A Knowledge-Based Approach to Pavement Overlay Design

STEPHEN G. RITCHIE

Described is the development of an initial prototype expert system to assist local engineers in designing the structural thickness of asphalt concrete pavement overlays. The system is called OVERDRIVE (OVERlay Design heuRIstic adVisEr) and is part of ongoing research at the University of California, Irvine, that is developing an integrated set of expert system tools for the analysis and design of highway pavement rehabilitation strategies. The paper provides an overview of expert systems concepts and overlay thickness design methods. A discussion of the OVERDRIVE system follows, including the main components of the first prototype, Version 1.1. It is concluded that a knowledge-based approach to pavement overlay design is feasible and, even in prototype form, OVERDRIVE is a potentially useful tool for local highway engineers. Ongoing research will refine and expand the knowledge base and user interface of OVERDRIVE to enhance its performance as an expert design tool.

In recent years, asphalt concrete pavement overlays have become the principal treatment used in the United States for rehabilitating deteriorated pavements subjected to moderate or heavy traffic. Highway agencies in the United States spend billions of dollars annually on such overlays, which comprise relatively thick layers of bituminous-bound aggregate placed over the existing pavement. An overlay can level out a distorted or rough road surface that is providing poor ride quality and high operating costs to users. It can also increase the structural capacity and service life of an existing pavement. The design life of an asphalt concrete overlay is typically 10 years, and sometimes it is as long as 20 years. Properly designed, an overlay can be a cost-effective means of correcting pavement deficiencies for a substantial period of time.

Three-quarters of the highway mileage in the United States is contained within local highway systems *(1)*, which are the responsibility of tens of thousands of cities, counties, and other local jurisdictions. Successful and cost-effective pavement rehabilitation strategies are generally developed by pavement engineering specialists who use their judgment and experience as well as empirically based design procedures. Typically, these experts are only to be found within federal and state agencies, universities, and private firms. In addition, although conventional computer tools are useful in the overlay design process, their role is limited because the tasks involved tend to be complex and ill-defined so engineering judgment must be relied on. The difficulties facing local highway agencies nationally are therefore not only financial but include the availability of, and access to, specialized human resources and expertise.

Department of Civil Engineering and Institute of Transportation Studies, University of California, Irvine, Calif., 92717.

The nature of this problem suggests that a new technological approach, involving knowledge-based or expert systems, could be especially useful *(2)*. Such systems are basically interactive computer programs that emulate the knowledge of a human expert to provide advice and guidance to local users.

In this paper is described the development of an initial prototype expert system to assist local engineers in designing the structural thickness of asphalt concrete pavement overlays. The system is called OVERDRIVE (OVERlay Design heuRIstic adVisEr) and is part of ongoing research at the University of California, Irvine, that is developing an integrated set of expert system tools for the analysis and design of highway pavement rehabilitation strategies. The paper provides an overview of expert systems concepts and overlay thickness design methods. A discussion of the OVERDRIVE system follows, including the main components of the first prototype, Version 1.1. It is concluded that a knowledge-based approach to pavement overlay design is feasible and, even in prototype form, OVERDRIVE is a potentially useful tool for local highway engineers. Ongoing research will refine and expand the knowledge base and user interface of OVERDRIVE to enhance its performance as an expert design tool.

EXPERT SYSTEMS

Knowledge-based expert systems are computer programs that have recently emerged from decades of research on artificial intelligence (AI). In general, AI is the study of how to make computers perform tasks that, currently, people perform better *(3)*. Such tasks include natural language processing, speech recognition, vision, and expert problem solving.

Expert systems are designed to emulate the performance of an expert, or group of experts, in a particular problem domain (such as pavement overlay design) through the use of symbolic reasoning. Expert systems therefore address "ill-structured" problems for which a numerical algorithmic solution is not available or is impractical; such problems are solved using expert knowledge, skill, judgment, and heuristics.

A review of potential applications of expert systems in transportation is reported by Yeh et al. *(4)*, and a state-of-the-art review of expert systems in transportation engineering is presented by Ritchie *(5)*. A recent symposium also elaborated on expert systems in civil engineering *(6)*. There are also several more general and comprehensive guides to expert systems *(7, 8)*.

An expert system is fundamentally different from a conventional computer program. One of the principal differences is the separation of domain knowledge and the inference or control mechanism. This distinction identifies two of the main components of an expert system, the knowledge base and the inference engine. The knowledge base is the power of an expert system in the sense that it contains all of the empirical and factual information for the problem domain. The inference engine decides how to apply the knowledge in the knowledge base in order to infer new knowledge. It is the control mechanism for the system that attempts to progressively solve each subgoal and thus the entire problem.

There are various ways to represent the knowledge in the knowledge base. The most common is by means of production rules, expressed as IF-THEN statements (e.g., IF surface course is asphalt concrete AND condition is excellent THEN conversion factor = 1.0). When the IF portion or premise of a rule is satisfied by the facts, the action specified by the THEN portion is performed. The rule is then said to "fire." There are two ways in which rules are accessed in a rule-based system: forward chaining and backward chaining. Forward chaining is an inference method that proceeds from information on the left side of the rules to derive information on the right. In other words, rules are matched against facts to establish new facts. Backward chaining involves starting with a conclusion or hypothesis on the right side of one or more rules and trying to establish the facts that would verify that hypothesis. Only rules that are relevant to establishing the hypothesis are executed. Backward chaining therefore proceeds from information on the right side to establish information on the left.

To build an expert system, a symbol manipulation language, such as LISP or PROLOG, can be used. These have been designed specially for AI applications. A variety of dialects exist, including increasingly powerful versions for microcomputers. In addition, a large number of shells or knowledge engineering tool kits are now available for microcomputers. These offer a faster route to expert system development but often involve some sacrifice in flexibility. In either case, the system developer (knowledge engineer) must acquire the expertise and knowledge of the expert or experts and encode it into the knowledge base. An iterative process of testing and refinement then ensues to ensure that the system reaches the desired level of performance.

Finally, it is important to note that although virtually all expert systems are knowledge based, the converse is not necessarily true. In other words, knowledge-based systems are a subset of AI programs, and expert systems are a subset of knowledge systems. A truly "expert" system implies the use of "expert" knowledge to attain high levels of performance in the problem domain. The iterative development process referred to earlier typically involves the successive refinement of an initial knowledge system to produce an expert system that performs at a level comparable to that of recognized human experts. Of course, not all knowledge-based systems need to perform at such a high level to be useful. The nature of real-world problems, and experience, indicates that a spectrum of knowledge-based tools is appropriate, including assistant, colleague, and expert knowledge-based systems.

OVERLAY DESIGN METHODS

Pavements with bituminous surfaces are often called flexible, in contrast with rigid pavements of portland cement concrete. The initial version of OVERDRIVE described in this paper focuses on the design of flexible asphalt concrete overlays on existing flexible pavement. The term asphalt concrete denotes a dense-graded road surface made of hot mineral aggregates plant mixed with hot asphalt. This is the highest type of dense-graded bituminous pavement and is suitable for even the most heavily traveled roads *(1)*.

The two most commonly used design methods for asphalt concrete overlays are component analysis and deflection analysis. These methods reflect empirically based design procedures developed during the last several decades for new pavements. In practice, effective application of the methods requires considerable engineering judgment.

The component analysis overlay design method involves a comparison of the existing pavement structure and a new pavement design for site-specific service conditions. The evaluation of the existing structure requires identification of each of the pavement layers (components) such as the surface course, base, and subbase (if any), as shown in Figure 1. The type, thickness, and condition of each layer must then be determined. Evaluation of the condition of each layer involves selection of a conversion factor that reflects the layer's structural adequacy. Even if the results of sampling and testing in-place materials are available, substantial judgment is required to effectively select the value of each factor. The factors apply reductions of up to 100 percent to the structural adequacy of each layer and can therefore have a major impact on determining the need for an overlay and its design thickness. Further, if either or both site-specific traffic data or subgrade soil strength are not available, judgment must be used to select appropriate design values.

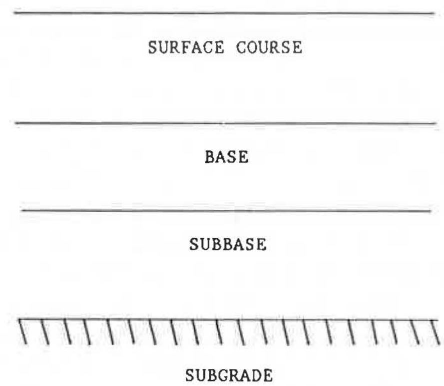

FIGURE 1 Cross section of typical pavement structure.

Deflection analysis design methods involve nondestructive testing of the pavement to yield measured surface deflection caused by a standard load. Although this method does not generally consider individual pavement layers, it directly reflects the effective strength and response of the in situ pavement structure to traffic levels and types. If the measured deflection is greater than an acceptable value, an overlay is required.

Component analysis is a traditional design method that has been used in various forms for many years. More recently, deflection-based procedures have begun to gain wide acceptance, particularly among state departments of transportation. Standard design guidelines, such as those of the Asphalt Institute *(9)*, suggest that it may sometimes be desirable to use both methods before making a final decision based on engineering judgment. However, a majority of local highway agencies in the United States do not own the equipment necessary to perform deflection tests. Many of the smaller agencies also do not have laboratory equipment or personnel and rely either on standardized pavement designs that have worked well in the past or on other judgmental or rule-of-thumb methods.

In building OVERDRIVE 1.1, the first priority was to build a knowledge-based system for overlay design using a component analysis design method. This method provides an improved and more rational overlay design procedure for many users. When implemented using a knowledge-based approach, a powerful design tool results.

DESCRIPTION OF OVERDRIVE

OVERDRIVE 1.1 is an initial prototype of a knowledge-based system to provide interactive expert advice and guidance on the detailed design of asphalt concrete pavement overlays to local highway engineers. OVERDRIVE is a part of a more extensive system named PARADIGM (PAvement Rehabilitation Analysis and DesIGn Mentor), a proposed integrated set of expert systems, now under development, for local highway agencies *(2)*.

The first expert system developed as part of the PARADIGM project was SCEPTRE (Surface Condition Expert for PavemenT REhabilitation). This system is described elsewhere *(10, 11)*. SCEPTRE evaluates project-level pavement surface distress and other user inputs to recommend feasible rehabilitation strategies for subsequent detailed analysis and design by OVERDRIVE. The two systems have been designed so that many of the inputs to SCEPTRE can also be used by OVERDRIVE. SCEPTRE has been developed using the knowledge engineering shell EXSYS *(12)* on a Compaq portable microcomputer (and runs on any MS-DOS–compatible PC). The system is rule based and uses a backward-chaining inference method. The knowledge base in Version 1.4 contains about 140 complex rules, derived from the combined expertise of two pavement specialists. SCEPTRE 1.4 currently addresses state-maintained flexible pavements in Washington State and has been made available for field testing in district offices of the Washington State Department of Transportation (WSDOT). Ongoing research will refine and adapt the knowledge base for local agencies.

Like SCEPTRE, OVERDRIVE is a microcomputer-based production rule system. OVERDRIVE 1.1 accesses its rules using a forward-chaining inference method and has been implemented using EXSYS. The system also interfaces with an external program to pass and receive values of design parameters.

The knowledge base of OVERDRIVE 1.1 is the result of knowledge engineering efforts with a pavement specialist combined with a synthesis of state-of-the-art and other reports, papers, and manuals relating to the Asphalt Institute overlay design method for asphalt concrete overlays on flexible pavement, *(1, 9, 13–15)*. The knowledge base contains more than 100 rules. It is expected that successive versions of OVERDRIVE will incorporate additional knowledge acquired from pavement engineering specialists. The natural evolution of the system's performance will be toward that of a human pavement expert, which is the ultimate objective.

OVERDRIVE is implemented as an interactive microcomputer program to make it accessible to a broad range of potential users and to permit relatively fast determination of overlay structural thickness requirements. This also allows quick assessment of the impact or impacts of varying assumptions and input values for design parameters.

Several major tasks are addressed by OVERDRIVE in formulating a recommendation for the structural thickness of a new overlay. These include determining the effective thickness of the existing pavement structure, determining a new full-depth asphalt concrete construction thickness, and assessing the consequent need for an overlay. Each of these tasks is discussed in more detail in subsequent sections.

EFFECTIVE THICKNESS

OVERDRIVE 1.1 is applicable to existing pavement structures containing up to three layers, excluding the subgrade, as shown in Figure 1. To design the structural thickness of an overlay using a component analysis method such as that of the Asphalt Institute *(9)*, the effective thickness of the existing pavement structure must be determined. The effective thickness of the structure is the sum of the effective thicknesses of each layer. Effective thicknesses are found by multiplying the actual layer thicknesses by appropriate conversion factors. Each effective thickness represents an equivalent depth of new asphalt concrete. To perform this analysis requires assessment of the following items for each individual structure:

- Number of layers (e.g., surface course only; surface course and base; surface course, base, and subbase);
- Thickness of each layer;
- Layer material type; and
- Layer condition.

Pavement segments in OVERDRIVE 1.1 are user defined and should be homogeneous with respect to geometry and features. A conversion factor based on the layer material type and condition is selected. This determination may be assisted by past records of design, construction, or maintenance; by field inspection; and if possible by at least limited sampling and laboratory testing of in-place materials (OVERDRIVE 1.1 does not provide guidance for such sampling and testing). Ultimately, however, the selection of each conversion factor involves engineering judgment. For example, asphalt concrete that is in very good condition with little cracking or rutting may be assigned a conversion factor of 0.9 to 1.0. Asphalt concrete exhibiting greater distress should be assigned a conversion factor in the range 0.5 to 0.8. Granular bases and subbases may be assigned values of 0.2, and so on. The effective thickness for the structure is then determined as follows:

$$\text{Effective thickness} = (T1)\ (S1) + (T2)\ (S2) + (T3)\ (S3) \quad (1)$$

where $T1$, $T2$, and $T3$ are the actual layer thickness for surface course, base, and subbase, respectively, and $S1$, $S2$, and $S3$ are conversion factors for each layer.

OVERDRIVE 1.1 includes three possible surface course layer types, eight base course layer types, and five subbase course layer types. The number of condition levels available for each layer varies between 1 and 28 depending on the layer and material. For example, the condition level, and hence conversion factor, for each surface course layer type is dependent on the extent and severity of alligator cracking in combination with the severity of rutting. Twenty-one possible condition levels result for a given surface course layer type.

To illustrate the rule-based knowledge representation relating to effective thickness determination in OVERDRIVE, consider the partial inference net in Figure 2. An inference net portrays all of the possible inference chains that can be generated by a set of rules. An inference chain indicates how the system uses the rules to infer a result and is formed by matching the IF portions of rules to the facts. The rules corresponding to the inference net in Figure 2 are shown in Figure 3. These rules are contained in OVERDRIVE's knowledge base and were created using the EXSYS editor. As a result of the first rule firing, the user is requested to enter the thickness of the existing surface course layer, in inches, because the numeric variable [SURFACE THICKNESS] has not yet been assigned a value. For the second rule to fire, the user is queried about the material type in the surface layer (this query is in the form of a multiple choice question), and the user indicates that there is an asphalt concrete surface layer. Finally, as a result of the user indicating that there is no alligator cracking or rutting present (in response to further queries by the system), the third rule would fire and a conversion factor of 1.0 would be selected. In response to a system query, the user can enter WHY, and the system will respond with the rule or rules it is attempting to verify, thereby revealing its reasoning.

Figure 4 shows two of the rules that are used to analyze the next possible layer in the existing structure, the base course. As a result of the first rule firing, OVERDRIVE attempts to apply the second rule and queries the user about the existence of a base layer. If such a layer exists, its thickness is determined and the system proceeds to establish the effective thickness of that layer, and then of the subbase layer (if one exists). If a base course layer does not exist because, for example, the existing structure is full-depth asphalt concrete, the appropriate conversion factors and thicknesses are deduced as shown in the ELSE part of the rule in Figure 4.

NEW FULL-DEPTH THICKNESS

Determination of the new full-depth construction thickness involves developing a new design for a full-depth asphalt concrete pavement over the existing subgrade. The procedures incorporated in OVERDRIVE 1.1 are based on the elastic layered theory approach of the Asphalt Institute. This approach assumes that the subgrade is infinite in the vertical direction and that all layers are infinite in the horizontal direction. It includes consideration of limiting strains, material properties, environmental considerations (temperature and frost effects), and traffic. The basic activities of OVERDRIVE in this overall task include:

- Subgrade assessment,
- Traffic analysis, and
- Design of new full-depth thickness.

The sequence of these activities is shown in Figure 5.

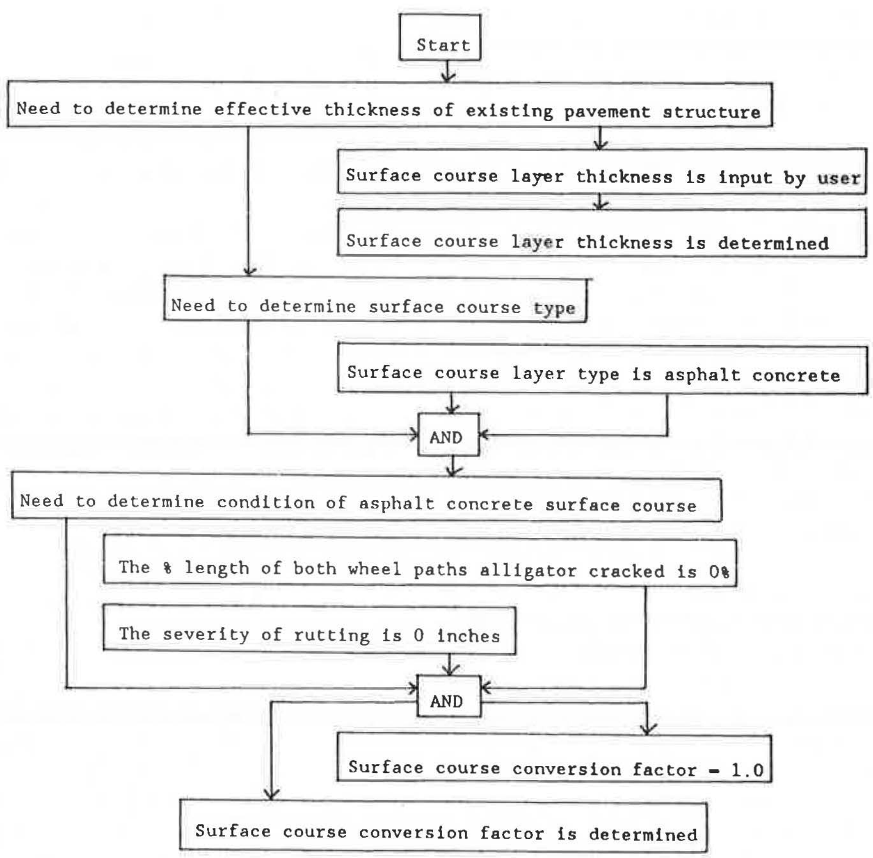

FIGURE 2 Partial inference net for surface course analysis.

```
RULE NUMBER:  1

IF:
        NEED TO DETERMINE EFFECTIVE THICKNESS OF EXISTING PAVEMENT

THEN:
        [T1] IS GIVEN THE VALUE [SURFACE THICKNESS]
 and    SURFACE COURSE THICKNESS IS DETERMINED
 and    NEED TO DETERMINE SURFACE COURSE TYPE

- - - - - - - - - - - - - - - - - - - - -

RULE NUMBER:  2

IF:
        NEED TO DETERMINE SURFACE COURSE TYPE
 and    SURFACE COURSE LAYER TYPE IS ASPHALT CONCRETE

THEN:
        NEED TO DETERMINE CONDITION OF ASPHALT CONCRETE SURFACE COURSE

- - - - - - - - - - - - - - - - - - - - -

RULE NUMBER:  3

IF:
        NEED TO DETERMINE CONDITION OF ASPHALT CONCRETE SURFACE COURSE
 and    THE % LENGTH OF BOTH WHEEL PATHS ALLIGATOR CRACKED IS 0%
 and    THE SEVERITY OF RUTTING IS 0 INCHES

THEN:
        [S1] IS GIVEN THE VALUE 1.0
 and:   SURFACE COURSE CONVERSION FACTOR IS DETERMINED
```

FIGURE 3 Rules corresponding to inference net.

```
IF:
        SURFACE COURSE CONVERSION FACTOR IS DETERMINED

THEN:
        NEED TO DETERMINE IF A BASE COURSE LAYER EXISTS

- - - - - - - - - - - - - - - - - - - - -

IF:
        NEED TO DETERMINE IF A BASE COURSE LAYER EXISTS

 and    IN THE EXISTING PAVEMENT STRUCTURE, A BASE COURSE LAYER EXISTS

THEN:
        [T2] IS GIVEN THE VALUE [BASE THICKNESS]
 and    BASE THICKNESS IS DETERMINED
 and    NEED TO DETERMINE BASE COURSE TYPE

ELSE:
        [BASE THICKNESS] IS GIVEN THE VALUE OF 0.0
 and    [S2] IS GIVEN THE VALUE 0.0
 and    [SUBBASE THICKNESS] IS GIVEN THE VALUE 0.0
 and    [S3] IS GIVEN THE VALUE 0.0
 and    BASE COURSE CONVERSION FACTOR IS DETERMINED
 and    BASE THICKNESS IS DETERMINED
 and    SUBBASE COURSE CONVERSION FACTOR IS DETERMINED
 and    SUBBASE THICKNESS IS DETERMINED
```

FIGURE 4 Example rules for base course analysis.

The two basic design parameters that OVERDRIVE attempts to determine in this phase are the subgrade modulus and the number of equivalent 18,000-lb single-axle loads [18-kip equivalent axle loads (EALs)] due to truck traffic during the user-specified design period.

Sampling and laboratory testing of subgrade materials are encouraged even if original design records are available. The results of this testing can provide an indication of the subgrade resilient modulus. However, when this is not available, as may be the case for many smaller local agencies, OVERDRIVE allows for a more subjective characterization of subgrade strength. Rules in the knowledge base allow the user to classify the subgrade into three categories for design purposes on the basis of subgrade characteristics. A summary of this is given in Table 1.

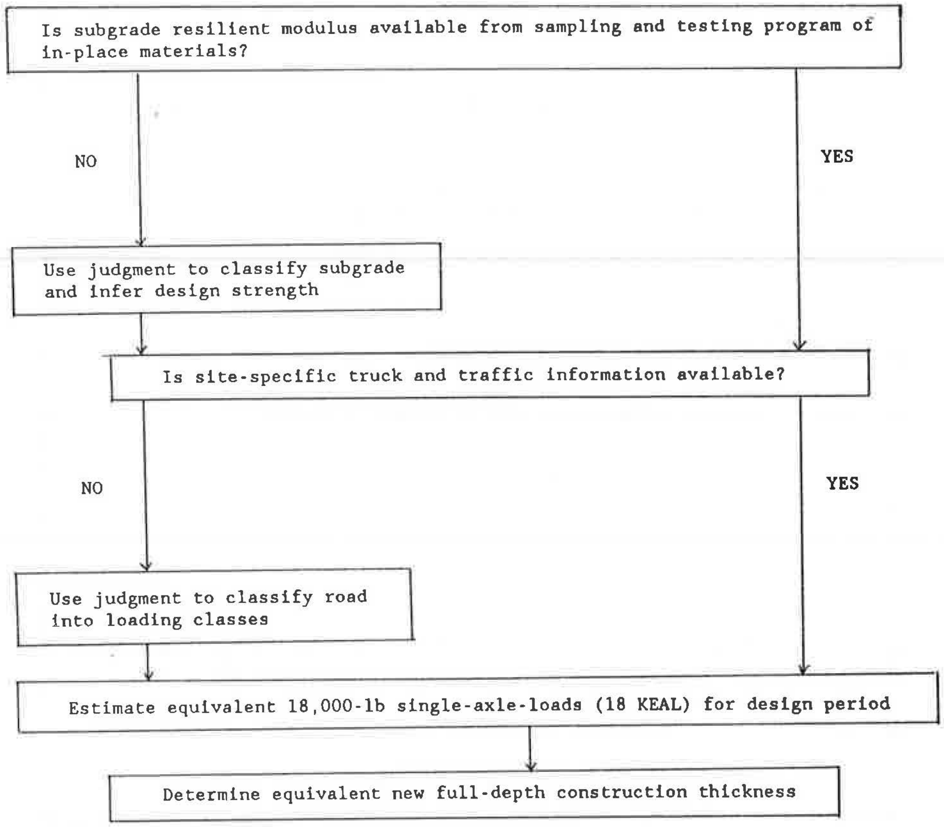

FIGURE 5 Sequence of activities for determining new construction thickness.

TABLE 1 SUBGRADE CLASSES FOR DESIGN PURPOSES *(9, 14)*

Soil Class	Characteristics	Design Modulus (psi)
Poor	Soft and plastic when wet, generally composed of silts and clays (CBR ≅ 3)	4,500
Medium	Includes loams, silty sands, and sand-gravels that contain moderate amounts of clay and silt; can be expected to lose only a moderate amount of strength when wet (CBR ≅ 8)	12,000
Good	Expected to retain substantial amount of strength when wet; includes clean sands and sand-gravels (CBR ≅ 17)	25,000

NOTE: CBR = California bearing ratio.

For the estimation of 18-kip EALs for the design period, several methods are provided in OVERDRIVE depending on the availability of site-specific truck and traffic information. If site-specific data are not available, OVERDRIVE queries the user to determine the appropriate traffic class (Table 2) with its associated estimate of 18-kip EALs. If site-specific data are available, several more detailed procedures are available to determine 18-kip EALs for the design period. The exact procedures and rules that are applied depend on the level of disaggregation of the data (e.g., ranging from average annual daily traffic and percentage trucks at one extreme to whether truck volumes can be estimated for single and multiple units by axle class). OVERDRIVE also provides for traffic growth factors over the design period, if the user so desires.

TABLE 2 ASPHALT INSTITUTE TRAFFIC CLASSIFICATIONS *(9, 14)*

Type of Street or Highway	Traffic Class	Estimated 18-kip EALs
1. Parking lots 2. Lightly trafficked residential streets and farm roads	I	5,000
1. Residential streets 2. Rural farm and residential roads	II	10,000
1. Urban and rural minor collectors	III	100,000
1. Urban minor arterial and light industrial streets 2. Rural major collector and minor arterial highways	IV	1,000,000
1. Urban freeways and other principal arterial highways 2. Rural Interstate and other principal arterial highways	V	3,000,000
1. Urban Interstate highways 2. Some industrial roads	VI	10,000,000

Having established both subgrade and traffic design parameters, OVERDRIVE then determines the new full-depth asphalt concrete construction thickness using the design chart shown in Figure 6. This chart is for a mean annual air temperature of 60°F with frost action possible. Design charts for other conditions can also be readily incorporated. In OVERDRIVE 1.1 the determination of new full-depth thickness is carried out by a conventional external program that is called by rules within the knowledge base. The design parameter values are passed out to

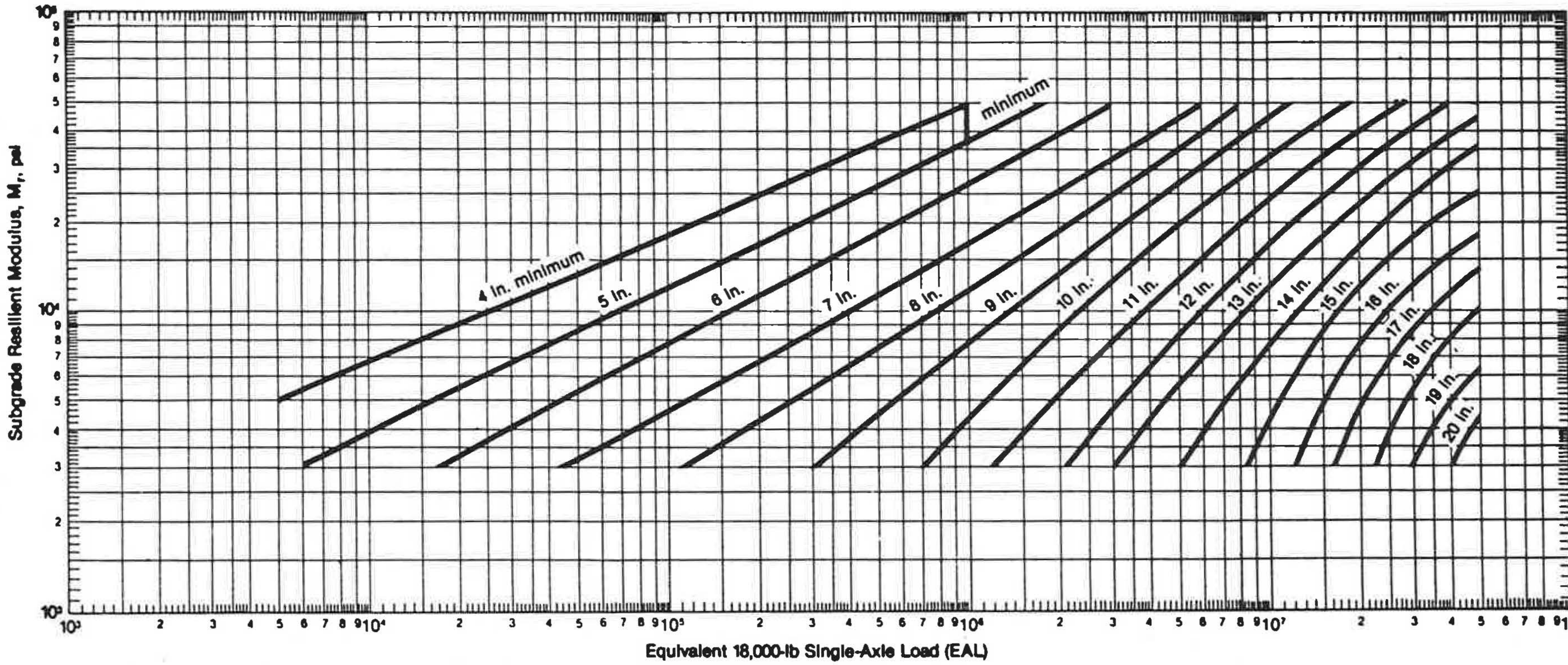

FIGURE 6 Asphalt Institute design chart for full-depth asphalt concrete pavement *(9)*.

this program, which essentially uses the look-up table representations of Figure 6, and the new design thickness is returned to OVERDRIVE to be used in determining the need for an overlay.

NEED FOR OVERLAY

Given the effective thickness and new full-depth construction thickness, it is a simple calculation to determine the structural design thickness of any required asphalt concrete overlay for the given service conditions. OVERDRIVE determines the overlay design thickness as

$$\text{Design thickness} = (\text{New full-depth thickness}) - (\text{Effective thickness}) \quad (2)$$

In practice, the design thickness must obviously be nonnegative. If the full-depth thickness is less than the effective thickness, this simply indicates that the existing pavement is structurally adequate for the specified service conditions. In this case OVERDRIVE informs the user that an overlay is not required to enhance structural capacity of the section.

It is important to realize that, even if the existing pavement structure is structurally adequate, there may be deficiencies related to the pavement's functional performance in terms of ride quality and safety, for which an overlay would be an appropriate or necessary solution. OVERDRIVE can provide qualitative advice to the user in such situations. For example, if a section of pavement has unacceptable skid resistance or hydroplaning potential, but is otherwise structurally adequate, it may be necessary to overlay the pavement or apply some type of corrective surface treatment. If rutting of the pavement is also present, an overlay may be the only appropriate solution.

The overlay design thickness recommended by OVERDRIVE 1.1 is rounded to the nearest 0.5 in. for the sake of practicality (0.5 in. is also the minimum recommended overlay thickness). However, a quick calculation demonstrates the potential impact on an agency's budget of putting down overlays that are even 0.5 in. too thick. At a cost of about $10,000 per inch per lane-mile for asphalt (material only), the additional cost associated with an overlay that is 0.5 in. too thick, for a two-lane highway with paved shoulders, is about $12,500/mi. In just 100 mi, this misallocation is well over $1 million, which is a substantial amount compared with the maintenance and rehabilitation budgets of many local highway agencies. This underscores the substantial benefits that can be derived from development of improved design tools, especially knowledge-based tools such as OVERDRIVE, in this domain.

Finally, a powerful feature that is exploited in OVERDRIVE is the ability of the user, at the end of a design session, to view and then change any of the inputs for that session and have OVERDRIVE automatically redesign the structural thickness of an overlay. If, because of the user's changes, OVERDRIVE requires further information, this will be requested from the user. However, it is not necessary for the user to reenter all of the inputs. This feature is invaluable in investigating the impact of design inputs and assumptions (e.g., in the characterization of existing pavement layers or the subgrade).

CONCLUSIONS

The development of an initial knowledge-based system for assisting local engineers in designing the structural thickness of asphalt concrete pavement overlays has been discussed. The prototype version of this system, OVERDRIVE 1.1, has been implemented as an interactive microcomputer-based tool. The user can query the system for its reasoning, and the system allows the user to selectively modify input values or assumptions and to quickly assess the impacts of such changes on the structural thickness of overlay required.

In general, the potential for knowledge-based systems to become useful engineering tools in this domain is thought to be high.

Future research and development of OVERDRIVE will involve expanding and refining the knowledge base, incorporating additional knowledge acquired from pavement engineering specialists, providing a life-cycle cost analysis of each design thickness, and addressing the issue of uncertainty inherent in system inputs and conclusions.

On the basis of research to date with OVERDRIVE, it is concluded that a knowledge-based approach to pavement overlay design is feasible and, even in its present prototype form, OVERDRIVE is a potentially useful tool for local highway engineers.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation. This support, and the assistance of J. P. Mahoney of the University of Washington, is gratefully acknowledged.

REFERENCES

1. C. H. Oglesby and R. G. Hicks. *Highway Engineering*, 4th ed. John Wiley & Sons, New York, 1982.
2. S. G. Ritchie. Expert Systems in Pavement Management, *Transportation Research*, Part A, 1987, in press.
3. E. Rich. *Artificial Intelligence*. McGraw-Hill Book Company, New York, 1983.
4. C. Yeh, S. G. Ritchie, and J. B. Schneider. Potential Applications of Knowledge-Based Expert Systems in Transportation Planning and Engineering. In *Transportation Research Record 1076*, TRB, National Research Council, Washington, D.C., 1986, pp. 59–65.
5. S. G. Ritchie. State-of-the-Art of Expert Systems in Transportation Engineering. In *State-of-the-Art of Expert Systems in Civil Engineering* (M. L. Maher, ed.), U.S. Army Construction Engineering Laboratory, 1986.
6. C. W. Kostem and M. L. Maher, eds. *Expert Systems in Civil Engineering*. Symposium Proceedings, ASCE, 1986.
7. D. A. Waterman. *A Guide to Expert Systems*. Addison-Wesley, Inc., Reading, Mass., 1986.
8. F. Hayes-Roth, D. A. Waterman, and D. B. Lenat. *Building Expert Systems*. Addison-Wesley, Inc., Reading, Mass., 1983.
9. *Asphalt Overlays and Pavement Rehabilitation*. Manual Series 17 (MS-17). The Asphalt Institute, College Park, Md., June 1983.
10. S. G. Ritchie, C. Yeh, J. P. Mahoney, and N. C. Jackson. Development of an Expert System for Pavement Rehabilitation Decision Making. In *Transportation Research Record 1070*, TRB, National Research Council, Washington, D.C., 1986, pp. 96–103.
11. S. G. Ritchie, C. Yeh, J. P. Mahoney, and N. C. Jackson. A Surface Condition Expert System for Pavement Rehabilitation Planning. *Journal of Transportation Engineering*, ASCE, Vol. 113, No. 2, 1987.
12. *EXSYS Expert System Development Package User's Manual*. EXSYS Inc., Albuquerque, N. Mex., 1987.
13. F. N. Finn and C. L. Monismith. *NCHRP Synthesis of Highway Practice 116: Asphalt Overlay Design Procedures*. TRB, National Research Council, Washington, D.C., 1984.
14. J. P. Mahoney. State-of-the-Art on Asphalt Concrete Overlay Design Procedures. Presented at Tri-Regional Pavement Rehabilitation Workshop, Salt Lake City, Utah, 1984.
15. *Interim Guide for Design of Pavement Structures*. AASHTO, Washington, D.C., 1972.