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A Knowledge-Based Approach to Improve Urban Transportation Decision Making

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ABSTRACT

This paper describes a microcomputer-based tool that has been developed to facilitate acquisition and improvement of skills in urban transportation decision making. This tool interfaces with a complex gaming-simulation model and involves a knowledge-based expert system, built using programming techniques from the field of artificial intelligence. The gaming-simulation model synthesizes the consequences of the decision-making activities of a Transportation Director (model user) in a city with urgent transportation needs. The role of the expert system is to advise users on how to achieve multiple street and transit system goals over a ten-year period, during which time several hundred decisions must be made. Each year, the expert system suggests actions to the user that can be used as possible inputs to the following year's budgetary and decision-making process. Results of limited tests to date indicate that this expert system permits achievement of performance levels that very few unassisted users can attain.

INTRODUCTION

Gaming simulation is a technique that can be of considerable educational value in transportation planning and engineering. Although based on abstractions of reality, gaming simulations can capture the most important features and interrelationships of a complex problem or system. Users can gain an understanding of the principal processes and consequences involved, without becoming immersed in detailed secondary issues. Ideas and alternative solutions can be tested at little real cost and with rapid response. Examples in the transportation field include the work of Ortuzar and Willumsen (1978), Willumsen and Ortuzar (1985) and Adiv (1986).

This paper describes a microcomputer-based tool that has been developed to facilitate acquisition and improvement of skills in urban transportation decision making. This tool interfaces with a complex gaming-simulation model and involves a knowledge-based expert system, built using programming techniques from the field of artificial intelligence. The gaming-simulation model synthesizes the consequences of the decision-making activities of a Transportation Director (model user) in a city with urgent transportation needs. The role of the expert system is to advise users on how to achieve multiple street and transit system goals over a ten-year period, during which time several hundred decisions must be made. Each year, the expert system suggests actions to the user that can be used as possible inputs to the following year's budgetary and decision-making process. Results of limited tests to date indicate that this expert system permits achievement of performance levels that very few unassisted users can attain.

OVERVIEW OF STREET OF THE CITY

Streets of the City is a gaming-simulation model that appoints the user as Transportation Director of River City, Michigan. This is a hypothetical central city with a declining population of 185,000 persons. River City has experienced budget problems in the last decate which have resulted in a severely deteriorated road system and inadequate bus service. The job of the Transportation Director is to succesfully implement a ten-year transportation improvement plan just approved by the eleven-member City Commission. This involves achievement of street and transit system goals set by the City Commissioners, and making several hundred decisions over the ten-year period. The game requires the user to participate in multi-objective decision making involving ill-defined tradeoffs. If annual performance is unsatisfactory, the supporting votes of City Commissioners are lost and ultimately the Director is fired. In our experience, most novice users (civil engineering undergraduates) get fired early in the ten-year period. Although they gradually become more expert in repeated playings of the game, relatively few survive to the end of the ten-year period and/or achieve all the goals.

Streets of the City was originally available commercially as software for several small microcomputers (Murray, undated), and was said to be derived from the actual experiences of the city of Grand Rapids, Michigan. Over the years, the program has grown considerably, and has been enhanced and completely recorded several times. The version described here is written in Domain Pascal and runs on an Apollo DN3000 workstation. In terms of its code, the program is now quite large and complex.

In Streets of the City, the Transportation Director is faced with eight goals, and associated target standards set by the City Commissioners, as follows:

Goal	Standard
1. Primary street reconstruction	Reconstruct 44 miles
2. Interstate highway construction	Build 16 miles
3. Street condition index	Reduce 60 percent
4. Traffic safety index	Reduce 60 percent
5. Bus fleet age	Reduce 60 percent
6. Bus ridership	Increase 4 times
7. Fleet downtime index	Reduce 60 percent
8. Service delay index	Reduce 60 percent

Initial conditions are randomly set, including construction costs (which increase each year due to inflation).

The types of decisions that Director must make for each year relate to the following:

a) Transit service

- -- number of routes (6-25)
- -- number of hours operated per day (12, 17 or 24)
- -- number of days per week (6 or 7)
- -- fare ($0.25 - $1.00).

b) Street construction bonds (years 3 and 7 only)

- -- the amount, in dollars; subject to the approval of the City Commissioners and a vote of the citizens. If the bond issue fails by large margin, the vote of a Commissioner is lost.

-- whether to make any of four pledges to neighborhood associations regarding street improvements over the next three years. Pledges that are not kept also result in penalties.

c) Property tax levy

-- the amount (up to $10M) and distribution requested from the City Commission for street and transit operations.

d) Street fund budget

-- amount to transfer (if any) between construction and operations accounts.
-- amount to allocate to maintenance and safety programs, and construction of primary roads and interstates (gas tax revenues, property tax levies, bond payments and carryovers from previous years are automatically incorporated).

e) Transit budget

-- amount to transfer from the operating account to the capital account for bus acquisition
-- the number of old buses to sell
-- the number of new buses to buy
-- the amounts to allocate to transit operations and maintenance needs.

f) Labor negotiations

-- management counteroffers to union demands for wage increases. Failure to reach a settlement results in a strike, with an arbitrator's decision on increased wages and severe performance penalties for the Director.

In the current version, the game can end in one of five ways, depending on the Director's performance. The alternatives are:

-- selection as U.S. Secretary of Transportation

-- promotion to Transportation Director of New York City

-- retention as Transportation Director of River City

-- demotion to Assistant Transportation Director of River City

-- being fired as Transportation Director of River City.

STREET-SMART

Background

STREET-SMART is a knowledge-based expert system created specifically as an adviser to users of the Streets of the City gaming simulation. STREET-SMART reflects a continuation of work begun several years ago at the University of Washington, involving Professors Jerry Schneider and Nancy Nihan in addition to the authors. STREET-SMART is microcomputer-based and is coded in muLISP. The version described in this paper is an initial demonstration prototype that is the subject of ongoing research.

Knowledge-based expert systems are computer programs that have recently emerged from decades of research into artificial intelligence. Expert systems are designed to emulate the performance of an expert in a particular problem domain through the application of heuristics and symbolic reasoning. Expert systems therefore address ill-structured problems, where a numerical algorithmic solution is not available or is impractical, and problems are solved using expert knowledge, skill, rules-of-thumb and judgment.

A state-of-the-art review of expert systems in transportation engineering is presented by Ritchie (1986), and a review of potential applications of expert systems in transportation is reported by Yeh, et al. (1986).

User Interface

Streets of the City and STREET-SMART currently run on separate hardware. However, the output of Streets of the City forms the input to STREET-SMART, and the output from STREET-SMART is user advice for input to

Streets of the City. Consequently, the medium for this transfer is the user, who runs both programs concurrently.

In addition, the network architecture employed in STREET-SMART provides the user with special abilities to interrogate the knowledge base. This allows the user to investigate relationships between factors that are important to the Director's performance, as well as to modify and even add relationships. Further discussion and illustrations of these features follows below in the Semantic Network section.

Knowledge Representation

In current expert systems research, several standard techniques have emerged for representing knowledge. These include rules, semantic nets, and frames. The most widely used method to date involves the use of production rules. These are expressed as IF condition THEN action statements, e.g., IF service delay index needs improvement THEN reduce fleet downtime index. When the IF portion or premise is satisfied by the facts, the action specified by the THEN portion is performed and the rule is said to "fire."

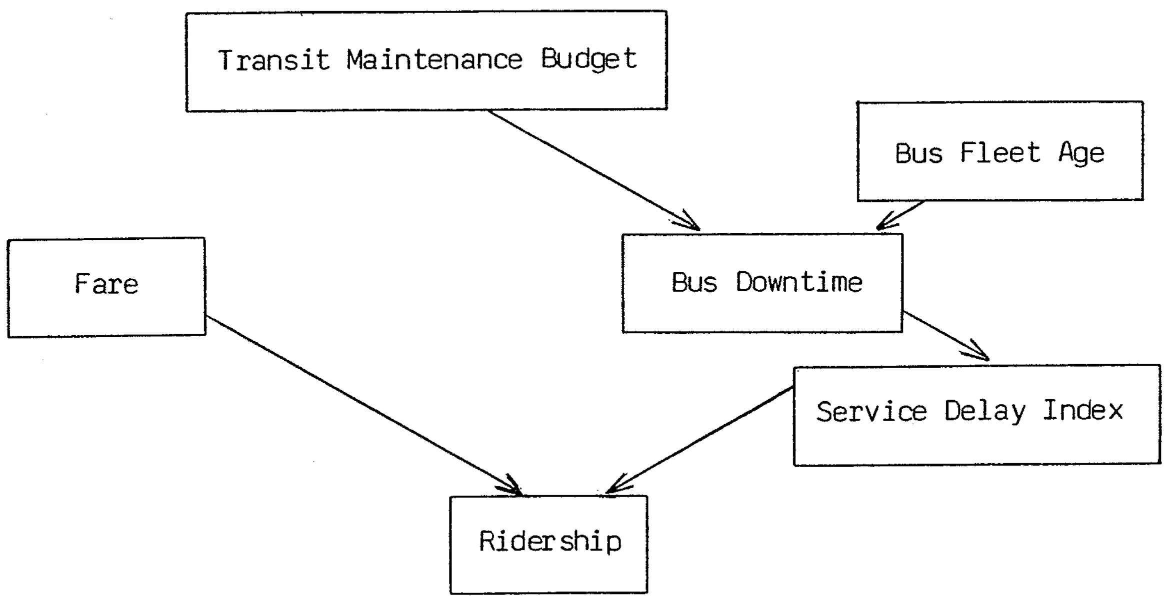
There are two ways in which rules are accessed in rule-based systems: forward chaining and backward chaining. Forward chaining is an inference method that proceeds from information on the left-hand side of the rules to derive information on the right. In other words, rules are matched against facts to establish new facts. Forward chaining results in the user inputting facts for all conditions into the systems before it establishes an appropriate conclusion. If there are many conclusions and hypotheses, and few input data, this method may be useful. In other situations, forward chaining may be inefficient in its input requirements. On the other hand, backward chaining involves starting with a specific conclusion or hypothesis, on the right-hand side of one or more rules, and trying to establish the facts that would verify that hypothesis. Therefore, only rules and facts that are relevant to establishing the hypothesis are executed.

Semantic nets and frames are both considered to be frame-based methods (Waterman, 1986). Semantic nets use a network representation of knowledge involving nodes connected by links or arcs. The nodes can represent objects, concepts or events while the arcs describe the relations between nodes. The nodes are usually organized into a hierarchy, with nodes low in the hierarchy automatically inheriting properties of those that are higher. A frame system is organized much like a semantic net, except that the nodes can be defined by a set of attributes (called slots) and their values. Each slot can have attached to it procedural code that executes when the value in the slot changes.

To date, there have been few applications of frame-based methods in transportation engineering (e.g., Hendrickson, 1986). STREET-SMART employs both rule-based and semantic net approaches to knowledge representation.

Semantic Network

A semantic network in STREET-SMART describes the relationships among all the factors and outcomes in Streets of the City. Each factor and outcome is represented as a node in the network. Links of the network describe relationships among the nodes. There are about 50 nodes and 100 links in the present version. There are also two types of links, "Affect" links and "Affected-by" links. Figure 1 presents an example and illustrates the following relationships: Bus Fleet Age AFFECTS Bus Downtime, Transit Maintenance Budget AFFECTS Bus Downtime, Bus Downtime AFFECTS Service Delay Index, Service Delay Index AFFECTS Ridership, and Fare AFFECTS Ridership.



SEMANTIC NETWORK EXAMPLE

FIGURE 1

Relationships among objects in the network are established by a network processor. This permits the user to investigate relationships between nodes, and to add new nodes and/or relationships using the following syntax:

(i) "What affects (object) directly?" This determines objects, or nodes, that have AFFECT links connected to the target object. For example, "What affects Ridership directly?," results in the response:

Ridership is affected by Fare, Service Delay Index.

(ii) "What will affect (object)?" This question determines all the nodes that directly or indirectly affect the target node. For example, "What will affect Ridership?," results in:

Ridership is affected by Fare, Service Delay Index.
Service Delay Index affected by Bus Downtime.
Bus Downtime is affected by Transit Maintenance Budget, Bus Fleet Age.

(iii) "Does (object 1) affect (object 2)?" This can confirm the relationship between two nodes. For example, "Does Transit Maintenance Budget affect Ridership?," results in:

Yes, indeed Transit Maintenance Budget affects Ridership.

However, the question "Does Bus Fleet Age affect Fare?," results in:

Sorry, not that I know of.

(iv) "Why does (object 1) affect (object 2)?" Such a question will trace the relationship(s) between two nodes separated in the network. For example, "Why does Transit Maintenance Budget affect Ridership?," results in:

Because Transit Maintenance Budget affects Bus Downtime,
Bus Downtime affects Service Delay Index,
Service Delay Index affects Ridership.

However, the question "Why does Fare affect Bus Fleet Age?," results in:

But it does not!

(v) "(object 1) affects (object 2)." This command enables new nodes and relationships to be established. For example, if one were to input, "Transit Marketing affects Ridership," a new node representing Transit Marketing would be created, together with two links between the new node and that for Ridership. Asking "What affects Ridership directly?," would then result in:

Ridership is affected by Fare, Service Delay Index,
Transit Marketing.

The semantic network structure in STREET-SMART also interfaces with a rule-based component of the knowledge base.

Rules

Rules in STREET-SMART are used to infer solution strategies in the form of advice to the user. These rules first assign weights to various nodes based on the previous year's performance. The worse the performance, the higher the weight. These weights are then stored within the semantic network. As necessary, the relationships among relavant nodes and their weights are retrieved from the semantic network to identify weak spots in performance, and causal factors. An example rule is:

IF (1) Street maintenance budget is greater than the minimum required street maintenance budget

(2) Allowed transfer is 25% between construction and maintenance accounts

(3) Street maintenance budget weight is greater than the street construction budget weight

THEN Transfer (street maintenance budget--minimum required street maintenance budget) (street maintenance budget weight/street construction budget weight) dollars from the street maintenance budget to the street construction budget.

Several advantages to using such a hybrid knowledge representation scheme include the separation of static, supporting knowledge from that used primarily for inferring actions, with a consequent reduction in the number of rules and the time to inference rules, and a more flexible environment for user explanation and knowledge-base modification.

EXAMPLE APPLICATION

The following example illustrates the interface between the user and STREET-SMART in one year of a particular run of Streets of the City. User responses in each section are underlined.

Please input the year you want to work on: 2

Please input the previous year's performance values.

Primary mileage: 101.5
Interstate mileage: 1.0
Street condition index: 10.4
Traffic safety index: 6.8
Ridership: 1,156,534
Downtime: 4.4
Service delay: 9.7
Votes: 11.

Property Tax Levy.

Street fund tax needs ($M): 2.15
Transit fund tax needs ($M): 0
I suggest the following:
Propose a tax levy of $7.4 M
What is the tax levy approved by the City Commission ($M): 3.29
I suggest the following:
Allocate $2.51 M to the street fund.

Street Fund Budget.

Operations budget on hand: 3,475,742
Minimum required maintenance budget: 2,368,318
Minimum required safety budget: 660,982
Construction budget on hand: 3,309,694
Primary road cost per half mile unit: 162,520
Interstate road cost per half mile unit: 812,601
Allowed transfer between either account (%): 50.
I suggest the following:
Make no transfer between operations and construction accounts
Construct 5 half mile units of primary road
Construct 2 half mile units of interstate
$2,613,832 for the maintenance budget
$861,909 for the safety budget.

Transit Fund Budget.

Operations budget on hand: 3,261,970
Minimum required maintenance budget: 276,781
Minimum required operations budget: 863,442
Bus fleet budget on hand: 88,000
Cost per new bus: 136,800
Allowed transfer from operations to bus fleet budget (%): 25.

I suggest the following:
Transfer $49,488 from operations budget
Sell 2 old buses
Buy 2 new buses
$1,518,416 for the maintenance budget
$1,694,065 for the operations budget.

Labor Negotiations.

What is the Union's 1st offer (%): 12.0

I suggest the following:
Offer a 7.2% increase

What is the Union's 2nd offer (%): 9.4

Is this the last round: yes

I suggest the following:
Offer a 9.1% increase.

The performance table that resulted be following STREET-SMART's recommendations in this fashion for the ten-year period is shown in Table 1.

In this particular run, six of the eight performance standards were achieved. The two that were not were construction of primary streets and interstates, where 32 miles and 12 miles, respectively, were constructed. However, at no time did the Director lose the majority support of the City Commissioners. In fact, at the conclusion of the ten-year planning period the Director was retained as Transportation Director of River City.

TABLE 1

SUMMARY PERFORMANCE TABLE

Year	Primary Streets	Inter-states	Street Index	Safety Index	Ridership	Age	Downtime Index	Delay Index
0	99.0	0.0	10.6	7.5	727,380	8.3	8.0	11.0
1	101.5	1.0	10.4	6.8	1,156,534	6.0	4.4	9.7
2	104.0	2.0	10.3	6.3	1,899,259	6.0	1.0	8.0
3	107.5	3.5	10.1	5.6	2,363,438	6.0	1.0	6.8
4	110.5	4.5	10.1	5.5	2,796,419	6.0	1.0	6.2
5	114.5	5.5	9.9	4.8	3,337,246	6.0	1.0	5.5
6	117.5	6.5	9.8	4.4	4,084,788	6.0	1.0	4.5
7	121.5	8.0	9.6	3.6	5,291,434	6.0	1.0	2.8
8	125.5	9.5	7.4	2.6	6,854,523	5.0	1.0	1.1
9	129.0	11.0	6.2	1.2	7,760,690	4.0	1.0	1.0
10	131.0	12.0	4.0	1.1	7,995,062	3.0	1.0	1.3
Plan	143.0	16.0	4.0	3.0	2,909,520	3.0	3.0	4.0

CONCLUSIONS

Although the performance and user interface of STREET-SMART can be improved in a number of ways, the results of limited tests to date indicated that even in its present demonstration prototype form the program permits achievement of performance levels that very few unassisted users can attain. Improvements that are being considered include further development and enhancement of the expertise embodied in STREET-SMART to try to achieve all performance goals within the ten-year period; enhancement of the explanation capabilities of the program, particularly regarding its suggestions within one year of a run; and improved intergration of STREET-SMART and Streets of the City, perferably in a microcomputer and/or windowing environment, so that STREET-SMART will automatically pick up the outputs of Streets of the City that the user must presently enter manually. In addition, consideration may be given to generalizing both programs to permit cities with characteristics different from River City to be addressed, e.g., different populations, growth patterns, budgetary experiences, goals, and performance standards. This could increase the utility of both programs substantially.

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