from what specification writers expect.

Unbiased pay schedules can be developed by permitting pay factors in excess of 100 percent to offset lower pay factors with the provision that total payment for any billing period cannot exceed 100 percent. Pay schedules of this type award payment in direct proportion to the quality of the product up to an expected pay factor of 100 percent at the AQL. This overcomes a basic deficiency of conventional pay schedules and tends to encourage contractors to perform at or just above the AQL.

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# Information Systems in Highway Construction: The State of the Art

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**This paper is the result of an in-depth analysis of automated data-processing techniques used in managing information that is normally generated during highway construction. Such information includes material availability, results of material testing, and quality-control decisions. Information systems used by New York, Colorado, Pennsylvania, Louisiana, Illinois, West Virginia, Georgia, and Minnesota are briefly reviewed. Three categories of material and test data information (MATTI) systems are discussed: batch information systems, on-line interactive information systems, and on-line interactive laboratory information systems. These systems represent the state of the art. Research indicates that there is currently insufficient coordination among the states in sharing experience in the development and use of MATTI systems. Because MATTI systems compete with other large users of computer resources, the need for careful planning is emphasized so that too-sophisticated systems are not developed where less-sophisticated systems are more than adequate. The need for multidisciplinary involvement throughout systems development requires greater emphasis.**

This paper is the result of an in-depth analysis of automated data-processing techniques used in managing information that is normally generated during highway construction. This information includes material availability, results of material testing, and quality-control decisions.

Information systems used in New York, Colorado, Pennsylvania, Louisiana, Illinois, West Virginia, Georgia, and Minnesota are briefly examined. Detailed descriptions of systems structure, use, and capabilities can be found elsewhere (1).

Three categories of material and test data information (MATTI) systems are analyzed: batch information systems, on-line interactive information systems, and on-line interactive laboratory information systems. These systems represent the state of the art.

## BACKGROUND

The increasing need for improved quality of highway materials has led to a search for new and more effective quality-control methods (2,3). This search began in the early 1960s with the application of statistical analysis techniques to material performance data and culminated in the implementation of statistically derived specifications for highway construction materials and procedures. Applying statistical quality-control methods to specification writing has now become standard practice. However, there is a continued need for the periodic updating of specifications and for more efficient methods of providing basic data for justifying adjustments to existing specifications. Manual methods for satisfying this need have been less than satisfactory (4). Efficient manual processing and monitoring of material information are practically impossible for large highway projects because of the difficulty in retrieving historical data and managing the more current accumulation. This management problem is not only due to tedious data-gathering procedures but also to inconsistencies in test-result recording procedures and filing methods used by various administrative districts within each state.

Recent efforts to improve the materials management process have focused on the adoption of the systems engineering concept. With this adoption, it became apparent that high-speed data processing is necessary for improving the standard written specification and test-reporting methods (5). Thus, the trend in the 1970s has been the use of high-speed electronic computers for providing continuous feedback related to material use, test performance, availability, specifications, and any pertinent recorded construction information. A variety of materials and test data management systems are in use in several states. These include systems developed for specific situations and selections from generalized data-base retrieval systems marketed today under various generic names. Such names as data management system, generalized information management systems, and file management systems are popular terms used today.

Basically, computerized information systems belong in two categories: (a) information analysis and (b) information organization and file search. Analysis normally consists of assigning a name to each stored item and to each search request. Organization and file search are concerned with the manner in which the stored information is organized in the file and with the corresponding search procedures. The more elementary systems search sequential files, use simple record structures, and provide only rudimentary report formatting facilities. The more sophisticated systems manage files via indexes or links and function in an on-line or quasi-on-line mode.

## PROBLEMS ENCOUNTERED

As the research was well in progress, it became apparent that data collection would be difficult. One of the most significant problems observed was a lack of detailed formal documentation of systems that were either in full operation, being developed, or in the implementation phase. Thus, informal reports designed for office use were used in compiling data on MATTI systems. A comprehensive literature search did not reveal any meaningful publication on the subject. This fact may have constrained the scope of the research, in that valuable contributions to the state of the art may well be lodged in MATTI systems other than those presented in this paper.

Some states, in the development of their system, used the most advanced technology in on-line interactive information systems. Others made use of the less-sophisticated batch information systems. These two extremes of approaches provide a wide range in the quantity of information made available but greatly reduced the possibility of a meaningful item-by-item comparison among systems. Although computer technology is the key to efficient storage and retrieval of information, it became apparent, as the research continued, that this technology was not being fully used by some states. Reasons for such practices could sometimes be traced to the reluctance of some transportation officials to use the state's centralized computer facilities because of the alleged inadequate service provided by some centers. Also related to these two major problems was the lack of uniform definitions for identical data-processing terms. These problems not only caused difficulty in seeking out meaningful information for each state but also restricted the research team from comparing all aspects of MATTI systems for all states visited.

## CLASSIFICATION OF MATTI SYSTEMS

There is a wide range in the capabilities of MATTI systems used today. Therefore, the classification of these systems makes it easier to compare those that possess similar capabilities. Classification also has the advantage of presenting distinct levels of sophistication and the various approaches for achieving the same objectives. MATTI systems may be classified in various ways so that specific hardware, operations, and user characteristics are structured in categories of accomplishment. For this research, it is more meaningful to adopt a classification method that clearly depicts user-hardware interaction. With this idea, the functional classification presented below has been adopted.

1. A batch information system is the least complex level of computer processing. At this level, stored programs are executed to process transactions only from a list of job requests. Advanced batch programs perform more complex computation and produce detailed reports of management operations.
2. In an on-line interactive information system, the user communicates with the computer facility via terminals, and requests are processed as they arrive. The user usually gets quick responses that are often used to further query the system for additional information or provide some form of input and output. In order to accomplish this, it is necessary to provide some method of time sharing, unless the system is dedicated to a single user.
3. In an on-line interactive laboratory information system, laboratory technicians communicate with the computer facility via terminals. Information is also transferred automatically from material-testing equipment to the main storage of the computer. All stored information is retrievable but can only be changed by authorized laboratory technicians.

## OBSERVED SYSTEMS

The analysis of the data collected in the eight states revealed that the application of a computerized information management technique to material-testing and construction data is the general trend. Three approaches have been identified: (a) batch information system, (b) on-line interactive information system, and (c) on-line interactive laboratory information system. Although there is adequate merit for using all of these approaches, there is no single approach that can be described as best. Each approach tends to satisfy specific conditions and has its advantages and disadvantages.

Batch processing was observed in Georgia, West Virginia, New York, and Minnesota. Although the actual operations of batch processing are standardized, there is some difference in the quality of service among these states. This difference appears to have no correlation with the computer hardware nor the expertise of the data-processing staff. The degree of emphasis on computerized highway construction information, the selection of highway data to be computerized, and the efficiency in data communication appears to be dependent on an undefined priority-determining mechanism adopted by the computer services centers and on whether the bureau of materials or material information ranks favorably on the priority list. Of the observed states using the batch-processing method, only West Virginia clearly enjoyed a good working relation with the state's computer service center. This good relation has fostered broad application of computer technology to diverse highway construction data and has generated a satisfaction about batch processing not yet observed in the other states. The West Virginia system can adequately accommodate the processing of information for which the turnaround time is not shorter than two days. Use of remote job entry-and-return peripheral hardware has potential for further shortening the turnaround time.

Colorado, Louisiana, and Illinois have adopted the on-line approach for processing materials and material-testing data. These states have capitalized on the instantaneous reporting and sorting capabilities of on-line systems and are experiencing relative success in applying the methodology to data required on a demand basis. A difference in the choice of computer hardware and information coverage exists. MATTI systems developed by these states possess similar data-interrogation capabilities (the ability to search, analyze, select, and print reports) but have adopted independent approaches for accomplishing the same objectives.

Of the eight states visited, only Pennsylvania developed an on-line interactive laboratory information system. This type of system is an outgrowth of the need to reduce laboratory paperwork via automatic transfer of test results from equipment to computer through which instantaneous reporting is possible. The system features minicomputers at the central laboratories and has distributive processing capability.

Pennsylvania's automated laboratory testing and reporting system is a classical demonstration of the use of minicomputers to complement batch operations that are scheduled in accordance with priorities determined by an external centralized data-processing unit. Of course, at the time of this reporting, the Pennsylvania system was still growing. Even then, some data-interrogating features were identical to those systems that used only giant equipment.

## BATCH VERSUS ON-LINE SYSTEMS

On-line interactive methodology with applications to material information has been observed in Colorado, Pennsylvania, Louisiana, and Illinois. The other states visited—Georgia, West Virginia, New York, and Minnesota—have favored batch processing. However, regardless of sophistication, the trend is in the direction of automatic management of highway construction information. The two distinct approaches offer different capabilities, but the on-line method has a superior capability. However, the superior capability of the on-line systems is only valuable if (a) there is need for quick response, (b) there is an assurance that new information is filed quickly, and (c) existing files are continuously updated.

On-line systems are noted for great demands on operating funds and computer time. Although on-line processing may provide immediate response to an information request and is amenable to nonskilled users, there is a tendency for developers to apply the technology to almost all construction information—even information that is rarely needed on demand. There is a large volume of construction information for which delivery within several days is viewed as timely and has no negative effect on existing quality-control and quality-assurance programs. For information with high flexibility in delivery time, a well-designed batch operation can provide a more-than-satisfactory performance.

On-line interactive information systems and on-line interactive laboratory information systems are inherently more complex than batch information systems. All interactive systems respond in an almost instantaneous manner. They often maintain a direct interface with the intimate originator (the customer) of a transaction, accept whatever demands are placed on it at the instant they occur, and maintain secure control over its data base and processing environment so long as there is a customer expecting service. A transaction initiated at one point in a day may interact with several other transactions occurring at other times of the day. All of these transactions affect a common data base. The system must maintain control over these interactions until the day is over. When all customers obtain answers for the services they requested, the system can be safely locked up. Any failure in the system that occurs during this entire stream of interactive processing may have an immediate and serious effect on the ability of the various users of the system to continue their daily activities.

This characterization of on-line information systems is in sharp contrast to a similarly structured characterization of batch information systems, which, by definition, aggregate transactions as they arrive into efficient processing groups. Inherent in the concept of batch processing is its relative inexpensiveness and the presence of several protective stages between the originator of the transactions and the system. Data provided by the originator are always edited, converted to machine format, and accumulated into batches of similar data many hours or days before processing.

Batch processing is almost always sequential, file-oriented, and multistaged; hence, the interaction between various transactions is trivial. Because of this staged handling of data, reliability and security are easily provided in the passing of data from one file to another with the maintenance of several generations of data for backup. The failure of a computer system in a batch-processing environment is often unobservable to the outside user because of the expected length of time between submission of each transaction and the return of results and the relative simplicity of backing up one batch-processing computer with another.

In contrasting on-line interactive system operations with batch processing, one finds the latter to be composed of simple questions and answers with a few interdependencies. Whereas the on-line interactive system answers more complicated questions, it requires much more complex answers with many greater interdependencies. For example, if a processing step is omitted in the initial design of a batch-processing system, the problem can often be corrected with an additional step. On the other hand, if a similar kind of error is made in an on-line interactive system, corrections may require redesign of the entire data base and have a serious impact on the equipment requirement and the performance of the system. If a batch-processing application exceeds its core memory allocations, the problem can be easily solved by fragmenting the application into several runs—the only difference being a slight increase in total processing time. The on-line interactive system makes highly integrated use of core memory, and, if the application exceeds the core budget, it may be necessary to get more physical core memory because no practical way may exist to fragment the application after it has been designed and programmed.

In summary, it is much more difficult to design an on-line interactive system than to design a batch-processing system because the entire on-line interactive system design must proceed from the outset as a completely integrated entity that considers all possible types of transactions, alone and in combination. Interactive systems generally cannot be handled by fractionalization into sequential runs and, hence, a failure to achieve system performance objectives at the outset cannot be corrected merely by spreading the work over a longer period of time. Throughout all phases of the system design (from concept through implementation to test), the system will be in much more intimate contact with the user environment than in a batch-processing application. A correspondingly higher quality of effort at each stage is required to ensure success. The development organization will be much more exposed to outside criticism than in the case of batch applications.

## INTERDISCIPLINARY TEAM IN SYSTEM DEVELOPMENT

The quality of the system design and, ultimately, of the system is highly dependent on the effectiveness of the dialogue between members of the design team and users. During the design effort, both parties are going through a process of problem solving and learning together. The design team learns more about the characteristics and idiosyncracies of the operating environment of the agency and about which computer-based functions will be critical, marginal, or not useful. The user, in turn, learns about the capabilities and limitations of the design team and the developing system and also about the cost and feasibility of various functions. It is critical, therefore, that the design team foster and nourish a cooperative learning climate characterized by mutual respect and confidence. Accomplishing this learning climate is facilitated by a team equipped with computer expertise as well as a knowledge of highway construction information and the expectation of various users.

At the outset of the design process, there may inevitably be considerable ignorance on both sides. Because people do not like to appear ill-informed, a defensive posture that inhibits the free exchange of information and ideas can easily be developed. This problem has no textbook solution, given the variety of possible personalities and situations. Suffice it to say that the interdisciplinary team should be willing to listen and should be adept at winning and keeping the confidence of the users.

A more straightforward aspect of coping with the learning process is for the interdisciplinary team to identify major areas of ignorance early in the initial design stage. The team, for example, may need to learn a lot about the flow of work, document preparation, and decision-making or management control processes in a user area. Correspondingly, the user may have considerable difficulty in stating his or her output requirements because of the user's unawareness of the capabilities and limitations of hardware and software. Once the major gaps in knowledge are identified, a variety of frontal attacks is appropriate—for example, data collections, interviews, seminars, sample program and output discussion, and work experience. It is important not to waste the user's time by using ineffective techniques or by rehashing old materials.

For the eight highway agencies covered by this research, two distinct data-processing environments were observed. The first environment is that in which the agencies make use of the state's or transportation department's centralized data-processing center. With this arrangement, the highway agency performs all tasks except those related to the mechanical information processing performed by computers and their peripheral equipment. The center provides processing services by means of terminals and transmission devices. The second environment is one in which the user-agency controls its environment. This environment allows the agency to be independent of other agencies that use a centralized data-processing center and to be independent of the needs of the centralized center for keeping its machine operational and upgrading its capabilities. For example, in periods when operators of centralized data-processing services are experiencing heavy demand for services, a problem of assigning priority develops, and operators usually take control of the machines and, thus, hinder first-call-first-served operations. This affects low-priority users.

Another disadvantage in using a centralized processing center can be identified as priority interruptions during development. A new application implemented by another agency may require relatively high machine priority in order to operate effectively in such an environment. This is most often true for an on-line application. This high-priority requirement may well interfere with other users of the center and cause conflicts between the needs of users. In addition, it may be that the response time of the new application suffers from contention with other applications for system resources, such as the operating system and direct access storage. Hence, the effect on the response time of a new application being implemented in an environment of centralized processing is relatively uncontrollable, compared with a situation in which the machine is owned and operated by an agency.

Moreover, the deciding factor in justifying the use of an in-house machine versus centralized data processing can be traced to cost. In analyzing the hardware and operating costs for implementing a large in-house machine, the agency or bureau must decide whether to use a full-cost or an incremental-cost approach. Full costing would charge all applications for the resources that are used directly plus a proportionate share of all other resources in the system that are shared. For example, applications would be charged for their use of the computer printout unit and peripheral equipment plus a portion of operating system memory space, floor space occupied by the machine, heating and cooling, and operational staff. It may be desirable in some in-house environments to consider incremental costing, but it must be recognized that there are a number of potential problems raised by this approach.

First, computer personnel expenditures constitute more than 50 percent of a total automated data-processing (ADP) budget and are greater than one-and-a-half times the expenditure for hardware. Thus, excluding these charges along with charges for floor space and system resources used by the operating system implies excluding the majority of all real costs. Second, the incremental-cost approach could be unfair to other system users. In addition, as the needs of the system user grow, additional memory and peripheral devices may have to be purchased. The incremental-cost users may have to justify this cost, and the costing approach may be converted from incremental costing to full costing. Finally, the degree of control of an in-house computer versus centralization could be based on the need to isolate specific applications from the effects of other applications in a central environment.

## SELECTING A MATTI SYSTEM

The degree of sophistication required for computerized management of construction information should be based on the following factors:

1. Willingness of employees to abandon old methods and adopt the proposed method (expressed willingness can be very deceptive; it is the spontaneous willingness resulting from high employee morale that should be of great concern);
2. Level of effort that will be made to inform and instruct all relevant personnel about the aims, objectives, operations, and procedures of the new system (a poor effort could result in inadequate use of a highly sophisticated system, thus nullifying anticipated benefits);
3. The responsiveness that is required for critical information needs (it is pointless to have a system that is capable of instantaneous on-line reporting if the same information is infrequently required and reports can be supplied in good time by less costly and sophisticated systems);
4. The quality of countinued training required to involve newly recruited personnel and to maintain the information-processing expertise, regardless of the job-changing habits of key technical personnel;
5. The quality of service available from a general computer center compared with that of a special local computer for providing ADP services to the suborganizational level with the responsibility of managing material information;

6. Whether direct user access to hardware is desirable and justifiable, compared with the creation of special staff positions for operating the computer machinery and processing information;
7. Future trends in the need for certain types of material information and the decreasing need for management of same;
8. Factual determination that current information is too voluminous to be manually or batch processed in a timely manner;
9. Availability of sufficient development, implementation, and operating funding (when funds are scarce, there is a tendency to merely search for inexpensive equipment to do the job, and often its compatability with existing equipment and future expansion is neglected; a staged introduction of equipment with long-term use should be considered so that both equipment purchase and data coverage can be phased; an open-ended system is most amenable to staged implementation); and
10. Experience of other states, which is very valuable.

## CONCLUSIONS

The reasons for developing a computerized materials and test data information system vary among states and depend mainly on the expertise of the technical staff and the availability and willingness of administrators to provide funds for its development and implementation. However, there are several essential benefits that are often quoted as the basic motivators behind computerization. It would be fair to say, though, that how well these benefits are realized depends on system sophistication and user acceptability. Probable benefits that can be derived from a computerized MATTI system include the following:

1. Simplifies data documentation;
2. Improves information accuracy;
3. Frees engineers involved with data manipulation so that their time can be directed at more creative exercises;
4. Provides timely access to stored data for verification of on-going operation, research, problem solving, and planning;
5. Reduces number of people needed for processing data;
6. Offers better control of the quality of highway construction materials;
7. Provides efficient and effective transfer of information;
8. Provides improved and timely monitoring of construction projects for compliance with specifications;
9. Maintains a continuous log of basic construction materials for specification development and adjustment;
10. Considerably reduces time spent in manually typing, auditing, or spot-checking test reports;
11. Eliminates final manual audit of testing compliance and the accelerated certification of construction items to the Federal Highway Administration (FHWA);
12. Centralizes storage of all highway construction information; and
13. Provides a more meaningful continuous record of the pattern of variation in personnel (contractors), materials, and machinery for subsequent statistical quality-control evaluation.

There is no doubt that MATTI systems have tremendous capabilities for managing information. But capability alone does not guarantee efficient system use. Hence, there is a need to encourage, when possible, meaningful participation of all potential users of a proposed system during its planning and development. An interdisciplinary effort has tremendous potential for reducing misunderstandings and petty favoritism.

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