The Status of Electronic Computation In Highway Engineering

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Initial applications of electronic computers in the highway field were developed about 1955. Since then there has been a broad acceptance of this device by highway engineering organizations and rapid progress has been made in expanding its use. This paper reports on the progress made during this period and on the current status of the use of electronic computers in highway engineering and administration, including the range of applications in use or in process of development and probable future trends. It also discusses actual and indicated effects of the adoption of high-speed data processing and computation on staffing patterns, organizational structure, and engineering and administrative procedures.

• ELECTRONIC COMPUTERS were first used in highway engineering in 1955. There has been broad acceptance of this device in the highway engineering profession and rapid progress has been made in extending its use. One state highway department after another has turned to electronic computation until today 43 of them are using electronic computers for engineering computations. Forty-one of these highway departments have installed their own computers, have trained their engineers to use them, and have established computer staffs to operate them. Beginning with the computation of earthwork quantities and traverses, the range of applications has grown to include to some degree practically every phase of highway engineering.

The July 1959 survey of electronic computer utilization in the state highway departments reveals the extent of the progress made. Taken together, the 41 state highway departments which have their own computers had completed a total of nearly seven hundred computer programs. The programs covered fiscal and statistical computations as well as engineering problems with the latter comprising about 90 percent. In addition, it was reported that 129 new programs were in process of development and that still another 159 programs were planned for development in the future bringing the grand total of computer programs completed, in process, and planned close to a thousand.

About 40 percent of these programs are for problems in the highway location and design field and the structural field. Other areas covered include highway planning, traffic analysis, surveying, soils, hydraulics, quantity computation, bid analysis, cost accounting, payroll and other fiscal operations, statistical analysis, inventories, highway needs data and a variety of problems in geometry and trigonometry of general application.

While complete data of this kind are not available for consulting firms, reports from various sources indicate that their progress is comparable to the progress made in the state highway departments. Most of the consulting firms specializing in highway engineering now use electronic computation and either have their own machines or have their work done by computer service organizations. This group has been very active in program development and has made substantial contributions to the advancement of computer utilization in highway engineering.

As indicated by the survey of the states, the preponderance of computer programming effort has been devoted to engineering problems. However, a good beginning has been made in the area of highway administration and there appears to be a trend toward increasing emphasis on administrative applications. The Bureau of Public Roads has completed a program for equipment cost analysis and is in process of developing a program for maintenance cost analysis. Connecticut has a program for estimating construction personnel requirements and is working on another which will provide progress reports on surveys, design and right-of-way acquisition. Iowa has a program for property and equipment inventory; Minnesota, for city and county construction needs for funds distribution; Colorado, for future fund requirements; Oregon, for depreciation and replacement costs for road sections; Hawaii, for project allotments; Ohio and Michigan, for estimating future income and expenditures; and Washington, for computing the highway department's cash position on a day-by-day basis. A number of states have programs for sufficiency rating, contract bid analysis, payroll and payroll distribution, construction cost indices and budgetary controls. Still other programs in the administrative field are in process of development or are planned for the future.

In the field of research, the electronic computer is proving to be a versatile and powerful tool, and the range of applications is growing constantly. Because large volumes of data can be processed and analyzed on the computer in a small fraction of the time required by other methods, studies can now be undertaken which formerly were considered impracticable. For example, in a research project for evaluating trip forecasting methods (*1*), it was estimated that 30 man-years would have been required to complete the task using a desk calculator. An electronic computer was used and the processing and computing operations were completed in 30 hours of actual computer time. This included additional computation not considered in the 30 man-year estimate. The computer has also proved to be a valuable aid in traffic accident analysis, studies of traffic movement and volume patterns, highway cost studies, structural research, soil consolidation investigations, statistical analysis of experimental data, and in other highway research activities. The electronic computer not only makes possible a substantial expansion in the scope of research but also permits more extensive investigation and more exhaustive analysis than otherwise would be feasible. In these ways, it serves as a powerful stimulus to further and more intensive research.

The very heavy burden of computer program development has been eased substantially through cooperative effort. Highway departments, consulting firms and others using the same make or model of computer, have joined forces through the medium of "user groups". These groups meet periodically to review progress made, to discuss common problems and to plan further development. Computer programs developed by one member of a user group are made available to other members thus tending to minimize duplication of effort and to assure maximum progress.

At the present time, twelve different makes or models of computers are being used on highway work by the highway departments and consulting firms. Each of these twelve types of computers has its own machine language or coding system and each has its peculiar operating characteristics. For these reasons, computer programs cannot be exchanged among all computer users in the same way that they are exchanged within a user group. To resolve this problem, the Bureau of Public Roads maintains a computer program library which operates as a central agency for the receipt and distribution of computer programs developed for use in the highway and bridge fields. Programs received are expressed in terms of the codes of the machines for which they were developed. Programs distributed are entirely free of such terminology and are in a form in which they can readily be coded for use with any digital computer. Priority is assigned to the conversion of programs to this library

form so that they can be made available to all users in the order of their usefulness. In this way, the Bureau of Public Roads Computer Program Library supplements the several computer user groups and makes possible complete program interchange regardless of the makes or models of computers used. Programs are contributed to the library by the highway departments, consulting firms, Federal agencies, educational institutions, computer manufacturers and others. Something over three hundred programs have been received to date for the program library. Of these, thirty have been analyzed and rewritten in library form.

Most of the state highway departments have centralized responsibility for computer operations in a distinct organizational unit usually independent of the technical divisions of the department. This unit, which is called the Computer Division, or in some cases the Computer Section or Computer Center, functions as a service unit providing electronic computing service to all segments of the organization. In most cases, it is organized to operate on what is known as the "closed shop" concept or some modification of it. In this mode of operation, the Computer Division has exclusive control of the computer and its associated equipment and is staffed to provide complete computer service. It has two primary functions—development and production.

Development covers the determination of feasible computer applications, collaboration with engineers and other specialists in the department in the development of procedures for the solution of specific problems and of computer programs for them, the revision and improvement of existing programs, the preparation of data sheets for use in submitting problem data for computation, and the preparation of manuals and other instructional material for use with each of the programs checked out for production.

Production covers the actual operation of the computer and its associated equipment in processing data and solving problems routed to the division including the review of incoming data and of computed results, the scheduling of work to insure efficient operation and effective service, the preparation of operating instructions and the maintenance of adequate operating records.

Staffing patterns vary with the size of the highway department, the type of computer used, and the stage reached in the transition to electronic computation. Initially, the work of the Computer Division is concentrated on development with little or no production. At this stage, the staff of the division may consist of from two to four programmers who operate the computer themselves in checking and "debugging" operations and one or more persons for punching cards or tape. Usually, the programmers are engineers drawn from the technical division of the department and trained in programming techniques. As computer programs are completed, the production load increases and a computer operator becomes necessary along with additional personnel for preparing input data and possibly others for operating ancillary equipment. Ultimately, production becomes the principal function of the division with development limited to an occasional new application and to the improvement of existing programs so that one or possibly two programmers may be adequate. The head of the Computer Division is, in most cases, an engineer with varied experience in the highway field selected from within the organization and trained in computer work.

With two exceptions, all of the highway departments using electronic computation have chosen to install their own computers rather than to use commercial computer service firms. The two exceptions are departments which are in process of exploring the use of electronic computation in their work. Because of the variations in the capabilities and costs of the several makes and models of computers on the market, no single criterion involving hours of use can be advanced on which to base a decision in the question of installation versus commercial service. This is essentially a question of relative costs. Where there is an appreciable volume of work which can be done on the computer, and this is true of all

state highway departments and many consulting firms, a cost comparison has invariably favored the installation of a computer within the organization. For smaller organizations, commercial service may prove more economical. There are now well established computer service firms which provide fast, dependable service for engineering computations.

Although the progress which has been made in the use of electronic computation in the highway field is truly remarkable, it is apparent that the potentialities of the computer have only begun to be realized. What has been accomplished up to now may be considered the initial phase of development in which effort has been concentrated on achieving as quickly as possible a high level of production in a broad range of applications. That this has been done so successfully is due in large measure to the fact that in developing computer programs the methods and procedures used have followed closely those used in manual computation. In general, the computations performed by the computer are virtually mechanized replicas of traditional manual computations. This has proved to be advantageous not only in accelerating program development but also in gaining acceptance of computer usage by designers and other specialists.

Now, however, with successful completion of this initial phase assured, highway administrators and engineers are in a position to evaluate more carefully the capabilities of the electronic computer in relation to their needs and to place greater emphasis on the development of procedures and methods more compatible with the computer's mode of operation.

Many engineering procedures and design methods which have become traditional in the highway field include practices, approximations and assumptions adopted solely to simplify the computations involved. The electronic computer, with its tremendous speed and its ability to handle lengthy complex calculations automatically in a continuous sequence, eliminates the need for such expedients. For example, when an electronic computer is used for location and design computations, profile elevations and cross-sections need not be taken at every station or half-station. They can be taken at irregular intervals as close together or as far apart as necessary to obtain an adequate representation of the terrain. In determining contours from spot elevations, in evaluating the accuracy of photogrammetric maps through the use of check profiles and in other operations of this general type, polynomial interpolation can be used in place of straightline interpolation to obtain a better correspondence to actual terrain conditions. In vertical alignment design, unequal-legged vertical curves can be used as easily as equal-legged vertical curves giving the designer much more flexibility in obtaining well-fitted, smooth-flowing grade lines. In structural design, the computer can solve a system of simultaneous equations just as easily as it can produce a solution from successive approximations.

In general, simplicity in design methods carries with it restrictions in range of application and sacrifices in accuracy. With the electronic computer, such simplicity need not be a factor for consideration. Emphasis can be placed on a systematic and rational treatment of a problem without particular regard to the length and intricacies of the mathematical manipulations involved. The use of analytic geometry in location and design can be thoroughly explored, more attention can be given to the use of coordinate systems as basic reference grids for many types of engineering problems, and the application of statistical analysis can be extended substantially. In the structural field, design problems can be viewed in the light of basic principles and rigorous mathematical analyses; design methods and criteria more closely related to the actual behavior of the structure in service can be developed; and more rational design specifications can be applied.

Greater attention can also be given to optimum design. Because the computer can complete an analysis in minutes as contrasted with hours or days by manual means, a much wider range of alternatives for a proposed project can be investigated than would otherwise be possible

in attempting to determine the most economical facility for the design criteria prescribed and the physical conditions involved. It is this application of electronic computation which offers greatest opportunity for monetary savings. Savings in construction and maintenance costs and in highway user costs achieved in this way may far exceed savings in design costs attained through electronic computation.

These are some of the things to which effort should be devoted in the next phase of development in the utlilization of electronic computers. There is need for a critical and objective examination of traditional concepts, procedures and methods; for precise definitions of basic objectives; for substantial amounts of "blue-sky thinking"; and for much research and experimentation.

Work along these lines is already in progress. At the Massachusetts Institute of Technology, under a cooperative agreement with the Massachusetts Department of Public Works and the Bureau of Public Roads, a new approach to the problem of optimum highway location and design combining photogrammetry and electronic computation (*2*) is in process of development. In this concept, called the Digital Terrain Model System, a band of interest covering the area to be investigated is selected by the engineer. A data coordinate system for the area is established and referenced to the State Plane Coordinate System. Terrain data is then taken from photogrammetric maps, or directly from aerial photographs mounted in a stereoplotter, in the form of coordinates of points along a series of parallel scan lines. The points are selected to represent, as truly as practicable, the surface of the ground and each point is defined by its three coordinates, x and y referenced to the data coordinate system, and z, referenced to an elevation datum plane. An automatic recording scanning device is employed which records the terrain data in a form in which it can be used directly as input for an electronic computer. In this way, the terrain data for the entire band of interest are recorded on rolls of tape or a deck of cards. The tape or cards are then fed into the computer and the coordinates are stored in the computer's memory thus forming a model of the terrain in digital form. Controlling dimensional data for each of any number of horizontal and vertical trial alignments are then entered in the computer which automatically produces alignment lengths, profiles, grades, and earthwork quantities, using the stored terrain data over and over again. From this information, the computer can develop construction costs for all trial alignments for combining with other costs in selecting the most economical route. This phase of the development project is nearing completion. Work is also in progress on computer programs for computing right-of-way costs and vehicle operating costs. These programs ultimately will become parts of a system of computer programs for benefit-cost studies.

A second new concept under study in this development project is called the Digital Cost Model System. It is similar to the Digital Terrain Model System in that the x and y coordinates of terrain points are the same; however, the z coordinates are in terms of dollars of cost rather than feet of elevation. The z coordinate for each point is the summation of the various costs involved in building the proposed highway through that point. By means of this digital model the actual path of least cost can be traced. Still other computer programs involving new concepts are planned. A section of Route 110 is being used to test the computer programs developed and to evaluate alternative techniques and procedures.

Work of this kind, directed toward the development of more efficient procedures and methods correlated with the electronic computer's capabilities and mode of operation, is sorely needed and should be extended into all phases of highway engineering.

Of comparable importance in the next phase of development of computer utilization are studies of existing practices in the light of the inherent characteristics of a centralized computer service. If electronic computers can be utilized most

efficiently in a central service unit, as indicated by experience gained thus far, it seems obvious that procedures, work flow patterns and schedules based on a coordinated functioning of the engineering staff and the computer unit must be developed. In a design operation, for example, the Computer Division can handle the computational burden quite satisfactorily but the engineer must do the engineering. These two parts of the design operation should be coordinated in such a way that both the engineer and the computer are used most effectively.

Efficient operation of the Computer Division requires careful scheduling of its work load—every problem cannot be solved immediately upon receipt of the problem data. On the other hand, efficient utilization of the engineering staff cannot be achieved if the engineer marks time while waiting for the results of the computation to be delivered to him. It seems evident that basic modifications in procedure, and perhaps in organizational structure as well, are necessary for overall operating efficiency. For example, instead of assigning projects to designers or design squads on a one-at-a-time basis, two or more projects might be assigned to each group or each engineer for concurrent handling. Alternatively, the entire design staff might be utilized as a working complex of specialists in the various phases of design. In either case, the engineer would act in a completely professional capacity, "multiplexing" his operations in much the same way as is done in other professional fields.

The development of work flow patterns and schedules for a system of this kind is clearly a formidable undertaking but one from which the returns, in terms of increased engineering productivity, could be substantial. Linear programming, a mathematical technique employed in Operations Research, has been applied to situations in industry of generally comparable characteristics with good results and appears to be equally applicable in this situation. For a specific program of projects to be advanced to the construction stage and with known engineering staff and computer performance capabilities, it should be possible to develop through the use of the linear programming technique, a detailed time schedule with all component operations properly interrelated, up to and including contract letting dates. Or, for specified contract letting dates, it should be possible to determine which projects can be handled by the available staff and which projects must be handled outside the department. The entire process can be programmed for the electronic computer to facilitate the initial analysis and the updating of the schedule from time to time as projects are added or deleted or as changes occur in the staff.

The linear programming technique is applicable to the coordination of any complex of interdependent activities and would seem to be a valuable device in other phases of highway administration, particularly in the long range planning of system improvements and in the planning and scheduling of construction and maintenance operations. A thorough investigation of its potentialities as well as those of other techniques employed in Operations Research might very well lead to a number of useful applications.

In the survey of the state highway departments mentioned previously, it was found that computer usage devoted to production, as distinguished from development, totaled nearly 1,300 hours a week of machine time for the 41 states which have their own computers. This is roughly equivalent to a working force of about 1,600 engineers and technicians. This is, of course, an interim figure. At the time of the survey, about one-half of the 41 states were operating their computers on a full shift basis, with a few using part of a second shift. Good progress is being made in the other states, however, and they should reach full shift operation in the near future. Further growth seems assured and with it will come the need to expand computer capacities. A number of highway departments have already reached this stage and have either installed a second computer or have replaced their first machine with a larger one. Although no one can foresee at this time the ultimate extent

of electronic computation in the highway field, it seems certain that there will be continued growth for a number of years and that the resultant increases in engineering productivity will be quite substantial.

Of equal or perhaps greater importance, however, are the potential benefits to the profession from the development of new concepts and methodology made possible by the electronic computer—more powerful techniques for planning and administration, more extensive research, more precise methods of analysis and design, more exhaustive investigations and more opportunity for the highway engineer to function in a truly professional way.

REFERENCES

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