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A KNOWLEDGE-BASED DECISION SUPPORT ARCHITECTURE FOR ADVANCED TRAFFIC MANAGEMENT

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Abstract—Fundamental to the operation of most currently envisioned Intelligent Vehicle-Roadway System (IVRS) projects are advanced systems for surveillance, control and management of integrated freeway and arterial networks. A major concern in the development of such Smart Roads, and the focus of this paper, is the provision of decision support for traffic management center personnel, particularly for addressing nonrecurring congestion in large or complex networks. Decision support for control room staff is necessary to effectively detect, verify and develop response strategies for traffic incidents. The purpose of this paper is to suggest a novel artificial intelligence-based solution approach to the problem of providing operator decision support in integrated freeway and arterial traffic management systems, as part of a more general IVRS. A conceptual design is presented that is based on multiple real-time knowledge-based expert systems (KBES) integrated by a distributed blackboard problem-solving architecture. The paper expands on the notions of artificial intelligence and Smart Roads, and in particular the role, characteristics and requirements of KBES for real-time decision support. The overall concept of a decision support architecture is discussed and the blackboard approach is defined. A conceptual design for the proposed distributed blackboard architecture is presented, and discussed in terms of the component KBES functions at an areawide level, as well as at the subnetwork or individual traffic control center level.

INTRODUCTION

Interest in advanced roadway technology research has gained momentum in recent years, with well-funded and well-defined initiatives underway such as PROMETHEUS (Programme for European Traffic with Highest Efficiency and Unprecedented Safety) and DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe), as well as several projects in Japan on advanced communication and control. A goal of these projects is to develop "intelligent" vehicle-roadway systems (IVRS), also sometimes called Smart Cars and Smart Roads. The IVRS concept involves the development and application of a variety of advanced technologies and automated control strategies to achieve significant areawide traffic operations improvements, resulting in increased road-based mobility and safety, and decreased environmental and economic impacts of traffic.

In the United States, an initial attempt is being made to formulate a national policy and research agenda on IVRS (U.S. Department of Transportation, 1989). Several states and large urban areas have launched their own efforts. Of these, California appears to be at the forefront, with on-going projects such as PATH (Program on Advanced Technology for the Highway), which is investigating automation, electrification and navigation technologies to increase capacity of the existing highway system (California Department of Transportation, 1989); the Santa Monica Freeway Smart Corridor Demonstration Project in Los Angeles, which will implement and test state-of-the-art traffic management and public access communication concepts on a major freeway and arterial corridor (Rowe, 1989; JHK & Associates *et al.*, 1989); and PATHFINDER, an in-vehicle navigation and information system, to be tested in the Smart Corridor project (Blackburn, 1989). Numerous federal, state and local agencies, consultants, and university researchers are involved in these efforts, in addition to private industry.

Fundamental to the operation of most of these IVRS projects are advanced systems for surveillance, control and management of integrated freeway and arterial networks. Traditionally, freeway and urban street systems have been treated as essentially independent entities (ITE, 1985). Van Aerde and Yagar (1988), among others, have discussed the benefits and challenges of integration.

A major concern in the development of Smart Roads, and the focus of this paper, is the provision of decision support for traffic management center personnel, particularly for addressing nonrecurring congestion in large or complex networks. Decision support for control room staff is necessary to effectively detect, verify and develop response strategies for traffic incidents. These are events that disrupt the orderly flow of traffic, and cause nonrecurring congestion and motorist delay. Nonrecurring congestion can be caused by accidents, spilled loads, stalled or broken down vehicles, maintenance and construction activities, signal and detector malfunctions, and special and unusual events.

The purpose of this paper is to suggest a novel artificial intelligence-based solution approach to the problem of providing operator decision support in integrated freeway and arterial traffic management systems, as part of a more general IVRS. A conceptual design is presented that is based on multiple real-time knowledge-based expert systems (KBES) integrated by a distributed blackboard problem-solving architecture. In practice, these KBES would typically be associated with multiple computer processing units, traffic control centers, transportation agencies and traffic subnetworks. The paper expands on the notions of artificial intelligence and Smart Roads, and in particular the role, characteristics and requirements of KBES for real-time decision support. The overall concept of a decision support architecture is discussed and the blackboard approach is defined. A conceptual design for the proposed distributed blackboard architecture is presented, and discussed in terms of the component KBES functions at an areawide level, as well as at the subnetwork or individual traffic control center level.

ARTIFICIAL INTELLIGENCE AND SMART ROADS

Artificial intelligence (AI) is an umbrella term that includes many subdisciplines, each intended to imitate some aspect of human thinking (e.g. vision, speech recognition, natural language understanding and expert problem solving). The goal of AI programs is to solve problems in a way that would be considered intelligent if done by a human. Rich (1983) has defined AI as the study of how to make computers perform tasks which, currently, humans perform better.

KBES computer programs are one of the most broadly successful products of AI research. They address ill-structured problems where algorithmic solutions are not available, are impractical or are inadequate. KBES emulate human problem-solving that involves specialized knowledge, judgement and experience. KBES applications in engineering typically involve integration of both knowledge-based and algorithmic approaches. Descriptions of conventional KBES technology are available in the transportation and civil engineering literature (Ritchie, 1987; Maher, 1987) and elsewhere (e.g. Waterman, 1986; Harmon and King, 1985).

However, real-time KBES represent a complex and demanding application of KBES technology, and one that has received little attention to date in the transportation field, despite some apparently high potential applications, including decision support in IVRS. Real-time KBES are appropriate where users, and thus productivity levels, suffer from cognitive overload in time-sensitive environments. The ability to filter relatively low-level and voluminous information and present an operator with fewer high-level analyses and recommendations is expected to be an important issue in incident detection and response for Smart Roads.

Although real-time KBES applications exist in industrial and military domains, to date there are no known development efforts or applications for integrated freeway and surface street traffic surveillance and control, other than for the Santa Monica Freeway Smart Corridor (Ritchie, Kay and Rowe, 1990). Foraste and Scemama (1987) have reported on a prototype KBES for selection of traffic signal timing plans in a congested surface street network in Paris, and Han and May (1988, 1989) have studied a KBES approach to incident detection in signalized street networks, using data from Los Angeles.

Significant opportunities exist for real-time KBES to provide decision support to traffic control room staff, even in some existing surveillance and control systems. More importantly, however, as the breadth and scope of these systems is vastly expanded to embrace Smart Roads concepts for both freeway and surface street systems, it will be increasingly difficult if not impossible for human operators to detect and review all "problem" locations, verify incidents, and develop and implement response strategies in a timely manner. Real-time knowledge-based systems provide an automated approach to reduce the operator involvement needed to identify true problem locations, determine alternative and consistent courses of action by all relevant agencies, and implement response plans, thereby reducing traffic delays associated with nonrecurrent congestion.

REAL-TIME KBES CHARACTERISTICS

A precise and generally accepted definition of "real-time" has proven elusive, although a commonly perceived characteristic of a real-time system is its speed of operation. To some this means faster than a human, or alternatively, responding to data at a rate as fast or faster than it is arriving. More generally, for an arbitrary state of the system and an arbitrary event, a response should always be available by the time it is needed, perhaps expressed by a specified maximum time interval (Laffey *et al.*, 1988).

A real-time KBES must satisfy demands that do not exist in conventional domains where the inputs and conclusions are static and time-critical responses are not required. Thus, more advanced features must be incorporated into a real-time system. These features also tend to characterize the limitations and inappropriateness of most conventional expert system development software tools for real-time KBES development. Several authors, including Laffey *et al.* (1988) and Moore (1987) have discussed the distinguishing features of real-time KBES. In terms of decision support for nonrecurring congestion on Smart Roads, the important characteristics and requirements are:

Truth maintenance

In a monotonic reasoning process, as used by most KBES today, all facts and conclusions remain true, and the amount of true information in the system grows steadily or monotonically. In a real-time traffic management KBES, detector data, other inputs and deduced facts may decay in validity over time, and cease to be valid beyond a certain interval. Previously established logical dependencies and conclusions must therefore be able to be retracted or modified in light of new information. Such reasoning is referred to as nonmonotonic. For example, over time, incident status and response strategies, including motorist information reports and advisories, will change as incidents are detected, verified, responded to and cleared. To address nonmonotonic reasoning and its associated issues, a real-time KBES must incorporate a system for truth maintenance or consistency management.

High performance

Very short response times are often required in the face of rapidly changing data. Although response times several orders of magnitude longer than some military real-time KBES applications should be acceptable, generation of incident response plans within several minutes will most likely be desired, including operator time for incident verification. Ideally, a response (preferably the "optimum") should be guaranteed within a given duration.

Temporal reasoning

This is the ability to reason about time-dependent events, sequences and relationships. The incorporation and representation of time-dependent heuristics, data and even dynamic models in a knowledge base will almost certainly be needed.

Asynchronous events

It should be possible for the system to be interrupted to process an unexpected or unscheduled event. The processing of synchronous events according to their importance should also be possible.

External and sensor interface

Conventional KBES are interactive and receive inputs from the user. Real-time systems typically gather data, sometimes for many thousands of variables, from sensors or via database interfaces, and provide continually updated displays to the user. Links to conventional packages and code such as C, Fortran and Pascal, etc., are also required.

Uncertain or missing data

The system should be able to recognize and appropriately process such data, including those from faulty or inoperative detectors.

Continuous operation

Twenty-four hour operation must be possible each day, even with partial failures of the monitored system, such as a temporary loss of communication links. A "graceful," rather than catastrophic, degradation of performance must also be planned for under such circumstances.

Focus of attention

This refers to the ability of the system to selectively focus its resources when a particularly significant event occurs, just as humans do, while maintaining peripheral awareness of the overall process. Concurrent focus on several individual problems (e.g. incidents), may also be required. This requires the application of metaknowledge, which is basically the ability of the system to reason about its own knowledge, and which aspects of it to apply in given situations.

A DECISION-SUPPORT ARCHITECTURE

Overall concept

The overall approach suggested in this paper for a real-time knowledge-based decision support system is based on several basic assumptions:

1. The objective is to develop a preliminary design at a conceptual level, focusing only on an AI-based solution approach to operator decision support for nonrecurring congestion. It is neither intended nor possible to discuss the many other functions of an advanced traffic management system, or the associated communications and networking details.
2. For simplicity, it is assumed that there are two principal operating agencies involved, which are responsible for the signalized surface street network and the freeway system, within the specified corridor or area. These agencies are a city and state department of transportation (DOT), respectively. Each agency may operate an existing surveillance and control center. These will be called the Street Traffic Operations Center (Street-TOC) and the Freeway Traffic Operations Center (Freeway-TOC). To coordinate the operation of these control centers, a new entity (but not necessarily a new facility) called Smart-Central will be established. Associated with Smart-Central would be a major relational database system to facilitate the networked linking of all agencies and their control systems. Together with the city and state DOT's, other actively participating agencies (in an operational sense) would likely include city police, state police or highway patrol, and transit agencies.

In addition, each participating agency is assumed to be supplied with a new local processing unit (node processor), as illustrated in Fig. 1. This need not be the case in practice, but simplifies the discussion. This processor handles data extraction and communications. Real-time KBES would interface to database servers on the node processors at each TOC and at Smart-Central (the physical location of which is not important). The Freeway and Street-TOC KBES would provide decision support pertaining to the freeway and surface street traffic systems, respectively, while the Smart-Central KBES

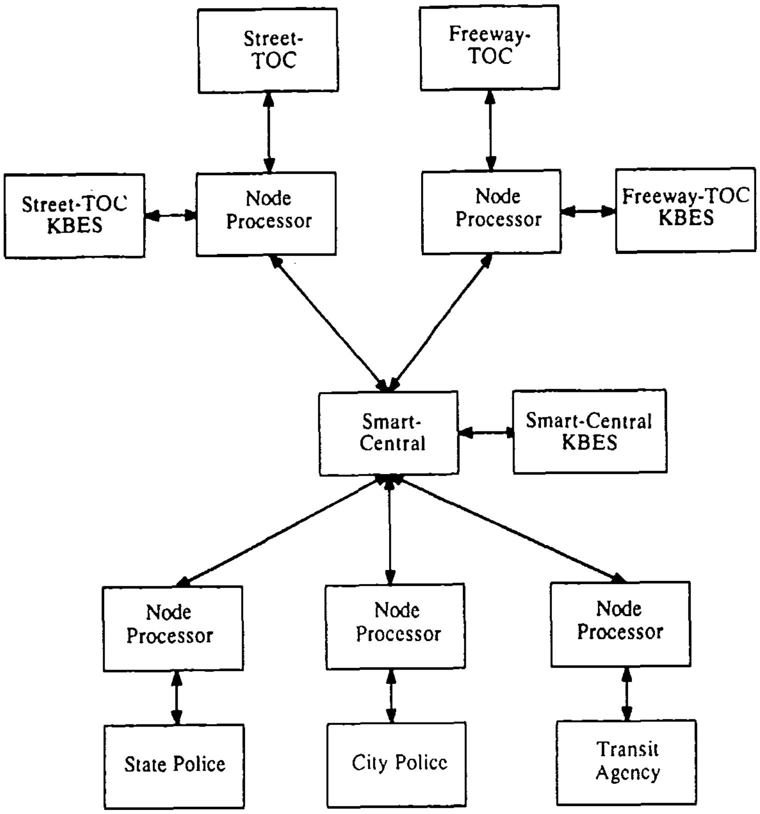


Fig. 1. Overall concept.

would optimize areawide conditions and coordinate response actions amongst all agencies.

This design envisions three networked real-time KBES running initially on separate microprocessors attached to the node processors at Street-TOC, Freeway-TOC and Smart-Central, with networked terminal displays at any or all of the city police, state police or transit agency communications centers, to permit viewing of various corridor status reports (and possibly to enable interactive data input to Smart-Central). Communications between the Smart-Central KBES and the Street and Freeway-TOC KBES would occur via the respective database servers using the blackboard framework discussed in the following section.

A major component of the Street and Freeway-TOC KBES would be their user-friendly operator interface (the Smart-Central KBES could probably be designed to run largely unattended). Initial user interfaces would utilize windowing techniques on dedicated workstation monitors. Subsequently, these interfaces could be integrated into regular operator terminal displays, to result in one integrated display environment, if desired.

The Street and Freeway-TOC KBES should permit stand-alone independent operation with respect to the surface street and freeway traffic systems. Although this concept involves some redundancy with the capabilities of the Smart-Central KBES, it permits continued operation of each TOC KBES in the event of a communication loss to Smart-Central. However, an overriding consideration is likely to be that this configuration is desired administratively and especially politically, by the individual agencies.

The primary intent of this design is to provide decision support to TOC staff, and to contribute to optimizing areawide or corridor mobility, through five integrated modules, as indicated in Fig. 2: (i) incident detection, (ii) incident verification, (iii) identification and evaluation of alternative responses, (iv) implementation of selected responses(s), and (v) monitoring recovery. In addition, timely and useful information could be provided to both police and transit agencies. An overview of these five modules follows.

The incident detection modules would complement existing and on-going research and development of algorithmic methods for incident detection on surface streets and freeways. This means that separate, and in most cases existing, conventional software at each TOC could be used to process detector data and act as a filter to identify potential incident conditions. The TOC KBES would only then be invoked after such conditions have been declared. This approach removes what could otherwise be an enormous processing burden from the KBES. However, in the case of the surface street system, considerable research is required to develop incident detection capabilities, which are now in their infancy. A greater basic research effort integrating al-

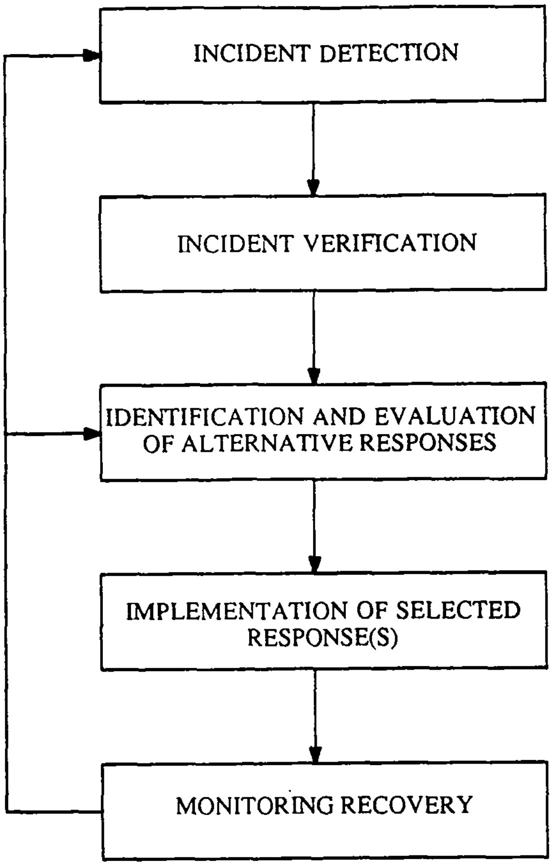


Fig. 2. Decision support modules.

gorithmic and AI-based approaches may therefore be required in this case, than for the freeway system.

The incident verification module would guide operators in verification procedures for the unusual conditions and suspected incidents identified in the detection module. This could include automatically selecting and activating appropriate closed-circuit TV cameras for operator viewing, and obtaining and assessing other supporting or negating data (e.g. 2-way radio calls from field personnel, and motorist calls from cellular telephones or nearby roadside callboxes). The final verification decision would be made by the operator.

The module for identification and evaluation of alternative responses would be a major module, relating to provision of assistance to both incident victims and affected users. It would require not only identification of feasible responses, but possibly on-line traffic network forecasting and modeling for evaluation and refinement of the alternatives. The conditions under which various responses should be considered would have to be identified, as would evaluation and selection procedures. Initially, preplanned and preagreed responses and actions could be jointly developed by the operating agencies, prior to development of an on-line modeling capability.

Current incident response methods in existing traffic management systems are often complex, and involve considerable operator judgement as well as familiarity with extensive procedures outlined in inaccessible and little-read reports and manuals. This situation will be exacerbated with the incorporation of additional Smart Roads alternatives to the list of possible responses, which includes:

(i) modifying surface street signal timing plans
(ii) initiating ramp metering changes
(iii) coordination of ramp meters and surface street traffic signal timing
(iv) activating freeway major incident traffic management teams
(v) dispatch of freeway maintenance crews
(vi) dispatch of City traffic control officers and/or traffic signal maintenance crews
(vii) locating and activating freeway mobile and ground-mounted changeable message signs (including composition of messages)
(viii) activating changeable message signs on surface streets and approaches to freeway access ramps (including composition of messages)
(ix) selecting and implementing signed traffic detours
(x) dispatch of tow trucks and emergency services on both the freeway and surface street system
(xi) coordination with other agencies and the media
(xii) issuing and updating real-time traffic reports and recommendations through motorist information systems, embracing for example, highway advisory radio, telephone dial-in services, cable TV, commercial radio and TV, in-vehicle navigation systems, and traffic information displays in major buildings, parking garages, fleet dispatch centers and computer bulletin boards.

The module for implementation of selected responses must therefore determine consistent courses of action by all relevant agencies, communicate these action plans to the agencies, and monitor confirmation of their implementation.

Finally, the module for monitoring recovery would attempt to assess the efficacy of the implemented response(s) by monitoring selected measures of effectiveness (MOE's), presenting these to the operator through graphical displays, and assisting the operator to determine if further responses are required.

A distributed blackboard model

A particularly suitable framework for integrating the knowledge-based decision-support systems discussed above is a distributed blackboard problem-solving model from the field of AI (Nii, 1986a, 1986b; Dodhiawala *et al.*, 1989; Walters and Nielsen, 1988).

Blackboard systems are so named because their structure and approach is analogous to a group of experts gathered around a blackboard solving a problem. The blackboard model first served as the basis of the HEARSAY-II speech understanding system (Erman *et al.*, 1980), which evolved from research on HEARSAY-I in the early 1970s (Reddy, Erman and Neely, 1973). HEARSAY-II responded to spoken queries about computer science abstracts in a database, based on a 1000-word vocabulary.

The essential components of a blackboard system are the blackboard database, and the knowledge sources. The blackboard database is a globally shared database, or repository of information, and the knowledge sources are independent specialists relating to an aspect of problem solving. The knowledge sources respond to and modify information on the blackboard opportunistically; that is, when they can advance the solution state, leading incrementally to a solution. One or more knowledge sources must also provide a control or scheduling function for choosing the next knowledge source to be executed. This overall structure is illustrated in Fig. 3.

A specific method of knowledge representation is not prescribed by the blackboard approach; different methods can be used by each knowledge source, providing all information on the blackboard can be used by any knowledge source needing it. As Nii (1986a, b) points out, the blackboard model does not actually specify the realization of a computational entity; rather, it is a conceptual entity that provides guidelines for the solution of a problem. Significant differences therefore occur, and are to be expected, in the design and implementation of blackboard systems, depending to a large extent on the requirements and nature of the application. Hendrickson and Au (1989), for example, have described an experimental civil engineering application for an integrated building design environment.

Parsaye and Chignell (1988) note that the blackboard model provides three distinct advantages: organization of knowledge into modular knowledge sources, integration of different knowledge representation methods, and execution in a distributed computing environment for greater efficiency. Although many, if not most, blackboard systems to date operate on a single processor, the model architecture readily accommodates distributed problem solving through the distribution of knowledge amongst the knowledge sources and the global blackboard database. This feature is particularly relevant to the present case, where knowledge sources representing the Street-TOC, Freeway-TOC and Smart-Central knowledge bases are implemented on separate processors. These knowledge sources execute independently (except for their implicit communication through the blackboard). Also, although initiation of knowledge sources proceeds serially, the simultaneous execution of knowledge sources can permit some degree of parallel processing. Thus, the proposed blackboard approach satisfies the need for

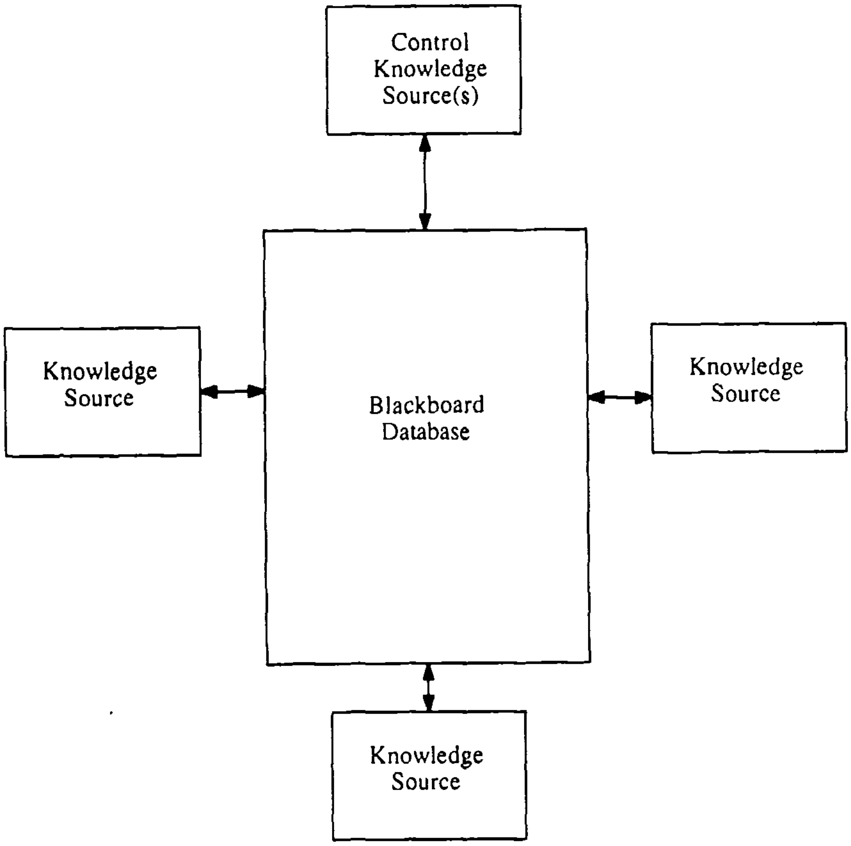


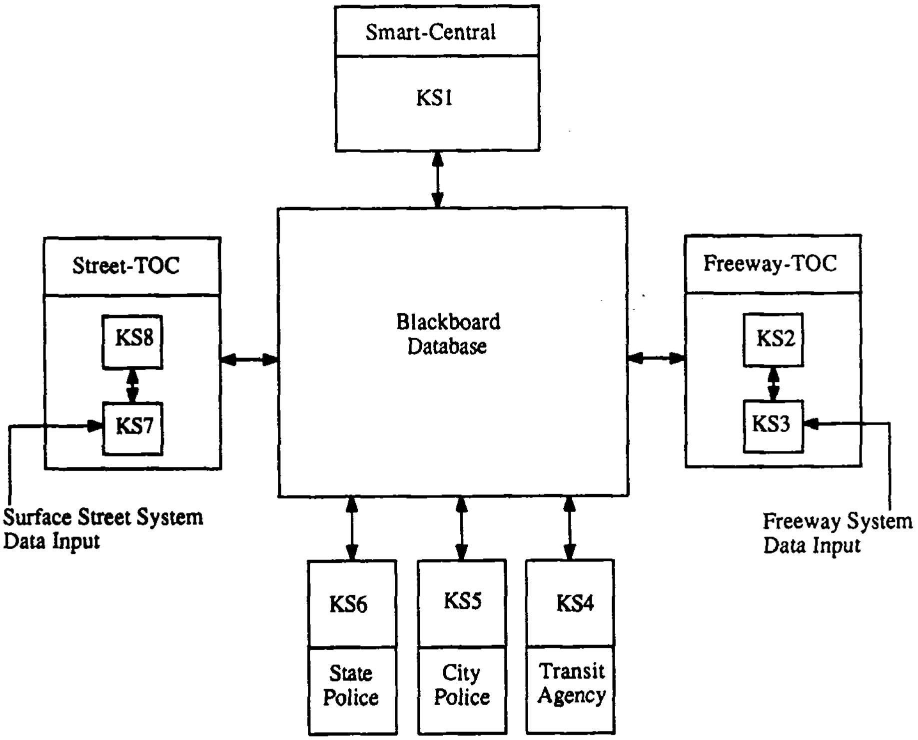
Fig. 3. Structure of a blackboard model.

a distributed or multi-processor implementation. Figure 4 illustrates this approach, which is derived from the overall concept presented earlier in Fig. 1.

Some further clarification of the principal blackboard components related to Fig. 4 is now appropriate.

Each independent knowledge source or specialist has a particular area of expertise, similar to the knowledge base in a conventional KBES. However, a variety of knowledge representation methods can be used, and some knowledge sources can consist entirely of conventionally coded procedural programs. Each knowledge source is designed to take actions, based on its reasoning, to modify the blackboard or control data structures, and in so doing advance the solution state. Only knowledge sources can modify the blackboard. Furthermore, each knowledge source should be able to recognize conditions on the blackboard that make it eligible to execute. The blackboard control mechanism then selects eligible knowledge sources to execute. In Fig. 4, although knowledge sources 3 through 7 could be procedural, they would still read data from and write data to the blackboard. Knowledge sources 3 and 7 could be based on existing TOC hardware and software for receiving, processing and filtering detector data for the incident-detection decision support modules at each TOC. As suggested earlier, these knowledge sources may integrate new algorithmic and AI-based approaches for improved incident detection performance. Knowledge sources 1, 2 and 8 are the real-time KBES for Smart-Central, Freeway-TOC and Street-TOC, respectively. These knowledge sources could be divided into subknowledge sources for the remaining decision-support modules listed in Fig. 2.

The blackboard is a globally shared database, changes to which provide the means of communication between knowledge sources. Direct communication between some knowledge sources could withhold from others relevant information or developing conclusions, and is therefore not permitted. The blackboard can also be divided into multiple subareas or panels (as well as into multiple blackboards). The data on the blackboard or its component panels are typically organized hierarchically, reflecting the suitability of the approach to problems that can be decomposed hierarchically. In such an arrangement, blackboard information at one level provides input to knowledge sources which then place new information at the same or higher levels. Raw data are often associated with the lowest level, and more highly processed information and more general knowledge with the higher levels. Reasoning that proceeds from low to high levels is termed "bottom-up." The five decision support modules illustrated in Fig. 2 implicitly involve a hierarchical, bottom-up approach that would be reflected in the blackboard database and the input/output dependencies of the knowledge sources.



Note: KSN = Knowledge Source N

Fig. 4. The overall decision-support blackboard model.

In Fig. 4, the Smart-Central knowledge source assumes the role of the control mechanism, monitoring changes on the blackboard and deciding what action to take next. Control can be exercised by placing information on the blackboard that will influence the knowledge sources, and through the selection of which knowledge sources to execute. Several types of control strategy can be used in selecting knowledge sources at any stage. As a result, knowledge sources respond opportunistically to changes in the blackboard. When an acceptable solution is found, or the system cannot continue due to lack of data or knowledge, the process terminates.

The function of this blackboard problem-solving model can be viewed in terms of the functions of its component KBES, at both the areawide (Smart-Central) and subnetwork (individual TOC) levels. For conciseness in the discussion that follows, reference to each knowledge source read/write function involving the blackboard is omitted. However, it must be remembered that the blackboard is the medium through which the knowledge sources communicate with each other in order to permit global sharing of information amongst all knowledge sources.

The Smart-Central KBES would be concerned primarily with incident conditions of areawide significance, requiring coordinated responses by more than one agency, or modification of a specific agency's locally developed response plan, as shown in Fig. 5.

Accordingly, the Smart-Central KBES would continually receive and synthesize verified incident reports (and response plans) from all agencies, to identify existing (and possibly potential) problems of areawide significance. The system could request and process detector data from each TOC to facilitate this process. When such problems are determined, alternative responses are identified and evaluated, a preferred response plan is selected and individual agency actions identified. These actions may confirm, modify or replace locally proposed agency actions, by either the Street or Freeway-TOC KBES. The Smart-Central KBES then sends messages to each agency advising of incident status and required response actions. Confirmation or otherwise of agency actions is received and logged. Incident recovery is then monitored with a view to the need for additional or different agency responses. When incident conditions affect one agency only, the Smart-Central KBES could largely hand-off to that agency, after approving response plans, and then continue to monitor areawide traffic conditions. In addition, as traffic conditions change, the Smart-Central KBES could be the entity to recommend activation of or changes to motorist information system messages.

The Street and Freeway-TOC KBES are similar in function, and so are discussed together. The operation of each is consistent with the five decision support modules that have already been discussed, and is illustrated in Fig. 6.

The operator would first receive a report of a suspected incident, stating the location and invoking conditions. The KBES would attempt to apply more refined tests employing heuristics and localized information to determine with greater certainty whether an incident exists or not. Guidance would be given to the operator on verification procedures, particularly involving the use of closed-circuit TV cameras, where available. The operator, with the assistance of the system, would then indicate whether the incident is verified or not. At the local level, alternative responses would be identified and evaluated by the system, with specific operator actions presented for implementation of the selected response plan. The system would automatically send an incident report and proposed response plan to Smart-Central, which in turn would authorize or

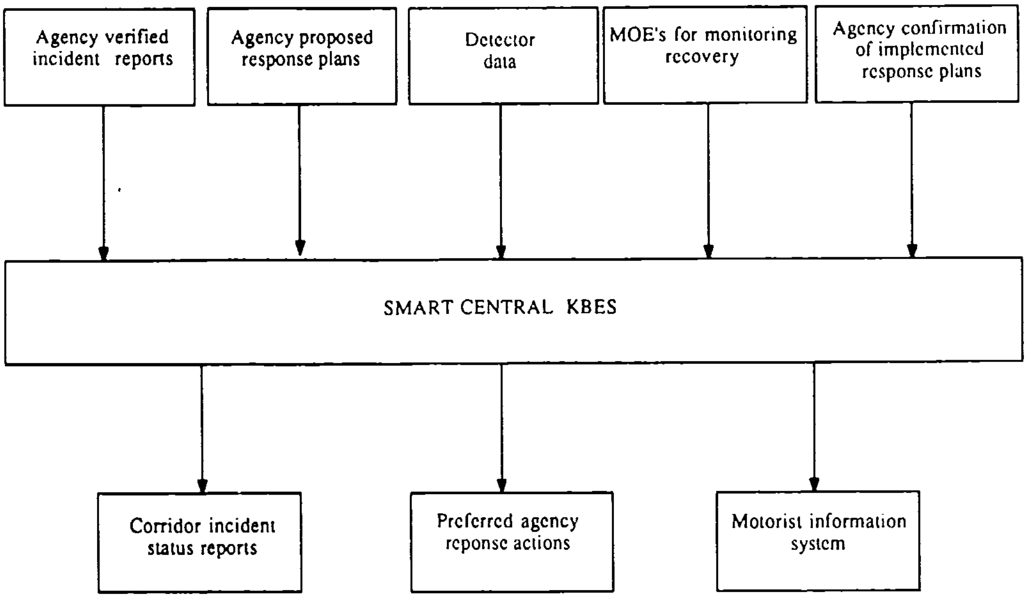


Fig. 5. Smart central KBES high level functions.

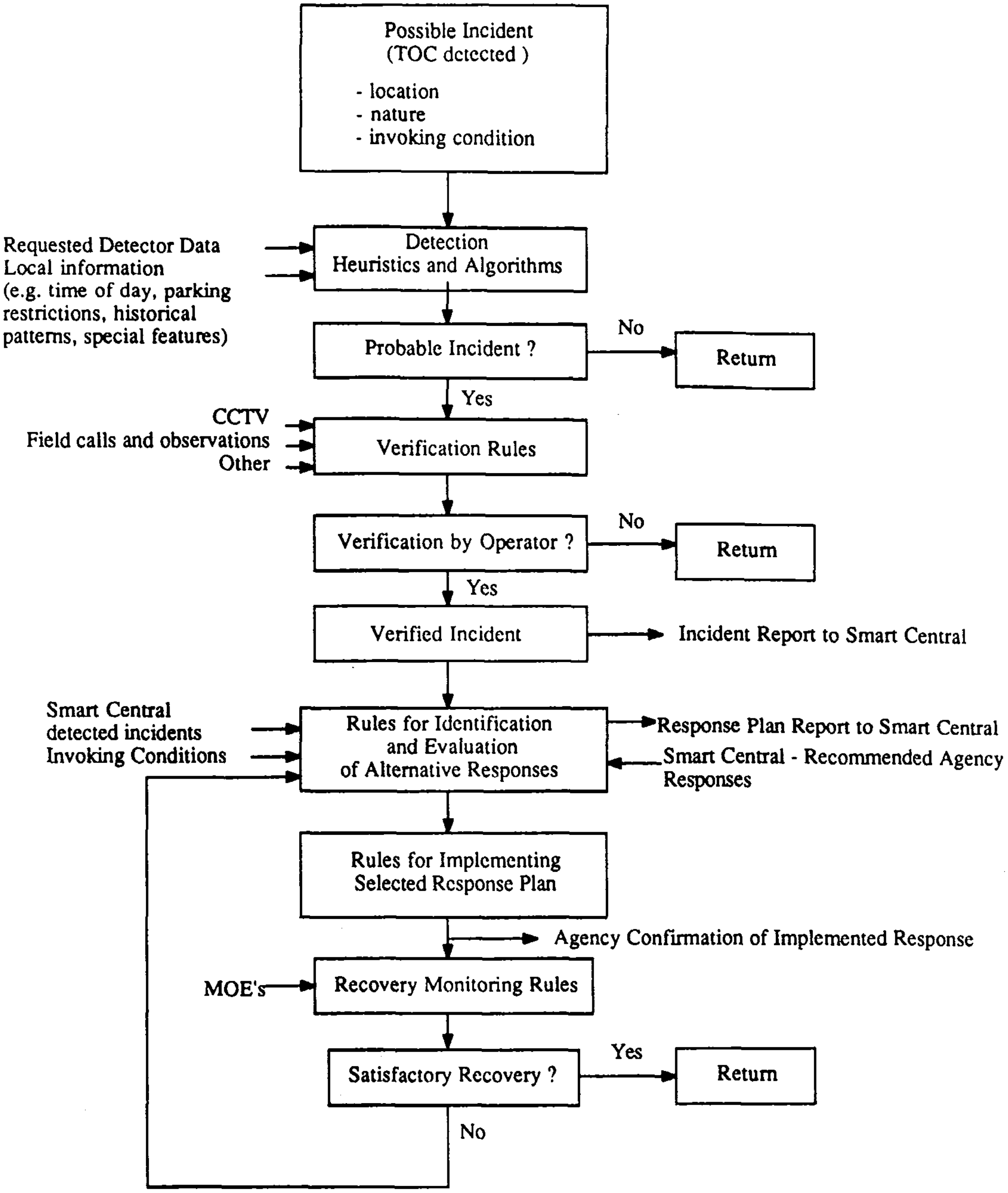


Fig. 6. TOC KBES functions.

modify the response plan. Once the response actions have been implemented by the operator, confirmation would be sent to Smart-Central. Through the incident recovery monitoring module, recommendations for further operator action may be made.

Several high-level window interfaces could be displayed to the operator in these KBES, including an incident status report for locally and Smart-Central detected incidents (showing if local incidents are also verified or not), an incident verification window listing suspected incidents and what operator actions to take for verification, and a response status report listing response actions and whether they have been approved by Smart-Central and implemented yet. An action box could also be displayed telling the operator what to do next. Underlying these windows, various menus, reports and graphical displays would be available to the operator.

KBES DEVELOPMENT SOFTWARE

An important element that must be carefully considered is the most appropriate KBES development and implementation environment.

Development tools to build expert systems can generally be divided into programming languages and knowledge engineering languages (Waterman, 1986). Programming languages include conventional problem-oriented languages such as Fortran, Pascal and C, and symbol manipulation languages such as Lisp and Prolog. Symbol manipulation languages have been designed specially for AI applications, but require the expert system developer to essentially start from "scratch" with respect to programming knowledge representation and control methods. On the other hand, knowledge engineering languages usually offer one or more knowledge representation methods, and an inference engine for accessing the knowledge, as well as a more extensive support environment. Knowledge engineering languages range from a large number of shells (a complete expert system with an empty knowledge base, to be completed by the developer using the system's support tools) that are now available for powerful general-purpose workstations and microcomputers, to sophisticated packages for dedicated AI hardware. KBES shells usually offer a faster route to system prototyping and development, and with the recent advances in both computer hardware and KBES software, provide a particularly cost-effective environment for both development and implementation.

However, as discussed earlier in this paper, conventional KBES development tools do not typically support the advanced features necessary in a real-time KBES. This particularly includes high performance (response time), temporal reasoning, nonmonotonic reasoning or truth maintenance, external interfaces to databases and conventional software and sensors, asynchronous inputs, and focus of attention. In addition, this conceptual design calls for distributed real-time KBES communicating via database servers to a blackboard database, directly through the network, and to remote terminals. An essential consideration is also that substantial KBES expansion may be required in the future (with further implementation of Smart Highway concepts), without degrading system performance.

Ideally, one would like a powerful, flexible, proven and easy-to-use real-time KBES tool, that would speed prototype development and permit implementation on a variety of hardware platforms.

While there are a great many KBES development tools available, many of which claim a real-time capability, few commercially available systems have been identified to date that are designed specifically for real-time applications, and which provide many of the required features. One such tool is G2 (Gensym, 1988), a recently available Lisp-based real-time expert system development tool. G2 provides a very powerful software development environment, and reflects many person-years of development effort. G2 also permits a highly graphical, easy-to-use, object-oriented operator interface to be constructed. We are now using G2, C, database management systems and a RISC-based workstation platform to conduct research into the development and implementation of initial elements of the approach presented in this paper for a knowledge-based decision support architecture for advanced traffic management.

CONCLUDING COMMENTS

This paper has proposed a novel AI-based solution approach to the problem of operator decision support in future integrated freeway and arterial traffic management systems. The approach involves implementation of a hierarchically-defined set of decision support modules within a distributed blackboard framework, emphasizing the use of real-time KBES. The current state-of-the-art of KBES technology and traffic surveillance and control systems now permits development of an initial prototype to proceed for significant portions of the overall decision support concept discussed in this paper.

However, a number of complex and challenging research and implementation issues are associated with the concepts presented, in both the near and longer term.

Ultimately, one can envision an integrated decision support environment incorporating not only the KBES architecture discussed in this paper, but also speech recognition, natural language understanding and machine learning capabilities. This would permit enhanced automation of operator and data input interfaces, allowing the system to anticipate many operator requests for graphic displays and recommendations, and to automatically learn from its operating experience in order to continually improve performance. Considerable basic research is needed in these areas. How to effectively utilize new, advanced computer architectures, especially involving parallel processing, must also be addressed. Of course, further research developing the fundamental traffic operations and control systems knowledge to be represented and used in such an AI-based decision support environment will continue to be vital.

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