Intersection Advisor: An Expert System for Intersection Design

DONALD A. BRYSON, JR., AND JOHN R. STONE

The Intersection Advisor is a prototype expert system that recommends geometric modifications to improve intersection operation. It complements existing microcomputer programs that consider the other two aspects of intersection design, volumes and signalization. Intersection Advisor is intended for eventual incorporation in a comprehensive, interactive intersection design package. M.1, a knowledge-based expert system development tool, was used to develop the Intersection Advisor to run on IBM or IBM-compatible microcomputers. During an interactive consultation the advisor requests information on the intersection volumes, critical movements, geometry, and constraints on approach improvement. It then recommends the most efficient improvements for each approach by generating one of nearly 600 possible reports. Recommendations are arrived at by determining an "ideal" lane configuration for the given traffic flows. The ideal design is checked against the improvement constraints, and a next-best design is selected, if necessary. The best feasible design is then compared with the existing design, and the user is informed of any modifications required. Intersection designs produced with the advisor compare well with those produced using the guidelines of the 1985 *Highway Capacity Manual.*

The operational characteristics of a signalized intersection are determined by the interactions of three basic components: traffic flows, geometry, and signalization. Intersection design involves the manipulation of geometry and signalization with respect to traffic flows in order to maximize operating efficiency (Figure 1). Optimization is difficult to achieve, however, because of the high degree of interdependence among the design parameters and the variety of constraints commonly encountered. Even experienced engineers cannot always determine the optimum design for a complex intersection, although their initial solution to a given problem is usually remarkably close. New engineers proceed by trial-and-error, gradually developing a "feel" for appropriate solutions. Obviously, there is systematic, reproducible reasoning involved—a combination of acquired factual knowledge and problem-solving techniques—that can be defined as expertise.

Computer techniques have had a significant impact on the design and analysis of signalized intersections. Capacity analysis programs (MCTRANS, CAPSSI, SIGNAL, CMA) have been available for some time, and the publication of the new *Highway Capacity Manual* (HCM) *(1)* has generated a number of new programs (SICA, NCAP, HCS) based on its methodology. Signal optimization programs, such as SOAP and INTERCALC, have also proven useful *(2)*.

Department of Civil Engineering, North Carolina State University, Box 7908, Raleigh, N.C. 27695.

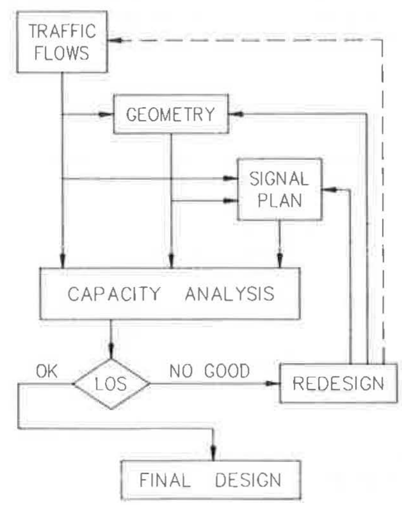

FIGURE 1 Intersection design process.

Existing programs are algorithmic in nature and deal with the numerical components of intersection design, such as volume-to-capacity calculations and signal optimization. These programs enhance the design process by increasing the speed and accuracy of calculation-intensive tasks. These procedural programs cannot, however, assure that the options being analyzed are necessarily reasonable, nor can they assure that the best alternative will be selected. They offer little guidance in deciding the best way to improve the operation of a deficient intersection. An engineer's experience and judgment are the most useful aids in solving this aspect of the design problem—in determining, for example, whether to add a turn lane or revise a signal plan, or both. When the engineer has chosen a design alternative, he must then determine the operating characteristics of the intersection either manually or by computer. The process is repeated until an acceptable design is achieved.

To provide an integrated, interactive environment for selecting and analyzing intersection designs, it is necessary to develop software tools that incorporate professional experience and judgment. These tools must be able to perform the kind of heuristic reasoning required to efficiently generate and evaluate options for improving a design. Such a system has the potential to greatly improve the existing design process by combining tasks that are currently performed manually or with various isolated programs (Figure 2). An essential component of this system is software that can handle the various aspects of geometric design.

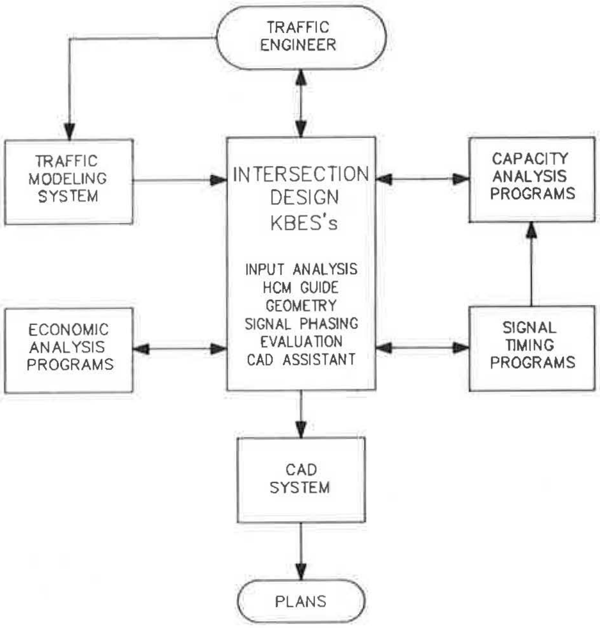

FIGURE 2 An integrated intersection design system.

The purpose of this paper is to demonstrate the applicability of knowledge-based expert system (KBES) technology to signalized intersection design, and to approach geometry in particular. The Intersection Advisor is a functional KBES prototype that recommends geometric modifications to improve the operation of signalized intersections. Like other knowledge-based systems, the advisor reproduces knowledge typically possessed by an expert in a particular field and reaches conclusions that lead to the solution of a problem by systematically applying appropriate reasoning techniques (rules) to its knowledge of the problem area (facts). Experience with the Intersection Advisor suggests that such a system has practical applications in making decisions concerning the geometric design of signalized intersections.

The geometric design problem and the objectives for the development of the Intersection Advisor are discussed. A sample problem is presented to familiarize the reader with the operation of the advisor and to lay the groundwork for an explanation of the solution strategy and its implementation in the knowledge base. The paper concludes with a discussion of results and their influence on the direction of future development of the Intersection Advisor.

INTERSECTION ADVISOR

Geometric Design Problem

Of the three design components described earlier (traffic flows, geometry, and signalization), only one, the geometric element, includes design variables essential for planning, design, and analysis. Of the parameters that the engineer can readily control, those with the greatest direct impact on intersection performance are the number of lanes per approach and the movements permitted from each lane. This was the specific area chosen to test the feasibility of applying KBES technology to intersection design.

The problem of determining the most efficient lane configuration for a given set or sets of turning movements is representative of the intersection design process as a whole. It incorporates both the generation of solutions (How can operations be improved?) and their evaluation (Which solution is best?). The lane geometry problem is narrow enough to provide a reasonably simple prototype yet complex enough to be challenging and realistic. The representational logic required to relate geometric features and traffic flows transfers directly to signalization and other problems. It offers a suitable foundation for the eventual development of a comprehensive intersection design system.

Guidelines for Development

Two major objectives guided the development of the Intersection Advisor. The first objective was to define a set of rules and facts for identifying the most efficient lane configuration for a given set of turning movements. This body of knowledge corresponds to the "expertise" of an experienced traffic engineer and reproduces the reasoning process he employs in developing an appropriate design. These rules are transferable to any KBES for intersection design.

The second objective was to define a logical system for representing the physical and operational relationships among approach legs, individual lanes, and turning movements. This representation scheme provides a framework for implementing the reasoning processes identified previously. The second objective is essential to an efficient interactive environment and applies directly to other aspects of intersection design. Successfully achieving these two objectives helps assure that the Intersection Advisor can be easily expanded from a prototype to a functional system, regardless of changes in the problem domain or in the implementation environment.

Several secondary objectives were also established: *(a)* Recommendations should be presented as incremental changes to an existing design rather than as a complete intersection. The use of an incremental approach as opposed to an absolute approach models typical intersection improvement projects and facilitates the evaluation of various alternatives, as in a cost-benefit analysis. *(b)* The user must be able to constrain the set of potential design solutions to reflect considerations such as limitations in right-of-way availability. *(c)* To provide maximum flexibility and ease of use, the user should be able to analyze individual components of an intersection without analyzing the intersection as a whole. *(d)* Recommendations should include an explanation of the anticipated impacts of the proposed modifications on intersection performance. *(e)* Input requirements must be simple, rational, and consistent with standard practice.

Simplifying Assumptions

It was decided to make the Intersection Advisor consistent with, and complementary to, the planning analysis methodology described in Chapter 9 of the *Highway Capacity Manual.* The advisor would address all of the parameters included in the planning method, with the goal of identifying the lane configuration that would most economically result in a sum of critical movements of fewer than 1,200 vehicles per hour. The set of intersections to be analyzed was limited to standard four-way intersections with no more than four lanes per approach (no severe skewing or offsets and no one-way streets). The solution set was limited to approaches with fewer than eight lanes (a maximum of three through lanes with dual turn lanes in each direction). The expertise incorporated in the Intersection Advisor was obtained from Chapter 9 of the HCM and from the authors' own experience in teaching and performing intersection analysis and design.

Using the Intersection Advisor

A consultation with the Intersection Advisor combines knowledge from two different sources—the user and the program itself. The user supplies his knowledge of a particular intersection in response to questions based on generalized facts and rules pertaining to efficient relationships between turning movements and lane geometry (Figure 3). For each intersection approach being analyzed, the advisor also asks the user to provide intersection volumes, critical movements, and the existing geometry. Turning movements and critical movements can be obtained from the simple manual planning analysis calculations described in Chapter 9 of the HCM or from other microcomputer programs [*3* and work by S. Gayle and J. Papaleo on Signalized Intersection Capacity Analysis (SICA) Using the 1985 *Highway Capacity Manual*, 1986].

User-supplied geometric information is determined from Figure 3 and input to the advisor in response to prompts. The combination of eight basic approach types and two critical movement conditions enables the user to choose from 16 different approach cases for a given set of turning movement volumes.

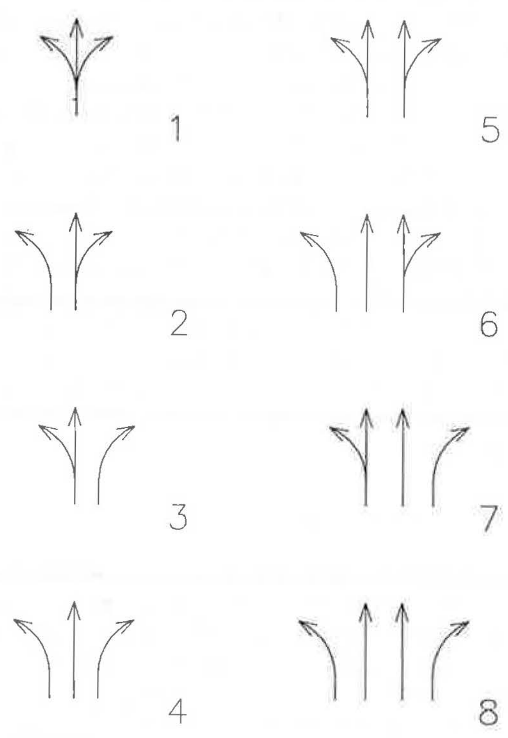

FIGURE 3 Basic lane configurations.

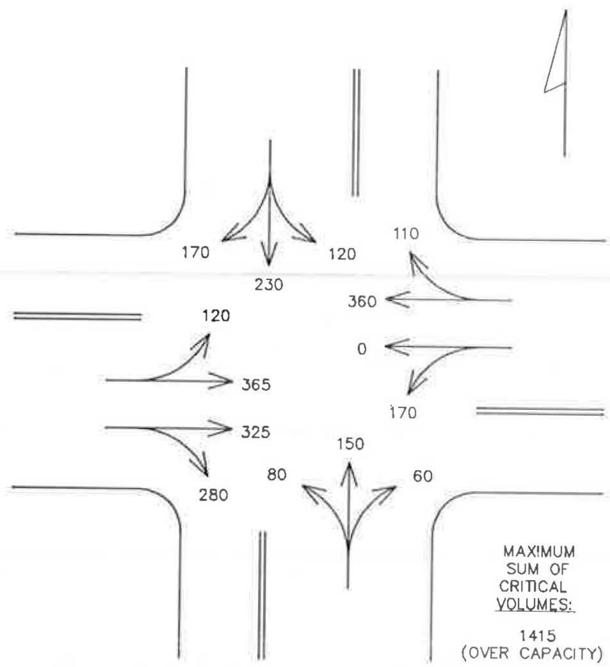

FIGURE 4 Initial conditions.

Finally, the advisor asks the user to specify the maximum number of lanes available for improving the approach. This allows the user to account for physical or right-of-way restrictions.

Sample Problem

To demonstrate how the Intersection Advisor is used, a consultation was run based on Sample Calculation 5 in Chapter 9 of the HCM. Figure 4 shows the geometry and lane volumes of the HCM problem. The existing intersection operates with an overcapacity critical movement summation of 1,415 vehicles per hour, and the HCM advises that "separate left-turn lanes might be considered for each approach, subject to physical constraints." This recommendation leads to a new critical summation of 1,135 vehicles per hour and improved intersection operation.

The Intersection Advisor, on the other hand, recommends the addition of separate left-turn lanes to only two approaches (Figure 5), a design improvement that, like the HCM approach, leads to a critical movement summation of 1,135 vehicles per hour. The advisor's recommendation, therefore, provides an equivalent improvement at half the cost. An argument for the HCM recommendation might be made, however, on the basis of symmetry. This type of policy issue will be addressed in future versions of the Intersection Advisor and is discussed in more detail later in this paper.

An excerpt from the consultation session follows.

Do you wish to consider improvements to the southbound approach?

> > yes.

Enter the number of southbound vehicles turning left during the design hour.

> > 120.

Enter the number of southbound vehicles turning right during the design hour.

> > 170.

Enter the number of southbound vehicles going straight during the design hour.

> > 230.

Are left-turn or through movements the critical movements on the southbound approach? Enter "left" or "thru."

> > thru.

Enter the code number (1–8) of the basic lane configuration corresponding to the existing southbound approach.

> > 1.

Enter the maximum number of lanes desired for the southbound approach.

> > 4.

Enter the maximum number of through lanes desired for the southbound approach.

> > 2.

Recommendations for southbound approach: Providing an exclusive left-turn lane (Lane Configuration 2) will significantly improve the critical through movement on this approach.

Four consultations of this type result in Figure 5.

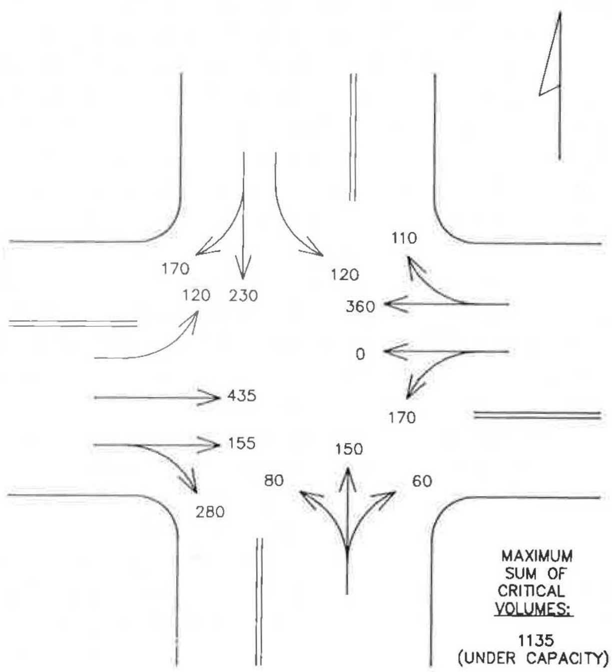

FIGURE 5 Solution recommended by Intersection Advisor.

KNOWLEDGE BASE

Solution Strategy

Appendix I to Chapter 9 of the HCM describes some general rules-of-thumb traffic engineers use to help determine a suitable lane configuration for a given set of traffic flows. These heuristic "suggestions" address such factors as the capacity of a given type of lane and the volumes and types of movements occurring in adjacent lanes. One such guideline states, "As a general suggestion, an exclusive right-turn should be considered when the right-turn volume exceeds 300 vph and the adjacent main-lane volume also exceeds 300 vphpl" (p. 9–64). The expert uses heuristic reasoning of this type along with pertinent standards and policy guidelines and the results of the planning analysis methodology to determine what, if any, modifications need to be made to the existing design. This is the body of knowledge required to meet the first objective in developing the Intersection Advisor, the capturing of expertise.

Before this knowledge could be incorporated into an expert system, however, it was necessary to meet the second objective, the development of an efficient representational schema. This objective was achieved by defining the configuration of lanes in a given approach as the basic logical unit in the knowledge base. Identifying the entire approach as a single entity eliminates the need to explicitly define the properties of each of the six lane types typically used in four-way intersections. This is a significant simplification because the properties of a given type of lane are often influenced by an adjacent lane. These interactions (such as the shifting of traffic between two lanes or the blocking of one movement by another) are implicit in the definition of each approach configuration. Furthermore, it is no longer necessary to prevent the occurrence of illogical lane configurations (such as a right-turn lane to the left of a left-turn lane). Assuming a maximum cross section of seven lanes, there are more than 300,000 ways of arranging the six different lane types. The incorporation of rules to eliminate all of the illogical and impractical solutions would involve considerable overhead, even in the simple problem domain of the Intersection Advisor.

Because the number of feasible configurations makes up a small fraction of the total number of possible configurations, the solution set and overhead are greatly reduced by predefining the acceptable approach configurations. The Intersection Advisor requires only eight basic lane configurations (Figure 3). Each one has specific properties that determine how it will handle various ranges and combinations of turn volumes. For a given set of traffic flows, one of these configurations will provide the most efficient service, based on the heuristic strategy implemented.

KBES Development Tool

Conceptually, traffic flows can be thought of as operands, and the basic lane configurations as operators, each of which has an associated cost. The result of an operation is a level of service. Thus the geometric design problem becomes one of selecting for a given operator the operand that provides a result above some minimum value at the lowest cost. Although this analogy is somewhat oversimplified, it serves to demonstrate how the geometric design process can be represented as a structured selection problem. Structured selection problems are generally appropriate for solution by knowledge-based systems. In particular, M.1 is well suited for solving this type of problem.

The Intersection Advisor was developed using M.1, a knowledge engineering software tool intended for the design and implementation of stand-alone expert systems on IBM personal computers or compatibles *(4)*. Although M.1 has limitations as a practical application tool, it does allow the rapid development of prototype systems and is useful for validating concepts and logic before intensive software development is undertaken.

An M.1 system consists of a knowledge base, a cache, and an inference engine. The knowledge base contains facts and rules pertaining to a specific application. The cache is the storage area for all intermediate and final conclusions, as well as all user input. The inference engine is the mechanism by which M.1 systematically searches for needed values in order to reach a particular goal. This search mechanism obtains values from the cache, from the knowledge base, or from the user. Figure 6 shows how the system architecture relates to the intersection design process in the Intersection Advisor.

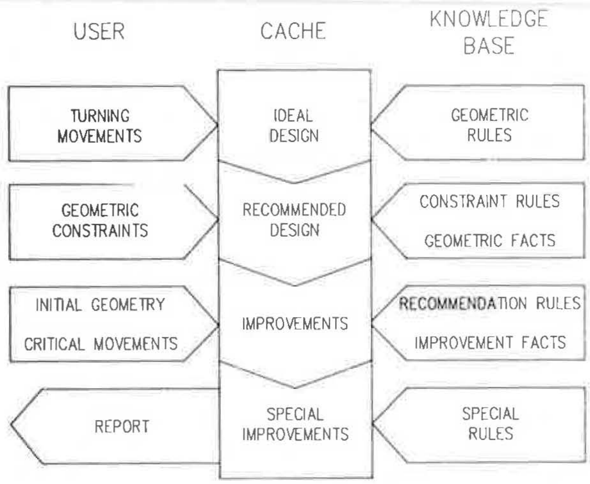

FIGURE 6 Organization of a consultation.

Implementation

The Intersection Advisor uses a set of mutually exclusive geometric rules to reach its first subgoal: selection of an initial "ideal" approach configuration that most efficiently accommodates the given turning movements. These rules involve a series of comparisons between the turning movement volumes and the capacity characteristics of the eight basic lane configurations (Table 1). Because there is always one ideal basic configuration for a given set of turning movements, as soon as a geometric rule has fired, the advisor proceeds to the next subgoal.

TABLE 1 DECISION TABLE FOR BASIC GEOMETRIC RULES

CONDITIONS	OPTIONS										
T < 450	T	T	T	T	T	T	F	F	F	F	ELSE
L < 100	T	T	T	T	F	F	T	T	F	F	
R < 300	T	T	F	F	-	-	T	F	T	F	
T+L+R > 450	T	T	T	T	-	(T)	(T)	(T)	(T)	(T)	
R+T < 500	-	-	-	-	T	F	-	-	-	-	
L+T < 400	-	-	T	F	-	-	-	-	-	-	
3L < R	T	F	-	-	-	-	-	-	-	-	
ACTIONS											
NUMBER OF IDEAL LANE CONFIGURATION	3	2	3	4	2	4	5	7	6	8	1

" - " indicates immaterial value.
"( )" indicates redundant value.

When the ideal basic configuration has been established, a set of constraint rules ensures that this design does not violate any restrictions, caused by physical constraints or limits in right-of-way availability, the user may have placed on approach expansion. The goal of these rules is to identify the best of the allowable basic lane configurations (the "recommended" configuration). If the constraint rules reject the ideal configuration, the advisor generates the next-best alternative by comparing the ideal design with the available approach cross section defined by the user. The properties inherent in the definition of each of the basic lane configurations supply enough information for the advisor to select the next-best configuration directly. It is not an iterative process. The recommended design is the one that most closely matches demand volumes without exceeding lane limitations.

The next subgoal is to determine the differences between the recommended and the existing design. These differences are defined in terms of improvements to the existing design. The Intersection Advisor uses a set of relational improvement facts and recommendation rules to describe the geometric and operational differences between logical combinations of existing and recommended designs. By combining knowledge of the inherent characteristics of the recommended configuration with the geometric and operational data provided by the user, the recommendation rules identify a specific set of modifications to improve the intersection approach. Together, these modification descriptions define every feasible transition from one basic approach configuration to another. The elimination of infeasible solutions from the solution set, combined with the approach-based representational scheme, means that only 56 modification descriptions are needed. This is a significant reduction, considering the total number of combinations of lanes that is mathematically possible. The Intersection Advisor provides a brief description of the nature and magnitude of the benefits expected if its recommendations are implemented, and it recognizes when the suggested improvements will require widening the opposite leg of the intersection.

Finally, there is a set of special rules that generates recommendations related to multiple turn lanes and very high through volumes. The three independent special rules complement the eight basic approach configurations and provide a total of 64 ultimate designs. In all, nearly 600 unique reports for feasible recommendations are possible for each approach analyzed because of the various combinations of ideal designs, recommended designs, modification descriptions, and special recommendations.

DISCUSSION OF RESULTS

Evaluation Strategy

Validating a knowledge-based expert system is not as straightforward as validating an algorithmic program. The nature of the problem is often such that there is no single solution that can be proven "best." Two experts can come up with different solutions to the same problem, both of which are acceptable and completely defensible, but neither of which is necessarily optimum. These differences can usually be attributed to variations in the policies or practices being followed. Most expert systems are derived from the knowledge of a single expert (or at most a small number of experts). They therefore reflect the policies and practices preferred by that expert. In evaluating the performance of expert systems, it is important to consider two questions. First, does the system accurately and consistently reproduce an accepted approach to the problem? And second, can the system be modified to reflect other valid policies and practices?

The design policy implemented in the Intersection Advisor is a conservative one. It encourages balanced volume-to-capacity ratios for all lanes and is intended to provide a basis for a signal plan that will offer a high level of service. The advisor concentrates on improving the operation of the entire intersection by increasing the capacity of each approach. This policy gives some consideration to critical movements, but otherwise it is not very sensitive to interactions between approaches. This is not a major limitation, however, because approach capacity is primarily a function of lane geometry, whereas conflicts and other interactions between approaches are highly dependent on signalization.

The results of dozens of test cases are consistent with this policy and with the guidelines and examples contained in Chapter 9 of the HCM. The test cases include simple design problems like Sample Calculation 5 in the HCM, intersections with severe improvement constraints, and those with volumes requiring up to seven lanes in each direction. A typical consultation lasts about 5 min, and most users find the advisor easy to run and understand.

In no case has it been possible to significantly improve the operation of an intersection by making improvements in addition to, or instead of, those recommended by the advisor. It should be noted that the advisor does not recommend the removal of existing lanes that are unnecessary because this would not typically be practical. The advisor will, however, suggest that existing lane uses be redefined if warranted. The advisor does have a tendency to overdesign in certain cases because it seeks to achieve a target volume-to-capacity ratio for each lane and does not consider signalization. The advisor also ignores intersection symmetry in making its recommendations. All of these traits are consistent with the planning method and with the advisor's design policy.

Not only can the Intersection Advisor accurately and consistently implement a specific design policy, its policy can be changed relatively easily. Constants in the geometric rules can be increased to reflect a lower acceptable level of service. Other modifications can be made to reflect a policy of more liberal warrants for exclusive left-turn lanes. Approach symmetry can be assured by adding several simple rules and modifying a few more. The ability of a simple prototype like this to reflect various policies and practices is significant. It emphasizes the potential of expert systems as practical transportation engineering tools. It also suggests a completely new application for the Intersection Advisor and related systems: as tools for evaluating various policies or changes to existing policies.

CONCLUSIONS

As a prototype system, the main purpose of the Intersection Advisor is to test the feasibility of a concept and to identify areas for future development. The advisor has demonstrated the feasibility of using a knowledge-based system to solve geometric problems in intersection design. Although the advisor in its present form may not be considered a useful design aid in terms of time savings or increased accuracy, it does make valuable contributions to the development of an integrated, interactive system for the design of signalized intersections. Continued progress in this area is the focus of further development of the Intersection Advisor.

Several improvements to the advisor are necessary if it is to become a more useful tool. The use of code numbers to represent lane configurations is inconvenient, so an icon-based graphics interface is planned. The problem domain must be expanded and generalized to contain the wide range of problems confronted in actual practice, including one-way streets and multileg and T-intersections. Parking conditions, pedestrian activity, and lane width need to be considered. The user should be able to specify a minimum desired level of service. The advisor should be able to select a design based on more than one set of turning movements (a.m. and p.m. peak hour volumes, for instance), and it should be able to determine critical movements from the information provided. Sensitivity to the interactions among approaches and to the performance of the intersection as a whole must be increased.

The enhancement that appears to be the most difficult to implement is generalization of the problem domain, particularly the inclusion of a graphic interface. The other improvements can be achieved through the addition of rules and facts to the knowledge base and by introducing a cyclic format to the solution strategy. The cyclic format would not be iterative but would allow the advisor to consider the intersection as a whole, including the influence of signalization, before making individual recommendations. A major decision about the future of the Intersection Advisor involves selecting the most appropriate hardware and software environment for its development. M.1 does not have the power and flexibility needed for the implementation of the larger design system. Nevertheless, it did provide a suitable environment for gaining a better understanding of the nature of the geometric design problem and for developing and testing a knowledge base and solution strategy that will be the basis for future efforts.

REFERENCES

1. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
2. *Microcomputers in Transportation: Software and Source Book.* Report UMTA-URT-86-1. U.S. Department of Transportation, Feb. 1986.
3. E. Shenk et al. *Prototype Highway Capacity Manual Programs for Intersection Analysis.* TTRC/FHWA, U.S. Department of Transportation, 1986.
4. *M.1 Reference Manual.* Teknowledge, Palo Alto, Calif., March 1985.