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16. Abstract

Bridge Rail EXpert System (BREXS) is an advisory system built to aid novice engineers in coping with bridge rail design and retrofit. Motivation for development of BREXS stems from a need to integrate domain expertise and knowledge from complementary disciplines. Development goals for this system are to incorporate bridge rail knowledge bases, bridge rail databases, existing analytical computer codes, and fuzzy logic decision-making capabilities. The development shell, NEXPERT *OBJECT* is used to build the knowledge bases. The integration of NEXPERT *OBJECT* and other supporting applications is carried out using calling-in integration schemes, in which the integration of BREXS focuses around a central control model. Knowledge bases categorized according to function are (1) Rail Selection, and (2) Retrofit Railing. A bridge railing database is customized for graphical display. Two algorithmic programs written in C and FORTRAN are used to check selected design parameters. The rail selection knowledge base provides a mechanism for choice of an optimum rail based on a set of criteria. These criteria include adherence to standard specifications, structural adequacy, benefit/cost ratio, safety, bridge geometry, climate, geographic location, and aesthetics. The retrofit railing knowledge base is used to choose an optimum rail as well as determine the optimum attachment position for projects involving replacement of rails. In addition, written specifications and graphical attachment details for the selected rail are provided. Target hardware and software is an IBM-compatible microcomputer with graphics capabilities that is running Microsoft Windows 3.0 or later.

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Knowledge-Based System for Bridge Rail Design

by

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Research Report 1240-2F

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

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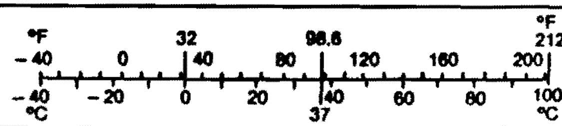

These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

ABSTRACT

Bridge Rail EXpert System, *BREXS,* is an advisory system built to aid novice engineers in coping with bridge rail design and retrofit. Motivation for development of *BREXS* stems from a need to integrate domain expertise and knowledge from complementary disciplines. Development goals for this system are to incorporate bridge rail knowledge bases, bridge rail databases, existing analytical computer codes, and fuzzy logic decision-making capabilities.

The development shell, NEXPERT *OBJECT,* is used to build the knowledge bases. Integration of NEXPERT *OBJECT* and other supporting applications is carried out using a calling-in integration scheme, in which the integration of *BREXS* focuses around a central control module.

Knowledge bases categorized according to function are (1) Rail Selection, and (2) Retrofit Railing. A bridge railing database is customized for graphical display. Two algorithmic programs written in C and FORTRAN are used to check selected design parameters. The knowledge base for rail selection provides a mechanism for choice of an optimum rail based on a set of criteria. These include adherence to standard specifications, structural adequacy, benefit/cost ratio, safety, bridge geometry, climate, geographic location, and aesthetics. The knowledge base for retrofit railings is used to choose an optimum rail as well as determine the optimum attachment position for projects involving replacement of rails. In addition, written specifications and graphical attachment details for the selected rail are provided. Target hardware and software are IBM-compatible microcomputers with graphics capabilities that are running Microsoft Windows 3.0 or later.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes.

KEYWORDS

Bridge Rail, Expert System, Fuzzy Logic, Heuristic, Highway, Human Expertise, Knowledge Acquisition, Knowledge Base, Retrofit, Transportation

ACKNOWLEDGMENTS

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IMPLEMENTATION STATEMENT

The main research objective of this project is to develop an expert system which helps in selecting and designing bridge rails. This system, called **B**ridge **R**ail **EX**pert **S**ystem or *BREXS*, is designed for use by both experienced and inexperienced design engineers at the district and local levels throughout Texas. In addition, its graphical, user-oriented interface facilitates operation by engineers with little or no computer experience. *BREXS* can be used for the following purposes:

1. Helping inexperienced engineers gain insight into how and why various types of bridge rails are selected or designed.
2. Encouraging more uniformity in the design or selection process at all district offices of TxDOT.
3. Optimizing the selection process according to four factors: cost, maintenance, safety, and aesthetics.
4. Expediting the process of retrofitting bridge rails on an existing bridge structure since critical review of the design can be made less time consuming.

To obtain these benefits, it is suggested that a copy of *BREXS* be installed on a microcomputer in each TxDOT district office. Moreover, the use of *BREXS* by design engineers and reviewers should be encouraged or even required. Further research is needed to investigate the best approach for making use of *BREXS* or other expert systems in the area of transportation-related safety structures.

Results of this study are available for immediate implementation by the Texas Department of Transportation.

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1. INTRODUCTION

1.1 BACKGROUND

Due to aging of transportation infrastructure in the United States, many highway bridges require updating of existing rails to meet current safety requirements. In addition to being a potential hazard to errant motorists, substandard and improperly designed bridge rails can cause significant damage to the bridge structure itself. Fig. 1 shows failure of a bridge slab that occurred when a large tanker truck crashed through a bridge rail on an elevated overpass structure. Not only was the superstructure severely damaged, but in its fall from the bridge the tanker impacted a column that supports the bridge (Fig. 2). If the column had received more damage, survival of the entire superstructure would have been in jeopardy. Even motorists traveling on other roadway levels can be affected by improperly designed or installed railings (Fig. 3).

FIG. 1. Damaged Bridge Slab and Safety Rail

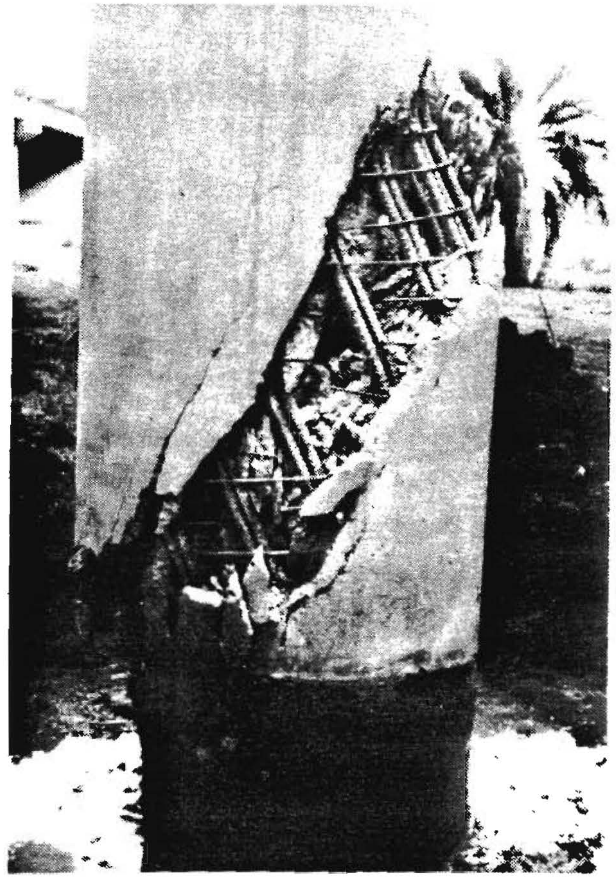


FIG. 2. Bridge Column Damage

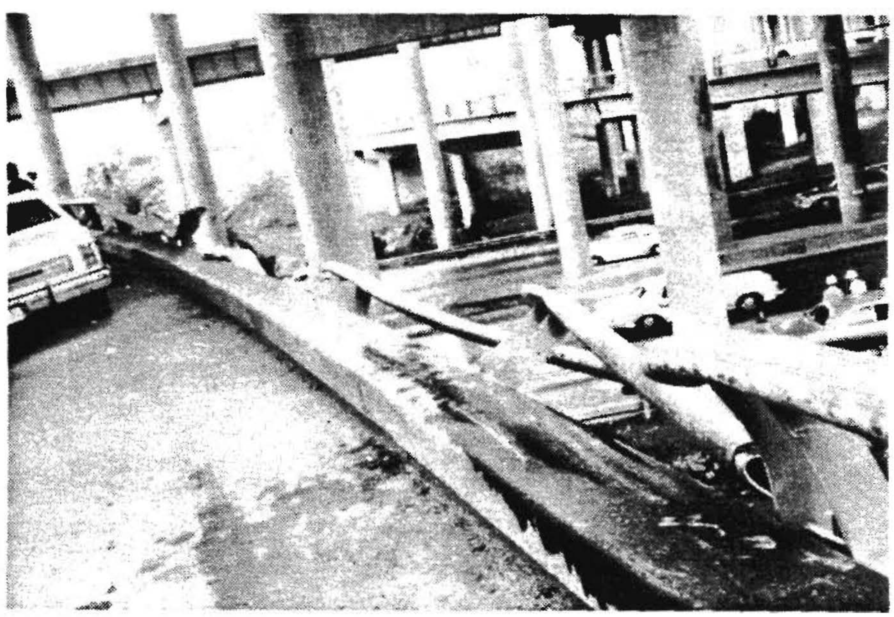


FIG. 3. Importance of Safe Bridge Railing to Other Motorists

Not only are railings on aging structures being carefully reviewed, but governmental jurisdictions are mandating that new bridges be equipped with safe, contemporary, containment rails. New railings are continuously being developed and crash-tested to fit new bridge design requirements (Fig. 4). In Texas alone, more than twenty bridge rails have been crash tested and certified as candidates for use on local and regional highways (Figs. 5 and 6). In theory, any standard rail approved by the state can be used in any location on any type of highway bridge. However, this generic interchange is not always practical and appropriate. Requirements for bridge railing performance differ significantly from site to site.

FIG. 4. Aesthetically-Pleasing Bridge Rail

Effective design of new or retrofit bridge rails depends on many interrelated factors. These include adherence to standard specifications, structural adequacy, tradeoffs between benefits and costs, safety of the habitat beneath a bridge, geometry of the structure, climate, geographic location, and aesthetics. Selection of the optimum rail that conforms to the above criteria is a challenging task. It requires a high level of knowledge and experience from complementary disciplines, such as structural analysis, highway safety, economics, maintenance, and construction, to help engineers make decisions on a case by case basis.

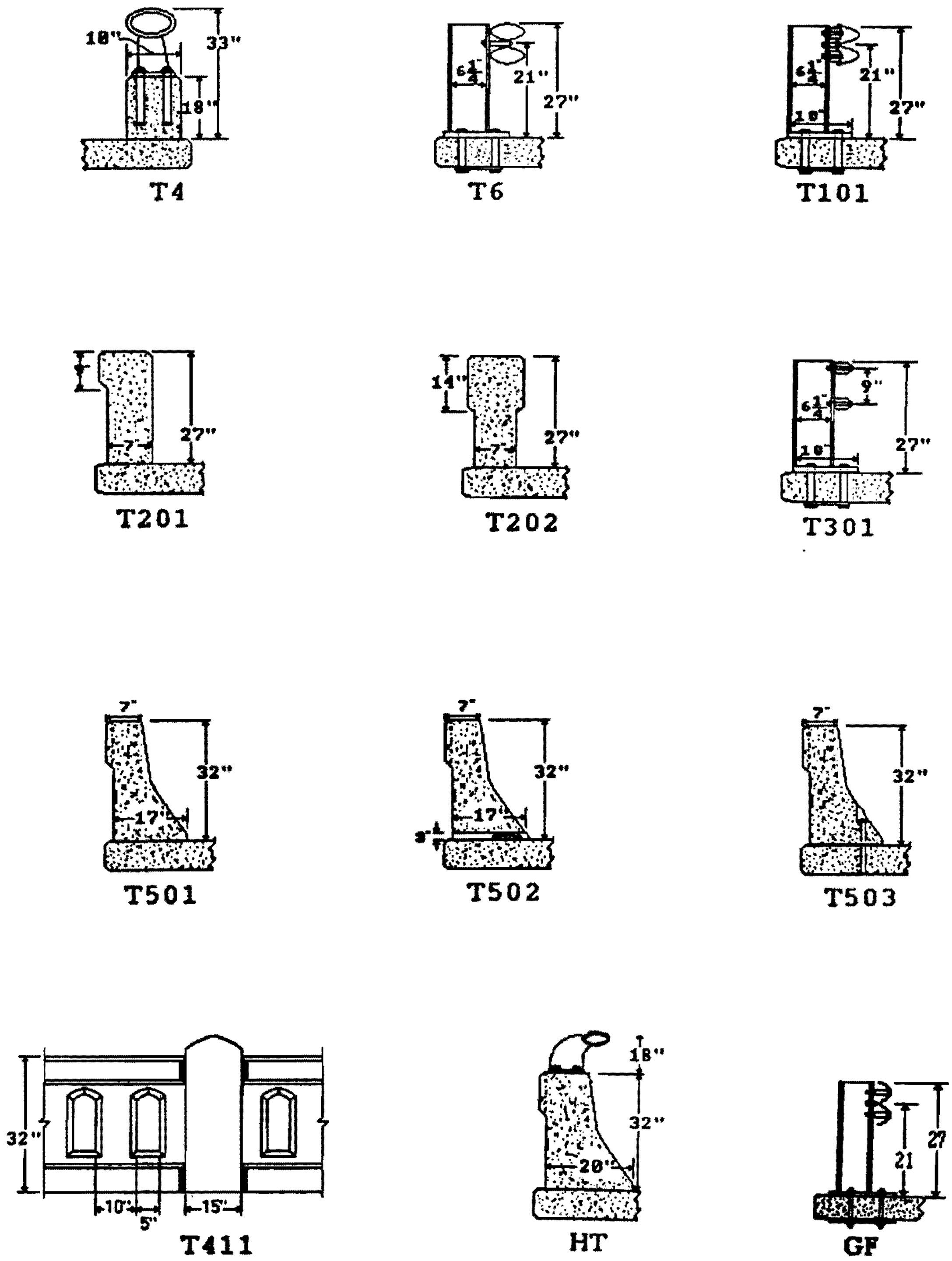


FIG. 5. Texas Standard Bridge Rails

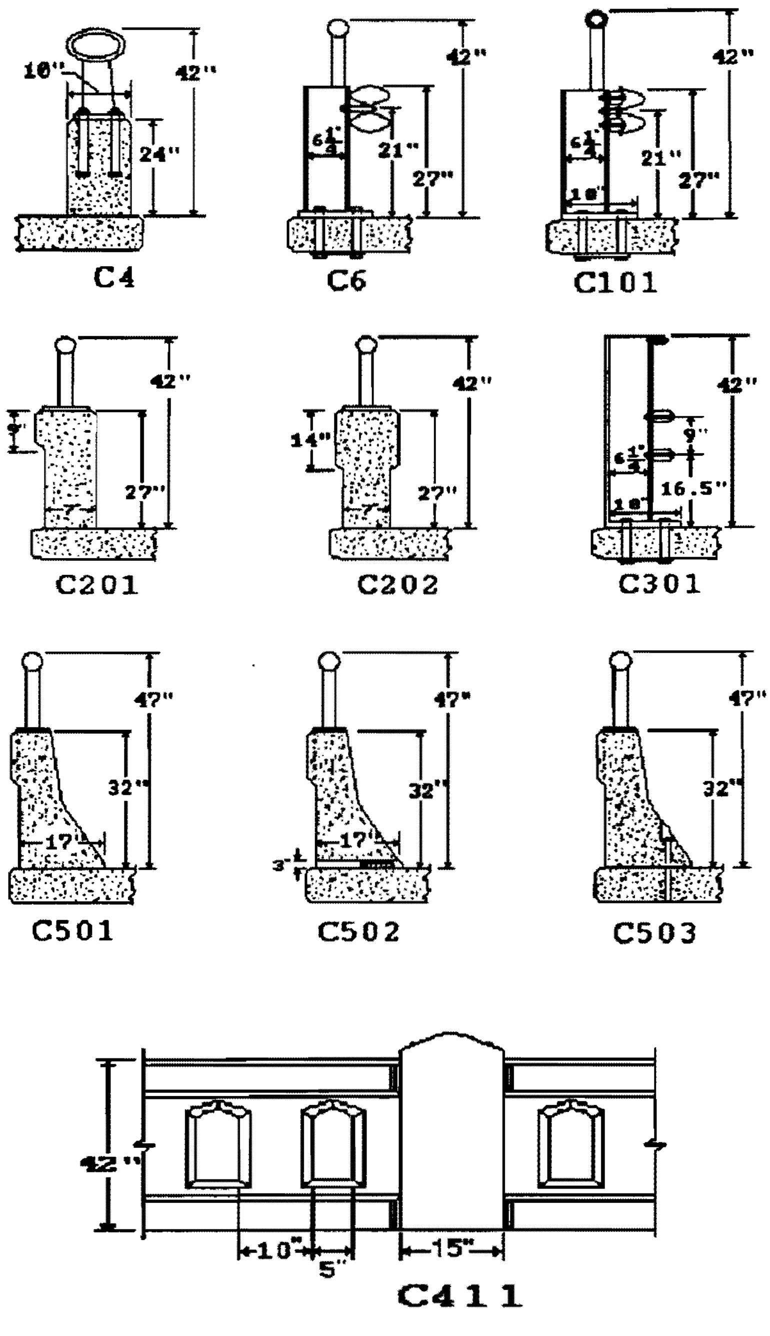


FIG. 6. Texas Standard Combination Rails

Motivation for development of an advisory system for bridge rail selection and design stems from a need to integrate domain experience from complementary disciplines such as structural analysis, maintenance, construction, and traditional design. Currently, these functions are available from experienced engineers scattered throughout the state. Use of conventional analysis codes to evaluate design parameters of bridge rails involves a steep learning curve and produces results that are not always trustworthy. In addition, human expertise is not conveniently accessible. District engineers disbursed throughout the state make decisions for rail selection and installation based on their own experience and preference rather than calling on guidance from a unified source. In particular, novice engineers often choose rails for use without consideration of the complete array of salient decision factors. Finally, while copious drawing and design calculations are stored for bridge structural members such as columns, girders, and slabs, no permanent documentation is available to describe rational used in selection of a particular safety rail.

Performance and cost of railing should correspond to the need of a particular site. Therefore, the objective of this project is to develop a knowledge-based system for selection of bridge rails on new construction and retrofit projects. This system employs technology developed by the artificial intelligence community to simulate or reproduce intelligent problem-solving behavior of experts in the domain of bridge rail design.

1.2 DESIGN OF NEW CONSTRUCTION SAFETY RAILS

Effective design and selection as well as proper installation of bridge rails for new construction projects depends on a large number of interrelated factors and requires a moderately high level of skill and experience. The chosen rail must satisfy considerations of safety, economy, and appearance. Olson (1974) suggests that bridge rails must meet the following service requirements:

1. Sufficient lateral restraint of selected range of vehicles.
2. Minimize vehicle decelerations.
3. Smoothly redirect a colliding vehicle.
4. Remain intact following a collision.
5. Provide protection for vehicle occupants and nearby pedestrians.

6. Have a compatible approach rail or other device to prevent collision with the end of the bridge rail system.
7. Define an ambiance of safety, yet permit adequate visibility.
8. Not project inside the face of any required curb.
9. Must be susceptible to rapid repair.
10. Give emphasis first to safety, second to economics, and third to aesthetics.

1.3 Design of Retrofit Safety Rails

In addition to the above requirements for new construction, retrofit rails must satisfy even more stringent parameters. A bridge design engineer needs to consider the existing rails and potential replacement rails from the standpoint of both geometry and strength of the bridge. The benefit-to-cost ratio, which shows the benefit of one alternate bridge rail selection in comparison to direct cost to the highway agency and society, also becomes a primary factor for consideration during retrofit railing projects. Michie et al. (1976) suggest that the following constraints be considered for retrofit design:

1. Most bridges of interest for retrofit purposes are narrow. Although pavements and shoulders of roadways have been widened, many highways have been left with narrow bridges because of the expense and technical difficulty required for their modification. Intense accident frequency rates at bridge ends have been attributed to minimum width of the passageway and the funnel effect of transition from a wide highway to narrow bridge. Consequently, a large number of bridges that may be candidates for a retrofit railing can ill afford to make further encroachment on the bridge deck roadway (see Fig. 7). Inadequate investigation of encroachment may lead to higher accident frequency rates. Accordingly, bridge rail retrofit design, if possible, should strive to maintain present bridge deck widths.

2. Curbs and walkways extending out into the roadway from a bridge railing installation are only marginally effective in redirecting errant vehicles. Furthermore, vehicles impacting curbs vault and may strike the backup structure in an unpredictable attitude. Latest design standards minimize use of curbs in front of longitudinal traffic barriers for this reason. Unfortunately, these curbs are an integral part of the structure on many existing bridges and cannot be removed unless major redesign of the bridge is performed. Accordingly, retrofit designs should fit existing curb considerations.

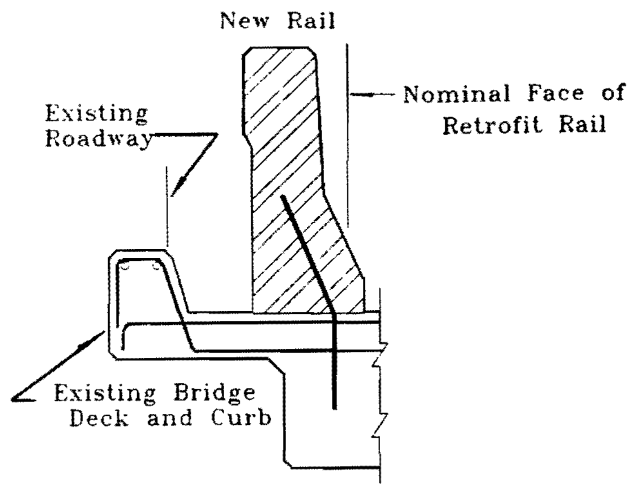


FIG. 7. Encroachment Introduced by Bridge Rail Retrofit

1.4 CURRENT APPROACH

The objective of this project is to develop a knowledge-based computer program that is a useful aid to engineers for the selection of bridge rails for new construction and retrofit structures. An overview of the knowledge-based software that has been developed to aid in the selection process is given in Chapter 2. Chapters 3-6 describe the primary sources of bridge rail knowledge and its acquisition and organization into a form that is useful for knowledge-based software. Supporting codes and the user interface are also described in this suite of chapters. Verbatim transcripts of taped interviews with engineering experts in the domain of bridge rails are listed in appendices. In order to ensure that the system suggests advice to users that has an acceptably high quality, special emphasis is placed on validation of the system. This four-stage process is described in Chapter 7. Numerous appendices also give details of the validation. Finally, readers are directed to a companion report volume (Roschke et al. (1991)) for details on installation and operation of the software.

2. Bridge Rail Expert System (BREXS)

2.1 Introduction and Objectives of *BREXS*

Bridge rail expert system (*BREXS*) is an advisory system built to aid novice engineers in coping with bridge rail design and retrofit. *BREXS* incorporates knowledge bases, databases, and other supporting analysis programs to select an optimal rail that meets the requirements of a particular bridge site.

Development goals for the *BREXS* system are to incorporate bridge rail knowledge bases, bridge rail databases, existing analytical computer codes, and fuzzy logic decision-making capabilities. The resultant system is intended to help less-experienced bridge engineers in choosing an optimum rail that conforms to standard specifications and satisfies service requirements. Furthermore, implementation of *BREXS* with the same standard guidance is designed to encourage uniform bridge railing practice across the state.

Knowledge and expertise extracted from bridge railing experts and many senior engineers in Texas is represented in the form of knowledge bases and databases. Knowledge bases, categorized according to function, are (1) Rail Selection, and (2) Retrofit Railing. A bridge railing database is customized for graphical display. Two algorithmic programs written in C and FORTRAN are used to check selected design parameters.

The rail selection knowledge base provides a mechanism for choice of an optimum rail based on the set of criteria described in chapter 1. No restrictions from existing bridge and rail types are considered in this knowledge base.

Similarly, a retrofit railing knowledge base has also been compiled. This knowledge base is used together with the rail selection knowledge base to choose an optimum rail as well as determine the ideal attachment position for replacement railing projects. Finally, this knowledge base provides written specifications and graphical attachment details for the selected rail that matches the given bridge deck configuration.

Once the inference engine has reduced the number of feasible bridge rail candidates to a small subset of total number of available rails, an external benefit-cost (B/C) algorithm is executed. To evaluate the relative merits of bridge rail alternatives, the B/C model compares benefits derived from use of each rail with options of no rail and each of the other remaining candidate rails. In some extreme cases, such as occur for low volume highways and very shallow crossings, the recommended strategy might even be to forego use of all bridge rails. A probabilistic encroachment model in the B/C code computes annualized costs of each alternative design over a given period of time.

BREXS is not intended to be used as the only source of reference in selecting bridge rails. However, it is intended to be used as a starting point in the decision process. Individual engineering judgement as well as advice from senior engineers should be incorporated into the final decision.

2.2 Hardware and Software Platform

The target hardware platform for *BREXS* is the Intel 80286/80386/80486-based family of microcomputers. While the system does not demand a high resolution graphics terminal, VGA resolution is recommended as the minimum standard display device. This hardware is chosen so that the system can be implemented in every highway district office in Texas, even in remote areas with limited computer resources. Furthermore, supporting analysis programs planned for integration were developed to run on this hardware platform. Finally, selection of this hardware avoids the laborious task of migrating existing programs from different platforms.

BREXS needs to correlate KBs and various types of supporting applications. Therefore, the major concern of *BREXS'* developers in selecting the expert system shell was the capability of integration. NEXPERT *OBJECT* was chosen based on this consideration. It is capable of calling conventional executable codes and various standard database applications. It also provides flexibility in the choice of a user interface. The developer has the freedom to choose to use either NEXPERT's interface or to apply an independent interface that has been customized. Direct communication with the NEXPERT kernel (bypassing its interface) is possible via the Application Program Interface (API) libraries provided by NEXPERT *OBJECT*.

BREXS' user interface has been developed around Microsoft Windows, version 3.0 (*Microsoft* 1990). *BREXS* utilizes Microsoft Windows' robust graphical user interface that features windows, pull-down menus, dialog boxes, and graphical capabilities. Microsoft Windows is also compatible with NEXPERT's API. A

Windows application must be written in C or assembly language. Programming a Windows application also requires a set of tools called the Software Development Kit (SDK). This package provides development tools such as Dialog Editor, SDKPaint, Resource Compiler, debugging and optimization tools, and a library of Windows function calls.

The following resources are needed to run *BREXS*:

Hardware Requirements

1. An IBM or compatible 80286, 80386, 80486 (or later versions) personal computer with a math co-processor.
2. A mouse.
2. At least 2 Megabytes of RAM.
3. At least 3 Megabytes of hard-disk space.
4. NEXPERT *OBJECT* run-time protection device.

Software Requirements

1. MS-Windows 3.0 or later versions.
2. *BREXS.*
3. NEXPERT *OBJECT* run-time version.

2.3 *BREXS* DEVELOPMENT PROCEDURE

Development of *BREXS* spanned a two-year period from August, 1989, to September, 1991. It involved 8 tasks as shown in Fig. 8. Each task was performed according to the order shown. However, individual tasks are not necessarily completed before beginning succeeding ones. Knowledge and information obtained from performing a task usually also provides useful information on how related tasks should be done.

The first three tasks involve acquisition of bridge rail knowledge. Details of these tasks are discussed in Chapter 3: Knowledge Acquisition. Task 4 concerns representation of knowledge so that the system can solve problems effectively. Essential elements of this representation are explained in Chapter 4: Knowledge Representation. Details regarding the user interface and integration of supporting analysis codes (Tasks 5 and 6) are presented in Chapter 5: System Architecture. Tasks 7 and 8 are explained in Chapter 7: Validation and Verification.

Task 1 **Get Acquainted with the Domain**

Task 2 **Knowledge Acquisition**

Task 3 **Develop Problem-Solving Strategy**

Task 4 **Build Knowledge Bases**

Task 5 **Build User Interface**

Task 6 **Integrate Supporting Analysis Codes**

Task 7 **Validate and Verify**

Task 8 **Revise**

FIG. 8. ***BREXS'*** **Development Procedure**

3. KNOWLEDGE ACQUISITION

3.1 DOMAIN KNOWLEDGE AND DOMAIN EXPERTS

Knowledge acquisition is a process by which knowledge engineers extract, organize, and implement knowledge and information that experts use to solve a particular problem. Assembling this knowledge is one of the most crucial and difficult parts in development of an expert system. A high degree of skill is required to extract and organize highly abstract knowledge into robust sets of rules, databases, and inference engines.

Similar to other domains, bridge rail knowledge can be extracted from textbooks, specifications, research reports, databases, and experience of transportation and structural engineers. Published and documented knowledge may be informative and relatively easy to obtain. However, it is usually so general and fundamental that novice engineers are familiar with its concepts. Thus, a sole source of this form of knowledge does not provide an efficient path toward solutions in bridge rail design.

The primary source of domain knowledge for *BREXS* is from domain experts themselves, the senior bridge engineers. Their heuristic knowledge provides an effective solution strategy for determination of the optimum rail cross-section and its location on the slab. The knowledge base developed from their rules of thumb conglomerates long term experience and skills obtained from solving problems in various aspects in bridge rail design. Heuristic knowledge supplies crucial information that makes *BREXS* capable of solving problems that are not tractable to a solution by conventional algorithmic programs.

Acquisition of knowledge used in bridge rail design in Texas involves interviews with two groups of people: Texas Department of Transportation (TxDOT) officials at the state level and TxDOT district engineers at the local regional level. Typically, design begins with district engineers who locate the bridge site, design the new or retrofit rail, and submit the proposed design to state level engineers for review and approval. TxDOT's state level officials review the bridge rail selection and, if necessary, suggest changes. They also prepare construction drawings and specifications. Fig. 9 shows the flow of cooperation in rail design between district engineers and TxDOT's officials. Clearly, knowledge from both groups of people is needed to complete the process.

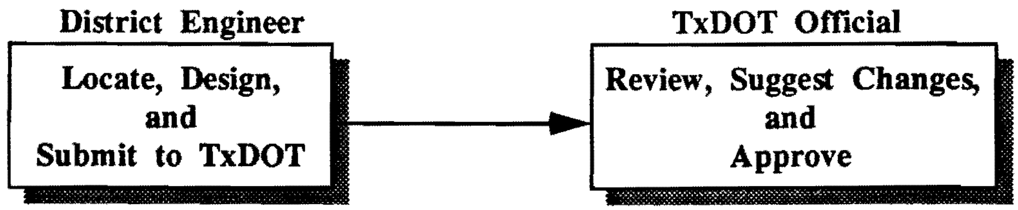


FIG. 9. Cooperation Between District and State Engineers

For development of *BREXS*, knowledge acquisition is conducted by interviews. In addition to safety and economical requirements, appropriate bridge rails must also satisfy geographical and demographic restrictions of the bridge site. TxDOT's bridge engineering experts and several experienced district engineers from a variety of locations around the state are interviewed to ensure compatibility of the knowledge base and database when used to select rails for specific locations in Texas. For instance, to avoid severe corrosion problems steel bridge rails must be discouraged on highways where deicing salt is frequently applied or in saltwater coastal regions. In dry, arid portions of the state blowing sand and debris may collect on a bridge where a solid rail structure is specified.

3.2 PROCEDURES OF KNOWLEDGE ACQUISITION

Five steps are used in acquiring knowledge for *BREXS*.

1. Become acquainted with domain knowledge.
2. Develop a problem solving strategy.
3. Acquire knowledge.
4. Document and extract rules.
5. Validate and verify.

3.2.1 Acquaintance with Domain Knowledge

As a first step it is necessary for knowledge engineers to obtain a working knowledge of the domain. A required background of understanding includes general philosophy of state transportation engineers, and concepts and terminology commonly used by bridge engineers. The first several weeks of *BREXS*' development were spent studying relevant materials such as specifications, standard design guides, research reports, and previously published literature in the field of bridge rails. General philosophy for bridge rail design was discussed with domain experts and experienced practitioners within Texas. No task-specific knowledge acquisition was conducted during this period.

3.2.2 Development of a Solution Strategy

After becoming familiar with bridge rail design, emphasis was placed on learning how problems in the domain are solved by experts. It was determined that even though the experts are very capable of solving problems, they sometimes have difficulty in conceptually explaining how a problem is analyzed. Furthermore, their reasoning methods are too complex for machine analysis. Therefore, it is advantageous to have an expert system that works with clearly defined basic information that can be structured for operation by a complex inference engine. To this end, working hypotheses about how experts solve problems in bridge rail design were developed. Fig. 10 shows a hypothetical problem solving strategy for *BREXS*. The process of retrofit and design of bridge rails is divided into sub-tasks. This approach has the advantage of allowing subsequent knowledge acquisition to focus on each sub-task and thereby ensure an optimum result. Furthermore, it also allows rapid prototyping for a small, closed sub-task of the complete task and then expansion to the complete task.

Validation of the developed working hypotheses was rigorously checked through discussions with domain experts. As a first approximation, the model differs from the actual process used by experts. Its purpose is to distill complex thinking into a form that takes advantage of machine computation. This simulated model is revised and tested many times as the system evolves. It should be noted that similarity of this hypothetical model with the experts' actual problem solving process is not the significant issue. However, a result that is congenial with that produced by domain experts is taken to be of ultimate importance.

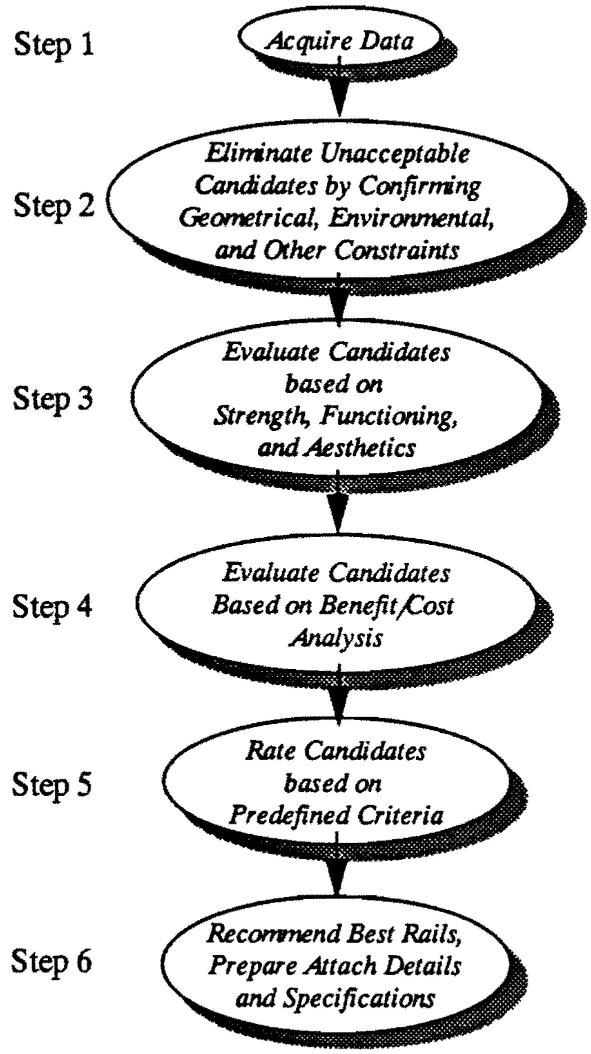


FIG. 10. Hypothetical Problem Solving Strategy

3.2.3 Acquiring Knowledge

As explained above, two useful sources of knowledge are documented and heuristic knowledge. References such as specifications, research reports, or other written materials are very helpful. They are generally well organized and ready for use. Initial knowledge can be extracted from these sources. For *BREXS*, a preliminary task is to select an effective bridge rail based on traffic data. AASHTO's *Guide Specifications for Bridge Railings* (1989) is used almost exclusively for this purpose. Several rules were also extracted from reports prepared by a domain expert (Panak 1989, 1990). These rules focus on eliminating unacceptable rail choices by adhering to geometrical and environmental constraints.

In addition, a series of interview sessions was held with highway engineers throughout the state of Texas. Audio tape recordings of discussions were transcribed to written form and a large number of useful rules were extracted. Documentation of the knowledge was found essential for accommodating implementation and validation.

Before each knowledge acquisition session with experts, *BREXS'* knowledge engineers selected the sub-tasks that were to receive primary emphasis. Each knowledge engineer prepared questions for discussion. The domain experts were not familiar with expert system terminology. It proved to be helpful to briefly explain motivation behind the line of questioning. Showing some portions of the prototype software also helped them understand their role in development of the expert system.

3.2.4 Documentation and Extraction of Rules

Knowledge acquisition of salient rules usually spans a period of several months to years. Documentation of each meeting is, therefore, necessary for future reference. For *BREXS*, all interview sessions were transcribed from their recorded audio tape formats along with the date and names of those in attendance. Three verbatim transcripts of the interview sessions are listed in Appendices II, III, and IV.

Rules were extracted from transcripts of these meetings. Most rules are in quasi IF-THEN form which is readily understood by the experts. Fig. 11 shows an example of the transcript and its corresponding extracted rule. An explanatory "BECAUSE" clause is appended to provide information on the expert's justification of the rule. This notation is also useful for developing the explanation facility.

TRANSCRIPT

Knowledge Engineer:	Does the Texas T6 rail have any problems when installed on a thin slab?
Expert:	That's an advantage of the T6 because it does not require as much anchorage as the T501, especially in a retrofit situation.

RULE

IF	Bridge deck is a thin slab
THEN	T6 is encouraged, especially in a retrofit situation
AND	T501 and T502 are discouraged
BECAUSE	T6 does not require as much anchorage as T501 and T502.

FIG. 11. Transcript Excerpt and Corresponding Rule

4. KNOWLEDGE REPRESENTATION

4.1 RULE FORMAT

BREXS employs two knowledge bases (KB): a knowledge base for new construction railing and a knowledge base for retrofit railing. *BREXS'* KBs utilize both a rule base and object oriented programming. Development of *BREXS'* KBs is carried out using an expert system shell called NEXPERT *OBJECT*. All rules in both KBs follow the format:

IF *(Antecedent)* **THEN** *(Consequent)*
DO *(Action1, Action2, ...)*

The terms "antecedent" and "consequent" refer to a proposition and a hypothesis, respectively. A proposition is a sentence that can be proved for its truth value. A hypothesis can be a phase or a sentence. The truth value of a hypothesis can be known by deduction.

Provided there is enough information, the antecedent can be proved either true or false. The information here refers to either data input by the user or information deduced by the inference engine. If the antecedent is judged to be true, then the consequent is (set to) true and actions take place. This situation is explained in short as "the rule is fired" among expert system developers. However, if the antecedent is false, the consequent (hypothesis) is set to false and no action takes place. An example of a rule is as follows:

[R1] **IF** *(the bridge slab is thin)* **THEN** *(encourage use of steel post type of rail)*
DO *(add T6, T101 to the list of candidates)*

If the bridge slab is proven to be thin, then the consequent (encourage use of steel post type of rail) is true and the rule is fired. Therefore, T6 and T101 are added to the list of candidate rails. However, if the bridge slab is **not** thin, the antecedent as well as the consequent are set to false, and the action is not performed.

The antecedent can be a formula which is a set of sentences joined by connectives: conjunctions (AND) or disjunctions (OR). The interpretation of a formula is made to conform to the standard truth table. For example, if the antecedent consists of two propositions: (a) the bridge slab is thin, and (b) the slab overhangs laterally from the girder more than 3 feet, and the connective between the two propositions is AND, the rule reads as follows:

[R2] **IF** *[(the bridge slab is thin) AND (the slab overhangs laterally from the girder more than 3 feet)]* **THEN** *(encourage use of steel post rail)*
DO *(add T6 and T101 to the list of candidates)*

The antecedent inside the square brackets [ ] is a formula of propositions (a) and (b) joined by the connective AND. The only case in which the antecedent is true is when both propositions are true. On the other hand, if the connective is OR, the antecedent is false only when both propositions are false.

As explained earlier, proving of a proposition can be made either by checking directly with the user-provided information or by deduction. In the case of deduction, the proposition such as *(the bridge slab is thin)* must be proven by a rule or a set of rules. An example that uses a single rule is:

[R3] **IF** *(the slab thickness is equal to or less than 8 inches)* **THEN** *(the bridge slab is thin).*

Therefore, to prove the truth value of the antecedent of [R1], the truth value of the consequent of [R3] must be known. The antecedent of rule [R3] can be evaluated by checking with the input data whether or not the slab thickness is equal to or less than 8 inches. The relationship between [R3] and [R1] is schematically presented in Fig. 12. The proposition: "Bridge deck is thin" serves as a consequent for rule [R3] and an antecedent for rule [R1]. The italicized phase on the right of [R1] is an action that is carried out if rule [R1] is fired.

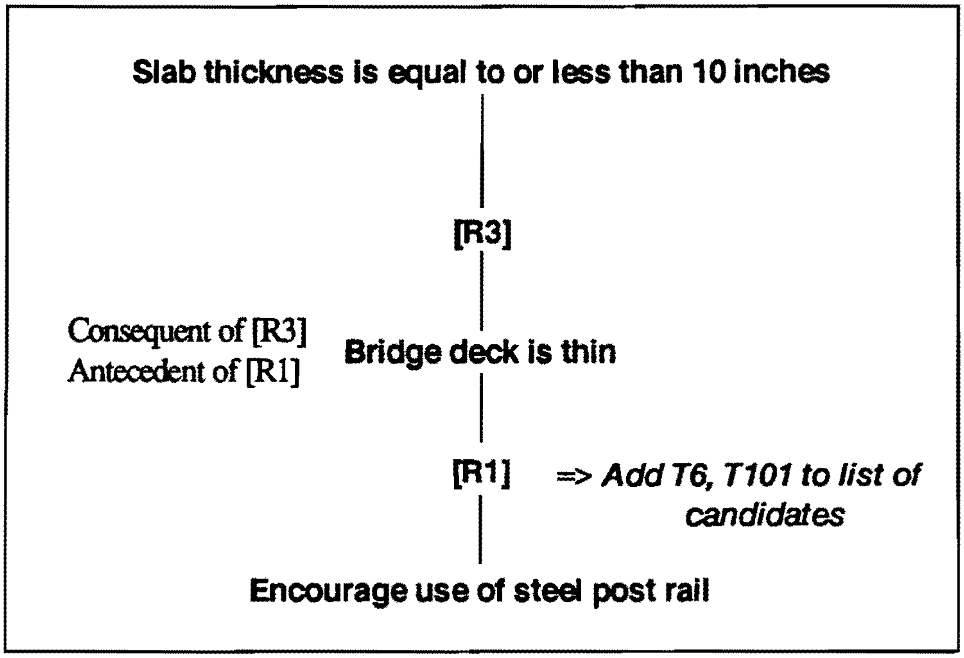


FIG. 12. Relationship Between Rules [R1] and [R3]

The relationship of [R1] and [R3] is typical and necessary among the rules. It leads to a network of rules that allows solving of more complicated problems. *BREXS'* rule networks are formed with more than 150 rules that have a complicated structure.

In standard logic, the proposition is a sentence that can be proven to be either true or false. However, in practice the proposition may not always be proven either true or false because of the lack of information. In this case, the proposition as well the formula containing this proposition will be set to NOTKNOWN. If the antecedent is NOTKNOWN, the consequent is also set to NOTKNOWN and no action is followed.

BREXS also takes advantages of object oriented programming. Data or hypotheses inside the KBs are treated as objects. An object may also belong to a class of objects. A class of objects is a group of objects that have the same group of properties. Instead of reasoning at the rule level alone, programming the reasoning around an object is sometimes more effective. Object-oriented programming also helps accommodate the search by matching the objects with certain aspects of properties. Properties can be inherited from the class level to the object level. For example, all members of a class of steel rails have the property that they may corrode.

The following section describes the structure and problem-solving strategy of *BREXS*' knowledge bases. New construction and retrofit knowledge bases consist of similar components, but each has different details. While these sections give the fundamental concepts as to how the KBs solve a problem, knowledge base maintenance and updating requires further familiarity with details inside the KBs. The development version of NEXPERT *OBJECT* is required in order to access *BREXS'* KBs.

4.2 KNOWLEDGE BASE FOR NEW CONSTRUCTION RAILING

The railing KB for new construction projects consists of three major clusters of rule networks. These three clusters are connected to the network counterpoint (finish) that is the final point of the inference process. Fig. 13 shows a schematic of the three clusters in the rule network. The three branches are executed sequentially according to rule priority. The higher the rule priority of a rule, the higher its evaluation priority. Hypotheses on the left in Fig. 13 are placed on the agenda for consideration in the order of priority, from highest at the top to lowest at the bottom.

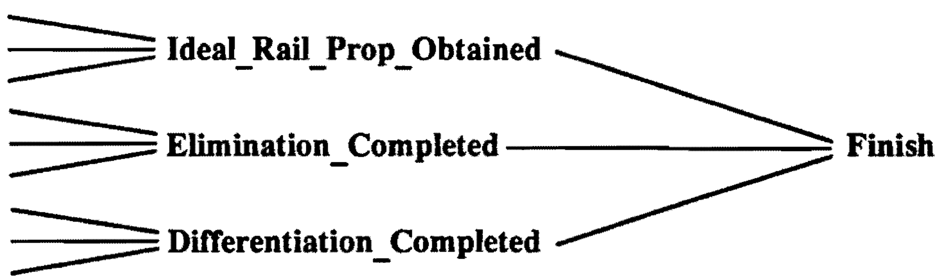


FIG. 13. New Construction Railing Rule Network

Ideal_Rail_Prop_Obtained is the branch of rule network responsible for processing the information volunteered by the control module and the information from the bridge rail database. It processes some raw data into a form that is useful for reasoning and stores it in appropriate slots. It also determines ideal performance of rails suitable for certain cases of data. Data used to determine the ideal performance are average daily traffic (ADT), percent trucks, type of understructure, and type of bridge structure. Categories of performance are high, normal, medium, and low. In many cases, the ideal performance cannot be clearly justified to fall into any of the four categories but a range of performance is chosen. For example, the ideal rail performance can be medium or low, normal or medium, and high or normal. Many other ideal rail properties are also derived for use in differential steps.

Elimination_Completed is the branch of the rule network responsible for deriving a set of candidate rails. A set of candidate rails is derived by matching the ideal rail performance to the performance of standard rails in the database.

Differentiation_Completed is the branch of the rule network responsible for differentiation suitability of each rail based on the input information. The weight of each of five parameters stored in the database is adjusted according to that aspect of rail performance. Fig. 14 shows detailed rules of the **Differentiation_Completed** network.

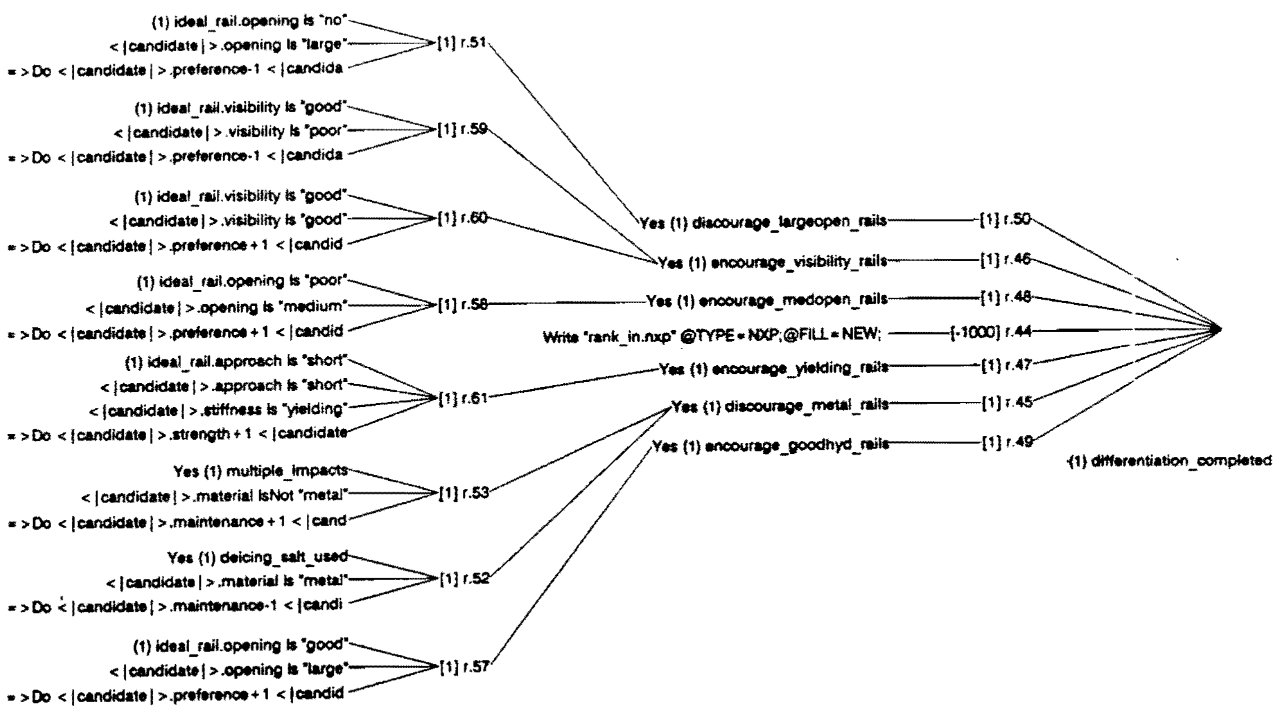


FIG. 14. EXAMPLE OF RULE NETWORK DETAIL

4.3 KNOWLEDGE BASE FOR RETROFIT RAILING

The retrofit railing knowledge base is structurally similar to that of the knowledge base for new construction railings. However, a cluster of networks that find optimal positions of candidate rails on a given bridge is added. Fig. 15 presents the four major clusters of this rule network.

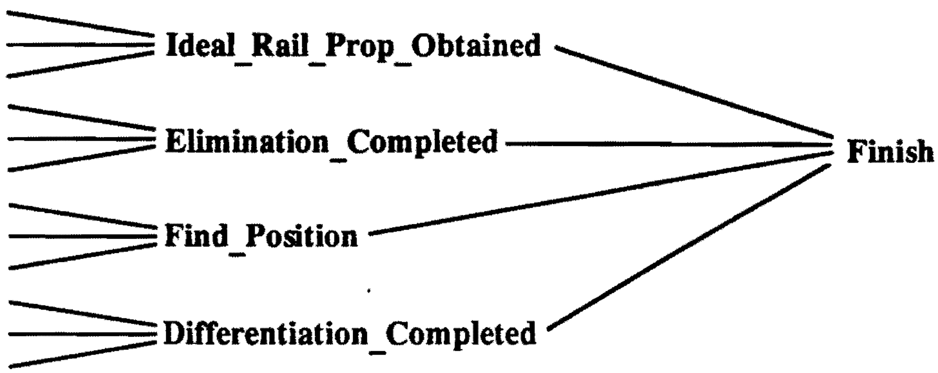


FIG. 15. Retrofit Railing Rule Network

The **Ideal_Rail_Prop_Obtained** rule cluster has responsiblities similar to the functions of its counterpart in the new construction cluster (see Fig. 13).

The **Elimination_Completed** rule cluster derives candidate rails based on the configuration of the existing bridge structure and traffic characteristics. In retrofit railings, the structural compatibility of the rail and the bridge deck is a major factor influencing the choice of a rail. Since the majority of bridge rail retrofit cases are on small highways with light traffic volumes and, oftentimes, the bridge slab is structurally vulnerable, a reduced level of performance of the rail is more tolerable than is a compromise on the strength of the anchoring for the rail. Initially, candidate rails are selected for consideration based on compatibility with the existing structure. Secondly, the candidate rails are checked to ensure that their performance is adequate with respect to traffic characteristics. Rails whose performance are very low are eliminated from consideration.

A cluster of rules titled **Find_Position** searches for an optimal position of each candidate rail. The optimal position is a position that does not overly encroach on roadway width, and yet allows for strong anchoring. This position depends on the configuration of the slab and the type of rail to be installed. The optimal position for each candidate rail is written to a file named POSITION.NXP. The control module reads this file to obtain the recommended position for each rail and passes them to a subroutine that graphically shows each rail on the slab in its optimum location.

Differentiation_Completed is a cluster of rules that evaluates candidate rails according to the five criteria explained earlier. The result of this evaluation is written to a file in NEXPERT spreadsheet format named RANK_IN.NXP.

4.4 CLASSES AND OBJECTS IN KNOWLEDGE BASES

Any word or phrase that is not predefined by NEXPERT *OBJECT* in a knowledge base is taken to be either an object or a class of objects. An object is an entity that can be characterized by a set of properties. A class is a collection of objects that share a set of properties. A class allows storage of information relevant to all objects in that class. It also enables searches for objects that meet specific conditions. This search process is usually called pattern-matching.

There is a class of objects called **Candidate** that is utilized in *BREXS'* knowledge bases. **Candidate** stores a group of rails qualifying as candidate rails. Fig. 16 graphically shows the class **Candidate** and its objects. Candidate employs a large set of properties. These properties include the information stored in the bridge rail database. Others are used in an *ad hoc* manner to accommodate the reasoning process.

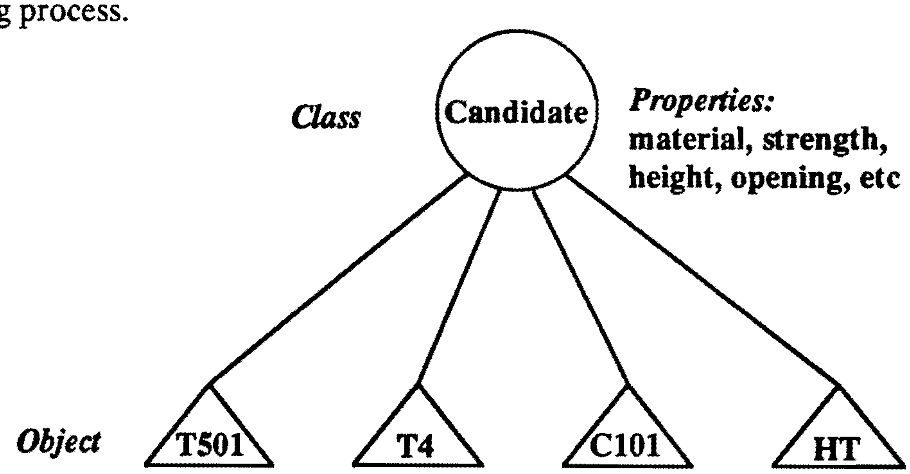


FIG. 16. Class of Candidates Containing a Group of Rails

Objects (rails) in **Candidate** are created dynamically. No object is statically assigned to the class. The knowledge base of *BREXS* derives a set of candidate rails and creates corresponding objects during the reasoning process. Dynamic objects exist only during execution and vanish whenever the inference engine is reset. Objects have a specific set of properties. Types of properties are float, integer, string, date, time, and boolean (true or false).

There are a large number of objects in the knowledge bases. Most of them insignificant with regard to the problem-solving strategy. NEXPERT *OBJECT* automatically creates as objects anything that is undefined. However, a few objects are worthy of special mention:

1. **Ideal_Rail:** This object and its property slots are used to store properties of an ideal rail for a given context of data. Properties of **Ideal_Rail** are derived from the **Ideal_Rail_Prop_Obtained** rule cluster. This object is useful for reasoning in the subsequent rule network.
2. **Bridge**: This object and its property slots store information regarding the bridge in question. Properties include length, width, curb width, etc.
3. Other single property objects such as **ADT, Percent_Truck, Understructure, Existence_of_Sidewalk** are used.

4.5 REASONING PROCESS

Once the user selects the **Run Advisory Program** menu under the **Execute** menu (Roschke 1991), the control module of *BREXS* invokes the NEXPERT *OBJECT* expert system shell, loads the knowledge base, volunteers data, and suggests the hypothesis **Finish.** At this point, the inference engine starts. Two major inferencing strategies employed by *BREXS* are backward chaining and exhaustive evaluation. **Finish** is first placed in the evaluation agenda. To prove the truth value of **Finish**, the truth value of the corresponding antecedents must be known; they are also placed into the evaluation agenda. Backward chaining propagates recursively from **Finish** to the left of the network until an end proposition is proved. Normally, propagation stops at propositions where truth values are known from volunteered data. Then, the inference engine proves or disproves the hypotheses placed in the evaluation agenda. This reasoning process continues until no more hypotheses can be proved.

At the end of the reasoning process, the knowledge base writes the results to a file name RANK_IN.NXP. This file contains candidate rail names and their weight of performance with respect to five aspects: strength, cost, maintenance, aesthetics, and personal preference. The contents of the file are written in the format required for NEXPERT spreadsheets. This file, along with the BCAP results file, is input to RANK.EXE where the candidate rails are rated and ranked.

5. System Architecture

5.1 Architecture of *BREXS*

5.1.1 Integration Schemes

Integration of NEXPERT *OBJECT* and other supporting applications can be carried out according to one of two general schemes: calling-in and calling-out. Calling-out refers to the scheme by which other applications are called and controlled from within NEXPERT. Controlling of the inference engine, user-interface, and external applications is centralized around the NEXPERT AI kernel. Calling-in refers to the scheme by which NEXPERT is called and controlled from a separate program written in C. NEXPERT's user environment is bypassed and its AI kernel is directly manipulated by the control module (Fig. 17). The AI kernel function is limited to directing the inference engines, while a specialty module controls the AI kernel and other components. Each scheme has advantages and drawbacks. Suitability of implementation of each scheme for a given system is system dependent. Considerations include the nature of the problem solving process, data exchange among components in the system, and choice of a user-interface.

BREXS applies the calling-in scheme because of the following advantages: (1) flexibility of control, (2) modularity of system architecture, and (3) choice of a graphical interface. However, there are also drawbacks associated with this scheme: difficulty of developing a control module and learning to program the user-interface.

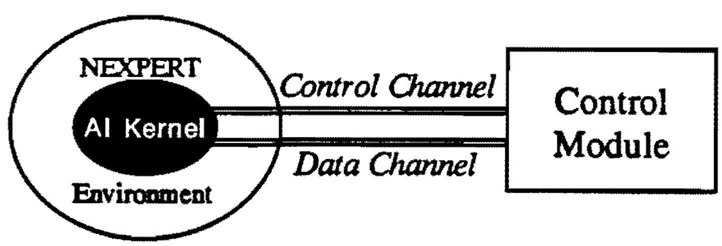


FIG. 17. Direct Communication Between NEXPERT Kernel and the Control Module

5.1.2 INTEGRATION ARCHITECTURE

Integration of *BREXS* focuses around a central control module. This model directs the inference engine, invokes analysis codes, initiates database queries, and supports the user-interface. Fig. 18 presents a schematic of *BREXS*' implementation of the call-in architecture of NEXPERT. The control module is written in C in association with Microsoft Windows 3.0 and NEXPERT *OBJECT* libraries.

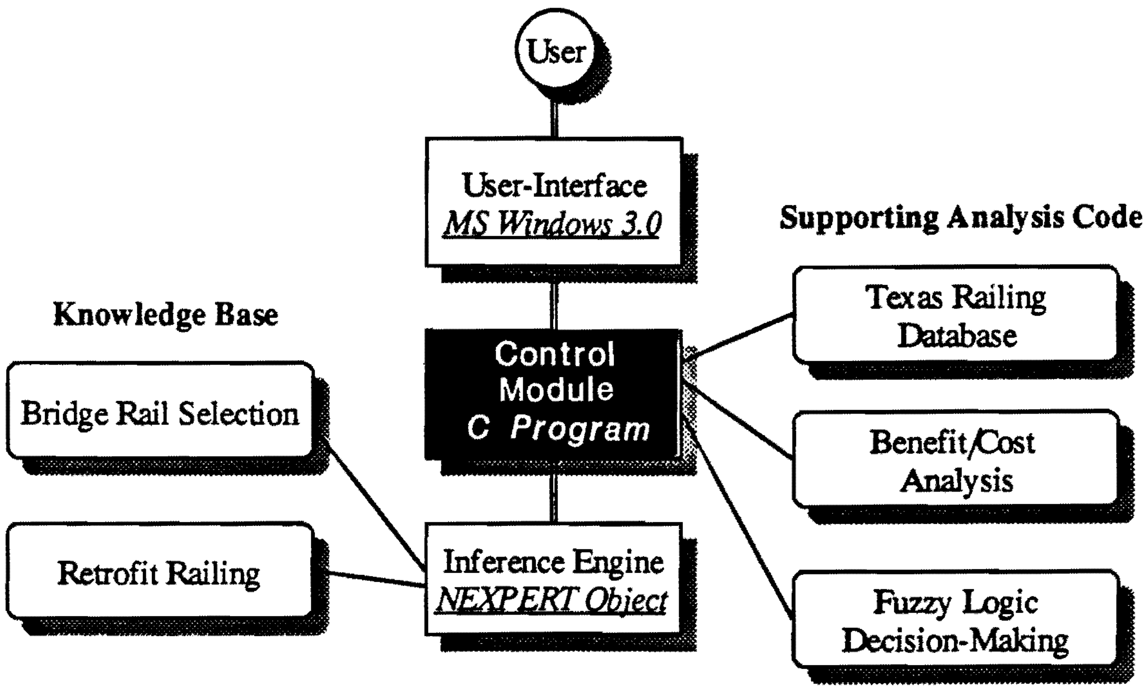


FIG. 18. *BREXS* Architecture

Microsoft Windows provides a robust graphical environment, fast and direct exchange of data between applications, and multi-tasking capabilities. Its libraries enable execution of a wide variety of analysis codes and databases from within a single environment. NEXPERT *OBJECT*'s C libraries allow for control of the inference engine from within Windows. Despite the fact that several different types of applications are called by the control module, use of individual modules is transparent and seamless to the user. Other than general knowledge of the capabilities and limitations of analysis codes that are to be called on, detailed user expertise concerning the input and output for each of the integrated codes is unnecessary.

The control model (1) interfaces with the user, (2) controls the interference engine, (3) controls supporting functions and analytical routines, and (4) exchanges data between modules. The end user directly controls execution of the inference engine of *BREXS* from a customized user-interface that features pull-down menus and windows. In addition to control of the system, a user can submit data, view results, and check and update a graphical database of bridge rails from the user-interface. Standard file management utilities such as open, save, edit, and print are fully implemented. Data exchange takes places via data files and random access memory in order to optimize speed and efficiently utilize memory and hard disk space.

5.2 CONTROL AND DATA FLOW

BREXS consists of a collection of functions written in C, a set of libraries linked to those functions, and an executable program. Fig. 19 shows the flow chart of control and data for these modules. The heart of the program is the knowledge base, named BREXS.KB, which is built using the NEXPERT *OBJECT* development shell. The advisory program uses this knowledge base to reason and reach conclusions about a certain case. A case is defined as a collection of data items describing conditions of a bridge, a highway, and other related information. A case can be saved to a file, read from a file, edited or manipulated. This is all done inside the control program or the user-interface. This section is also responsible for data checking and making sure that the advisory program runs correctly.

Running the advisory program means using the NEXPERT run-time shell, along with the NXPW Dynamic Linked Library, to reason and reach a conclusion. The current case data are sent to NEXPERT where a function call starts its inference engine. Results are saved to the RANK_IN.NXP file. This file is read, when needed, in the control program and results can be displayed or saved for future reference.

The output from NEXPERT is manipulated and used to reach final conclusions about the current case. Output from the Benefit-to-Cost Analysis Program (BCAP) is also used to help reach final conclusions. Data for the current case is used to compile an input file to the BCAP.EXE program. The BCAP program also uses a database of information about rail types, saved in the BCAP.DBF file. The output of BCAP is saved to a file named BCOUTPUT.TMP. The control program uses this file to extract information and then, finally, to call a ranking function that ranks candidate rail types according to selected weights of importance.

In addition to using the knowledge base in BREXS.KB, NEXPERT *OBJECT* also makes use of a database of information about rail types that is saved in DATABASE.NXP. Information contained in this file can be viewed and edited in *BREXS*. Users can also view cross-sections of rail types in the database. These drawings are saved in bitmap files with a name that has the format *railtype*.DIB (Device Independent Bitmap).

The control program also accesses help files using the Windows Help system. Help files are written in RTF format, using Microsoft Word for Windows, and then compiled using the HC command of the Windows-SDK (Microsoft 1990). These files display information about *BREXS* and its operation along with definitions of each data item and other related words.

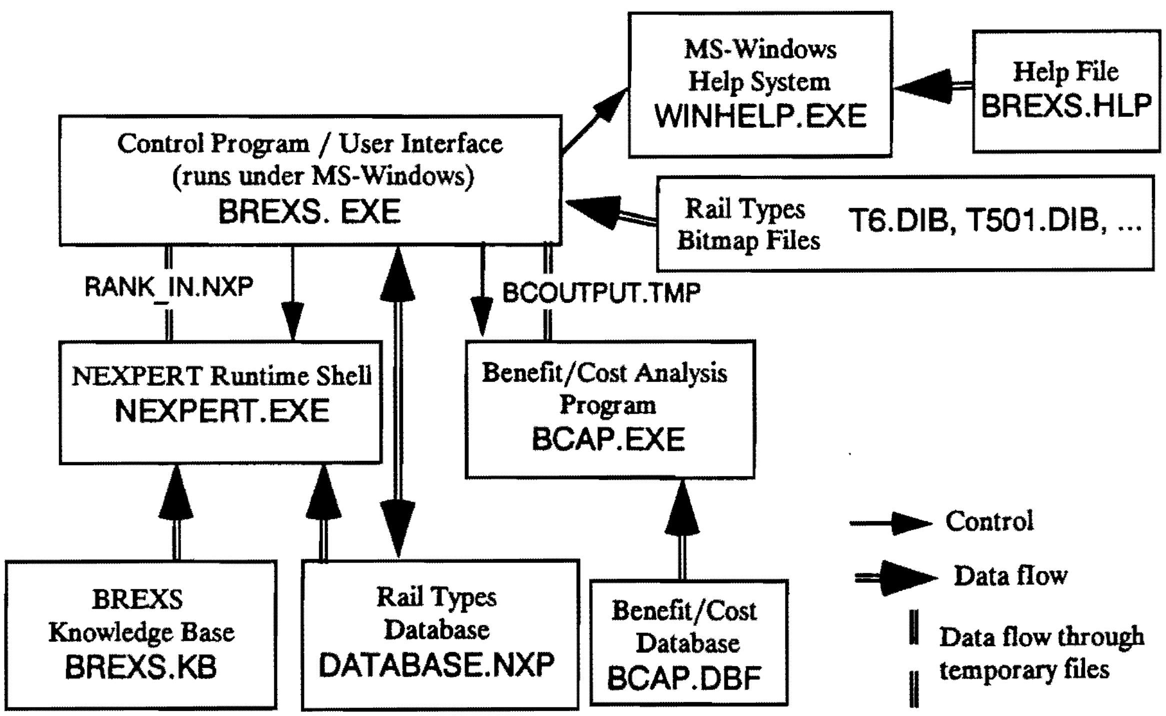


FIG. 19. Structure of *BREXS*

BREXS consists of 70 functions written in the C language that are grouped into 23 files and 12 supporting files. It is compiled and linked using Microsoft C, version 5.1, NEXPERT's NXPW.LIB, and Microsoft Windows Software Development Kit libraries.

5.3 Building of *BREXS*' Control Module and User Interface

BREXS is built in the same fashion as other Microsoft Windows applications. There are 24 source files written in the C programming language that contain the WinMain function and windows functions. The WinMain function, an entry point of the application, is contained in the main program named BREXS.C. Twenty-three other source files contain references to *callback functions*, i.e. functions within *BREXS* that are called by Windows. Most of the functions performed by the Windows files correspond to the commands listed in *BREXS*' menus. For instance, NEW.C, which corresponds to the New submenu under File menu, opens a new data file. In addition to the C language source files, there is also a module-definition file (BREXS.DEF), a resource script file (BREXS.RC), and resource files (BREXS.DLG for dialog boxes, BREXS.ICO for icons, and *.BMP for drawings of rails). A dialog file is created by the Dialog Editor. Other resources can be created by SDK Paint. Dialog Editor and SDK Paint are Windows programming tools that are part of the SDK. Further details concerning Windows programming can be found in Microsoft Windows Software Development Kit manuals or other Microsoft Windows programming guide books.

Fig. 20 shows the steps used in building *BREXS*. It should be noted that while Windows and C run-time libraries are linked with the object files by the linker, NEXPERT *OBJECT* libraries are not linked at this time. Instead NEXPERT libraries are linked dynamically with *BREXS* at run time. This practice is referred to as dynamic-linking and the libraries are called Dynamic-Link Libraries (DLLs). DLL allows several applications to share a common set of routines, thus reducing the size of the program and optimizing use of high-speed memory.

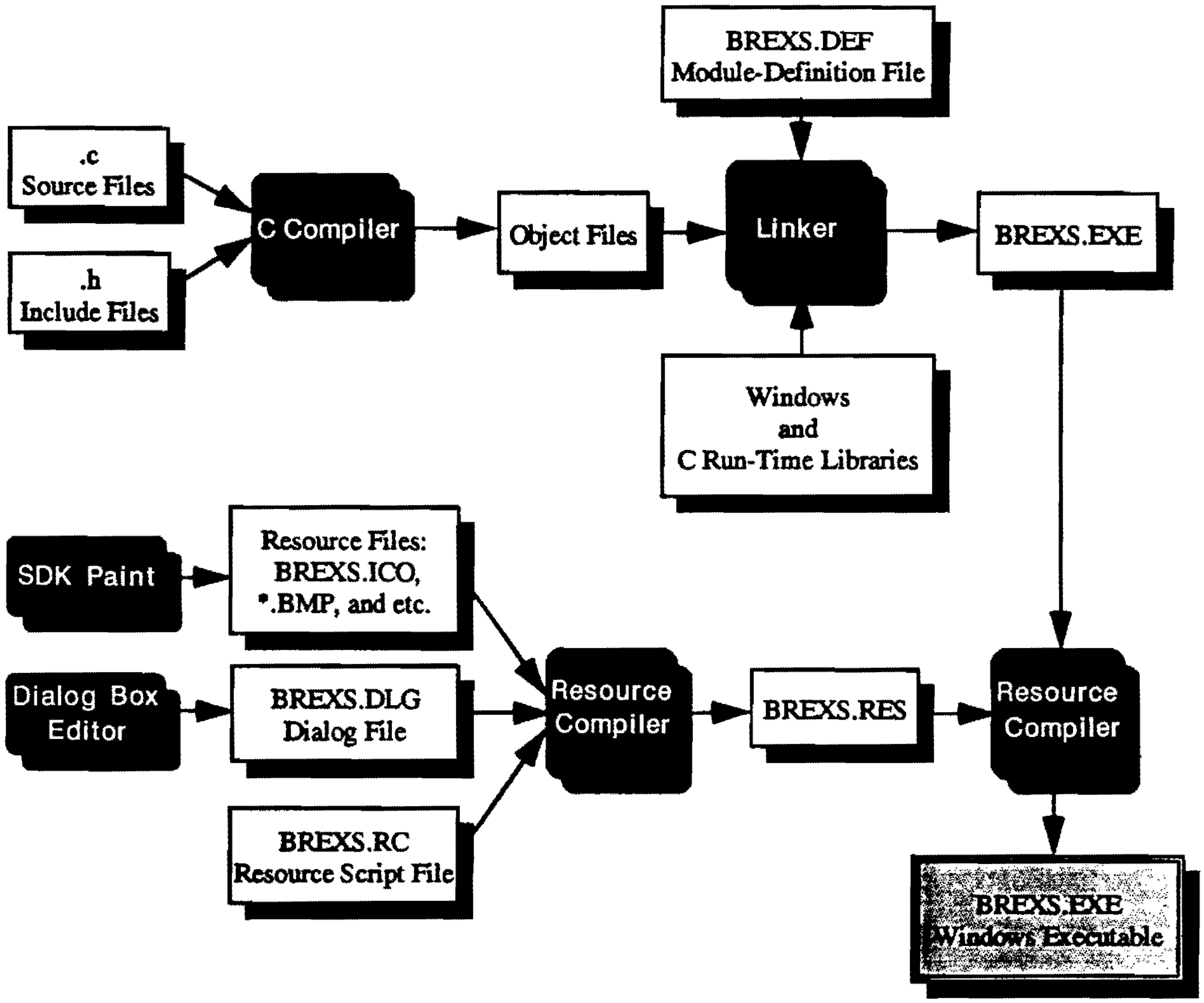


FIG. 20. Building of BREXS' Control Module and User Interface

5.4 MAINTAINING THE SYSTEM

Maintenance of *BREXS* can be categorized into two tasks: control and user-interface, and knowledge base. For control and user-interface maintenance, the programmer must have a good understanding of the C programming language, Windows programming, expert system development, and programming of knowledge bases. Knowledge and skill on usage of supporting tools such as the C compiler and Microsoft Windows Software Development Toolkit are also mandatory.

From time to time *BREXS*' knowledge bases may require maintenance and revisions in accordance with new or updated standards for bridge railings. To maintain the knowledge bases, a thorough understanding in the problem solving strategy, knowledge representation, and system architecture is required. Despite the fact that *BREXS* functions as a Windows application, changes of knowledge bases are allowed without the need to recompile the source codes of *BREXS* as long as the input and output of the KBs are not changed.

Further details on functions and files are documented in a Technical Memorandum on *BREXS* Software Maintenance (*Technical* 1991).

6. Fuzzy Logic Decision-Making

6.1 Multi-Objective Decision Making

In general, precise assessment of engineering information is difficult to obtain. The greater the precision required for the assessment, the greater the difficulty. Furthermore, as the assessment scale becomes more refined it becomes more sensitive to noise, and consequently more error prone (Yager 1981). Decision making by human beings is a process that is normally performed in an imprecise context. To aid in selection of a bridge rail from a list of candidates, a decision making method based on fuzzy logic is implemented to *BREXS*. Fuzzy logic is a mathematical framework that allows calculation of the truth value of a formula by deduction of the truth value from the input information. It is different from conventional logic in that it allows the usage of intermediate truth values between true and false. In other words, fuzzy logic decision making is a process by which a decision is formed under the context of imprecise information.

Rating and ranking the overall performance of a set of candidate rails requires a computational mechanism to aid in making a decision. Candidate rails in *BREXS* are considered according to the following 5 criteria (sometimes referred to as objectives):

1. Strength
2. Cost
3. Maintenance
4. Aesthetics
5. Personal Preference

For illustration purposes let {Rails} be a set of candidate rail types and {Criteria} be a set of criteria or objectives of concern. *BREXS* requires a process that forms a decision for the purpose of selecting the optimum choice from the set {Rails} based on their performance of the set {Criteria}. This process is commonly referred to as multi-objective decision making. To evaluate each alternative, assessment of performance is based on the set of criteria. In the bridge railing domain, there is no consensus on a methodology to evaluate the overall performance of each type of rail. Oftentimes, a decision on the choice of a rail is based on an individual's subjective assessment.

In *BREXS* evaluation of candidate rails is based on fuzzy logic reasoning that uses the 5 criteria shown above. The method has been shown (see Chapter 7) to adequately represent and rank their overall performance and to satisfy individual preferences of bridge engineers testing the program. The criterion of Personal Preference is loosely named to represent any consideration that does not fall into one of the other four criteria. It can be used to represent the policy of a district or personal preference of an individual engineer for a given type rail. For multi-objective decision making, assessments as well as relative importance of each criterion for each alternative are required in order to form a recommendation. Assignment of relative importance values allows for compensation of positive and negative assessments of each rail type. The more important an objective, the more significant is its effect on the final decision and vice versa. Fig. 21 shows a general scheme of multi-decision making.

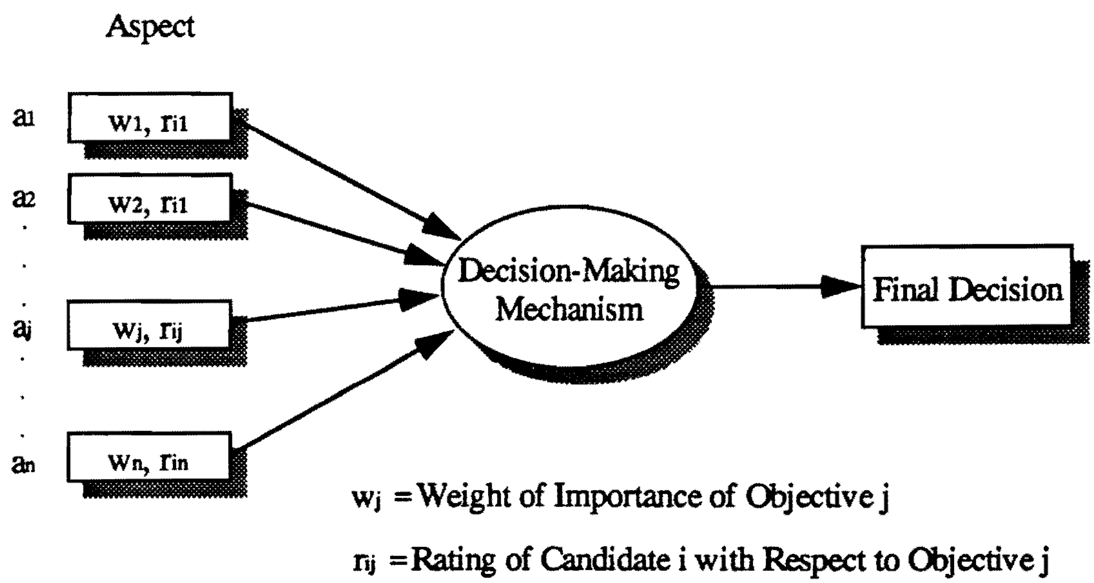


FIG. 21. General Scheme of Multi-Objective Decision Making

6.2 YAGER'S METHOD OF DECISION MAKING

The decision making mechanism used in *BREXS* is based on Yager's (1981) method. Rating and weight of importance information are represented as fuzzy sets.

$A_j(r)$ is taken to represent the rating of rail r based on criterion j. In a mathematical context, the decision function D is the solution that satisfies all objectives A_1 ***and*** A_2 ***and*** ..., ***and*** A_5. Bellman and Zadeh (1970) suggest that the appropriate mathematical form for an ***and*** operation is the ***min*** operator. The ***min*** operator was originally used for intersection of fuzzy sets by Zadeh. Therefore, the decision function is

$$D(r) = \text{Min}\,[A1(r), A2(r), \ldots, Ap(r)] \quad (1)$$

where each r is a member of {R}. The optimal solution r* satisfies

$$D(r^*) = \text{Max}\,D(r) \quad (2)$$

However, the weight of importance for various objectives must be considered. Denote αi as the weight of importance of objective i. Therefore, the decision function with the inclusion of the weight of importance is

$$D(r) = \text{Min}[(A_1(r))^{\alpha 1}, (A_2(r))^{\alpha 2}, \ldots, (A_p(r))^{\alpha p}] \quad (3)$$

Yager suggests further that $(Ai(r))^{\alpha i}$ can be found from

$$(Ai(r))^{\alpha i} = \text{Max}\,(\alpha i', A1) \quad (4)$$

where $\alpha i'$ is the complement of αi. Thus,

$$\alpha i' = (1 - \alpha i) \quad (5)$$

calculates the complement of αi. In this way Eqs. 2-5 are used to calculate the final decision for the multi-objective decision making with consideration of weight of importance.

In *BREXS* the general (default) ratings of the standard Texas rails for the five criteria obtained from district engineers around the state are stored in the railing database. These ratings represent the performance of each rail under general conditions. The knowledge bases of *BREXS* are modified to reflect this rating according to the particular context of the problem. For example, if deicing salt is used, the rating of metal rails is decreased for the criterion of maintenance. Weight of importance is obtained from user input. An engineer has the freedom to give the relative weight of importance to optimize the solution based on his or her preference.

Table 1 shows an example of decision making using Yager's approach to fuzzy logic for a ranking of the T501 and T4 rails. The overall rating for the T501 and T4 rails is 5.0 and 6.0, respectively. Therefore, T4 is the preferred rail of choice in this case.

TABLE 1. Decision Making Example

			T501		T4	
	α	$\alpha' = (10 - \alpha)$	A	A^{α}	A	A^{α}
Strength	9.0	1.0	7.5	7.5	7.0	7.0
Maintenance	7.0	3.0	8.0	8.0	6.0	6.0
Cost	4.0	6.0	5.5	6.0	4.5	6.0
Aesthetics	5.0	5.0	4.5	5.0	7.5	7.5
Preference	6.0	4.0	7.0	7.0	6.0	6.0
		Overall Rating →		5.0		6.0

7. SYSTEM VALIDATION

7.1 INTRODUCTION

In this chapter a procedure is described that is used to validate *BREXS*. The approach is developed especially for validating a knowledge-based system that has more than one expert. It is based on four qualitative measures that are designed for problems being solved by multiple levels of experts whose authority and expertise can be modeled hierarchically. Development of test cases and performance measures is discussed. Based on the level of agreement with human experts and the Turing test, it is shown that an early prototype version of *BREXS* exhibited a relatively high level of expertise. Some system deficiencies of the prototype were manifested and several features of the final version of *BREXS* were modified based on the results of the validation tests.

An expert system such as *BREXS* is developed in an evolutionary or an exploratory manner. This means that a working system is developed as quickly as possible to meet initial desired capabilities, and then modified and expanded until it is capable of performing in an adequate way. During the evolutionary process, tests need to be performed to validate operation of the system. Validation, as often referred to in software engineering, is the process of substantiating that a system performs with an acceptable level of accuracy (O'Keefe et al. 1987). Validating performance does not merely mean evaluating the results or measuring the output of the system. It is important that the reasoning process itself be evaluated and validated as well, especially when judgments on overall performance are based upon extrapolations from representative instances of behavior (Buchanan et al. 1983). Although the validation of traditional algorithmic software is a relatively well-defined process and uses methods that have been tested and proven to be effective, validation methods for knowledge-based systems have not been formalized.

Expert systems can be divided into several categories depending on their domain, the type of problem they solve, and the way knowledge is represented. Another division can be made according to the number of human experts that are involved in development of the expert system. Here the focus is on a system with multiple experts. This does not simply mean that there is more than one expert, but rather that each expert makes a unique contribution to the solution of the problem.

More specifically, expertise is modeled in a hierarchical manner where experts at high levels have more authority, and usually more expertise, than those at lower levels. Principal differences between a system developed with multiple experts and one developed with a single expert are in the knowledge acquisition and validation processes. Consistency of knowledge between experts is an issue that should not only be of concern at the time of system release, but also profitably monitored during development of an expert system with multiple experts.

Turing (1963) was the first to use a blind evaluation method to validate machine intelligence. He suggests that if a human, after simultaneously interrogating a machine and another human with both of their identities concealed, cannot differentiate between the two, then the machine is considered to be intelligent. The Turing test, or a variation of it, is the most widely used qualitative method for validating expert systems. It is often preferred over other testing methods because it eliminates, or greatly reduces, any biases that testers or evaluators might have toward computer programs. That is, it provides an objective measure.

Culbert, Riley, and Savely (1987) discuss differences between expert systems and conventional software, and how these differences affect the validation process. One of the issues mentioned is the complexity associated with multiple experts. The authors suggest that a panel review method be used for verification and validation to solve these problems. The panel is to review both the procedure to resolve a problem and the analysis techniques used to develop this procedure. System users, independent domain experts, system developers, and managers comprise the panel. Exhaustive testing through simulation is suggested as the method for final validation. Due to high cost this method is not usually feasible.

An expert system is considered valid if and when it meets certain criteria. These include accuracy, appeal, face validity, precision, Turing test, reliability, and robustness (Geismann and Schultz 1988). In general, a level of performance should be developed from the intersection of these criteria such that it reflects initial design requirements. During the validation phase the system is to be evaluated according to stated measures. In the case of systems making use of multiple-level experts, a performance measure should be used so that the final delivery system is acceptable to experts at all levels.

7.2 STAGES OF VALIDATION

Here, a method of validation is proposed for application to *BREXS*. The method is qualitative and combines four stages of validation (Fig. 22) for knowledge from multiple experts. First, a face validation stage makes preliminary tests on the system and the results are compared with the performance of human experts. The purpose of face validation is to ensure that the formulated problem contains the entire actual problem and is sufficiently well-structured. This stage is carried out in three phases. The first phase involves members from the development team. The second phase employs potential users or experts at a low level in the hierarchy of expertise. The third phase involves engineers more knowledgeable about the domain, such as those experts at a high level in the hierarchy.

The second stage of the validation uses the Turing test. As described in section 7.1, this test compares the performance of human experts and the knowledge-based system without the evaluator knowing the subject performer's identity. It eliminates any bias, either towards or against, computer systems. In the case of multiple experts, the Turing test also helps to measure consistency between experts.

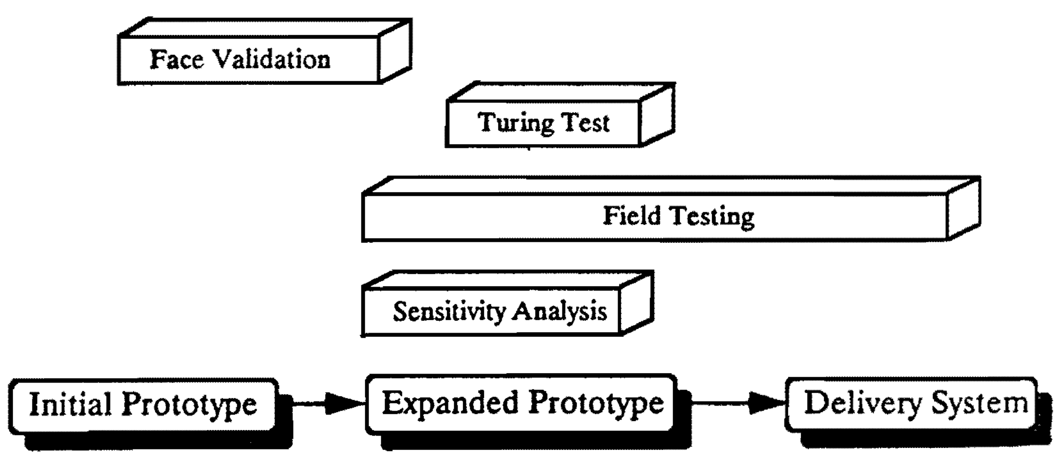


FIG. 22. Schedule of Development Life Cycle and Validation Approaches

The field testing stage uses a prototype of the system to stimulate performance under actual conditions. Engineers that do the evaluations are asked to report problems and provide feedback on the system's performance. However, this approach can only be used with non-critical systems where errors can be tolerated, at least in the developmental phase of the expert system.

Sensitivity analysis, the final testing stage, is achieved by analyzing the effect of changing system parameters or input variables on system performance. This is a systematic approach that is especially useful when experts are asked to assign certainty factors that can be altered as desired. It also gives insight to the reasoning process, and helps verify not only the system's final results, but intermediate results as well.

The four stages in Fig. 22 are qualitative techniques that use subjective comparisons. They lack the mathematical precision of quantitative techniques, but are more flexible and less demanding (O'Leary et al. 1987). Moreover, they are especially appropriate for demonstrating validity of prototype systems where time and cost are major constraints.

7.3 APPLICATION TO *BREXS*

Validation started early in the development process with the initial prototype of *BREXS*. Face validation was performed by having the state expert review the prototype and inspect the knowledge embedded in it. Tests were conducted by knowledge engineers on the development team and results were compared to answers from human experts. At this stage, only experts at the state level were involved. Two issues were of concern: knowledge representation and accuracy of the solution. The validation of the initial prototype verified feasibility of the system. The system was then ready to be expanded.

Knowledge acquisition and formulation, and user-interface programming were performed in an iterative manner. After each addition of rules to the knowledge base, the system was tested for accuracy and completeness of solution by members of the development team. They were also aided by independent experts in the domain. Testing of the user-interface functions and features was another part of the face validation approach. Appendix VI shows the questionnaire used for this evaluation. Initial reviewers of the user-interface were independent testers that had no knowledge of the bridge rail domain. Later, engineers involved in bridge design also filled out the evaluation forms. The reasoning process was checked by means of the transcript generation capabilities of NEXPERT *OBJECT*. Expansion of the prototype concluded approximately 12 months after the initial prototype was approved.

Test cases for the face validation approach were chosen to cover the entire range of variables. There was no set limit on the number of cases. Tests were done in a guided manner, in that they were directed toward proving that certain sets of rules are correct. There was no means of measuring the accuracy of the solution. The system output was mainly checked for erroneous or illogical conclusions both in intermediate and final results.

The second stage of validation, field testing, started after face validation tests were successfully completed. Four TxDOT sites were selected for testing: Bryan, Houston, and San Antonio district offices, as well as the Austin state-level office. Each site was provided with the latest version of *BREXS* along with a user's manual (Roschke et al. 1991), a set of test forms, and detailed testing instructions. Appendix VII shows a sample test form. Engineers at local district offices independently conducted 10 to 20 tests using projects under current construction or retrofit bridge rail cases. For each test, TxDOT engineers were instructed to perform the following steps: (1) fill out case data on the first two pages of the test form, (2) fill out the table in the test form based on their own judgment, (3) run *BREXS* using the case data, and (4) provide comments on the results.

Field testing started with the Bryan district office. Fifteen test cases were run at this site. Ten of these were actual cases of bridge rail installation that had been supervised by that office. These ten cases later became part of the set of standard test cases that were run in other districts. For the other five cases, some input parameters of a corresponding real case were modified in order to test the system under abnormal conditions.

The Houston district office served as the next test site. An engineer ran the 10 standard test cases that were collected from the Bryan district office. Due to time constraints, only six other test cases were compiled. This sample is not large enough to cover the entire range of actual projects supervised by the Houston district office, but it does provide a reasonably good sample.

The third test site was the San Antonio district office. Engineers at that site were asked to run a set of 10 standard test cases, half of which were from Bryan and the other half from Houston. In addition to this, evaluators ran 10 other test cases using data from projects supervised by their office.

The choice of the three test sites was based on two factors. The first factor is their proximity to the location where *BREXS* was developed. The other more important factor is that each site provides a distinct set of conditions to test. In Bryan, most of the projects involve rural roads with at most a few thousand vehicles of traffic per day. Most of the projects in Houston involve 3- or 4-lane highways with heavy traffic and severe conditions. Finally, in San Antonio the district office handles cases with conditions that lie between the other two extremes. Therefore, the combination of these three locations provides the opportunity to test the system under most of the commonly occurring conditions in the state. Field testing lasted for two months. Although this approach was the most time consuming of the validation procedures, it provided important feedback on the system.

After collecting test cases from these three sites, a Turing test was conducted. An expert at the state level was interviewed for this purpose. For each test case, the expert was asked to review the input data, suggest a solution and then examine different solutions and attempt to identify which one was generated by *BREXS*. The Turing test was delayed until after field testing was conducted so that it could be run using actual cases from various districts, and to collect answers to those cases from local experts.

Test cases for the Turing test were prepared so that the identity of *BREXS* was concealed. Advice from human experts was expressed in the form of a table in which each rail type was either strongly recommended, recommended, slightly recommended, or not recommended (see Appendix VII). Output from *BREXS* was in the form of a ranked list of recommended rail types, each having an associated weight. This list was mapped into a table identical to the one used by human experts. Thus, the identity of *BREXS* could not be distinguished based on its format.

The final validation stage uses sensitivity analysis. This was carried out by members of the *BREXS* development team using some of the test cases and results obtained from district offices. Each of these test cases was used as a reference case for each of the sensitivity tests. About 30 input parameters were systematically varied while system output was monitored for changes. One parameter was varied at a time, while all other parameters were kept constant. Parameters were not varied in equal increments but adhered to ranges implied in the rules. For example, the average daily traffic (ADT) affects the final conclusion of the system when it is below 10,000 vehicles per day (vpd). Alternatively, it affects recommendations in a different way if the ADT is between 10,000 and 15,000 vpd. Hence, ADT values were chosen to be 9,000, 12,000, 17,000, and 25,000 vpd so that they fall within one of the specified ranges.

After performing sensitivity analysis tests on two cases, it was determined that some variables affect the system output much more than others. These variables were placed into one of two groups. The first group included ADT, percent trucks, and type of understructure. The second group included the five weights of importance. More thorough sensitivity analysis tests were performed on each of these groups to determine their effect on the system output and to verify their influence and interaction. A reference case taken from the set of test cases collected from the TxDOT district offices was chosen for each of the two groups.

During the validation phase a certain minimum acceptable level of system performance is set. If the validation method shows that *BREXS* reaches or exceeds that level, then validation stops. Otherwise, *BREXS* has to go through one more iteration of expansion, and an additional validation. The acceptable performance level was set according to the following standards:

(1) The system should have an adequate level of agreement with local experts as well as with state experts. The level of agreement should be comparable to that found among human experts.

(2) In the Turing test, the system should yield at least 80% uncertainty in the expert's judgement. That is, the subject of the Turing test should not be able to identify *BREXS* in more that 20% of the total number of test cases.

(3) Sensitivity tests should show that the system is sensitive to changes in input parameters to a reasonable degree. The system should not be overly sensitive, or totally insensitive to changes in input parameters.

7.4 RESULTS

7.4.1 Field Testing

The goal of field testing is to ensure that *BREXS* performs adequately under real conditions in the domain of its application. This means that the system needs to meet the following objectives:

(1) Generate an accurate solution.

(2) Provide a user-oriented interface, including a help facility.

(3) Degrade gracefully when dealing with problems at the border of its knowledge.

Since the problem that *BREXS* solves has no single correct answer, accuracy of the solution is difficult to measure. Instead, what is measured during field testing is the degree of agreement between human experts and *BREXS* with regard to final recommendations. In order to measure this agreement, engineers were asked to provide answers in a form similar to that which *BREXS* generates. It is important to note that in real situations human experts do not solve these problems in the same manner that was required during these tests. Usually, after carefully considering all salient parameters, a human expert selects only one rail type for installation. By comparison, these tests require engineers to categorize each of the rail types.

Cases from the three geographical test sites were inspected and analyzed. For each test case a "score of agreement" was issued. This is a number that lies between 0 and 100 and is calculated based on the following factors:

(1) Agreement in the type of rail that is most highly recommended.

(2) Agreement in the number of alternative rail types.

(3) Agreement in ranking the rail types.

(4) Agreement in the types of rails that are not recommended.

(5) Agreement in reasoning.

The more that two answers agree, the higher the score. A score of 100 means a perfect match between the conclusions of *BREXS* and those of a human expert. As an example, Appendix VIII shows recommendations of local experts in Bryan and Houston, the state expert, and *BREXS* for test case number 1707. Table 2 shows partial scores of agreement between these recommendations in each of the four categories: Strongly Recommend, Recommend, Slightly Recommend, and Do Not Recommend. For example, comparing the first column in the recommendations of Bryan and Houston, there is an agreement in only one (T501) of the many recommended rails. A score of 10 out of 25 was given for that category. Comparing Bryan and the state expert in the same category, there is an agreement in two (T501 and T202) of the three (T201, T202, and T501) recommended rails; also the third rail (T201) is recommended in another category. In this case a score of 22 out of 25 is assigned.

TABLE 2. Partial Scores of Agreement for Test Case Number 1707

	Strongly Recommend	Recommend	Slightly Recommend	Do Not Recommend	Total
Bryan vs. Houston	10	0	0	0	10
Bryan vs. State Expert	22	0	0	8	30
Bryan vs. BREXS	20	15	0	10	45
Houston vs. State Expert	15	5	15	5	40
Houston vs. BREXS	0	15	15	5	35
State Expert vs. BREXS	20	10	20	20	70

Table 3 shows the results of analyzing all test cases collected from the individual test sites. The first and second columns indicate the location and number of test cases evaluated at each site, respectively. The third column shows the average score of overall agreement, while the last column indicates the average score of agreement for the most highly recommended rail(s). These results indicate that *BREXS* has different levels of agreement with different experts. This is because each human expert involved in these tests solves the problem in a unique way. For example, an engineer at the Houston district office has a different answer than an engineer in San Antonio for the same test case. *BREXS* has the highest correlation with engineers at the Bryan district office. The fourth row in Table 3 combines the average scores of local experts in the Bryan, Houston, and San Antonio district offices. Comparing this combined overall score with the average overall score of the state expert at Austin shows that *BREXS* has a higher level of agreement with local experts than with the state expert. However, the average score for the most highly recommended rail according to the state expert is higher than that for the district (local) experts.

TABLE 3. Scores of Agreement between *BREXS* and Human Experts

Test Site Location	Number of Test Cases	Average Score of Overall Ranking	Average Score of Top Recommended Rail
Bryan	12	68.8	78.3
Houston	16	57.9	48
San Antonio	19	54.6	64.4
Local Experts (Total)	47	59.35	62.37
State Expert in Austin	15	39.9	66.13

Furthermore, the fourth column of Table 3 shows that there is a relatively high level of agreement in the most highly recommended rail(s) at most test sites. This means that if *BREXS* were to suggest one rail type, instead of a list of several rails, it would have more than a 60% chance of coinciding with the recommendation of human experts. This number, if taken absolutely, might lead to a preliminary conclusion that the level of agreement between *BREXS* and human experts is not satisfactory. To suggest a more complete analysis, this degree of agreement needs to be compared to the degree of agreement among human experts.

Using the above-mentioned technique, test cases were evaluated for agreement among human experts. Tables 4, 5, and 6 show scores of agreement between engineers in the Bryan, Houston, and San Antonio district offices and the other human experts, respectively. That is, each table shows scores of agreement between experts in one district and those in the two other districts, as well as the score of the state expert in Austin. These tables have the same format as Table 3 including the combined score of local experts.

Results shown in Table 4 indicate a relatively low overall level of agreement among experts at the local level. This level of agreement is almost equal to the overall level or agreement with the state expert in Austin. As for agreement in selection of the most highly recommended rail, results show that the level for this rail is higher than that of the overall score. Results also indicate that the state expert tends to agree more with the engineer at the Bryan district office than with other local experts' choice for the most highly recommended rail.

Table 5 shows that engineers at the Houston district office tend to agree more with local experts than with the state experts. The levels of agreement that this table shows are the lowest between all other experts, including *BREXS*. Table 6 shows that engineers at the San Antonio district office agree more closely with the state expert than with the other local experts. However, if only Bryan and the state expert are compared, the results show an almost equal level of agreement. Finally, the level of agreement between *BREXS* and the state expert can be compared to the level of agreement between local experts and the state expert (the last row of Table 3, versus the last row of Tables 4, 5, and 6). Although all scores of agreement with the state expert tend to be low (less than 40), *BREXS* consistently has the highest score.

TABLE 4. Scores of Agreement between Experts at Bryan District Office and Other Human Experts

Test Site Location	Number of Test Cases	Average Score of Overall Ranking	Average Score of Top Recommended Rail
Houston	10	26.4	33.2
San Antonio	5	48.2	68
Local Experts (Total)	15	33.67	44.8
State Expert in Austin	9	34.2	56.44

TABLE 5. Scores of Agreement between Experts at Houston District Office and Other Human Experts

Test Site Location	Number of Test Cases	Average Score of Overall Ranking	Average Score of Top Recommended Rail
Bryan	10	26.4	33.2
San Antonio	9	31.33	31.56
Local Experts (Total)	19	28.74	32.42
State Expert in Austin	15	28.53	25.32

TABLE 6. Scores of Agreement between Experts at San Antonio District Office and Other Human Experts

Test Site Location	Number of Test Cases	Average Score of Overall Ranking	Average Score of Top Recommended Rail
Bryan	5	48.2	68
Houston	9	31.33	31.56
Local Experts (Total)	14	37.35	44.57
State Expert in Austin	10	52.55	65.7

When collecting test cases from a test site, knowledge engineers conducting the tests briefly interviewed design engineers in order to solicit comments on overall performance of the system. All engineers who tested the system commended it in many respects. Almost all of them appreciated the Windows-Icon-Menu-Pointing (WIMP) interface which makes the program easy to learn and use.

As for overall system performance, all testers gave positive remarks. Each engineer said that *BREXS* is very helpful because it provides an environment in which to carefully weigh a wide variety of aspects when dealing with bridge rail selection. Many of the design engineers had helpful remarks about the system. One suggested the inclusion of pedestrian rails into the database of rail types and supported his suggestion with proofs of their use. Other engineers detected some minor errors in the data checking and file handling of the user-interface program. Finally, several comments were made concerning a desire for an improved explanation facility.

7.4.2 Turing Test

A variation of the Turing test was conducted with the state expert in Austin as explained in sections 7.1 and 7.3. In validating expert systems, a Turing test is usually conducted with two sets of answers. One set belongs to a human expert, and the other set belongs to an expert system. However, because *BREXS* has multiple experts, results from three tests were presented to the state expert who was the subject of this Turing test. That is, the state expert reviewed sets of recommendations by two of the local experts and a ranked list that was the output from *BREXS*. This was done to reduce the chance from 50% to 33.3% that the state expert could simply guess the recommendation of *BREXS*.

Fifteen cases were presented to the state expert. Out of those, he managed to correctly identify *BREXS* twice. Out of the remaining 13 cases, 8 were incorrectly identified. That is, the state expert mistook the answers of local experts to be those of *BREXS*. In the remaining 5 cases, the state expert was uncertain as to which answers were recommendations from *BREXS* and which belonged to a human expert.

In most of those five "uncertain" cases, one answer was excluded and the choice was narrowed down to one of two rails. In four out of these five cases, the state expert incorrectly identified the expert system. A summary of the Turing test results is listed in Table 7. It shows that *BREXS* was identified in 20% of the total number of cases.

TABLE 7. Turing Test Results

Action Taken by Test Subject	Number of Test Cases	Percentage
Identified BREXS	2	13.1%
Identified BREXS with uncertainty	1	6.67%
Chose human expert	8	53.33%
Chose human expert with uncertainty	4	26.67%
Total	15	100%

7.4.3 Sensitivity Analysis

Because of the relatively large number of input parameters and the time constraints imposed on the development of *BREXS*, only five sensitivity test were conducted. In two of these tests a reference case was chosen and input parameters were changed, one at a time, while the output was observed. Appendix IX includes a summary of values chosen and the effect(s) of change, if any. After studying the first two test cases and from previous experience, it was determined that there are two groups of parameters that have the greatest effect on the system output. Consequently, in the other three tests, the effect of changing parameters in each group was studied.

In the first test, the system behaved in a predictable manner. This means that when the parameters were changed, the resulting effect was justified in all but one case. This was the case where the Percent Trucks parameter was changed to 20%. The output of the system is a list that includes more rail types than in the reference case. In the second test, the system also behaved as expected except for two cases. These were cases where Potential Turning Movement and Visibility for Safety Required parameters were changed to "true." The system should have shown slight changes in its conclusions, but instead, there were no observed changes from the conclusions of the base case.

In the third test the parameters ADT, Percent Trucks, and Type of

Understructure were changed according to all possible combinations. ADT was set to one of five values: 9,000, 12,000, 17,000, 25,000, and 60,000. Percent Trucks was set to one of four values: 5%, 10%, 20%, and 30%. Type of Understructure was set to creek, river, or highway. Therefore, the total number of possible combinations is 60. Out of these 60 possible combinations, the system generated 15 different output lists of bridge rails. Most of these lists included the same group of rail types but according to different numerical rankings. The number of rails in the output lists ranged from five to ten types.

The fourth and fifth tests investigated the effect of changing the weights of importance on system conclusions. There are five categories for the weight of importance parameters, and each can be set to a value between 1 and 10. Therefore, the total number of possible combinations for one test is equal to 105. If the duration of each case is only one minute, it would take 139 days to complete one test. Consequently, each category was set to only one of three values: 1, 5, or 10. This reduced the number of possible combinations to approximately 35 (since some combinations, such as all ones or all fives, are redundant). Only 30 out of these 241 possible combinations were run. The system generated thirteen different solutions in one test and eight different solutions in the other test. The difference between solutions is in both the number of suggested rail types and their ranking.

7.4.4 Discussion

The results presented in the previous section yield a measure of the level of performance for a prototype of *BREXS*. From the results of field testing, it can be concluded that *BREXS* shows an acceptable level of agreement with human experts at the local level. However, when compared with rails recommended by district level engineers, *BREXS* has a lower level of agreement than is desirable, although local experts do not show an appreciably higher level of agreement with the state expert. This means that the level of expertise of the prototype version of *BREXS* lay somewhere between that of the state expert and local experts.

The expert taking the Turing test was able to identify *BREXS* in only 13.1% of the cases. Although the total number of test cases was relatively low, these results lead to the conclusion that, at this stage in its development, the advice of *BREXS* could not usually be distinguished from that of human experts. This supports the conclusion drawn above about the acceptably high level of expertise that the *BREXS* prototype exhibited. The Turing test contributed to the conclusion that the knowledge base was not yet complete, and that some factors, such as the effect of the length of the bridge, were missing. This conclusion was not drawn from the results of the Turing test itself, but from observations by the state expert during the test.

Results of the sensitivity analysis showed that the *BREXS* prototype had an acceptable level of sensitivity. If the sensitivity of *BREXS* is compared to the level of sensitivity that human experts possess, *BREXS* showed greater sensitivity. This conclusion is not quantitatively supported but is made on the basis of observations made on the methods that human experts follow to select bridge rails. Finally, sensitivity analysis revealed some minor errors in the knowledge base that needed to be corrected.

From the discussion above, it is concluded that *BREXS* required some additional modification before the final phase of development was complete. Although its overall performance level was adequate, it would benefit from minor modifications in its knowledge base and the user-interface program. These modifications would render it suitable for another iteration of validation. If this second iteration were carried out, the same validation method and performance measures would be applied that were used in the first iteration. Budget and time constraints prevented this second iteration from being undertaken. Ideally, the process would be continued until a very high level of performance is achieved.

8. CONCLUSIONS

8.1 CAPABILITIES OF *BREXS*

BREXS is divided into two main parts: new construction and retrofit. In the first part, the main objective is to solve the problem of optimal selection of a bridge rail type given the conditions of the new bridge, its location, and optimization factors. To achieve this objective, the user provides a complete set of data, runs the advisory program, and then reviews the results. *BREXS* is capable of performing these three basic functions plus some additional ones.

With *BREXS*, input data can be edited, reviewed, saved to a file, read from a file, and printed. Users are warned when the input data is not reasonable. After a complete set of data items is entered, the advisory program can be run with one command. Users are not required to answer any other questions, or set other options. Results of the current case can be displayed in a separate window, saved to a file, and/or printed. Old files from previous sessions can also be accessed.

In addition, a database of rail type information can be accessed. Records in the database can be easily edited or deleted, and new records can be inserted. *BREXS* provides a means of viewing cross-sections of rail types, one at a time, in a separate window. This feature can be activated simultaneously with the database access to provide a complete reference to a rail type. A help facility is also available for users at any point. The help menu is indexed by the available options and can also be accessed based on key words. It provides an on-line user's manual.

As for the second part of *BREXS*, the objective includes the selection of a rail type and the optimal placement of the selected rail on the bridge. The user-interface provides the same features as the new construction module. In addition, the user can access a program that draws the existing bridge and a rail type. Users can select any of the recommended rail types to be drawn. The drawing shows two rails: one that is placed at the recommended optimal distance (and cannot be moved), and the other that can be moved to observe effects of change. The configuration can be sent to a printer or other hardcopy device at any point.

The advisory program is capable of recommending rail types each of which has an associated weight. This process depends on the case data and the chosen optimization factors. Users can optimize the choice over five factors. These are:

cost, maintenance, safety, aesthetics, and personal preference.

8.2 LIMITATIONS OF *BREXS*

As with most expert systems, *BREXS* was designed to solve one specific problem in the domain of highway bridge design. Its scope is limited to the selection of rail types. *BREXS*'s output is given as a set of options or alternatives with weights associated with each alternative. *BREXS* does not always give the "best" answer, because sometimes a single best answer does not exist or is not known.

The method by which *BREXS* was developed included extracting knowledge from several domain experts. It was assumed that these experts represent a fair sample of the expertise that *BREXS* is replicating. It was not feasible to interview engineers at each of the many TxDOT district office to solicit knowledge about the domain. Therefore, the knowledge bases may lack information that is helpful to engineers making decisions for rail selection.

In the retrofit case, *BREXS* was enhanced with a graphical program that helps users visualize the selected configuration of slab type and rail type. This program is limited in its capabilities and can be further improved.

Although the prototype version of the program was submitted to a thorough validation process, the final version has not been subjected to another round of validation tests. Use of the program in district offices throughout the state will serve as the best check on its performance. Careful engineering judgment should always be applied to suggestions made by *BREXS* even after prolonged use of the system.

Appendix I. References

Bellman, R. E., and Zadeh, L. A. (1970). "Decision-making in a fuzzy environment," *Management science*, vol. 17, no. 4, pp. B141-B164.

"Benefit to Cost Analysis Program, Volume 2, User's Manual," (1988). *FHWA Publication No. TS - 88*, RD - 89-175 to 181, Turner-Fairbanks Highway Research Center, McLean, VA.

Buchanan, B., et al. (1983). "Constructing an expert system," *Building expert systems*, Hayes-Roth, F., Waterman, D., and Lenat, D., eds., Addison-Wesley, Reading, MA.

Culbert, C., Riley, G., and Savely, R. T. (1987). "Approaches to the verification of rule-based systems," SOAR Conference, NASA/JSC, Houston, TX.

Geismann, J., and Schultz, R. (1988). "Verification and validation of expert systems," *AI expert*, 3(2), 26-33.

Guide Specifications for Bridge Railings. (1989). American association of state highway and transportation officials, Washington, DC.

Michie, D. J., Bronstad, E. M., Kimball, C. E., and Wiles, O. E. (1976). "Upgrading safety performance in retrofitting traffic railing systems," Research Report, Contract DOT-FH-11-8100, Southwest Research Institute, San Antonio, TX.

Microsoft C 5.1 Optimizing Compiler. (1987). Microsoft Corporation, Redmond, WA.

Microsoft FORTRAN, 4.1 Optimizing Compiler. (1987). Microsoft Corporation, Redmond, WA.

Microsoft Windows Software Development Kit, Guide to Programming, Reference Tools, Volumes I and II. (1990). Microsoft Corporation, Redmond, WA.

Microsoft Windows User's Guide. (1990). Version 3.0, Microsoft Corporation, Redmond, WA.

Mitri, W. A. (1991). "Validation of expert systems with multiple experts," thesis presented to Texas A&M University, College Station, Texas, in partial fulfillment of the requirements for the degree of Master of Science.

NEXPERT Object Programmer's Reference Manual. (1991). version 2.0, Neuron Data Inc., Palo Alto, CA.

O'Keefe, M., Osman, B., and Smith, P. (1987). "Validating expert system performance." *IEEE expert*, 4(2), 81-89.

O'Leary, D. (1987). "Validation of expert systems - with applications to auditing and accounting systems." *Decision sciences*, 18(3), 468-486.

Olson, M. R., Ivey, L. D., Post, R. E. (1974). "Bridge rail design, factors, trends, and guidelines," National Cooperative Highway Research Program, *Report Number 149*, Transportation Research Board, National Research Council, Washington, DC.

Panak, J. J. (1989). "Appropriate Timing of Bridge Railing Improvements, presented at the 63rd Annual Highway and Transportation Short course, Texas A&M University, College Station, Texas, 1989.

Panak, J. J. (1990). "Status of Texas Bridge Railing," presented at the Federal Highway Administration Region 6 Bridge Design Conference, Fort Worth, Texas.

Prerau, D. S. (1987). "Knowledge acquisition in the development of a large expert system," *AI magazine*, summer, pp. 43-51.

Roschke, P. N., and Premthamkorn, P. (1990). "Expert system for bridge rail retrofit and design: architecture and knowledge acquisition," *OECD workshop on knowledge-based expert systems in transportation*, Vol. 1, Technical Research Center of Finland (VTT) and Organization for Economic Co-operation and Development, Espoo, Finland, pp. 267-282.

Roschke, P. N., Premthamkorn, P., and Mitri, W. A. (1991). "User guide for bridge rail expert system (*BREXS*)," *Report FHWA/TX-92/1240-1*, Texas Transportation Institute, College Station, TX.

Ross, H. E., Jr., and Sicking, D. (1984). "Benefit cost analysis of roadside safety alternatives," *Transportation research record 1065*, Transportation Research Board, Washington, DC.

Technical memorandum on BREXS. (1991). Submitted to TxDOT, Austin, TX.

Turing, A. (1963). "Computer machinery and intelligence." *Computers and thought*, Feigenbaum, A., and Feldman, J., eds., McGraw-Hill, NY.

Waterman, D. (1986). *A guide to expert systems*, Addison-Wesley Publishing Company, Menlo Park, CA.

Yager, R. R. (1981). "Concepts, theory and techniques: a new methodology for ordinal multiobjective decisions based on fuzzy sets," *Decision sciences*, American Institute for Decision Sciences, Atlanta, GA.

Zadeh, L. A. (1965). "Fuzzy sets," *Information and control*, vol. 8, no. 3, pp. 338-353.

APPENDIX II. KNOWLEDGE ACQUISITION TRANSCRIPT ON BRIDGE RAIL SELECTION

December 6, 1990
at
TxDOT, Austin, Texas

Participants: John Panak (**JP**), Mark Bloschock (**MB**), Wajeeh Mitri (**WM**), Prakit Premthamkorn (**PP**), and Paul Roschke (**PR**)

WM: My basic question is: what do you exactly do in a retrofit situation? In other words, what are the inputs, the outputs, and the process in between?

JP: Somebody has already determined that the existing bridge rail is deficient, which usually means it was built prior to 1965. There is a gray area of two to three years. Prior to 1965 the spec. required minimal railing [????], after that time [they required] the heavier loading requirements. Most of the railings built since that time will meet even current criterion as far as withstanding [????] although there are some deficiencies in some of those earlier railings, like the T1 rail, for instance. We've agreed with the Feds that we won't accept it as an acceptable railing unless it's retrofitted with the T101. So that's one retrofit scheme for T1, to turn it into T101 and it becomes acceptable. So, they make the decision that the existing railing is going to be retrofitted, and the next question is: with what type of railing? Usually the choice is T501. Primarily because of the emphasis [????] on retrofitting with T501 or even new construction with T501. More and more people are realizing that there are objections, primarily in urban areas, to the T501 shape or barrier shape. So now they are looking at other types of retrofits. We have retrofitted with T201 and to my knowledge, we haven't retrofitted with T4 railing. There's a big number of bridges that are retrofitted with T6 especially those that are curbless now. If it's curbless, then retrofitting with T6 is an excellent choice because then you don't have to beef up the edge of the slab. The existing pan form bridges that have the wide overhangs that are as much as 1 foot 9 inches, can be retrofitted satisfactorily with type T6 because that [????] overhang does not require [????] withstand an impact from heavy railings. So, we discourage, in fact now we don't even allow, the use of T501 or any of the heavier railing on pan form overhang. There's been a number of jobs built out there with retrofits in overhangs with T501. They just went out and poured some concrete thinking that would solve their problems..... But a T6 retrofit is good for a thin overhang or for one that is curbless now, or for one that's got water that comes over the top of the bridge ...... But the district usually dictates or decides what type of railing they're going to use with, sometimes, input from us. They'll pick up the phone and they'll send a sketch and say "Can we retrofit this and, if so, how?" They'll send some sketches. For years I've been sending sketches that look very similar to this [T501R drawings] and that's how this sheet got developed, in 19 whenever. And that has worked pretty well. Unfortunately, even though there's this little black box over here that says this sheet is intended to be used as a guide, that you're supposed to work out your details specific to your case, many jobs go out in which they just throw this sheet in the plans, and they put so many linear feet of retrofit, and the basic design is left out to the resident engineer and the inspector at the site. And they are not dummies, they can follow these rules in the guidelines, but it's not a good practice because then the contractor does not know exactly how many bolts he has to drill. He has to interpret this and do his own design before he bids the job. That's not so bad if the retrofit is a small part of the contract. But if it's just a retrofit contract, which in a lot of times that's all it is, then the retrofit can be a significant item. So, the districts should be giving us details of the existing structure.

PR: Let me back up a little bit, John. Do they do a benefit-cost, the districts? Do they do any benefit cost [study] to determine how close to the road to put it or is that a function of the bridge geometry? Do they do any benefit cost at all?

JP: To my knowledge they do not do any formal benefit cost.... They would rather retrofit with something that they know is going to be accepted by Austin and the Feds. They know that the barrier shape is acceptable. They know that the local Feds are somewhat [????] about approving a type T6 retrofit in high traffic areas. Our Feds don't like that.... He's got it set in his mind, that type T6 is a weak railing. And it's partly because of the way it was presented to him originally, being equivalent to guard fence. So he has it set in his mind that it is equivalent to guard fence. Well, it is one step up from a guard fence, but it's a step down from T501.

WM: But it's cost per linear foot is...?

JP: They're about the same thing.

WM: Again, going back to my question, what are the variables that enter?

JP: Usually, existing bridge width is a constraint that the districts have to work within. And, that's why they don't mind using the T101R or the T6, because they can push it as far as possible. And most of the districts recognize that putting a T501 on a little old bridge that's 26- or 24-foot wide acts as a constriction on traffic. And it's a severe hazard because if you've got two-way traffic over a 24-foot wide bridge, with the old railing people felt comfortable with that, but you put the T501 on there with the nominal face of the railing at the same location as the old rail and the traffic moves in about a foot to 18 inches closer to the center line as they cross the bridge, the so-called shy distance. So, it's not a good solution. That's why retrofitting with T6 is a good choice. But now that criteria is not written in any kind of rule....

WM: Going back to what you've mentioned, you said that districts should have more details, rather than just throwing in this sheet. Why is that so? What could be different in this sheet than an existing bridge?

JP: You've got an existing bridge that typically might look like this [referring to the T501R sheet] it's got a roadway width that's measured, for awhile the roadway width was measured to the top of this curb, and then after some time the roadway bridge was measured at the bottom of the curb. There are narrower versions of that in which this overhang here is this type. There's a version where you have an old post that's bolted to the outside and the guard fence is attached to that. And believe it or not, they measure that as the roadway width. They use that extra 6 inches as part of the roadway. So, as soon as you take a bridge that, on paper, has a 28- or 24- or 26-foot roadway width existing and you retrofit with this T501, then you're constricting the width. And so to be able to maintain as much width as possible, you need to shove your retrofit as far out as possible. And to do that you've got to look at the specific details of the existing bridge. So they need to detail this [the T501R sheet] and they also need to show the size and type of the existing reinforcement that's in there to give the contractor an aide as to where he should be drilling those holes. If he can anticipate that he has to drill in this top of this curb and knowing that's he's going to hit some reinforcing, he needs to know that, ahead of time, so he can plan for it.

PR: Part of our input, then John, might be to ask the user: where's your rebar and how much is it? Would that be a fair question to ask the districts to provide?

JP: Where's the existing rebar and what's its spacing?

WM: So, the existing rail is one part of the problem.

JP: The existing curb, or slab is part of the problem and the existing rail.

WM: The other part is the new rail and how it fits in with the bridge in place of the old rail.

JP: Right. Now sometimes we would widen a bridge -- this is very typical. We widen on one side instead of both sides. It's cheaper to widen more on one side than to widen equal on both sides. Although geometrically it's necessary to widen on both sides. And if you widen on one side then you have to retrofit on the other side. You have a little bit more flexibility there on the lateral positioning of that retrofit. You can move it in and have an easier retrofit and widen the bridge a little farther on the other side. Now, the geometric widths are usually set by the districts at the time of widening.

PR: They call out clearances that they want? What do you mean by geometric widths?

WM: Roadway widths.

JP: Or where the center line is. But that can be adjusted 3 to 6 inches with a little bit of negotiations on our part with the districts. It's not a real critical problem.

WM: Why is it easier to [retrofit on widening]?

JP: Well, for two or three reasons. Stage construction of the widening is usually a problem. We have an existing bridge that has existing railing and what we'd like to do is to widen enough on one side to maintain a lane of traffic out there. You widen it and you put up the new railing. Then when you take down the old railing, assuming [that] you don't have a curb there that you have to break off, but even then sometimes you have to break off that curb. What you do during the period you're taking off the curb and still trying to maintain traffic over here, you've got to have a barrier between traffic and that curb removal operation. So, the traffic control during construction gets to be a severe problem on the selection of what goes where and how wide and which goes at what time.... So each bridge is almost a unique design problem not just from the retrofitting but from the traffic handling.

WM: So you look into that too?

JP: Our districts do, yes. That affects the choice of railing. Sometimes, the traffic handling itself affects the choice of bridge width. Sometimes they'll make a bridge that's wider than it needs to be for the roadway and the ADT, just because they recognize that physically they cannot do that widening and let the traffic be running. And it's traditional in Texas that we keep traffic moving. If you've got a 4-lane facility we traditionally keep 2 lanes of traffic moving in both directions. Very rarely do we go down to one lane in both directions when we've started off with two lanes. You go into other states and they will close the interstate down, or at least close it down and have one way traffic. I've seen that happen. Out in the rural areas if we have a two lane bridge we maintain, if at all possible, two lanes of traffic during construction. And again that's just the way Texas seems to operate.

PR: Is there a kind of rule of thumb. if you had say a two lane bridge [with] traffic in each direction, is there a minimum width beyond which you'll be in trouble? You mentioned 24 feet for example.

WM: It's 10 feet lane during construction and 12 feet otherwise.

PP: With widening, you have the existing rail that meets the current standard do you still consider retrofitting?

JP: If the existing railing is acceptable and they widen on the other side, then a lot of time that existing railing will remain in place with no change. Sometimes the districts says: well there's an existing T101 railing there, or an existing T1 which is acceptable with minor retrofit. They widen the other side with T501 and then they'll come back and then retrofit this side with T501. That's not very common though because they want it to look the same.

PP: How about the rail that have a lot of accidents? For example, if you had a T6, do they consider changing that to a stronger rail?

JP: Yes, they do consider that, especially if it's a T1 railing that has a lot of maintenance problems associated with the anchorage and that's the choice of the districts. They also have their minds set. They think that any kind of railing that has a guard fence on it is a maintenance problem. And it is to a degree. There is less of a maintenance problem with T6 than there is with T101. Because T101 with the guard fence covering, when it has a brush hit it flattens the guard fence and then that has to be replaced. Structurally, the railing is still acceptable because the tubes that are behind it were not damaged but maintenance has to go out there and put a new piece of guard fence, they think. The T6 is not quite so susceptible to that. It can take a brush hit and the fact that it's a tube and seam welded top and bottom, it doesn't flatten out. So, it can take more of a brush hit before it deforms enough to the point where it has to be replaced. But it's just a little bit more of a brush hit before it deforms to the point where that section needs to be replaced. We've just recently gotten into the mode where T4 now is stocking type T6 railing parts. It came as a surprise to me about three or four years ago to discover that they were not stocking the parts, that it's wasn't available to our maintenance people for fixing the T6. So they had to take the W-beam section and physically weld it themselves, and that got to be a nightmare. So we got our maintenance procurement division to now stock the parts. And I anticipate that now that the stock is out there that there are going to be more and more maintenance people that will try to retrofit on their own a bridge with T6 railing. Our maintenance people are pretty tricky. They build railings themselves and it never comes through here for review. And it's more power to them. They're doing a good job.

PR: How about talking about the bridge in Caldwell. On our way over here, there's one where there was a widening or retrofit or something, but the existing rail was left and inside was placed a T501. How was that decision taken? Even if you don't know that particular case, can you guess?

JP: That was widening of a pan form. That's a pan form bridge. I think it was significantly widened at one side because they wanted to have that sidewalk. There's a [traffic] railing and a pedestrian railing on the outside.

PR: How would they make that decision to use that barrier? Would the pan form dictate that?

JP: Somebody made a decision in the district that they want to separate the pedestrians from the traffic.

WM: It may be adjacent to a school or something of that nature and the resident engineer or the district engineer wanted the pedestrians to have a safe [????], and they just did it.

JP: But as to the choice of whether to put that T501 barrier there or some other barrier between the sidewalk and the cars, to my knowledge that's the only choice that's ever used.

WM: I've seen T202 as a barrier between pedestrians, and T201. Those are the only ones that we've ever seen do that separating.

PR: Let's say you didn't have a pedestrian rail, but you had an old rail, for some reason. Does it happen ever that you want to leave that and add on the inside?

WM: You're taking away from your roadway, I don't think [that's what you want].

JP: But that's been done. They leave the existing rail, an old pre 1965 railing, if it's tall enough it can be left as a pedestrian railing. You move inside with the barrier railing and then widen the other side significantly and you moved your roadway.... That's been done in few cases, but again that's a unique situation. We have the Corpus Christi harbor bridge in the same way. The existing railing was a nice painted steel railing, and it was part of the appearance of the bridge. So when we rehabilitated that structure partly at my insistence, I said let's keep that old railing. We took it off completely, sent it back to the shop, repaired it, refabricated some parts, completely regalvanized it and reinstalled it in the same location on the new deck and then put a T501 shape inboard at about 3 or 3.5 feet as the traffic railing. So now, there is a pedestrian walkway that's narrower than it's supposed to be but it is a pedestrian walkway that's 3.5 feet wide. From a distance the appearance of the bridge is not changed.

WM: Was there a pedestrian walkway prior to that?

JP: No. But pedestrians walked across it anyway.

WM: So you've built a sidewalk or a curb?

JP: No, the slab is at the same surface as the pedestrian walkway. There's no raised sidewalk.

WM: Typically, the times that I've seen us protect pedestrians we haven't been building up a sidewalk there, but we've been going with the slab level. Is that correct John?

JP: Except in urban areas, you have sidewalks that are coming up to the bridge and people don't want to [????] down, but that's done too.

PR: Wajeeh, do you understand the process? Without a lot of detail, John, district goes to look at bridge, bridge is old, district man says "Oh, I think I should fix this." Without too much political detail, how does that go?

JP: More so than not they are forced to [????] the railing now because they are doing work on that stretch of highway. And the current criteria that the feds are imposing on us is that if you're putting any kind of money into widening or improving the roadway coming into that bridge on that quarter mile or half a mile or 2 mile stretch of highway, and it includes the bridge, and if that bridge has existing old deficient railings on it then you must retrofit the rail. They don't like that, and I understand their problem. It costs a lot of money to retrofit that old railing even though what they are trying to do is to maintain better and safer traffic in those 2 miles coming in to the bridge. Usually it's forced on them, rather than a choice.

WM: Is this done on projects with state money or just with where federal money is involved?

JP: It's not supposed to make any difference. If it's state money there is a directive out there that Mr. Oltsman wrote when he was still head of D8 that stated that even though you're using state money, the bridge railing should be retrofitted as if it was a federal project. Now, our districts have come around that a little bit sometimes. What makes more of a difference if they document that they have honest intentions and plans to rehab that bridge, either widen it or replace it or redeck it within an x number of years, let's say within 5 years or 10 years. If they say in 1996 we're going to replace that bridge then it would be more of a reception given in Austin to granting them a design exception to mandating that old deficient railing for the next 5 years even though today they're putting an overlay and shoulder widening on the approaches.

WM: Ok John, because of these factors, that there are some exceptions, and it goes into money business, and so on, factors that we can't model, or are very hard to model, we are going to assume that it's already been decided that we need to retrofit. What do we do next?

JP. Then, somebody has to select the type of retrofits. They select the types based on traffic control, and cost and type of railing that can be retrofitted to the bridge structure.

WM: Does this mean that you can't match any type of rail to any bridge?

JP: It's back to that thin overhang problem on pan forms. If they know they've got a thin overhang and they insist that they have to have a railing on that overhang they you have to put a T6. If they can move the railing in, or if they don't have structural problems on mounting the railing then they a have a choice of what kind of railing they retrofit with.

WM: Let's assume that they chose a kind of railing and it was a T501, what's next?

JP: They should look at the existing bridge reinforcement and geometry.

WM: Anything in particular?

JP: The thickness of the deck, the configuration of the curb, both vertically and horizontally, and the reinforcement pattern in there. They should also look at the abutment wing walls and how they are going to be affected by this retrofit and is it possible to remove the wing walls and terminate your retrofit on the bridge and attach your guard fence at that point. If you have to put a short section of retrofit and attach it to the wing wall then that's another significant problem. Usually it has to be done, but sometimes on these little bridges we have flared wing walls that come out at the end of the bridge, flare. Those can be removed, and you can bury a post in the ground that's within 3.5 feet of the end slice on the, say, T501. Sometimes you can't do it within those 3 to 3.5 feet, but then you can cantilever your T501 past the end of the bridge by a foot or two and have some expansion material separating it from the top of the old wing wall, and that way you don't have to have a wing wall retrofit detail. So that needs to be looked at. And that's why I like to see them develop some specific details for the given bridge, rather than just throw this sheet in the plans and nobody knows what to do at the end of the bridge. Ideally, the designer needs to look at the existing plans.

WM: He takes the existing plans, he has the T501 and wants to match them together, that's what you're saying? You're asking the designer to give some details on how to match the existing rail and bridge with the rail to retrofit with, right?

JP: Right.

WM: What kind of variables do you have in there [in the T501R sheet]. Is it just a standard design, you just plug them in and they go together like Lego pieces or is it more than that?

JP: He needs to look at the details of the reinforcement, he needs to look at the abutment details and see what would be the best choice as to where to terminate the retrofit railing. He needs to make that decision based on the geometry of what's there.

WM: What else is involved? The width of the road is also involved, so that's also a factor, right? Where to place the rail?

JP: The lateral placement of the railing. He could sometimes make a more appropriate placement of the retrofit railing by moving the railing in, slightly. Let's say it's a 44 foot wide roadway now, which is two 12-foot lanes and two 10-foot shoulders. That's a very typical bridge out in the country. Ten foot shoulder is way more than adequate but it is a shoulder width that's being designed today, we might be able to demonstrate that we structurally attach a retrofit railing inboard of that 44-foot roadway by about 6 to 8 inches especially if it's one of these curbed conditions. It's easier to bolt this thing down by moving it inboard slightly and encroach on the shoulder width. So one of the questions he has to ask is: will Austin accept a 9-foot 6-inch shoulder as a design exception? If they do, I'm going to have to justify it on the basis that would give me a more structurally adequate retrofit. Normally that's granted, but he has to make that as a formal request as part of his review process, to get a design exception to reduce shoulder width. If he starts off with a 2-foot shoulder, if it's an old 26-foot roadway which has a 1- or 2-foot theoretical shoulder, or no shoulder, then nobody is going to want him to move it in. An 8-foot shoulder you could pinch down with a design exception. If you're on the inside of a multi-lane facility where you got say an 8-foot shoulder on one side and a 4-foot shoulder on the inside, that 8 foot shoulder can be reduced by 6 inches, but the 4-foot shoulder on the inside would probably not be acceptable to be reduced.

WM: So lateral placement is one thing, the other thing is how to attach.

JP: Where to terminate the retrofit? Where's the most appropriate location to terminate the retrofit railing? Sometimes it's not at the end of the wing wall. Sometimes, it's a long wing wall at some location, or even right at the beginning of the bridge because of the joint that's always there between the end of the bridge and the wing wall. There's usually some type of an expansion joint. And it's best not to have a little short chunk of T501 railing that's 8 feet long. There's a lot of old bridges out there that have wing walls that are 6, 8 or 10 feet long. And trying to retrofit a short chunk of concrete on there with that wing wall that's underneath, usually may be 8 inches thick, and trying to drill and grout enough anchorage into that to hold that little short chunk of T501, you're really introducing a hazard and a weak point that if somebody does hit it at that point it's going to [????].

WM: So, the questions you have to answer are two so far. The lateral placement, and where to terminate. Any other factors, or things that you should look at or questions that you should answer?... What should be included in the drawings that the districts should provide?

JP: They should provide, if, let's say it's a T501 retrofit, they should do the interpretation of what the spacing of the bolts or the bars are. And where are they laterally placed, based on the guidelines that are given on the retrofit sheet. That should be one of the information, quantities or items that's given on the plans to the contractor. So he knows how many bolts to order.

WM: So that's a variable too? Depending on the existing conditions and the rail to retrofit width.

JP: Well, it's a variable that's extracted either from this sheet or from another sheet or if somebody makes the calculation as to how many bars or how many bolts that it's going to require to retrofit this rail. And that should be given on the plans. So, anchor bolts at 4 foot 6 inch spacing max, or whatever it is, dowels at 10 and a half inches.

WM: And this is not a standard, it's a variable?

JP: No, it's a variable, [????] it's extracted from this table.

WM: Now, each of these drawings [in the T501R sheet] is a guideline for a different case?

JP: Yes, it's just a guideline, it's not exactly the way to do it.

WM: You can say that these are some rules written in a graphics form rather than in a text form!

JP: Right.

WM: Could you explain one of those to me? What is it saying to the engineer?

JP: What it's saying is that if he has this situation....

WM: Could you explain this situation.

JP: We've got an existing curb here and the existing [????]. And he decides, based on his wisdom, exactly where the face of this new railing is. He knows where this is going to be. So knowing that, the best place to drill a hole through here is at the tow of this curve. And it's easier to drill so that you're not crowding this radius here. He needs to come in here an inch or so to drill this hole. So he decides in his wisdom where to put this hole. But he can't put the hole too far because then the bolt is going to encroach on the reinforcement, there's not enough cover on the bolt. So we recommend that that's normally 11 inches from the back of the railing to the position of where that bolt is.

WM: Where is that? Is that number 4.

JP: That's this "D" dimension. D is usually 11 inches. So, if he selects 11 inches as the position of this bolt in relation to the backside of the rail, then the table tells him that with an 11-inch deep hole, then the bolt goes in 59.7 inches, maximum. Well, the designer should not use 59.7.

WM: That's this way?

JP: Yes, along the bridge. He should use something a little less than that based on his existing bridge's distances between expansion joints. He ought to look at the bridge and its' probably got 60-foot span on it. He should say: Well I've got 60 feet in there, how many times does 59.7 inches go into that? So based on that he determines how many bolts per unit that he should put in there and then he's going to have an end distance that's going to be say half of that. So then he should specify on his retrofit sheet that the bolts are going to be placed at 58 inches maximum, even though the table says 59.7.

WM: So that's only recommended?

JP: Yes, that's the recommended minimum spacing. He may find, after he went through that, that it would be more advantageous to waste another bolt, to put in another bolt. If he does that, then he might find that moving this point further out or further in a half inch one way or the other could theoretically use the same number of bolts. If I'm moving it out it makes the reinforcement and slip form easier. If I'm moving it in, it makes the railing stronger. But it's a very minor point. The emphasis that I keep trying to make is that the designer needs to look at the existing bridge. He ought to make himself a sketch, to scale, of the existing bridge curb, or bridge edge, and put his retrofit railing, to scale, in that zone and see how it's going to fit.

PR: But that would be something we could help you with computer graphics-wise. For example, I'm not sure how with mouse or with input or some such thing, we draw those to scale and then he says well, maybe I'll have a T411 and set it up there. Would that be helpful to draw to scale?

JP: The ones that are most helpful to draw to scale are the T501 because of this sloping surface and the conflict of the reinforcement with the sloping surface and the curb. We've got little details on here that says that if the bars conflict with the place of this old curb then you chip behind it to provide a minimum of half inch cover behind the bar. If he sees that he's got to chip off that edge of that old curb for the whole length of the bridge, he may say: Well it would be cheaper if I move the whole railing in by 3 inches to avoid having to do that. But then he has to recognize that if he moves it in 3 inches, does his anchorage then become [????]. On a pan form you can't do that because if you use this bar then you have to have a minimum of...; we have it set up for a minimum of 10 inch depth here. If you move it in too far then you go into a bolt situation. And we have had situation where they drill through the pan here and put a bolt, and then have a big washer up underneath and a bell washer to allow the bolt to be placed. It works. So there aren't any clear cut cases.

WM: And these are just guidelines telling them tha?. Are these [drawings] all the same? I'm still not sure.

JP: No, it's just some typical old bridges.

WM: So, this is a different case from say this one. But how is it different? This has a cub and this doesn't, right?

JP: Yes, this shows how to retrofit if you've got slabs that are over 12 inches thick. We're recommending that you use the dowels. If they're over 6.5 inches thick then you can drill through them and put a bolt, so that implies that if you have a slab that is 12 inches thick then you can still drill all the way through. That would be a choice. It would be good because you don't have to put in so many bolts as you do out. And should be a choice given to the contractor. Or the designer, in his wisdom , he has enough experience to know that it's cheaper to drill through 12 inches of concrete and put a bolt than it would be to drill 10 inches in that 12-inch slab and put lots of dowels. That would be my choice. I would still want to use bolts.

PR: Could you send us to a reviewer?

JP: Yes, Richard Morgan is a good one, and so is Wayne Gomez and [????]. Those are the three prime plan reviewers that we have and Sam Brooks. Those four guys are pretty well-trained into watching for potential retrofit problems when they come in.

WM: What are some typical problems?

JP: A typical problem is inadequate details. And sometimes we let the job go out with inadequate details, figuring that it has to go and that's it's not so complicated. Others they retrofit it in ..., they've got deficient anchorage or the wing wall just won't fit or the thickness of the existing wing wall is such that you can't retrofit the way they show on plans. It's just a lot of things that I think [????].

PR: Would, say, Sam Brooks be looking at a bridge today, a review?

JP: In most of those, if he sees that a job has retrofit rail he sends it to me. He just marks it for me.

PR: I thought these reviewers only sent them to you when it's a special questionable case?

JP: They've been sending them all to us. But usually they're not a big problem.

WM: Again, let me go back. How does the process go? The districts do the designs for the case, and they send it over here?

JP: All bridge plans come through here for review.

WM: And who gets to review them?

JP: One of the four plan reviewers. And then it's sent to the design section for structure review, foundation review, and construction review. And then if there is a railing retrofit they pass it to me. And now I've got one other person that is doing those checks. He's recently transferred to the construction section.

WM: And then what happens?

JP: Then it goes back to the plan reviewers and if we've made comments on the plans we have not addressed those comments ourselves by calling the district people that prepared the plans. This is usually the way they like us to do it. If you've got a severe problem, then we call the district and talk to the designer, try to come to an agreement as to the changes that need to be made on the plans. Then we mark those changes on the drawing and it goes back to the plan reviewer. Then it's up to the plan reviewer to find the tracings and negotiate with the district as to how the changes are to be made. Sometimes we actually make the changes ourselves. Sometimes the drawing tracings are sent back to the district. Sometimes the tracings are not even in here yet. All we've got are drawings and the districts makes the corrections and sends the traces in.

PR: Do you let the contracts out of here?

JP: We let the contracts out of our highway design division. We provide a plan review process for all the plans that have the bridge items in them. If it's a roadway contract we never see it. If it's a roadway contract and a bridge contract combined then we see it. If it's got an unusual overhead [????] bridge in it we see it. If it's got a standard [????] bridge in it we don't see it because the D18, the safety division, is confident enough to do the plan review of those.

PR: Is there any way we could observe any of those review guys?

WM: Do you have any old cases we could look at?

APPENDIX III. KNOWLEDGE ACQUISITION TRANSCRIPT ON RETROFIT RAILING

May 24, 1991

at

TxDOT, Austin, Texas

Participants: John Panak (**JP**), Prakit Premthamkorn (**PP**), Paul Roschke (**PR**), Bing Wang (**BW**)

* T6 retrofit sheet dated Jan. 90 was shown to JP.

PP: Has the T6 retrofit sheet been revised since the date shown here?

JP: Looks like it hasn't been revised since then. I think this is the most up-to-date version.

* [JP did find out at the end of the meeting that there was a newer version of T6 retrofit sheet, and made a blue print for researchers.]

PP: Suppose we are given a pan form bridge with overhang and we have to place a rail on the overhang slab. We'd rather use a bolted-to-deck type of rail like T6, right?

JP: Yes, I think the T6 has a good chance of being a good railing on a thin slab. A strong railing on a thin slab looks strong but it develops some strength of the railing it's going to break the slab off. I have a actual photograph of that situation.

* A sheet of bridge structure types was shown to JP.

PP: I'm trying to classify the types of bridge structures based on their bridge deck configuration. I have summarized the types of bridge structures shown in your paper ["Current Bridge Railing Practice / Retrofitting Bridge Railings," October 23, 1986]. Are those drawings pretty much covering all types of bridge structure used?

JP: It pretty well covers most types of bridge structures used except that there are some variations of the dimension like the width of the curbs.

PP: Did we used the box beam bridge structure before 1964? Or is it a newer type of structure, because I saw it in the current railing standard drawings?

JP: No, I don't think so, not the box beams. Texas box beams were not used until 1974, 1975 or something like that. The Texas box beam has the same outside configuration like an I beam. [He sketched a detail similar to those shown in the standard drawings]. Even box beams were not used until 1974. That doesn't mean there is no retrofit with box beams. Actually, this drawing [T6 retrofit sheet] is set up basically for bridges with curbs or without a curb.

PP: We don't put a curb on the current bridge structures?

JP: Right, we don't build curbs on newer types of structures anymore unless we have a sidewalk. Newer means since about 1970. Most of these bridge are predate 1950. That why the current drawings don't have curbs. But retrofit has to deal with existing bridges which may have curbs. And that is one of the major problems of the retrofit because we always have to fit a retrofit rail on a bridge with curbs although occasionally it doesn't have a curb; but most of them have curbs. As indicated on the T501 retrofit drawings, many of them have curbs, parapets. That's a common rail that needs to have the retrofit capability.

* JP showed an old standard railing drawing file.

JP: These are the old railing standards. These are typical for the old standard (attach rail posts to the side of a bridge with curbs). You can see a lot of these out there. It's not really railing but it's just a delineator. Its got no strength, so what we're trying to do is put in a retrofit that can fit onto the curbs. That's very typical. And this is typical for culverts; we still build culverts with 8" or 10" curbs on them to retain the fill.

PP: How thick is the culvert?

JP: Anywhere between 6" to 8" or 8.5" or something like that. They are not very thick.

PP: Can we say that for cast-in-place type of railings, they prefer a stronger support (e.g. beams or girders instead of a thin overhang slab) because we need to place dowels into it?

JP: Yes, I think so.

PP: What about the bolted-to-deck type of railings? Are they weaker?

JP: There are many situations where we install the bolted-to-deck type to the deck because we can't move the railing to the beams because it narrows the roadway width. I think it is weaker than the other but neither of them has been tested. It's just an analysis.

PP: You have prepared many T501 retrofit details in this paper ["Current Bridge Railing Practice / Retrofitting Bridge Railings"]. Have you ever prepared details for other types of railings?

JP: No, we don't. These are the only sketches we have [T501 only].

PP: For bridges with girders, do we always deal with the long overhangs?

JP: Yes, except the case of curved beams where the girders are placed near the edge of the deck slab.

PP: Can you put dowels into a prestressed beam?

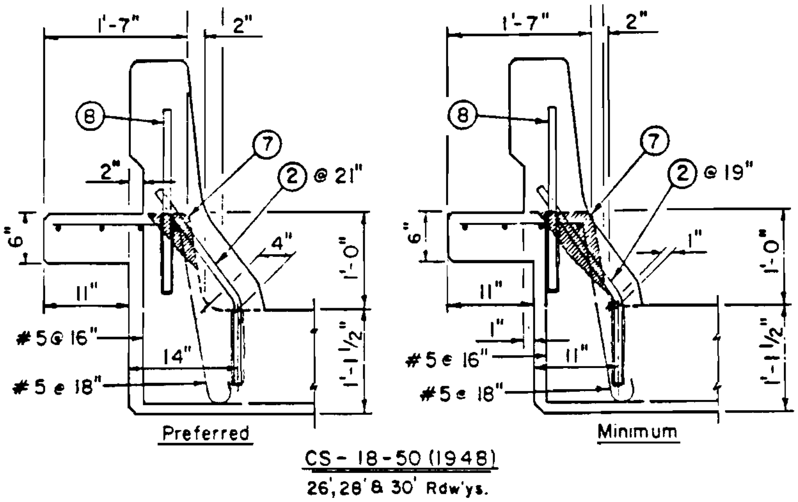
JP: Right, but there is a constraint. You always have to put a dowel at least 3" from the side of the girder and put a bolt 2"-3" outside the face of the girder. So there is a 6-inch zone where you can not do anything.

PP: Are you concerned about the prestressing strands?

JP: No, there is no strand in that part of the girder except for the end supports, but it causes only local effects.

PP: Are there standard widths for the wide curbs?

JP: They are either 1'-5" or 1"-7. And for narrow curbs, they are either 8" or 10."



* Above leftmost picture was shown.

PP: Why is the left preferred over the right picture?

JP: Primarily because we can place the dowels at the middle of the wall plus if we move the rail close to the outer edge of this wall, we have to break an awful lot of this curb and wind up with less concrete covering. So doing it this way, we have a reasonably strong anchorage.

PP: We also don't want to place the rail on the roadway side of the curb because it encroaches on the roadway width, right?

JP: Right, it's better to encroach on the roadway as for the design exception of the roadway width than moving the rail out too far. The Fed. will go along with that. They will accept a reduced roadway width if we believe it's necessary to provide the strong anchorage to the new railing. Unfortunately, there are some districts with a mineset that they have to maintain the exact 28-foot roadway. What I am trying to encourage people is that a 27-foot roadway with a 6-inch deficiency on both sides is better if you can provide a better railing than keeping the 28-foot width and have a weak railing.

PP: What is the minimum acceptable roadway width if we have to encroach on it?

JP: Well, the minimum is 11 feet.

PP: How about 10 feet?

JP: That is not recommended except for very rare cases.

JP: I think we talked before that the user has to input the data to show the retrofit geometry on the screen. We're going to ask questions as to the height, width of the curb, thickness of slab, outside face of the beam, etc?

PP: What we have in mind is letting the user identify the type of bridge, then showing him a picture, and asking him to fill in the size of components.

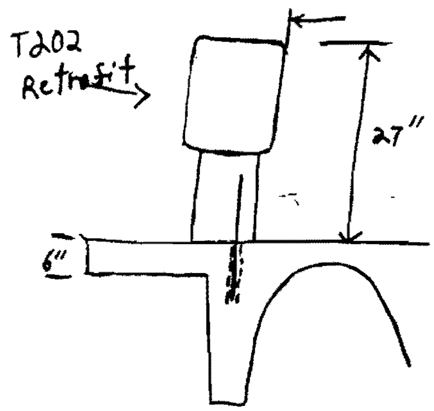
JP: That's a good idea. Very good.

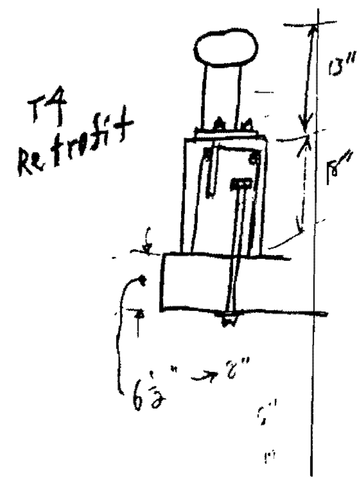
PP: You prepared retrofit details only for T501 and T6. Why you didn't do ones for others?

JP: Don't have the time. That's what you suppose to do.

PP: Can we use any rail for retrofit?

JP: Yes, now we've only got T501 and T6 as retrofit schemes. I'd like to be able to use T202 as a retrofit railing. It has an application of retrofit on bridges that don't have curbs. That would be a good retrofit for a rail like this [drew pictures shown below].





PP: Why did you say it is an excellent choice? Is it better than the T501?

JP: Because it's good for drainage purpose, being able to drain the water off the roadway. T202 was originally developed for the panhandle area [of Texas] to allow snow to blow off the roadway. And now the people are using the T4 again and it can be used for retrofit. There is no reason why we can not retrofit with T4 [sketched a detail for T4].

PP: How thick can the slab be?

JP: It can be anywhere from 6.5" to 8." I would not retrofit it to the pan form overhang because it is only a single layer of the steel reinforcement out there but two layers on the slab like this. It is really a mistake we have made for many years.

PP: What if the slab is thicker than 8"?

JP: Then you put a dowel probably. And we don't have any 9" slabs or 10" slabs. It goes from 8" to about 12" You just don't ever see anything like 9 or 10 inch slab but over 12" slab.

PP: In general, the retrofit details of T501 are applicable to other cast-in-place type of railings?

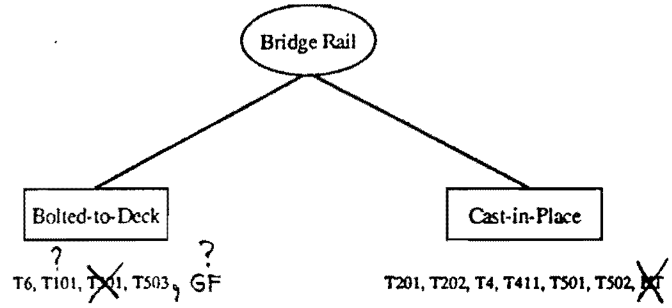
JP: Yes, like the T4, T202, very similar details, right.

PP: Same for T6 and bolted-to-deck types of rails?

JP: Not quite, because T101 and T301 have to have a stronger anchorage but the details could be similar.

* A set of criteria concerning retrofit railings was shown to JP.
    (1) Strength of the Anchorage *(dowels ,bolts)*
    (2) Introduced Encroachment *(reduced roadway width)*
    (3) Ease of Construction *(bolts @ 5' cc easier than dowels)*
    (4) Cost *(low weighted)*
    (5) Drainage *(JP suggested)*
    (6) Personal Preference *(JP suggested)*

PP: This is a set of criteria we may use for considering a retrofit. Do you agree? Please comment.
JP: Strength concerns about dowels and bolts. Encroachment on the reduced roadway width. About ease of construction, bolts are more likely to be easier but it is getting more difficult if the slab is more than 10" thick, so probably dowels should be used. About the cost, retrofit costs are hard to estimate. I am not really sure that cost is going much of the concern on retrofit. It should be weighted with a low weight factor. Retrofits are expensive no matter how you do it. Actually, I think retrofit with the T6 is most likely to be the cheapest.
PP: Does ease of construction imply cost?
JP: Sometimes but not always. There is no correlation between them. Personal preference should be added to the list too. Deck drainage is also one concern. A lot of old bridges have openings allowing the water to drain down the deck. And then when you retrofit, you still need to maintain this drainage capability. One of the things that affects retrofit is whether there is a construction joint at the surface between curbs and bridge deck or not. If it is monolithic, it's hard to remove the curbs. But if there is a construction joint, we can break them off a lot easier.
PR: How would the expert system get the information for the bridge configurations?
PP: We talked about this earlier. We're going to asked the user to identify the configurations by name of bridge structure types, then show him a picture, and have him fill out the dimensions.
PR: How well or what percentage the types of bridge structures shown here cover the possible types of existing bridges?
JP: It pretty much covers most of those used through 1960. And after that we started using curbless structures.



* A taxonomy of bridge rail types based on construction method was shown.

JP: To be honest with you, we probably won't retrofit with T101 and T301. I guess some districts might want to retrofit with T101. I don't know whether it is justified to use these rails for retrofit. Possibly with T101 but not with T301. You can retrofit with T503. T6 is a common retrofit railing.

PP: How about T411?

JP: We can conceivably retrofit with T411 in some locations. I don't think we would ever retrofit with an HT. It would require reconstruction of the structure. Probably with additional beams, replacement of the outside beams or whatever. The rest of these could be retrofit. We have retrofitted with T201 and T202. We haven't retrofit with the T4 because it just hasn't been used in recent years. It is a maximum railing. You can see through it. There are lots of advantages to using it.

PP: How can we differentiate the use of railings in the same group?

JP: (Pause)

PP: Let's put it this way, does the configuration of the existing structure affect the choice of retrofit or not?

JP: Yes, if there are curbs, my choice is pretty much degenerated down to T501 cast-in-place railings. I guess you can retrofit with the T201 also.

PP: Can we use T502?

JP: Yes, if there is no drainage hole in the curbs otherwise you can not integrate it with the existing curbs. You need to remove the curbs to use T502.

PP: Can we use T4 with curbs?

JP: I don't know. That is a good question. We can cast the 13" wall for T4.....[sketched a detail]. That is a reasonable retrofit so T4 can be definitely used with curbs. Having curbs or no curb is what affects the choice a lot.

PP: What should we use to retrofit long overhangs?

JP: For long overhangs and you can not move in the rail because it's going to narrow the roadway width a lot. I would use T6.

PP: But can we use T101?

JP: That was for a panform which always has 6" thick overhangs. But for a thicker slab you may also use T101 or T503.

APPENDIX IV. KNOWLEDGE ACQUISITION TRANSCRIPT ON RETROFIT AND DRAW PROGRAM

June 6, 1991
at
TxDOT, Austin, Texas

Participants: John Panak (**JP**), Prakit Premthamkorn (**PP**), Bing Wang (**BW**)

[A software specification of RETROFEX was presented to JP.]

PP: Here is the software specification for the retrofit railing expert system.
JP: So we can move the rail laterally on the slab. That sounds good.... What is the DRAW program you're talking about here?
PP: It's actually a menu under the Execute menu. When the user clicks the Execute, Run Advisory Program, Show Transcript, and Draw submenu will show up.
JP: OK, so something will come up on the screen with DRAW.
PP: If the user chooses DRAW, he'll get a list rails good for retrofit. And he can pick any rail to show it with the bridge deck in question on the screen.
JP: All right. So this is what you're going to build on, right?. Sounds good. So what is your process you're going to go through on retrofit?
PP: RETROFEX will be called and comes up with a list of rails.
JP: Somehow we have to input the configuration on the existing bridge with enough information. We have to know the location of beam, curb, dimensions. Suppose the user gets a drawing of a bridge and rail in an optimal position and he doesn't like it; can he move the rail to the other position. Will the program show the new position of anchorage? And if he moves too far out on too thin of a slab, will the program tell him he can't?
PP: Well, the program will issue a warning that he can't move the rail too far out where the anchorage can not be placed. And if he moves too far inside the roadway, the program will give a warning about the roadway width if it is too narrow.
JP: The warning statement should tell the user to submit a request for permission when the roadway width is narrower than the existing roadway. If the optimal position of the rail reduces the roadway width, then we have two conditions: (1) Move the rail out, if possible, and (2) Request a design exception.
PP: Most of the retrofit cases will narrow the roadway. So they will fall into the second case, right?
JP: Usually.
PP: The exception is if the curbs were knocked off and a T6 was used?
JP: Right. It may be that the roadway is too narrow and the district has already decided they don't

want to narrow the roadway width anymore at all and it's possible to move the rail out. We need a third choice. That would be the reconstruction of the outside portion of the bridge. This is not a good solution. It's better to move the rail out or have a deficient shoulder width. The deficient width is really the Feds. best solution.

BW: A narrow roadway means less than 12 ft/lane?

JP: No, it's narrower than what the designer feels is appropriate for that particular roadway. It's the function of the design traffic such as ADT, design speed and etc. You don't need to calculate it. What you need to do is ask a question: "What is the required design width of the roadway?"

BW: Should the user know that?

JP: Yes, he should know that. Let him input the design width and what is the actual width. We should define the width to the toe of curb because on many old bridges that measures the roadway width to the top of the curb. Most bridges we retrofit have curbs. It's not many, if any, that we retrofit that don't have curbs. What else is he going to get from the program? Is he going to get the anchorage types and information?

PP: We can give something like the spacing of the anchorage.

JP: Does the program make a suggestion on what rails to retrofit?

PP: Yes, it does. It will give a set of rails with retrofit potential and their rating just like for the new construction.

JP: One of the big conditions for retrofit is what to do with the ends, the wing walls. The wing walls sometimes effect the position of the new railing.... How are we going to retrofit to the bridge that has curved wing walls or some kind of situations like this? So there is a whole series of questions that need to be asked to define the wing wall problems so that the geometry of the wing walls are identified.

APPENDIX V. KNOWLEDGE ACQUISITION SURVEY

To the best of your judgement and according to your own expertise please fill in each table below as follows:

(1) Rate each rail, relative to the other rails, according to each of the four characteristics. Use a scale of 1 to 10 as follows:

- *Strength*
  10 means a very high performance, or very "strong" rail.
  1 means a very low performance, or "weak" rail.
- *Maintenance*
  10 means a rail requires minimum maintenance.
  1 means a rail requires heavy maintenance.
- *Aesthetics*
  10 means it is the most pleasant looking rail.
  1 means it is the least pleasing rail.
- *Personal Preference*
  10 means that you prefer this rail more than all other rails.
  1 means that you do not prefer this rail at all.

Note that more than one rail can have the same rating.

(2) If the cost associated with each rail in your district is significantly different than the given statewide average cost, please give your estimated cost and the number of projects in the columns provided.

T Type Rails

Rail	Strength	Maintenance	Aesthetics	Personal Preference	Statewide Avg. Cost	Your Cost	Number of projects
T6	3	2	8	5	29.91		
T101	6	3	8	5	36.61		
T201	10	10	6	7	15.00		
T202	10	10	9	9	31.51		
T301	6	3	7	1	55.00		
T4 (STEEL)	9	7	7	8	25.14(1)		
T411	10	8	10	10	(2)		
T501	10	10	7	10	20.58		
T502	10	10	7	10	23.87		
T503	8	9	6	8	38.99		
HT	10	7	6	5	13.15		
Guard Fence(3)	1	1	6	7	11.49		

C Type Rails

Rail	Strength	Maintenance	Aesthetics	Personal Preference	Statewide Avg. Cost	Your Cost	Number of projects
C6	2	1	7	2	45.00		
C101	5	2	7	2	43.54		
C201	10	8	6	8	36.48		
C202	10	8	7	7	50.11		
C301	6	3	7	1	(2)		
C4 (STEEL)	9	7	7	8	26.07		
C411	10	8	10	10	75.72		
C501	10	8	6	2	(2)		
C502	10	8	6	2	(2)		
C503	8	7	5	2	(2)		

(1) Last usage of T4 was 1979. This average is for 1977-1979.
(2) No rail of this type was built in the period Aug., 1989- Sept., 1990.
(3) On bridge length culverts.

Name of person filling in this form:

Address:

Telephone:

Date:

APPENDIX VI. USER-INTERFACE EVALUATION QUESTIONNAIRE

Name:______________________ **Date:**__/__/____

Part A (answer this part after running the test cases provided)

1. How would you rate the BREXS user's guide in its ability to help you run the program?

   a) Very good b) Good c) Fair d) Poor e) Very poor.

2. How would you rate the user's guide explanations and definition of the technical terms used throughout program?

   a) Very good b) Good c) Fair d) Poor e) Very poor.

3. Do you have any comments about the user's guide?

4. Did you have any difficulty in editing the data? If yes, in which part, and how?

5. Did you encounter any problems while running the advisory program? If yes, please describe.

6. Do you have any comments regarding the advisory program and/or the data-editing part of BREXS?

Part B (Answer this part after using the features of BREXS that were not used in Part A)

1. Did you encounter any problems while using any of the features of BREXS? If yes, please explain.

2. Was the display of cross-sections for the rail types clear? And did you find it helpful?

3. Was the database access self explanatory, or did you need help in using some of the features provided? Please explain.

4. Did you use the Help option, and how would you rate it?
   a) Very good b) Good c) Fair d) Poor e) Very poor.

5. Are there any features that you think need to be added to the BREXS? Please explain.

Part C

1. Did you encounter any problems while running any of the test cases? If yes, please explain.

2. Do you have any comments on the performance of the system under the test cases you chose?

3. Did you get results for all the test cases you ran? If not, please explain.

4. In your opinion, which data item affects the results most?

Filenames where data and results are stored:

APPENDIX VII. BREXS TEST FORM

Date: __/___/_____ Saved to file: ________

Project ID: CSJ: ______-_____-_______
HWY: ..__________ ___________
County: ____________________
Loc/Stream: __________________

Roadway Data:

Design Speed:
- 30 mph
- 40 mph
- 50 mph
- 60 mph
- 70 mph

Type of Roadway:
- Frontage Road
- One Way
- Two Way
- Main Lane

Average Daily Traffic = ___________x 1000 vehicles per day.

Percent Trucks:
- 0%
- 5%
- 10%
- 15%
- 20%
- 25%
- 30%
- 35%
- 40%

☐ Record of multiple impacts? TRUE FALSE
☐ Potential turning movements? TRUE FALSE
☐ Visibility for safety required? TRUE FALSE

Bridge Data:

<u>Choose the correct answer:</u>

Bridge rail offset:
- 0 - 3 ft.
- 3 - 7 ft.
- 7 - 12 ft.
- More than 12 ft.

Type of understructure:
- Low occupancy or shallow water
- Deep water (> 10ft.) or high occupancy land
- Highway with an ADT of _________x1000 vpd

<u>Answer the following:</u>

Grade in traffic direction = ________ %
Degree of curvature in traffic direction = ________degrees
Curvature length = ____________ feet.
Length of bridge = ____________ feet.
Clear Roadway Width = ____________ feet.
Thickness of slab = ____________ inch.
Maximum approach length = ____________ feet.
Height above understructure = ____________ feet.

☐ Bridge has sidewalk? TRUE FALSE
☐ Bridge length curvert? TRUE FALSE

Environment Data:

<u>Choose the correct answer:</u>

Bridge Location:

- Rural
- Urban

☐ Deicing salt used regularly? TRUE FALSE

☐ High velocity hydraulics required? TRUE FALSE

Construction Data:

<u>Choose the correct answer:</u>

☐ Construction phasing to be followed? TRUE FALSE

☐ Temporary rail used? TRUE FALSE

☐ Temporary rail will be used as a permanent rail? TRUE FALSE

Weight Of Importance:

<u>Enter a number between 1 and 10 for the relative importance of the following categories:</u>

Cost = ________

Maintenance = ________

Strength = ________

Aesthetics = ________

Personal preference = ________

Expected Results:
(Please fill in this section before running the advisory program)

Rail Type	Strongly Recommend	Recommend	Slightly Recommnend	Do Not Recommend
Guard Fence				
T6				
T101				
T201				
T202				
T301				
T4				
T411				
T501				
T502				
T503				
HT				
C101				
C6				
C201				
C202				
C301				
C4				
C411				
C501				
C502				
C503				

Comments

Name of person filling in the form:____________________

(Please attach a hardcopy of the results of this case)

APPENDIX VIII. SAMPLE OF FIELD TEST RESULTS

Recommendation of local expert in Bryan for Test case number 1707.

Rail Type	Strongly Recommend	Recommend	Slightly Recommmnend	Do Not Recommend
Guard Fence				X
T6				X
T101				X
T201	X			
T202	X			
T301				X
T4				X
T411				X
T501	X			
T502				X
T503				X
HT				X
C101				
C6				
C201				
C202				
C301				
C4				
C411				
C501				
C502				
C503				

Recommendation of local expert in Houston for test case number 1707.

Rail Type	Strongly Recommend	Recommend	Slightly Recommnend	Do Not Recommend
Guard Fence				✓
T6			✓	
T101			✓	
T201			✓	
T202			✓	
T301			✓	
T4		✓		
T411				✓
T501	✓			
T502	✓			
T503	✓			
HT	✓			
C101				✓
C6				✓
C201				✓
C202				✓
C301				✓
C4				✓
C411				✓
C501				✓
C502				✓
C503				✓

Recommendation of the state expert for test case number 1707.

Rail Type	Strongly Recommend	Recommend	Slightly Recommnend	Do Not Recommend
Guard Fence				X
T6			X	
T101			X	
T201		X		
T202	X			
T301				X
T4			X	
T411				X
T501	X			
T502		X		
T503				X
HT				X
C101				
C6				
C201				
C202				
C301				
C4				
C411				
C501				
C502				
C503				

Recommendation of BREXS for test case number 1707.

Rail Type	Strongly Recommend	Recommend	Slightly Recommnend	Do Not Recommend
Guard Fence				✓
T6			✓	
T101			✓	
T201		✓		
T202	✓			
T301				✓
T4		✓		
T411				✓
T501		✓		
T502		✓		
T503		✓		
HT				✓
C101				✓
C6				✓
C201				}
C202				}
C301				}
C4				}
C411				}
C501				}
C502				}
C503				}

APPENDIX IX. RESULTS OF SENSITIVITY ANALYSIS

Test No. 1

Variable	New Value	Effect
Design Speed	30 MPH	No Change
	40	No Change
	60	T202 rank increased
	70	T202 rank increased
ADT	0.5 vpd	No Change
	15 vpd	T202 rank increased
	30 vpd	T202 rank increased
Roadway Type	Frontage Road	No Change
Percent Trucks	0%	No Change
	10%	No Change
	20%	T202 rank, more rails
	40%	HT rank increased
Multiple Impact?	True	No Change
Potential Turning Movement?	False	No Change
Visibility for Safety Required?	False	No Change
Rail Offset	3 - 7 ft.	No Change
	7 - 12 ft.	No Change
	> 12 ft.	No Change
Type of Understructure	Creek	Whole list changed
	River	No Change
Length of Bridge	35 ft	No Change
	500 ft..	No Change
Width of Bridge	20 ft.	No Change
	50 ft.	No Change
Thickness of deck	5 in.	No Change
	7 in.	No Change
Maximum Approach Length	30 ft.	No Change
	70 ft.	No Change
	120 ft.	No Change
Bridge Height	15 ft.	No Change
	35 ft.	No Change
Pedestrian Traffic?	True	List has C type rails
Bridge Length Culvert	True	No Change
Bridge Location?	Rural	T411 deleted from list
Deicing Salt Used?	True	No Change
High Velocity Hydraulics?	True	No Change

Test No. 1, continued

Variable	New Value	Effect
Construction Phasing?	False	No Change
Temporary Rail to Be Used?	False	No Change
Temporary Rail to Be Used as Permanent Rail?	False	No Change
Weight of Importance (W.O.I.): Cost	1 5 10	T411 weight increased T411 weight increased No Change
(W.O.I): Maintenance	1 5 10	T4 weight increased No Change No Change
(W.O.I.): Strength	1 5 10	No Change No Change No Change
(W.O.I.): Aesthetics	1 5 10	T5xx weights increased T5xx weights increased No Change
(W.O.I): Personal Preference	5 10	No Change No Change

Test No. 2

Variable	New Value	Effect
Design Speed	30 MPH	No Change
	40	No Change
	50	No Change
	60	No Change
ADT	5 vpd	T202 added, HT deleted
	15 vpd	T202 added, HT deleted
Roadway Type	Frontage Road	No Change
Percent Trucks	0%	T202 & T201 added
	10%	T202 & T201 added
	40%	HT rank increased
Multiple Impact?	True	No Change
Potential Turning Movement?	True	No Change
Visibility for Safety Required?	True	No Change
Rail Offset	3 - 7 ft.	No Change
	7 - 12 ft.	No Change
	> 12 ft.	No Change
Type of Understructure	Creek	No Change
	River	No Change
Length of Bridge	35 ft	No Change
	500 ft..	No Change
Width of Bridge	20 ft.	No Change
	50 ft.	No Change
Thickness of deck	5 in.	No Change
	7 in.	No Change
Maximum Approach Length	30 ft.	No Change
	70 ft.	No Change
	220 ft.	No Change
Bridge Height	18 ft.	No Change
	36 ft.	No Change
Pedestrian Traffic?	True	List has C type rails
Bridge Length Culvert	True	No Change
Bridge Location?	Rural	T411 deleted
Deicing Salt Used?	True	No Change
High Velocity Hydraulics?	True	No Change

Test No. 2, continued

Variable	New Value	Effect
Construction Phasing?	True	No Change
Temporary Rail to Be Used?	True	No Change
Temporary Rail to Be Used as Permanent Rail?	True	No Change
Weight of Importance (W.O.I.): Cost	1 10	T411 rank increased T411 rank decreased
(W.O.I): Maintenance	1 5 10	T4 weight increased No Change No Change
(W.O.I.): Strength	1 5 10	No Change No Change No Change
(W.O.I.): Aesthetics	1 5 10	T5xx weights increased T5xx weights increased HT weight decreased
(W.O.I): Personal Preference	5 10	No Change No Change

Test No. 3

ADT x1000 vpd	Percent Trucks	Type of Understructure	Result
9	5	Creek	List 1
12	5	Creek	List 2
17	5	Creek	List 2
25	5	Creek	List 3
60	5	Creek	List 3
9	10	Creek	List 1
12	10	Creek	List 2
17	10	Creek	List 3
25	10	Creek	List 3
60	10	Creek	List 3
9	20	Creek	List 4
12	20	Creek	List 5
17	20	Creek	List 6
25	20	Creek	List 7
60	20	Creek	List 8
9	30	Creek	List 9
12	30	Creek	List 10
17	30	Creek	List 10
25	30	Creek	List 10
60	30	Creek	List 10
9	5	River	List 11
12	5	River	List 3
17	5	River	List 3
25	5	River	List 3
60	5	River	List 3
9	10	River	List 3
12	10	River	List 3
17	10	River	List 3
25	10	River	List 3
60	10	River	List 3
9	20	River	List 3
12	20	River	List 3
17	20	River	List 3
25	20	River	List 7
60	20	River	List 7
9	30	River	List 9
12	30	River	List 9
17	30	River	List 9
25	30	River	List 9
60	30	River	List 9

Test No. 3, continued

ADT x 1000 vpd	Percent Truck	Type of Understructure	Result
9	5	Highway	List 11
12	5	Highway	List 3
17	5	Highway	List 12
25	5	Highway	List 12
60	5	Highway	List 12
9	10	Highway	List 3
12	10	Highway	List 3
17	10	Highway	List 12
25	10	Highway	List 12
60	10	Highway	List 12
9	20	Highway	List 12
12	20	Highway	List 12
17	20	Highway	List 12
25	20	Highway	List 7
60	20	Highway	List 7
9	30	Highway	List 9
12	30	Highway	List 9
17	30	Highway	List 9
25	30	Highway	List 9
60	30	Highway	List 9

Sample Output Lists

List 3

Rail Type	Weight
T202	7.0
T4	5.0
T501	4.0
T502	4.0
T503	4.0
T411	4.0

List 9

Rail Type	Weight
HT	7.0
T4	5.0
T501	4.0
T502	4.0
T503	4.0
T411	4.0

List 12

Rail Type	Weight
T201	7.0
T4	5.0
T201	5.0
T501	4.0
T501	4.0
T503	4.0
T411	4.0
T6	3.0
T101	3.0
T301	3.0

Test No. 4

Cost	Maintenace	Strength	Aesthetics	Personal Preference	Result
5	1	1	1	1	List 1
10	1	1	1	1	List 1
1	5	1	1	1	List 2
1	10	1	1	1	List 3
1	1	5	1	1	List 4
1	1	10	1	1	List 5
1	1	1	5	1	List 6
1	1	1	10	1	List 7
1	1	1	1	5	List 8
1	1	1	1	10	List 9
1	5	5	5	5	List 6
10	5	5	5	5	List 6
5	1	5	5	5	List 6
5	10	5	5	5	List 10
5	5	1	5	5	List 6
5	5	10	5	5	List 11
5	5	5	1	5	List 8
5	5	5	10	5	List 7
5	5	5	5	1	List 6
5	5	5	5	10	List 12
1	10	10	10	10	List 13
5	10	10	10	10	List 13
10	10	10	10	10	List 13
10	1	10	10	10	List 7
10	5	10	10	10	List 7
10	10	1	10	10	List 13
10	10	5	10	10	List 13
10	10	10	1	10	List 14
10	10	10	5	10	List 10
10	10	10	10	1	List 13
10	10	10	10	5	List 13

Sample Output Lists

List 6

Rail Type	Weight
T202	7.0
T6	5.0
T4	5.0
T501	5.0
T501	5.0
T502	5.0
T503	5.0
T101	5.0
T201	5.0

List 7

Rail Type	Weight
T202	7.0
T4	5.0
T201	5.0
T501	4.0
T502	4.0
T503	4.0
T6	3.0
T101	3.0
T301	2.0

List 13

Rail Type	Weight
T202	7.0
T4	5.0
T201	5.0
T501	4.0
T502	4.0
T503	4.0
T6	2.0
T301	1.5
T101	1.0