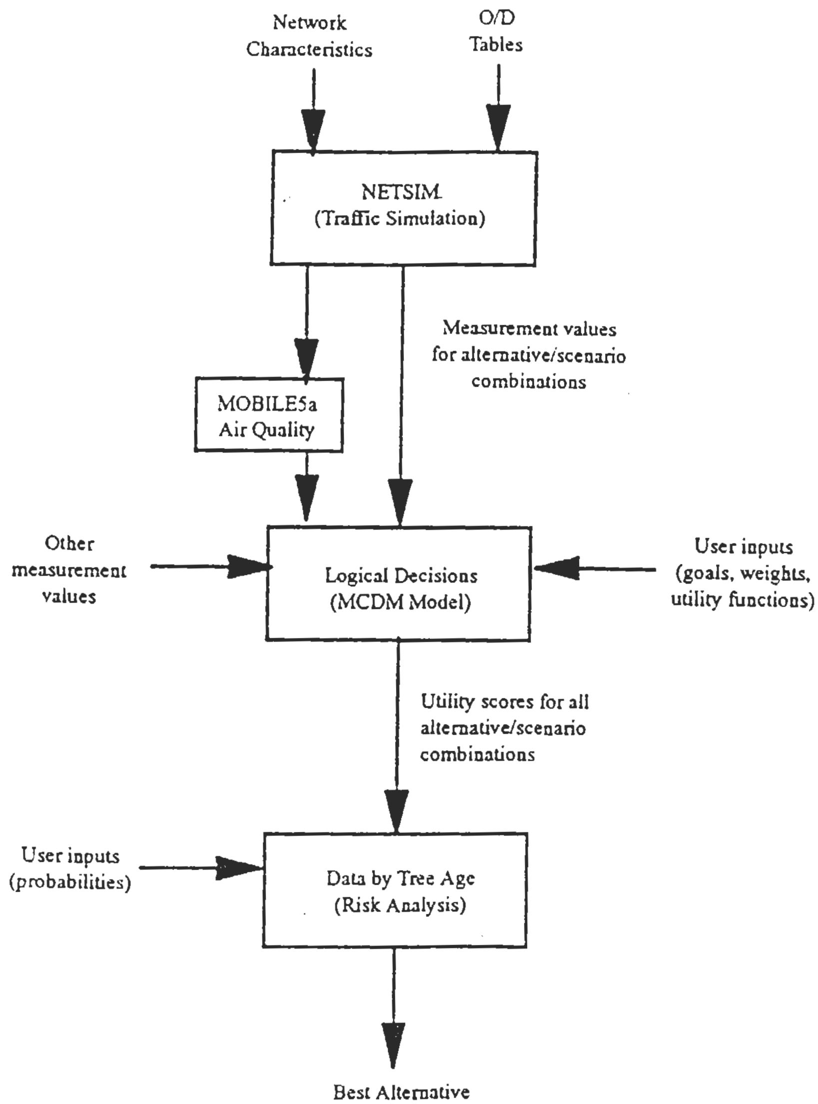

Figure 4. Modelling framework.

Output from the MCDM model consists of utility scores for all alternative/scenario combinations. This output, along with user supplied probabilities, is then input to the RA model which determines the "best" alternative. Because commercially available software packages are used for the MCDM and RA modelling, that part of the overall process can be completed with relative ease.

V. AN EXAMPLE - THE ROUTE 99 CORRIDOR

The 4.8- km (3-mile) Route 99 corridor in the Town of Wethersfield, Connecticut, shown in Figure 5, served as a test application of the process. The City of Hartford is to the immediate north of the corridor.

Because the cooperating agencies did not want to complicate on-going studies, several of which are controversial, the approach taken for this test case was a retrospective one. The corridor had recently undergone improvements, and the process was applied to the conditions existing in the corridor *prior* to the improvements. At that time, Route 99 was a two lane major urban arterial with numerous commercial developments and strip shopping centers on both sides. Note also that I-91 shares the corridor and that Route 99 can serve as a diversion route should an incident cripple operations on I-91.

The goals hierarchy for the MCDM portion of the process is shown in Figure 6. Note that there are 17 measures arranged in six major groups reflecting tradeoffs beyond just congestion. For this example, only two alternatives were considered - do-nothing and increased transit. The uncertainties involved were projected economic growth of the region (high or low) and, in the case of the transit alternative, transit demand (high, medium or low).

Table 1 gives the values of the measures for each alternative/scenario combination. As noted earlier, those measures related to traffic, e.g., person km/h (mph) and emissions, were obtained from the simulation model NETSIM and, in the case of emissions, the air quality model MOBILE5a. Many of the other values were assumed for this simple example. Measures such as citizen reaction and environmental justice are on user-defined ordinal scales varying from 1 (no impact) to 5 (large impact). Figure 7 shows the utility functions assumed for these two measures. Note that both of the curves are monotonically decreasing, reflecting a decrease in utility with an increase in impact. The utility function for citizen reactions shows an accelerated decrease in utility with increased impact. The weights used are shown in Figure 8. Note that the weights under the "Overall Utility" goal sum to one. The weights given for the various measures under the eight sub-goals sum to their respective weights under the overall goal. For example, the sum of the "Air Quality" weights is 0.15.

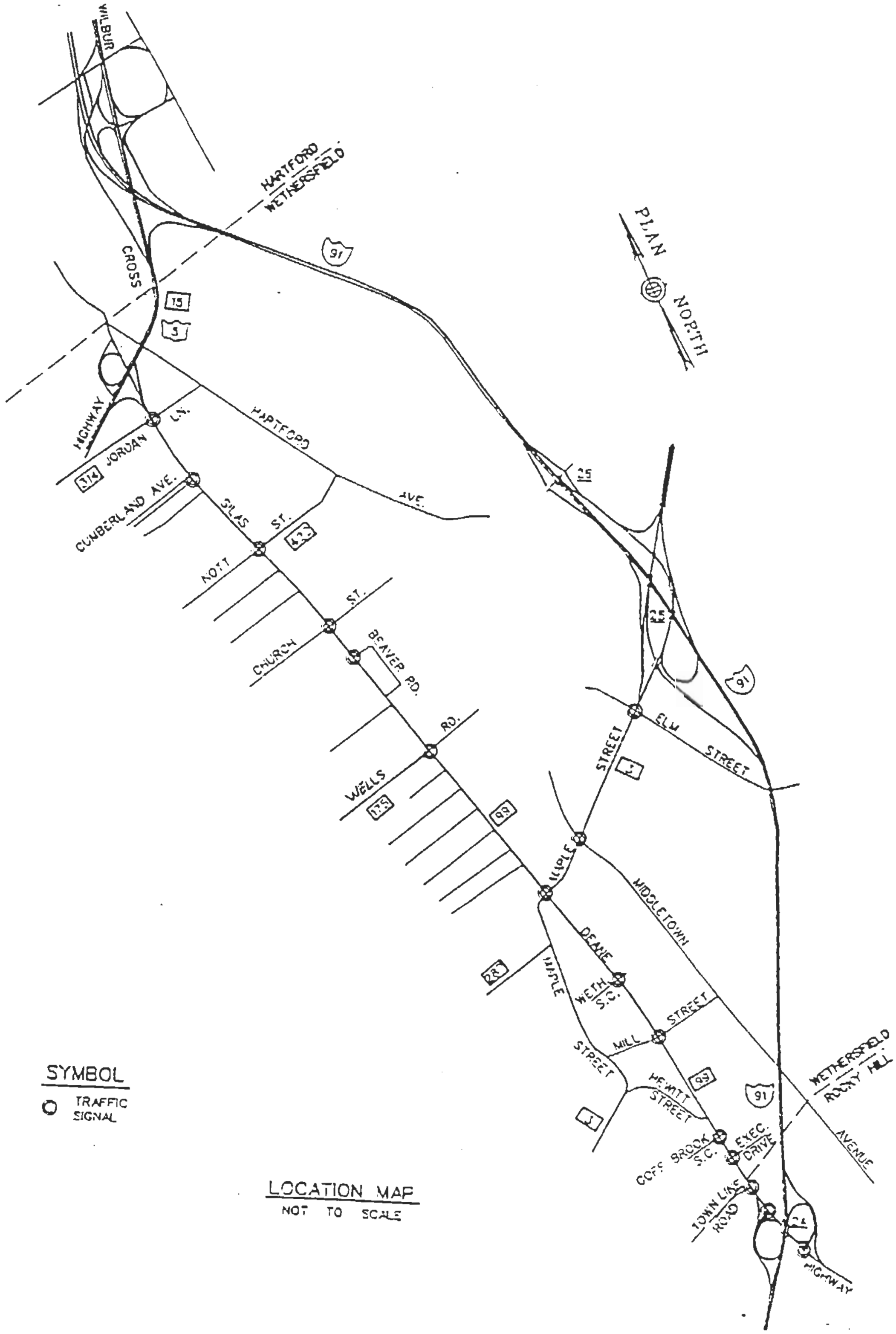

Figure 5. The Route 99 corridor.

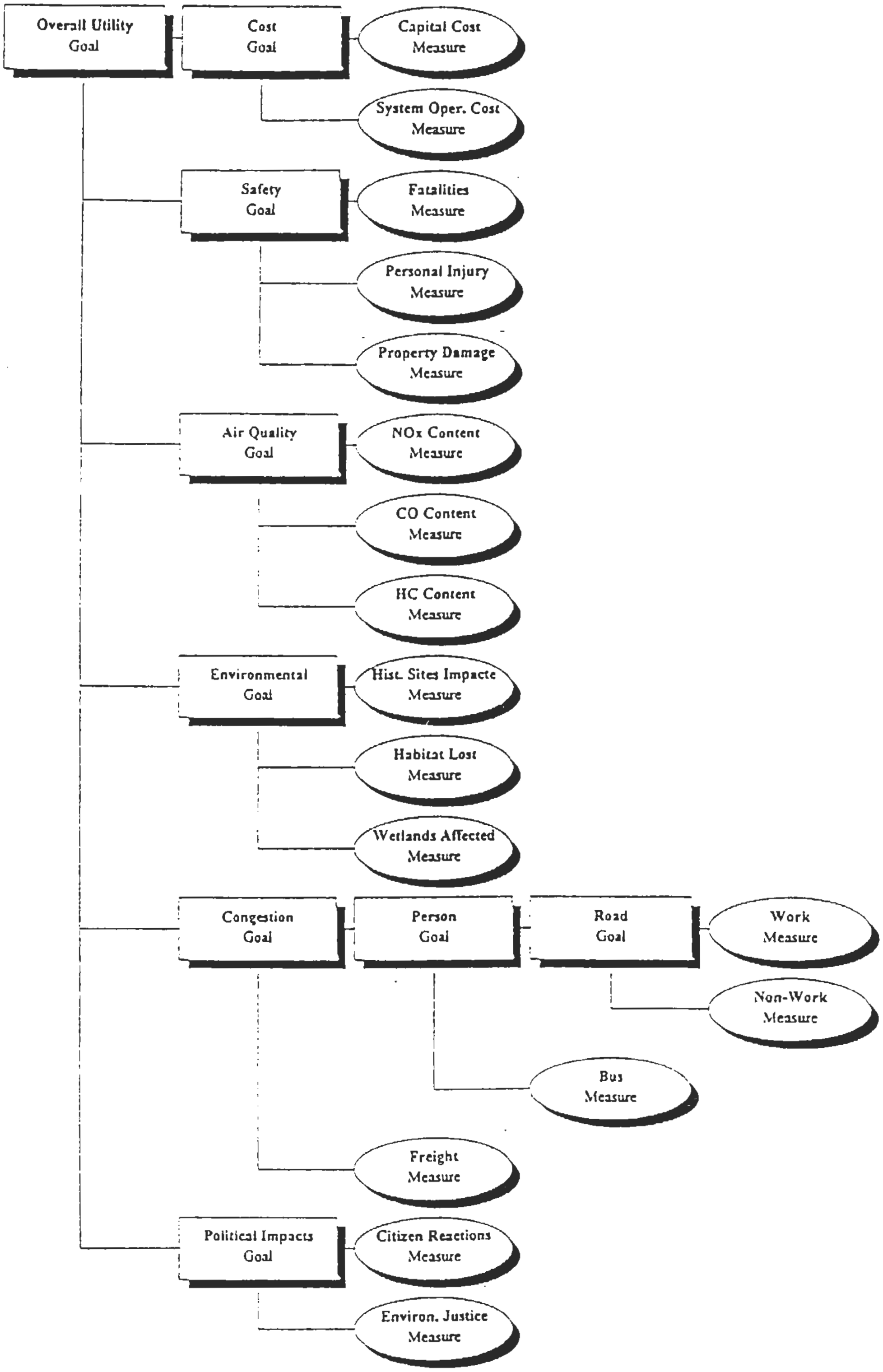

Figure 6. Goals hierarchy for the MCDM Model.

Table 1. Measure values.

	Do Nothing		Transit					
	High Econ	Low Econ	High Economic Growth			Low Economic Growth		
			High demand	Med demand	Low demand	High demand	Med demand	Low demand
Capital Cost ($M)	0	0	25	25	25	25	25	25
Sys Oper Cost ($M)	0	0	1	1	1	1	1	1
Fatalities (/year)	3	3	1	1	1	1	1	1
Pers (Inj/yr)	8	7	3	3	3	3	3	3
NOx (1000gm)	4.053	3.951	5.824	4.694	4.046	5.174	4.560	3.947
CO (1000gm)	24.816	22.638	24.191	24.171	24.186	24.937	23.280	22.894
HC (1000gm)	4.656	4.323	4.648	4.637	4.668	4.856	4.461	4.390
Hist Sites Impacted	1	1	2	2	2	2	2	2
Habitat Lost	1	1	2	2	2	2	2	2
Wetlands Affected	0	0	10	10	10	10	10	10
Freight (pers-mph)	5696	5827	5623	5786	5772	5489	5696	5782
Work (pers-mph)	60303	60610	56048	58929	60035	54708	58014	60133
Non-work (pers-mph)	140707	141423	130779	137502	140083	127653	135366	140310
Bus (pers-mph)	39173	40471	195262	120560	40088	190546	118686	40152
Citizen Reaction	1	1	1	1	1	1	1	1
Environ. Justice	2	2	2	2	2	2	2	2
Property Damage ($/year)	30000	30000	10000	10000	10000	10000	10000	10000

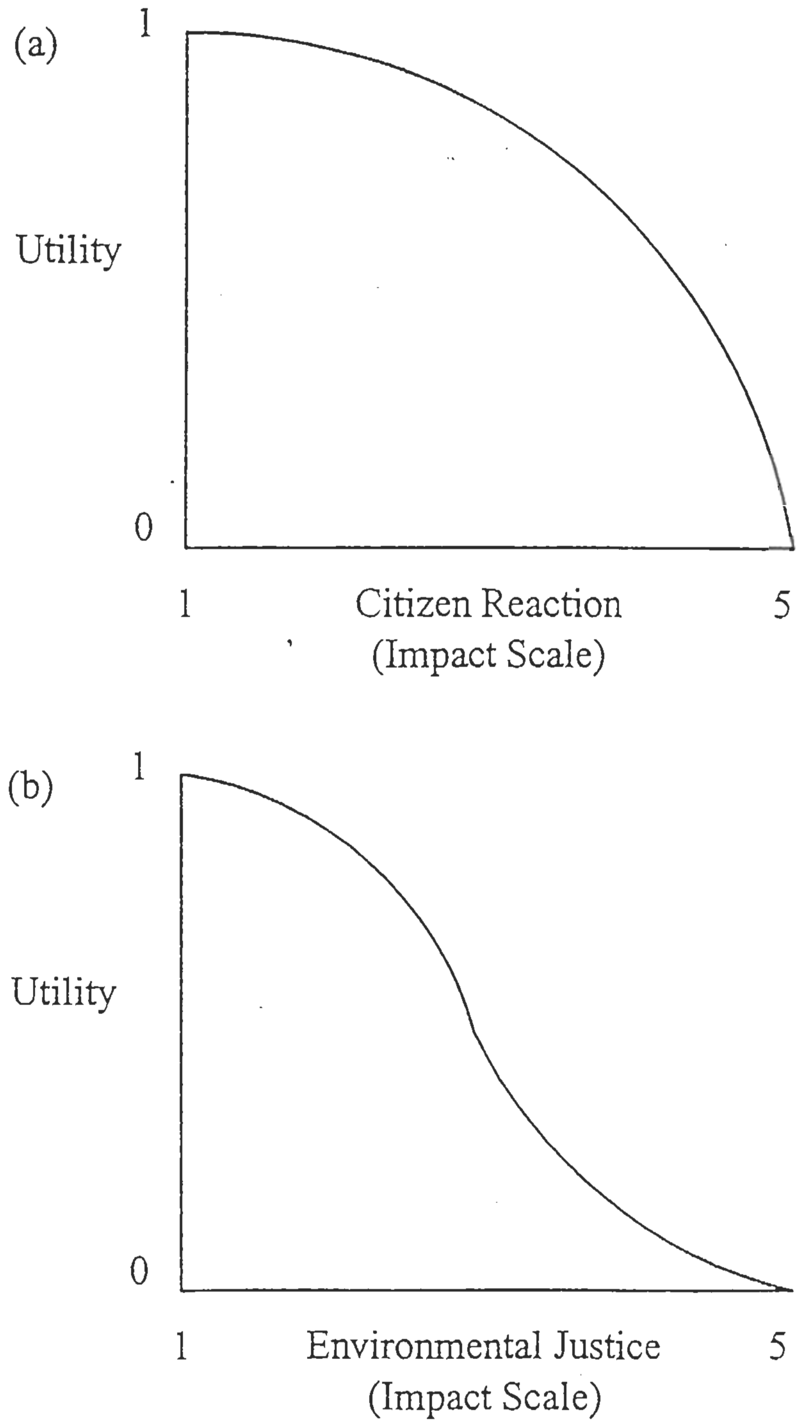

Figure 7. Utility functions for (a) Citizen Reaction and
(b) Environmental Justice.

Weights under Overall Utility Goal

Congestion Goal weight = 0.30
Air Quality Goal weight = 0.15
Cost Goal weight = 0.15
Safety Goal weight = 0.15
Environmental Goal weight = 0.15
Political Impacts Goal weight = 0.10

Weights under Congestion Goal

Person Goal weight = 0.2100
Freight Measure weight = 0.0900

Weights under Air Quality Goal

NOx Content Measure weight = 0.0500
CO Content Measure weight = 0.0500
HC Content Measure weight = 0.0500

Weights under Cost Goal

Capital Cost Measure weight = 0.0750
System Oper. Cost Measure weight = 0.0750

Weights under Safety Goal

Fatalities Measure weight = 0.0900
Personal Injury Measure weight = 0.0450
Property Damage Measure weight = 0.0150

Weights under Environmental Goal

Wetlands Affected Measure weight = 0.0600
Hist. Sites Impacte Measure weight = 0.0450
Habitat Lost Measure weight = 0.0450

Weights under Political Impacts Goal

Citizen Reactions Measure weight = 0.0700
Environ. Justice Measure weight = 0.0300

Weights under Person Goal

Road Goal weight = 0.1260
Bus Measure weight = 0.0840

Weights under Road Goal

Work Measure weight = 0.0882
Non-Work Measure weight = 0.0378

Figure 8. Example of weights for MCDM model.

The output of the MCDM model is shown in Table 2 for each alternative/scenario combination. It can be seen that the highest utility (0.7846) is associated with the do-nothing alternative with low economic growth. In order to determine the preferred alternative, however, it is necessary to account for the uncertainties involved. This is done using the decision tree shown in Figure 9(a), where the probabilities shown on each of the branches have been assumed. The analyzed decision tree is shown in Figure 9(b). As may be seen, the resulting preferred alternative is do-nothing with an expected utility of 0.7335.

Table 2. Example of utility score output from MCDM Model.

Ranking for Overall Utility Goal

Alternative/Scenario	Utility
Do Nothing/High Econ	0.6568
Do Nothing/Low Econ	0.7846
Transit/High Econ/Low Demand	0.6717
Transit/High Econ/Medium Demand	0.6810
Transit/High Econ/High Demand	0.5848
Transit/Low Econ/Low Demand	0.7332
Transit/Low Econ/Medium Demand	0.6760
Transit/Low Econ/High Demand	0.4998

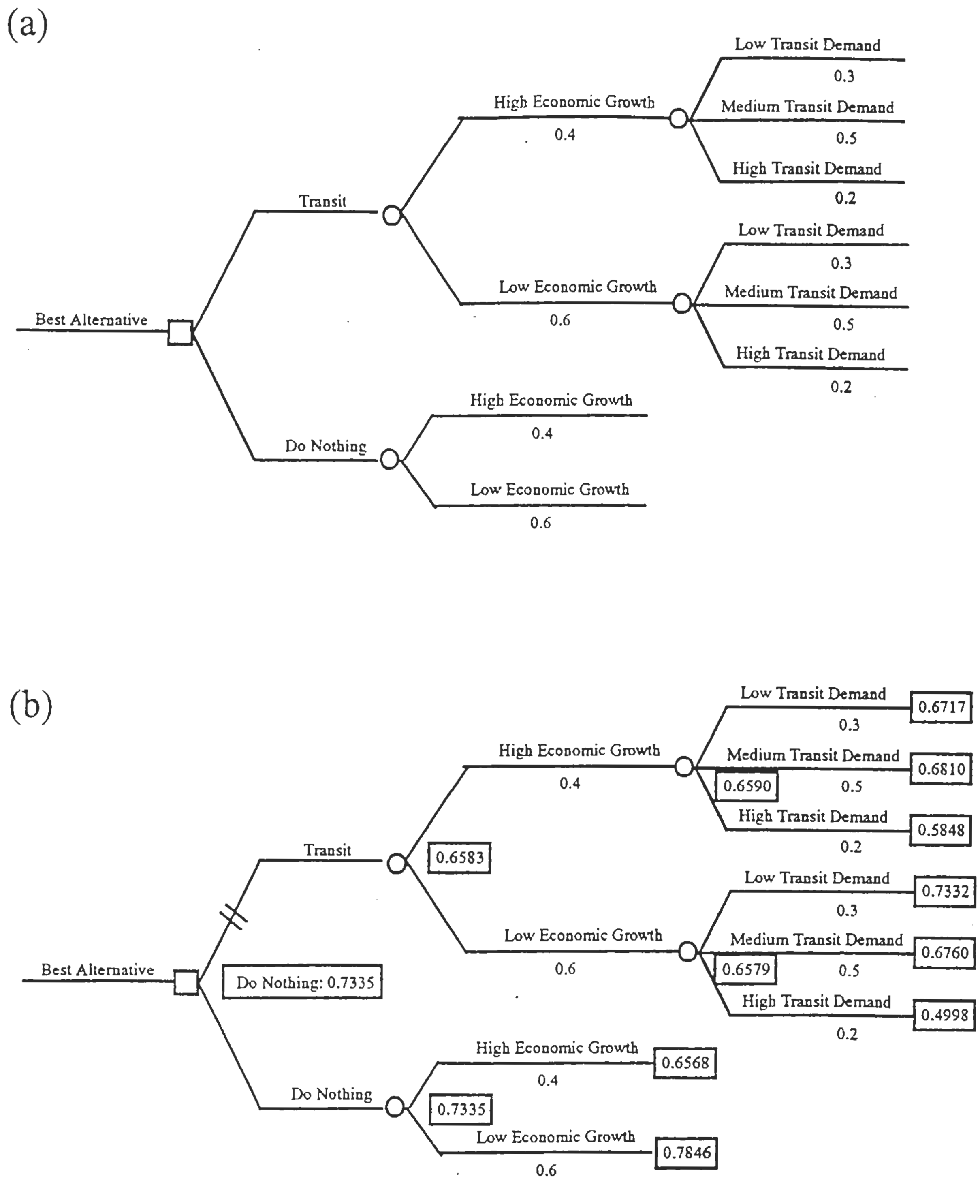

Figure 9. (a) Decision tree and (b) analyzed decision tree.

VI. SUMMARY AND CONCLUSIONS

Even though the prescribed ISTEA management systems are no longer required, most states and MPOs have experienced benefits from developing and implementing them. This paper describes an application of two operations research decision making tools, MCDM and RA, for the implementation of a congestion management system for selecting among corridor improvement options. The concepts underlying these tools are well proven in other application areas in the operations research literature. They are quite helpful for choosing among competing alternatives when the decision maker is forced to satisfy several potentially conflicting objectives in the face of uncertainty about the future operating environment.

These two tools were combined along with transportation system modeling techniques. Each alternative is defined to have certain consequences with respect to the decision maker's goals. These consequences are then represented by one or more measures which gauge compliance with the goals. The measures are estimated or forecast by appropriate models; here congestion and vehicle travel measures are modeled using trip tables generated by the UMTA Four-step modeling process and by traffic simulations generated using NETSIM. Other quantities are forecast using Air Quality models, or are estimated. Uncertainty in the future operating environment is also included in the procedure.

The procedure is demonstrated through a simple application in a suburban Connecticut highway corridor. Two alternatives were compared, an improvement in transit service in the corridor, and doing nothing. The procedure was applied, considering traveler response to the improved transit service and the preferred alternative was revealed. This limited example shows how the procedure can be applied to other corridors, with more alternatives and with more complicated modeling of measures.

This method has been demonstrated to recommend an optimal alternative for a transportation system investment decision considering multiple objectives as well as forecast and conditional uncertainties, both prevalent in transportation investment decisions. The concepts involved are easy to learn and require no mathematics beyond simple arithmetic. Off-the-shelf software is available to implement these tools; this software is easy to install and use, as it is designed for management professionals with little computer expertise. The software also provides sensitivity analysis along with the optimal decision to show the factors and objectives to which the estimated utility ratings are most sensitive. This helps the decision maker to judge which goal weights are most critical to establish with greater certainty.

There are several ways in which this procedure can be made more effective for ongoing implementation. Use of Geographic Information System coverages would make reporting of information to stakeholders more convenient. Full integration of the traffic and air quality forecasting models into the procedure would permit smoother application. The procedure, as described here, must be set up individually for each traffic corridor to be studied. Implementation of the suggested enhancements might permit the procedure to model an entire region, with subareas extracted as needed without excessive labor involved with setting up the modeling framework.

REFERENCES CITED

(1) Schwartz, W. and M. Francois. States and MPOs Continue CMS Activities, In *Congestion Management News*, *ITE Journal,* Vol 2, No. 4, ITE, Washington, D.C., July 1996, pp. 9-10.

(2) Nash, A. California Congestion Management Program, *ITE Journal*, Vol. 62, No. 2, February 1992, pp. 29-32.

(3) Kurtz, B. Regional Mobility and the Congestion Management Program, *American Public Works Association Reporter,* Vol.58, No. 11, Nov. 1991, pp. 10-11, 28.

(4) Mcleod, D. *Florida Department of Transportation Memorandum,* Broward/Gainsville CMS Coordination Meeting Summary. Feb. 16, 1994.

(5) *Texas Department of Transportation Memorandum*, Congestion Management System Development (2/1/94).

(6) *"North Carolina Congestion Management System".* North Carolina Department of Transportation, June 1994.

(7) Arnold, E. D., Jr. Evaluation of Congestion Reducing Measures Used in Virginia, *Transportation Research Record 1404*, Transportation Research Board, National Research Council, Washington, D.C., 1993, pp.4-7.

(8) O'Brien, Amy, and Jacobson, Leslie. Freeway and Arterial Management Effort: Addressing Traffic Congestion in Washington State. In *TR News 153*, Transportation Research Board, National Research Council, Washington, D.C., March-April 1991, pp.10-15, 56.

(9) Hoeft, Brian. "Developing Congestion Management Systems", In *TR News 173*, Transportation Research Board, National Research Council, Washington, D.C., July-August 1994, pp. 26-28.

(10) Lindley, Jeffrey. Congestion Management Systems: Requirements and Opportunities, In *Transportation Research Circular 404,* Transportation Research Board, National Research Council, Washington, D.C., March 1993, pp. 71-73.

(11) Orski, Kenneth. The Politics of Traffic Congestion, In *ITE Journal*, Vol. 59, No. 2, ITE Washington, D.C., February 1989, pp. 31-32.

(12) Arnott, Richard, and Small, Kenneth. The Economics of Traffic Congestion, In *American Scientist*, Vol. 82, Society of the Sigma Xi, September-October 1994, pp. 446-455.

(13) Flynn, L. New Act Mandates New Management Systems, In *Roads and Bridges*, March 1992, pp. 34-38.

(14) Fleet, C. R. Transportation Data Needs: Programs for a New Era: Implications for State DOTs and MPOs, In *Transportation Research Circular 407*, Transportation Research Board, National Research Council, Washington, D.C., April 1993, pp. 23-35.

(15) Johnson, B. H. and M. J. Demetsky. Geographic Information System Environment for Transportation Management Systems, In *Transportation Research Record 1429*, Transportation Research Board, National Research Council, Washington, D.C., 1994, pp. 67-73.

(16) *ISTEA Management Systems Geographic Information Systems - Transportation Server Net Prototype Pooled Fund Study: Phase A Charter*, March 1, 1994, http://WWW.bts.gov/smart/cat/charter.html

(17) Federal Highway Administration, *Three Day Training Course: Congestion Management for Technical Staff*, NHI Course No. 15259, April 1994.

(18) Federal Highway Administration, *Metropolitan Planning and Technical Report: Congestion Management Systems*, USDOT Report No. 2, 1994.

(19) Levinson, Herbert, Pratt, Richard, Bay, Paul and G. Bruce Douglas, "Methods to Quantify Congestion", *NCHRP Report Draft Version*, 1994.

(20) *Congestion Management Systems for Connecticut: Proposed guidelines for developing congestion management systems in the State of Connecticut,* Connecticut Department of Transportation, June 16, 1994.

(21) Won, Jaimu, Multicriteria Evaluation Approaches to Urban Transportation Project", In *Urban Studies,* Vol. 27, No.1, pp. 119-138, 1990.

(22) Giuliano, Genevieve, A Multicriteria Method for Transportation Investment Planning, In *Transportation Research A*, Vol. 19A, Feb. 1985, pp. 29-41.

(23) Bielli, Mauri, A DSS Approach to Urban Traffic Management", *European Journal of Operational Research 61*, 1992, pp. 106-113.

(24) Gomes, Luiz, "Multicriteria Ranking of Urban Transportation System Alternatives", *Journal of Advanced Transportation,* Vol. 23, No. 1, 1989, pp. 43-52.

(25) Kulkarni, Ram, Burns, Robert, Wright, John, Apper, Bryan, Bailey, Thomas, Noack, Stephen, Decision Analysis of Alternative Highway Alignments, *In Journal of Transportation Engineering,* Vol. 119, No. 3, ASCE, pp. 317-332.

(26) Ossenbruggen, Paul, *Systems Analysis for Civil Engineers*, John Wiley and Sons, New York, N. Y., 1984, pp. 181-185.

(27) Khisty, C. Jotin, Matching Planning Styles and Roles in Transportation to Conditions of Uncertainty and State of Technological Know-How, In *Transportation Research Record 1364,* Transportation Research Board, National Research Council, Washington, D.C.,1992, pp. 139-143.

(28) Lewis, David, The Future of Forecasting: Risk Analysis as a Philosophy of Transportation Planning, In *TR News 177,* Transportation Research Board, National Research Council, Washington, D.C., March-April 1995, pp. 3-9.