AUTOMATED CONSTRUCTIBILITY ANALYSIS OF WORK-ZONE TRAFFIC-CONTROL PLANNING

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ABSTRACT: Constructibility, in simple words, is the ability to construct effectively. This study involved the development of a prototype system to perform highway constructibility analysis of traffic-control planning (TCP). The results of meetings with personnel at the Texas Department of Transportation (TxDOT) indicated that work-zone traffic control is one of the most critical factors impeding the constructibility of highway projects. The lack of personnel, the inability to fill the knowledge void caused by transfer or retirement of experts in the field, and the inability to effectively learn from mistakes are some factors that indicate a need for advanced automation techniques in the highway construction industry. The prototype system developed included a database module (CONTRAF), an expert system module (TRAPS), and a fuzzy scheduling module. It is developed to provide designers and construction managers with generic constructibility recommendations on traffic control, and direct access to a constructibility database, before the final TCP is designed. Once the final TCP is developed, the system helps in phasing the activities, calculating the fuzzy durations of the activities, and linking the activities to a project-management software for project scheduling.

INTRODUCTION

Constructibility, as defined by the Construction Industry Institute (CII), is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives (Construction 1986). Constructibility is defined as a measure of the ease or expediency with which a facility can be constructed. Finally, constructibility is often portrayed as integrating construction knowledge, resources, technology, and experience into the engineering and design of a project. It optimizes the following project elements from start to finish:

1. Overall project plan
2. Planning and design
3. Construction-driven schedule
4. Costs or estimates
5. Construction methods (Russell et al. 1992)

HIGHWAY PROJECT CONSTRUCTIBILITY

This research focuses on the highway construction industry and highway project constructibility. Highway project constructibility can be particularly challenging for a variety of reasons.

> For example, some highway construction technologies are changing rapidly, and, as with most construction, the work force is transient and site conditions can vary greatly. Nearly all projects are subjected to severe public scrutiny involving open competitive bidding, thereby separating the planning and execution phases and largely precluding a fast-tracked approach to construction. Design standards, authored by a multitude of organizations, abound and often limit, if not discourage, selective innovation. The requirement for nonproprietary specifications often leads to vagueness. In general, the perception is that project durations are longer than necessary and that construction costs can probably be lowered. As a result, specifications supportive of constructibility become an important element for improving project performance. (Hugo et al. 1989)

WORK-ZONE TRAFFIC CONTROL PLANNING

The success of a highway construction project hinges on adequate traffic-control planning necessary for the project. Traffic-control planning should be an integral and integrated part of the total project planning and design effort. It is desirable to discuss traffic control needs and limitations at a predesign meeting and then to consider traffic handling throughout project development. Poor accommodations for local and through traffic can result in unanticipated costs to rectify traffic-management difficulties, schedule delays due to traffic conflicts with construction operations, and above all, safety hazards to motorists and construction workers (Russell et al. 1992). Thus, construction experience input and consultation of lessons learned regarding traffic management can be very beneficial to an effective traffic control plan. Traffic-management decisions usually result in a trade-off among motorist inconvenience, construction efficiency, and public and worker safety. During reconstruction of an interstate interchange on a project, a constructor at the Wisconsin Department of Transportation (WisDOT) remarked that work would take two to three months under staged traffic while it would take only one month if a detour was used to reroute traffic (Russell and Swiggum 1994a).

Determination of whether or not the project site is open to traffic and the method of traffic staging is performed prior to awarding the construction contract. This means that careful assessment should be given to area characteristics and traffic patterns to create an optimal traffic-control plan that will minimize project delay, minimize motorist inconvenience, and maximize safety of the traveling public and construction crews. Often, however, this is not the case, resulting in the project manager and contractors developing traffic-control plans during construction. As the first step in the work-zone traffic-control-planning process, an organized effort should be made to assemble pertinent information and facts, which may have a bearing on traffic control. Three basic categories of input should be gathered (Federal 1988):

1. Description of the planned work activity
2. Existing traffic conditions
3. Description of the roadway and related features

The type and location of work will determine the degree of

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impact of the work, and also the data needed for traffic-control planning. For example, consider the following work activities:

1. Construction of curb and gutter may have little or no disruption of traffic.
2. Addition of a new lane, reconstruction of a freeway ramp, or pavement resurfacing may have a fairly extensive impact on traffic.
3. Replacement of a bridge or culvert may involve roadway closure and detours, with extensive disruption to traffic (Federal 1988).

Each of these activities, because of the type of work and/or its location relative to travel lanes, will have a different impact on traffic. As a result, each activity will warrant a different level of data collection. Very little input may be needed to plan the traffic control for curb and gutter construction on a low-volume, low-speed residential street. On the other hand, extensive information about work activity, traffic conditions, and the roadway may be needed in the traffic-control plan for a bridge-replacement project on an urban freeway. The foregoing three basic categories of input may be further subdivided into the following subcategories, depending on the type of project (Federal 1988).

Description of Work Activity

1. Type of construction
2. Magnitude of work
3. Tentative schedule

Traffic Data

1. Twenty-four hour volume counts
2. Daily and seasonal volume variation
3. Hourly volume counts

Roadway Data

1. Right-of-way limitations
2. Cross section (number of lanes, lane widths, shoulder widths, etc.)
3. Type and location of traffic-control devices (TCDs)
4. Description of suitable detour routes

Traffic-Control Plan (TCP)

A TCP is a scheme for handling traffic through a specific highway or street work zone or project. These plans may range in scope from a very detailed TCP, designed solely for a specific project, to a reference for a typical plan or section of the *Manual on Uniform Traffic Control Devices* (MUTCD) (State 1980). The degree of detail in a TCP will depend on the project complexity and the traffic interference with construction activity (Federal 1988).

Planning Process

The overall purpose of the planning process is to select the most appropriate traffic-control strategy. "Work-zone traffic-control strategy" is defined as the basic scheme of moving traffic through or around a construction, maintenance, or utility activity. The type of work zone is the most significant element of the control strategy, which also includes length of work zone, time of work, number of lanes, width of lanes, speed control method, and right-of-way control method (Federal 1988). The selection of the most appropriate strategy begins with identifying alternative work-zone types and constraints, followed by evaluating costs and traffic impacts, and finally resulting in selection of the best traffic-control strategy. The process includes a feedback loop through which the project design and the work procedure can be modified to enable implementation of a better strategy. This feedback is necessary because the original project design and/or construction procedure may have imposed severe constraints on the possible control strategies. It may be possible to relieve the constraints with design changes that do not affect the functional objectives or violate the design criteria. The suggested planning process involves nine steps, described as follows:

1. Assemble data—describe construction and provide all required input data.
2. Determine extent of roadway occupancy—a first-level assessment of roadway capacity.
3. Identify feasible work-zone types—which work-zone types may be appropriate for this type of construction.
4. Analyze volume/capacity relationships—a more detailed analysis of capacity constraints, queue lengths, and delay.
5. Analyze capacity improvement techniques—if problems exist, what methods may reduce delay and congestion.
6. Define alternative strategies—which strategies are shown to be practical and implementable.
7. Quantify impacts—an approach to cost-effectiveness analysis of the chosen alternative strategies.
8. Modify work-zone procedures—as required, modify the project design or schedule in response to problems.
9. Select preferred strategy—document implementation plan [Texas Department of Transportation (TxDOT) (1989)].

TCP Scheduling

The scheduling of major highway construction projects is conducted in phases. They are divided into phases depending on the type of construction, location of the roadway, traffic conditions, and other constraints. Each phase is again subdivided into stages depending on the complexity of work involved in that particular phase. Some examples of stages are: "place temporary concrete widening on westbound lanes," "erect overhead signs necessary for traffic control signing," "relocate concrete temporary barriers (CTB) as shown in plans," etc. The scheduling of these stages are normally conducted by project managers or traffic design engineers, based on their experience and judgment, or from data got from similar projects. Often, the stages do not finish on time, as estimated. This is because there are so many unknown and uncertain factors, such as the weather, labor skills, management experience, technology involved, equipment used, site conditions, traffic, etc., which affect highway construction projects. The level of knowledge, experience, and judgment of the management team often has a great influence on the timely completion of a given project.

PROBLEM

Most highway construction projects are characterized by: traffic problems, a substantial number of changes, poor planning, disputes, cost overruns, poor safety practices, and time delays (Russell et al. 1992). An effective constructibility review process has the potential to incorporate into design documents the best practices, guidelines, checklists, and lessons learned from previous projects, thereby improving the ease of construction and reducing life-cycle costs. Studies indicate that overall, constructibility is not being implemented to its full potential in the highway sector (Construction 1993). This may be due to both a lack of understanding among agencies of how to implement a constructibility work process and a lack of awareness of the potential benefits of a formal program. However, this trend is changing with more transportation agencies

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recognizing the success of constructibility in other construction sectors and, thus, initiating investigations toward implementing constructibility. A recent trend toward total quality management (TQM) has strengthened the motivation for soliciting construction's input prior to the start of construction. There is also a lack of awareness of the concept of constructibility in the highway sector. Even the agencies that practice constructibility do not have a formal program (Anderson 1994).

Traffic control is one of the most critical constructibility issues confronting highway projects. A poorly designed TCP could result in: unanticipated costs to rectify traffic-management difficulties, schedule delays due to traffic conflicts with construction operations, and inconvenience to the public using the roadway (TxDOT 1989). A TCP is completely dependent on the experience and judgment of the project-management team. Specific individuals with an organization may possess engineering knowledge and experience with regard to certain issues. However, this engineering knowledge and experience is not always captured and made available to other personnel. Thus, the experience only benefits a limited number of projects. In addition, the knowledge may be lost with those individuals upon their transfer to another organization or retirement. New personnel filling the vacant positions must then, often, learn by experiencing the same successes or difficulties as their predecessors did. The obvious result is increased costs of operations either through lost opportunity for improvement or repeated mistakes.

The scheduling of the TCP is again conducted by project managers based on their experience and judgment. They estimate, approximately, the duration of each stage without taking into account the uncertain and unknown factors like weather, site conditions, technology involved, equipment used, etc. Most agencies do not even use a critical path method (CPM), a proven project-management technique, to estimate the duration of their projects. This results in a lot of delays and untimely completion of projects.

TRAPS SYSTEM OUTLINE AND MODULES

This prototype system was developed to aid traffic engineers, construction managers, and other highway design personnel in the analysis of traffic-control planning and scheduling, a critical constructibility issue. The constructibility analysis includes the following: an automated way of capturing and storing constructibility lessons learned from completed projects, an effective manner of querying and accessing these lessons when starting on a new project, an intelligent way of providing constructibility recommendations on traffic planning (based on certain input conditions), an accurate way of estimating uncertain construction stage (activity) durations (using fuzzy logic), and a way of scheduling the traffic-control plan. The system was developed on an IBM 80486 platform, using the following windows software: Microsoft Visual Basic 3.0; Microsoft FoxPro 2.5, and Microsoft Project 3.0.

The overall system architecture is shown in Fig. 1. It efficiently integrates the three different windows software packages. The system is very user-friendly. It utilizes input from the user on the input project conditions (type of construction, roadway details, traffic details, and other related data). Based on these conditions, it gives constructibility recommendations on traffic control. It also provides the user with an option of linking to the constructibility lessons-learned database on traffic control, CONTRAF. Based on the initial constructibility recommendations and the information retrieved from CONTRAF, the user is expected to analyze all possible alternatives and devise the best possible TCP. Then, the user is expected to input this final TCP into the system. The system helps in the appropriate staging and phasing of the TCP, and also calculates the fuzzy duration period of each activity in the TCP. Finally, it links to the project-management software, Microsoft Project, to perform the scheduling of the project and to generate Gantt charts. The Gantt chart is then embedded back into the system from Microsoft Project, to give the user a graphical view of the completion dates of various activities in the project.

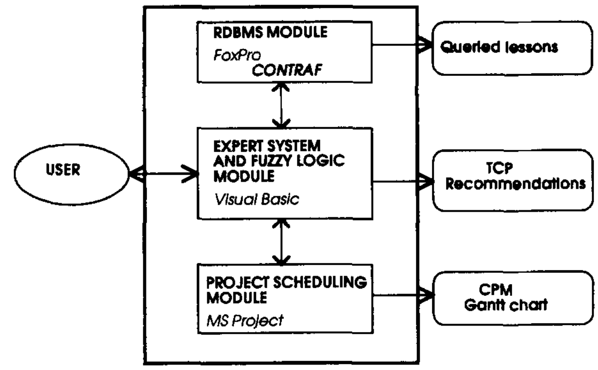

FIG. 1. Overall TRAPS System Architecture

Lessons-Learned Database System—CONTRAF

A challenge for any constructibility analysis is in developing the capability to learn from past successes and difficulties and either repeat or avoid the same actions in the future. To start the constructibility database on traffic control, the user first sees the main application menu. From this menu, the user may select the specific information as needed for querying, inputting, or just looking at records in the database. The main menu consists of four options, corresponding to the four database tables.

General Constructibility Information

This module consists of very general but useful constructibility information for design personnel, traffic engineers, construction managers, and other users. This module is more of a training module. It has some information on the formal definitions of constructibility and details on when and how to implement constructibility on a highway project. It has a detailed and graphical constructibility—implementation road map, specifying the project stages and decisions management should take to effectively implement constructibility (Construction 1993). It also has 17 constructibility concepts from the CII constructibility-concepts file, in a separate database table, *conconce.dbf.* These concepts can be queried by the user according to the concept number or the project phase.

Lessons Learned from a Project

This is the most important module in CONTRAF, as it provides a means for entering traffic-control lessons into the database through a very detailed and user-friendly screen format. Presently, there are lessons learned from five highway projects executed at TxDOT in the database table, *conlesson.* The fields in the database table include project name, project identification, road location, kind of roadway, road detail, kind of road work, daily traffic volume (vehicles per day), lessons learned, cost savings, schedule savings, person who submitted it, and the date on which it was submitted. To collect consistent data, two forms for documenting ideas and suggestions had to be provided to the different personnel in charge of highway projects. The first form helped in capturing very generic information on highway constructibility, and the second form collected detailed information on traffic control.

The participants could document any suggestions for improvement or issues that require additional attention. Recording the difficulties encountered on projects, which may be

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avoided in the future, are also suitable use for the log. These logs can be entered into the database using a screen formatted almost similar to the suggestion log. Once these lessons are entered into the database, they could be queried using the browser screen according to road location, kind of road, or, for that matter, any of the 12 fields in the *conlesson* database file.

Constructibility Checklist on Traffic Control

The lessons learned from projects become part of a checklist, if they are found to be relevant and necessary items to be verified on future projects. This decision should be taken by project managers or experienced personnel. Currently, there are 52 items in the *concheck* database. These items on the checklist were all obtained from manuals and from domain experts on traffic-control planning and scheduling. The traffic design engineer or any user of the CONTRAF database should review each of the items in this checklist before the final TCP design is complete.

Constructibility Guidelines on Traffic Control

This is the last module in the CONTRAF database. If any item in the checklist is found to be applicable to most projects, general and broad in nature and approved by experienced project managers to be "best practices," they are classified as guidelines or best practices. There are presently 37 items in this database called *conguide.* They were compiled from interviews of domain experts in the traffic planning area, and from documents and manuals. The format and capabilities of this module are very similar to the aforementioned three modules.

TRAPS—DECISION SUPPORT SYSTEM

As shown in the system architecture in Fig. 1, TRAPS consists of the following modules:

1. The expert system module
2. The database module (CONTRAF)
3. The fuzzy-logic-based scheduling module

All three modules are linked to each other. The expert system module is the heart of the system, and helps in the interface and data exchange from the other two modules. Each of these modules, including their development and working principles, are explained in detail in the following subsections.

Expert System Module

The system begins with this module and it controls the execution of the other modules. It provides constructibility recommendations on traffic control, based on project conditions. The two most important phases in the development of this prototype expert system (Liu 1994) module were the knowledge-acquisition and knowledge-representation phases.

Knowledge Acquisition

The goal of the expert system module is to provide traffic designers or engineers with very general constructibility recommendations while they are designing traffic-control plans. So, knowledge engineering was executed with this goal in mind. The knowledge was extracted from two sources: domain experts, which included design engineers, construction managers, and traffic engineers; and related literature, which included traffic-control planning manuals, specification books, and other documents. The knowledge-acquisition process from the domain expert was conducted through a series of interviews with personnel at District 12 of the Texas Department of Transportation, Houston; Metro; and Sylva Engineering Corporation. This phase was the most time-consuming and challenging part of the research. This was mainly because the domain experts were not familiar with the concept of constructibility. There were also a number of uncertain variables present in the decision process, which were highly subjective in nature. The extra set of input conditions varied completely from project to project.

The input variables were divided into three basic categories: description of work activity, traffic data, and roadway details. They were divided into subcategories such as kind of construction, kind of roadway location, kind of facility, traffic volume, kind of work operation, possible traffic-management strategy, availability of detour or shoulders, etc. Input to these are based on the complexity of the project. Based on these inputs, IF . . . THEN decision rules were formed from the knowledge supplied by the experts and the literature. The IF part of the rule consists of any possible value the mentioned input variables can have. For example, "kind of facility" could have any of the following values: "freeway," "minor arterial road," "major arterial road," "two-lane roadway," etc. There can be more than one input variable in the IF condition and this is accompanied by the AND condition. Based on the IF conditions, the expert's recommendation or conclusion is put in the THEN part of the decision rule. In this way 48 rules were developed as part of the knowledge-acquisition phase of the prototype expert system module. An example of a decision rule is as follows:

IF	kind of construction is lane-widening or increasing
AND	location is rural
AND	traffic volume is high
AND	suitable detour is not available
AND	enough shoulder space is not available
THEN	work during off-peak hours (weekends or nighttime) basis and put down asphalt-stabilized base for widening of the shoulder, because can be compacted and driven on the same day. Can work overnight too. Do it the same way on both sides of the roadway.

Knowledge Representation

The decision rules form the basis for development of the knowledge-representation part of the expert system. This section of the system has five parts: file management, rule-base creation, execution (chaining), viewing the premises or rules, and the help section, as shown in Fig. 2. These parts help improve the overall user-friendliness and visual effectiveness of the system. On starting the program, the user sees the screen shown in Fig. 2; then the user can open a project or a rule base, if he/she has already created one. In this case, he/she should open the rule base *rulebase.rul*, as the work-zone traffic-control rules are stored in this file.

The file-management module manages related files. It can open rule bases as well as save rules, attributes, and choices. The user can load existing projects or rule bases into the application using this module.

The rule base has three editors—choice editor, qualifier editor, and rule editor. The user can set up his/her own qualifiers (attributes), choices, and decision rules and save them in a database. The user can also add, delete, and modify items in the choice lists, qualifier lists, and the rule list.

The execution module allows the user to run the system according to the forward-chaining inferencing mechanism. The forward chaining is more effective for this application of constructibility decision making for the work-zone traffic-control planning problem. Forward chaining proceeds from premises (or data) to conclusions, and is said to be data-driven. Since

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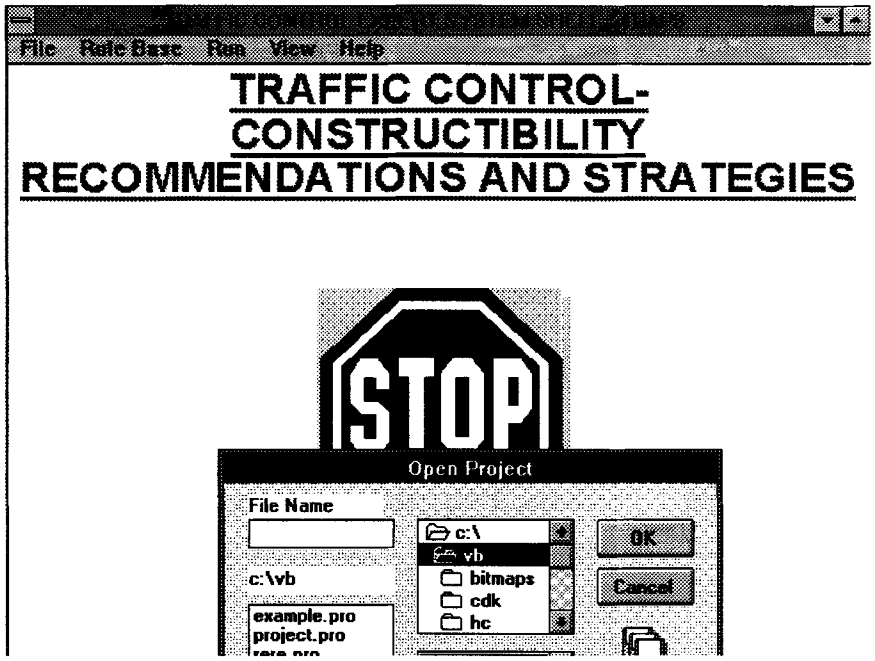

FIG. 2. Opening Screen of TRAPS

there are only a few premises and many possible conclusions, the forward chaining is the best strategy (Ignizio 1991). The user is asked a series of "yes/no" questions, his/her responses are compared with the knowledge base, and conclusions are formulated. If all the conditions in the IF part of a rule are true, then that rule gets fired and the conclusion (THEN part) is recorded. This way the program searches through all the decision rules to check their validity. All the recommendations are shown in a separate screen. There are a set of general constructibility recommendations for traffic control, applicable to all projects.

The "view" module helps the user view all the decision rules, attributes (qualifiers), and choices in the database. Finally, the "help" screen introduces the user to this application and indicates the procedures to follow. It improves the user-friendliness of the application.

Constructibility Database Module

This module provides a media for personal knowledge and experience from one individual to become public knowledge within the project team. The issue of a globally accessible collection of engineering knowledge and experience is the premise for developing the constructibility database. The expert system module helps the user, a traffic engineer or a designer, to get basic recommendations on improving constructibility before developing the TCPs.

TRAPS contains the constructibility lessons-learned database module (CONTRAF), fully integrated and linked to it. The user can link to the four database tables, namely, *conconce*, *conlessons*, *concheck*, and *conguide*, from the main system itself, where the constructibility lessons-learned database file is linked to the main application. The user can access constructibility-concepts information, work-zone traffic-control lessons-learned information from old and similar projects, traffic-control checklist-items information, and constructibility guidelines or best-practices information, respectively. Using this database link, the user can and is expected to look into all related information, to design the traffic-control plans (Fig. 3).

Fuzzy Scheduling Module

Scheduling of construction activities with an uncertainty content requires incorporating the subjective knowledge of construction experts as well as their experience and judgment. There are many uncertain factors that affect an activity's duration, including weather, labor skills, level of experience, technology involved, equipment used, etc. When an activity duration is uncertain, it is best to estimate its duration in linguistic terms, rather than in numeric terms. Fuzzy logic best represents situations where memberships in sets cannot be defined on a definite "yes/no" basis, as in the case of many highway construction activities.

Once the expert system module generates with constructibility recommendations, the user can further his/her knowledge by querying necessary items in the constructibility database (CONTRAF) module. Based on the expert system suggestions and information gathered from the database, the user is expected to analyze all possible traffic-control alternatives and devise a final traffic-control plan, consisting of details of the different stages of construction. Each stage is further subdivided into phases depending on the complexity of the project. The system provides very effective and user-friendly screens to stage the TCP, and also provides the user with the capability to further divide each stage into phases, as shown in Fig. 4.

The activity duration of each phase in the traffic-control plan is calculated by comparing fuzzy numbers based on the probability measure of fuzzy numbers. The fuzzy durations are represented by trapezoidal fuzzy numbers (TrFN). Four different estimates of the duration of the uncertain activity are obtained from the user (expert scheduler) in linguistic terms, as in the earliest duration to finish the activity, the latest duration to finish the activity, and the most likely interval of duration between which the activity can be completed. The Lee-Li (1987) method of comparing fuzzy numbers is used to calculate the fuzzy activity duration for each phase in the TCP using the following:

$$m(A) = \left[\int x\mu(x)\,dx\right] \Big/ \left[\int \mu(x)\,dx\right] \qquad (1)$$

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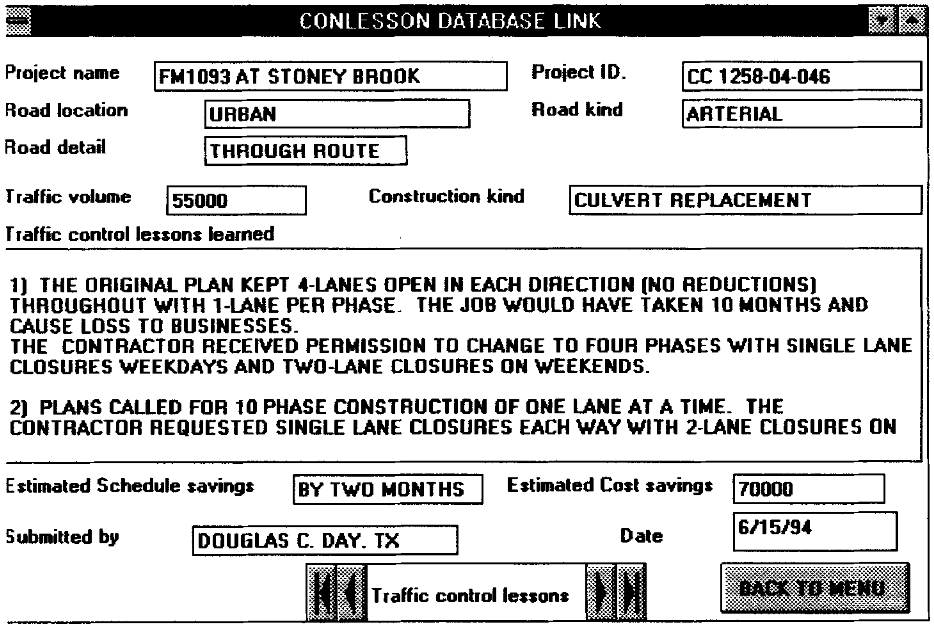

FIG. 3. Link to Constructability Lessons-Learned Database

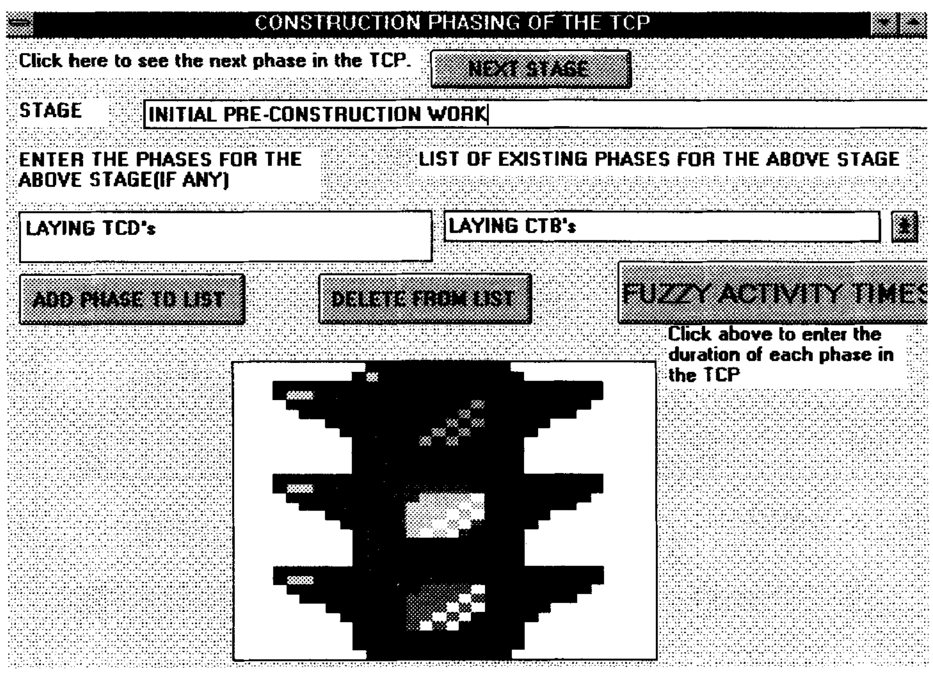

FIG. 4. Staging/Phasing of TCP

where $m(A)$ = mean duration of the fuzzy activity A; $\mu(x)$ = trapezoidal membership function; and x = activity duration.

The system provides a very graphical and user-friendly screen (Fig. 5), which helps the scheduler calculate the fuzzy duration of each phase in the TCP. These fuzzy durations and phases of the final plan are linked to the Microsoft Project for windows, a project scheduling and management software to generate the scheduling of the highway project. The user can provide start and/or end dates, precedence constraints, and lead/lag times. Based on the inputs, the system provides a Gantt chart and other schedule details of the various phases in the traffic-control plan. Then the system can embed Gantt charts, early start schedules, late start schedules, and other project details from the project-management software into a separate form in TRAPS. The user is given the freedom to go back and forth between Microsoft Project and TRAPS and reviewing any tasks or the duration or any other necessary project item. This way, all the tools and capabilities of the project-management software, Microsoft Project, are made use of by the TRAPS. All project information and Gantt charts obtained from Microsoft Project can be embedded in TRAPS.

Validation at TxDOT

The application program and various softwares used were installed on a laptop 80386 computer and taken to the design and traffic department for demonstration and validation. The working details of the system were explained and four cases were run through the system. Then, a four-page questionnaire was distributed to the experts for their opinions and comments on the system. The domain experts who validated the system included a traffic-control engineer, an assistant district design engineer, and a district pavement engineer, all with TxDOT. The validation process went quite well and the following were

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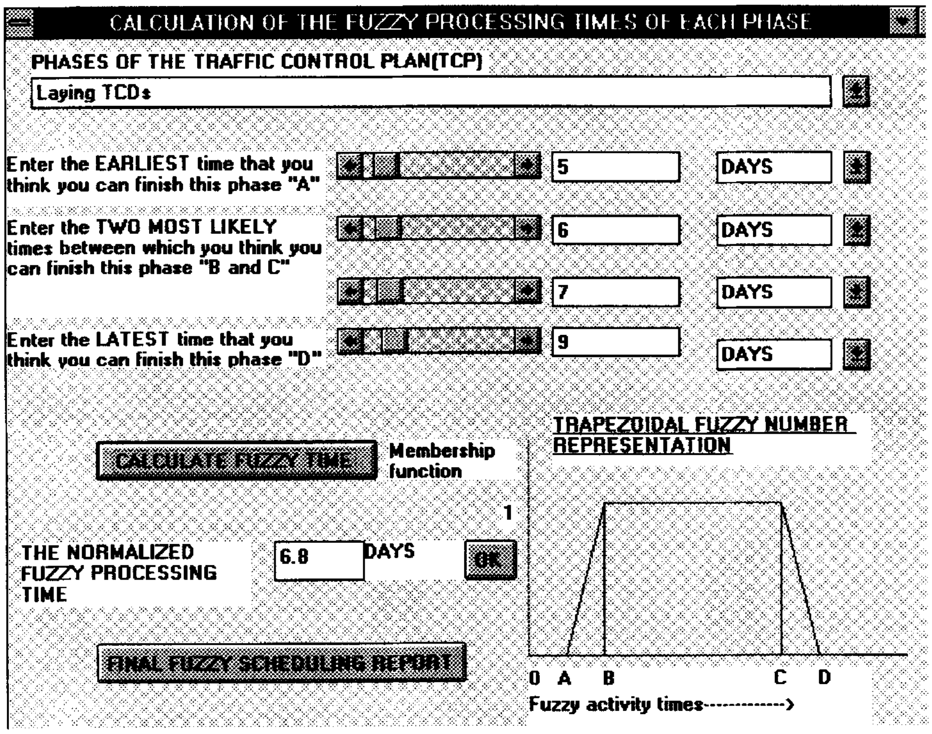

FIG. 5. Screen to Calculate Fuzzy Durations of Activities in TCP

some of the conclusions the domain experts reached on the system:

1. Overall, all of them were satisfied with the system and the research, and gave excellent reviews.
2. The design department commented that they did not possess the software Microsoft Project; instead, they use Primavera for scheduling. So, they expressed a desire to link the given program with Primavera. This would make the system more useful to them.
3. All the experts agreed that the constructibility lessons-learned database would greatly improve project qualities. Presently, they do not possess any means to store lessons from old projects.
4. They recommended the expansion of the rule base and also stressed more detail-oriented rules to serve specific purposes.
5. On the scheduling of the activities, the experts pointed out the need to delineate what is meant by month (30 days) and day (8 hours): We have some projects based on working days that we estimate as 13 days/month and also calendar day jobs. We also have projects where limits are placed on the hours of work, this could be less than eight hours or around the clock operation.
6. About the constructibility database, the experts observed that: "This procedure would have to be accepted and required by management due to the many area engineers with responsibilities for the outcome."
7. The experts doubted that the fuzzy-logic-based activity-duration estimation program could provide accurate scheduling results. This may be because the mathematical and theoretical details involved in the calculation were not explained.

CONCLUSIONS

The research involved identification of critical factors affecting highway constructibility and the development of a prototype computer system to improve the constructibility of TCPs. When the system was taken to TxDOT for validation, they were very satisfied with the results of the research and expressed interest in extending the research. It was also concluded that the highway construction industry is lagging behind in the use of technology. There is a need to realize the importance of keeping up with technological advancements, to improve and better manage projects. Constructibility needs to be stressed and included as a part of the project-development process to achieve better results.

ACKNOWLEDGMENTS

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