INCORPORATING PRACTICAL EXPERIENCE IN THE CONDUCT AND MANAGEMENT OF RESEARCH

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•THE purpose of this paper is to discuss the incorporation of practical experience in the conduct and management of research. The paper is general in tone in order to include in the audience research managers who function at the policy-making level in the formulation of research programs. The discussion on formally including practical experience in research programs is divided into the following parts: (a) its necessity (why); (b) a methodology for doing it (how); and (c) the benefits (advantages) in terms of (b).

Before proceeding further, it is appropriate to establish the general framework for the discussion. First, only applied research, which is defined as research for the purpose of solving current or foreseeable practical problems, is considered. Second, the discussion is oriented toward pavement problems, although the concepts expressed are of wider applicability.

The solution to practical problems is obtained from relevant information that is or can be made available. The development of solutions depends on the investigator's ability to formulate hypotheses that can be tested with available information and can be further verified through the conduct of well-developed experiments. The information for doing this comes from two sources: (a) research and (b) practical field experience. Except where one is directly involved, this information is acquired primarily through the study of published materials. Discussion with experienced individuals does result in practical field experience being included into the system, but this is done in an unstructured fashion and the effect is minimal. Consequently, it is the published information that plays the dominant role in shaping research programs and in developing solutions. Because of this, research is often conducted in areas where there is a considerable body of existing knowledge. It is easier to formulate a problem on which there is considerable information than to develop research questions on problems on which there is little information. This research might not be the most appropriate from the standpoint of solving practical problems and hence from the research manager's viewpoint cannot be considered the best investment of funds.

It is safe to conclude that, compared to the information generated by observation and field experience, the great majority of the information generated in research is published. When one realizes the extent of the highway system and the number of man-years of experience that has been built up by knowledgeable and experienced individuals, it becomes obvious that a most valuable storehouse of knowledge has been inadequately utilized by researchers and research managers. This information is certainly complementary to that generated by research and, it may be argued, is more valuable because it represents field conditions. Because of these considerations, it is necessary that a methodology be developed that can utilize this information in the development of a strategy for obtaining solutions to practical problems.

METHODOLOGY

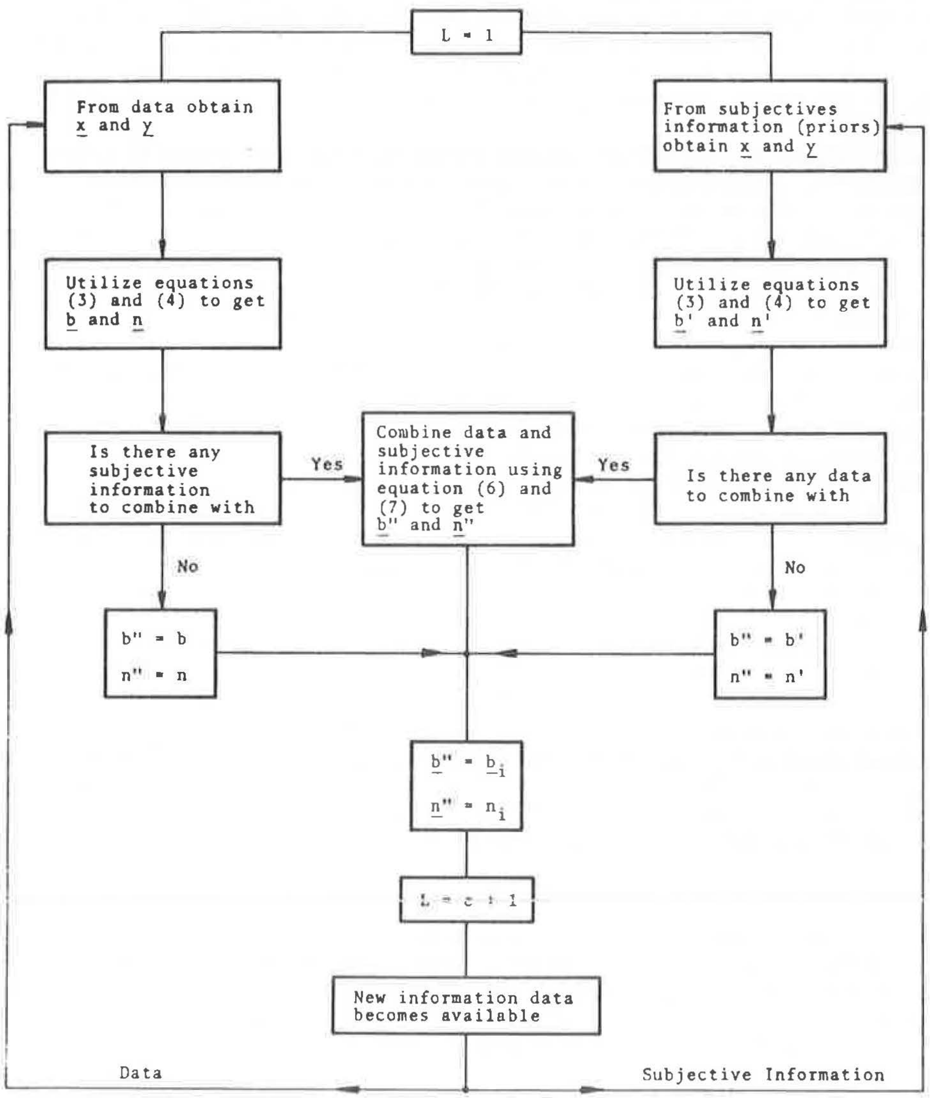
The methodology presented will utilize the cumulative experience of engineers working in the area of design, evaluation, construction, and maintenance of pavements, together with laboratory data, data from special test sections, and analytical studies. The most important feature of this approach is that it can utilize information from all these sources and place them in a consistent and compatible format for use by the practicing highway engineer. Research and field experience can be brought together to assist in solving the problem.

The methodology for such an approach is based on Bayesian decision statistics. Using this approach, it is possible to extract the past experience of engineers in a meaningful statistical format similar to data obtained from experiments. New experience gained from observation of field performance or test data can be combined with previous experience using Bayes' formula to arrive at posterior information. Such an approach, while new in the highway field, is well established for decision-making in other fields and areas of transportation engineering (1).

The general methodology is presented in simplified form in Figure 1. The key concepts are as follows:

1. Interim solutions and research programs developed on the basis of published information are based on "partial" state of knowledge. Such strategies for solving prob-

Figure 1. General methodology for combining subjective and objective information to represent current state of knowledge.



lems are formulated without the inclusion of a great deal of the experience that has been gained in the performance of the highway system because this experience resides in the subjective evaluation of experienced engineers. It is believed that only a small percentage of this information has been published.

2. To develop solutions, including the formulation and conduct of research programs, a "more complete" state of knowledge should be developed. This can be done by extracting the subjective information from experienced engineers and combining it with the available published information.

3. The state of knowledge developed in item 2 can be updated periodically as new information becomes available. This new information will come from laboratory and analytical research and from observations of performance. In this context, the existing highway system can be considered as a large-scale experiment. The methodology will provide a rational method for designing feedback systems and, more significantly, will provide a means for including this information (experience) into the design process.

The methodology is described in a series of steps that generally follow the approach in Figure 1. Theoretical aspects are omitted in this discussion but are given in the Appendix.

Step 1. Identify and Rank Factors That Have Significant Influence for a Particular Problem

Based on the available information, a list of those factors that are considered to have a significant influence on the problem should be prepared. This list should be circulated to experienced engineers, who should be asked to rank the factors in order of importance and add any that had been omitted from the list. In selecting the engineers, emphasis should be placed on design and materials engineers from state highway departments with suitable geographic distribution, since the opinions of researchers will, in general, have been considered in the context of published information.

Step 2. Obtain Subjective Information of Experienced Individuals on Influence of the Significant Variables

To obtain the desired information from the appropriate individuals on a systematic basis requires designing a suitable questionnaire, implementing the questionnaire, and arranging the data in suitable statistical format.

Designing the Questionnaire—The questionnaire is prepared to extract (a) range, mean, and coefficient of variation of each variable and (b) information regarding the influence of the independent variables on the dependent variable that defines the problem (e.g., fatigue cracking). In formulating the questionnaire, attention must be paid to the background and training of the individuals who will be asked to respond to the questionnaire. In some cases it will be necessary to go through a number of iterations before a satisfactory questionnaire is designed.

Implementing the Questionnaire—Individuals with experience in the field under study should be located. As in Step 1, emphasis should be placed on materials and design engineers from state highway departments and the major climatic subdivisions of the United States should be covered. It is suggested that the questionnaire be implemented on a personal basis (interview). Utilizing the interview process has three significant advantages: It permits an explanation of the basic philosophy of the method; it provides an opportunity to explain statistical concepts to individuals when necessary; and it provides an opportunity to explain questions that may be stated in terms that are outside the usual thought process of the individuals interviewed. It is also important to recognize that the personal explanation and individual participation will greatly increase the acceptability of the results of such research into practice.

Arranging the Data—Based on an examination of the data and discussions with experienced engineers, a relationship (equation) between the dependent variables and the independent variables can be postulated. Based on techniques of information theory, the subjective information can be equated to experimental data. This requires equating the experience of the engineers to a certain number of experiments.

Step 3. Assemble Objective Information

Objective information, in the form of both laboratory and field data, should be assembled. The relationship developed between the dependent and independent variables in Step 2 is utilized to analyze the data. The results are placed in the same form as the information obtained from implementing the questionnaire. In some cases, if substantial published data are available, Step 3 may be conducted prior to Step 2, and the relationship between dependent and independent variables is postulated on the basis of objective data.

Step 4. Combine Information to Develop State of Knowledge

The information obtained in Steps 2 and 3 can be combined to develop the state of knowledge. This is done utilizing Bayes' formula. The theoretical basis for doing this is presented in the Appendix.

Step 5. Recommend Solutions and Formulate Research Programs

Utilizing the updated relationship developed in Step 4, sensitivity studies can be conducted to evaluate the relative influence of various factors on the problem. Solutions and research programs can now be developed utilizing these sensitivity studies, which are conducted on the basis of a more complete state of knowledge as developed in Step 4.

Step 6. Continue Evaluation and Modification of Programs and Solutions

In the classical approach, evaluation and modification would require a factorial design of experiments. In the approach outlined above, a single set of experiments is unlikely to have any significant effect on the cumulative experience of engineers as determined in Step 4. Therefore, continuing evaluation will be based on incorporating the results of continuing research and the experience being gained by engineers on the basis of the performance of the highway system to update the existing state of knowledge. In this context, this step will consist of designing feedback and information-gathering systems and detailing the procedure for combining information as it becomes available with the previously available information to obtain a new state of knowledge.

It is envisioned at this time that the total data-gathering process will include three sources of information: subjective priors, feedback, and special test sections, as follows:

1. Subjective priors—The fastest way to expand on the existing information is through the quantification of engineering experience. By this procedure, a great amount of data can be generated over a relatively short time. There are limitations regarding this procedure. Probably the most significant one is that engineers who are interviewed can best speak with confidence only about their personal experience, which itself is limited to "what is" and not so much about "what might be". For example, if one is interested in exploring recommendations regarding the use of thick asphalt layers, it may develop that field engineers have very little experience with this type of design. Nevertheless, experienced engineers can be asked to extrapolate on their experience if the weighting assigned to such experience is modified and the confidence is reduced.

2. Feedback system—To supplement, reinforce, or negate existing information, a field feedback system can be developed. Three aspects are required for this system: (a) the development of a model for statistical analysis, (b) the field quantification of the input variables required by the model, and (c) the field evaluation of performance. Such a feedback system would require time to develop and implement. However, such a system is feasible and does not require special construction, since the existing highway system would be utilized. It does require special measurements of both the dependent and independent variables.

3. Test sections—If the information from subjective priors and the feedback system is sufficiently definitive, implementation can be initiated without further delay. However, in the event that further documentation is considered necessary, a series of field test sections can be programmed.

Step 7. Research Special Problems

As has been pointed out, there is the case when, because of new materials, new methods of construction, or other factors, there is very limited prior experience. In such cases, people may be asked to extrapolate data, based on their previous experience. However, to rely on this extrapolation alone can be very misleading. Therefore, in some cases, it will be necessary to conduct laboratory research, carry out analytical studies, and implement special field experiments.

MAJOR ADVANTAGES

The major advantages accruing to the methodology described are as follows:

1. Information from both laboratory and field research and field experience can be combined in a rational and consistent manner for the development of research programs and the conduct of research for the solution of practical problems.
2. The experience of practicing engineers, which is the greatest collection of valuable information on the performance of pavements under a variety of conditions, can be utilized in the development of design recommendations. This will increase the likelihood of acceptance of the results obtained through the proposed methodology by the practicing engineer.
3. The methodology provides a means for updating information as new information becomes available.
4. It provides a basis for designing performance monitoring and information feedback systems.

FINAL REMARKS

In the formulation of research programs and in the development of solutions for practical problems, there is a significant deficiency in that we do not formally consider the knowledge that is present in the subjective opinions of practicing engineers. Considering the cost of research programs in terms of money and talent and the cost of applying solutions that are not suitable or acceptable to the practicing engineer, it is imperative that the experience of the practicing engineer be utilized.

The theoretical concepts for utilizing subjective opinions in the decision-making process are well developed. It remains for research managers and researchers to utilize these concepts in their work. The methodology for doing this is briefly outlined in this paper. It is hoped that this paper will stimulate enough interest for the ideas expressed to be implemented in practice.

ACKNOWLEDGMENTS

Many of the ideas contained in this paper were developed during the conduct of research associated with NCHRP Project 9-4.

REFERENCE

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APPENDIX

THEORETICAL BASIS FOR COMBINING DATA AND SUBJECTIVE INFORMATION

As indicated in previous discussions, it is the objective of this procedure to combine the subjective evaluation of experts in the field with actual experimental data to obtain the total available state of knowledge. Therefore, the basic question is how to combine the data and the subjective information (prior) in a meaningful way. The formulation not only should be able to handle the analysis of this subjective information but should also be able to combine future experimental data with subjective information. The theoretical basis for combining the data and prior is discussed in the following paragraphs.

The theoretical basis of the method depends on Bayesian statistical theory. Basically, the methodology combines the experimental data (called sample likelihoods) with subjective or experience-based data (called prior) to get combined information (called posterior information). In general, for any kind of prior and sample information, one could come up with posterior information by means of Bayes' formula. This approach is neither analytically nor numerically tractable for most situations. However, if the sample and the prior information belong to a special family of distributions, called conjugate distributions, then the posterior distribution can be obtained by simple numerical calculations. Thus, for example, if the sample data have normal distribution with a specified precision and the subjective data have normal distribution, then the posterior distribution is also normal. We utilize these conjugate distributions in our further development.

It is assumed that the data-based information is in the form of a regression equation where it is assumed that errors have Gaussian distribution. If we wish to use a conjugate distribution for priors, then it should be in the form of a normal regression process. Consider, for example, a generalized normal regression process. Let Y_1, $Y_2, \ldots, Y_i, \ldots, Y_k$ be dependent variables generated by independent variables X_{ij} according to the model

$$Y_i = \sum_{j=1}^{r} X_{ij}\beta_j + \epsilon_i \tag{1}$$

The number of independent variables is denoted by r. Now, the values of β_j s can be calculated either from data or from priors. Let the data matrix $\underline{X}$ be

$$\underline{X} = \begin{bmatrix} X_{11} & X_{12} \ldots & X_{1r} \\ X_{21} & X_{22} \ldots & X_{2r} \\ \cdot & & \\ \cdot & & \\ \cdot & & \\ X_{k1} & X_{k2} & X_{kr} \end{bmatrix} \tag{2}$$

where $X_{11} = X_{21} = \ldots X_{k1} = 1$.

Each row in the above matrix represents one set of data points. Thus, if we have 150 data points, then k = 150. Then, using data, the regression coefficient vector $\underline{b}$ can be found as

$$\underline{b} = (\underline{X}^t\underline{X})^{-1}\underline{X}^t\underline{Y} \tag{3}$$

where $\underline{X}^t$ is the transpose of matrix $\underline{X}$, and $\underline{Y}$ is the dependent vector. Let

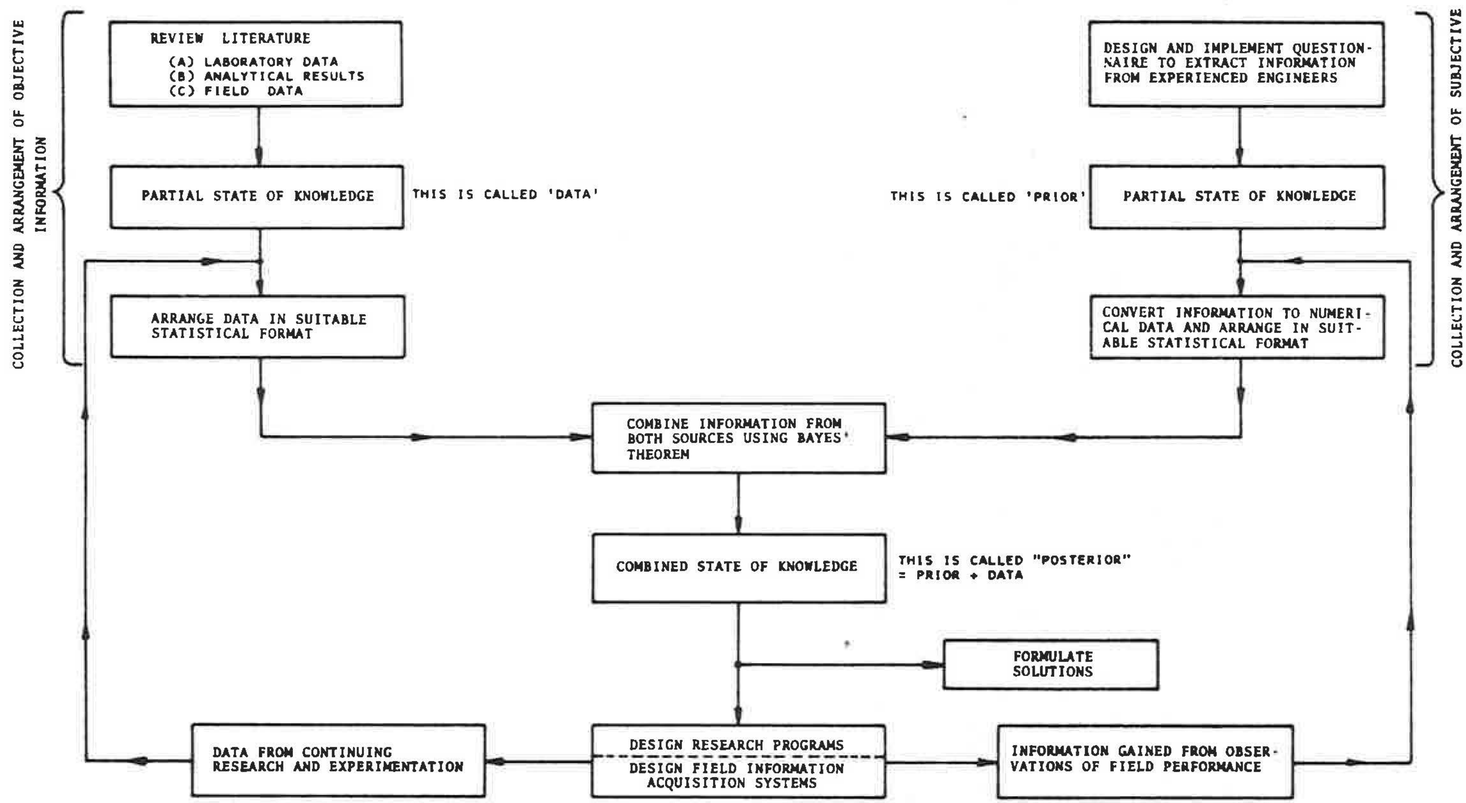
$$\underline{n} = \underline{X}^t\underline{X} \tag{4}$$

Then,

$$\underline{b} = (\underline{n})^{-1}\,\underline{X}^t\underline{Y} \tag{5}$$

We can also obtain the values of $\underline{b}$ and $\underline{n}$ from subjective information. Let us call these prior matrices as $\underline{b}'$ and $\underline{n}'$. The procedure for doing this is explained in the example.

Figure 2. Schematic representation of procedure for combining data and priors.



Then, if one wishes to combine data-based information with the prior information to obtain posterior information, the following simple manipulation yields the desired results:

$$\underline{n}'' = \underline{n}' + \underline{n} \tag{6}$$

and

$$\underline{b}'' = (\underline{n}'')^{-1} (\underline{n}\underline{b} + \underline{n}'\underline{b}') \tag{7}$$

For the derivation of these two results, see Raiffa and Schlaiffer (2). The variance matrix of the posterior regression coefficients ($\underline{b}''$s) is given by $(h\underline{n}'')^{-1}$, where $h = 1/\sigma^2$ is defined as the precision of the process.

Thus, if we wish to combine priors of two experienced engineers, the only thing we have to do is to obtain the $\underline{n}$ matrix and the $\underline{b}$ matrix for these two. Then, the combined information is obtained by means of the above relationships. Such a formulation allows us to keep track of our information at any given time, and the updating or combining of future information is systematic and rational. In all of this description, we have kept the basic notion that the process by which one accumulates experience or one accumulates data-based information has the same type of statistical variability. The procedure for combining priors and data is shown schematically in Figure 2.

REFERENCE

2. Raiffa, H., and Schlaiffer, R. Applied Statistical Decision Theory. Harvard Univ. Press, 1961.