# The Engineer's Approach to Electronic Computing Methods

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● THE glamorous and exciting descriptions of giant electronic "brains" so common in today's press have attracted the attention of all highway engineers. In highway research design, construction, and administration, computation by hand has long been a bottleneck preventing rapid fulfillment of ever expanding construction requirements. Each engineer, therefore, wants to learn what electronic computers can do to increase his output and remove the bottleneck. The purpose of this paper is to provide guideposts for the engineer who wishes to evaluate electronic methods with reference to his specific problems.

## DEFINITION

An electronic computer is a very fast calculating machine with the ability to memorize numbers and instructions. To solve a problem on an electronic computer, the engineer must reduce his method of solution to a very detailed list of instructions. The instructions, when memorized by the computer, will be executed at lightning speed to arrive at an answer. Desk calculators, which have no memory, have their arithmetic speed geared to the speed of the operator and are not classified as computers. It is important to note that the computer does not replace the calculator. The computer, the calculator, and manual arithmetic supplement each other to provide more answers in less time to the great variety of problems facing highway engineers. An electronic computer is not an electronic "brain." A brain is capable of making calculations and memorizing information; but, in addition, a brain can analyze data, draw inferences, make decisions, exercise judgment, and exhibit emotion. These things an electronic computer cannot do. But in its simplemindedness, an electronic computer is more useful than a brain since it is too unimaginative to make mistakes.

### Basic Components

1. Input. Means of entering instructions and data for each problem into the compute Information must be written in some electronic or mechanical code that the machine can read. Typical input media are punched cards, keyboards, punched paper tape, and magnetic tape. In general, a special transcription of data is required to prepare the input records (for example, survey notes must be copied from the field book to the punched card in order to feed them into the IBM Type 650 Magnetic Drum Computer when running the standard earthwork volume computation). This may represent additional work not required in a hand calculation. On the other hand, the transcription may eliminate work. Such a case occurs when punched cards are prepared automatically from readings obtained by a Kelsh plotter (in a device built for Ohio) and no field books are neede

2. Arithmetic and Logical Unit. Electronic circuits that can add, subtract, multiply, divide, and compare numbers. The circuitry of most computers contains built-in checking features that prevent the wrong answer from occurring without detection.

3. Control. Electronic circuits that interpret instructions and execute them by directing the operation of the other components.

4. Memory. High-speed storage for instructions and data. Each item stored in the memory has an address that enables the control unit to locate it directly and rapidly. The larger the memory, the more complicated the problem that can be solved at high speed. When the set of instructions exceeds the capacity of the memory, the computer has to refer to the slow input for the additional instructions. Typical memory units store data on the surface of magnetic cylinders that rotate at high speed past reading devices or in tiny magnetic cores, in vacuum tubes, or electromagnetic relays.

5. Output. Means of producing usable results. Output generally takes the same forms as input. An additional important form of output is the printed page. Printers

can be controlled to prepare reports, tables, lists, vouchers, and even graphs. By taking advantage of output flexibility, many manual operations can be eliminated.

It is important to note that there is no component in the computing system that thinks. The engineer still does all the thinking—the computer only does the arithmetic. In fact, by relieving him of hand calculations, a computer allows the engineer to spend the majority of his time on creative and supervisory projects.

## Available Computer Systems

1. Analog. The computer does not accept digits; instead it measures quantities. Gears or electronic circuits within the computer can be arranged to look like a physical problem and as the measurements are fed in one end, results come out of the other end of the machine. Since the circuits will differentiate and integrate, an analog computer is often an excellent tool for solving differential equations. It is usually inexpensive (less than $50,000) but limited in speed, accuracy, and versatility. Analog computers are most often found in research organizations where numerical solutions to problems are hard to formulate but where approximate answers are acceptable as a guide to further experiments. They are also useful in devices such as aggregate mixing scales where the computed results are subordinate to the act of measurement. Numerous electronics and instrument manufacturers produce a wide variety of analog computers.

2. Digital. The computer accepts actual digits and alphabetic characters and performs arithmetic in the manner of a desk calculator. All data must be converted to digits before it can be entered into the computer. Because all mathematical and logical problems (with the exception of some unsolvable problems and some problems for which no solution has been proven) can be solved by the rules of arithmetic, a digital computer is completely versatile. It is limited only by its speed and capacity. As a result, digital computers are preferred to analog except when analog-to-digital conversion is prohibitively expensive or when mobility and field conditions are critical. Digital computers, since they deal with numbers, are generally produced by the manufacturers of business machines Digital computers can be subclassified as:

a. Slow speed—speed per operation measured in the tens or hundreds of milliseconds (0.001 sec = 1 ms). Slow computers are usually desk size and have typewriters for input and output. They depend on the operator for many directions and store only a small set of instructions. They cost under $50,000 and are very easy to operate; therefore, they are useful in laboratories and engineering sections for short non-routine computations.

b. Intermediate speed—speed per operation is less than 10 ms but more than 1 ms. Costing from $50,000 to $400,000 depending on versatility, capacity, etc., the intermediate-speed computers offer the most advantages to large engineering organizations. One such machine could handle all the earthwork computations for a large state plus bridge computations, accounting, etc., in a single shift of operation The computer requires a staff of programmers and operators to keep it busy, but it is easy to use on both scientific and accounting calculations. Modular in design a small computer installation can be gradually expanded to meet changing requirements.

c. High speed—speed per operation less than 1 ms. Simple operations are completed in a matter of microseconds (0.000001 sec = 1 μs). High-speed computers are the real giants. In cost they range from about $1,500,000 up. Most such computers, although general purpose, are designed to do some jobs better than others. Thus, a high-speed, scientific computer will be faster at arithmetic than a high-speed data processing machine but not so good at reading and writing. No high-speed computers have yet been placed into operation solely for highway computations. Although this would not be impossible, it is unlikely that any single highway engineering organization could generate enough work to keep a high-speed machine busy year round. However, certain jobs that exceed that capacity of smaller machines can be solved, by a giant computer rented only for the time required.

## ECONOMIC JUSTIFICATION OF USE

The only justification for the use of electronic computation methods is economy.

This economy need not refer to a money saving; any economy of manpower, materials, or time is reflected in a lower unit cost of construction. It is necessary for the engineer to determine whether electronic methods will lower his unit costs and, if so, what type of computer will yield the greatest reduction. He can learn the value of electronic methods only by studying his requirements and existing procedures. Then, with the assistance of computer experts, manufacturers' representatives, and short training courses he can compare the relative cost of various systems.

To evaluate the use of computers in his organization, the engineer should answer the following questions:

1. Am I missing deadlines?
2. Are my engineers and engineering aides at their desk calculators more than a few minutes a day?
3. Am I accepting inferior designs because there is no time for analyzing alternates?
4. Am I losing the statistical value of performance data because I have no one available to process it?
5. Do I spend too much time on accounting and administrative paperwork?
6. Am I unable to take on more construction obligations because my office staff is overloaded?

If the answer to any of the above questions is "yes," an electronic computer may be worthwhile. The organization should appoint a computer committee to investigate the problems in detail and solicit expert advice on how to correct the problems through mechanization. Preferably the committee should contain members from each division of the organization—engineering, research, and administration—to provide a complete picture of requirements

The committee will find certain specific processes which can be automated but, which by themselves, do not justify the expense. Several processes, however, can often be performed by a single computer, the cost of which is less than the accumulated savings from all the processes. Such is the case with a large group of engineering problems:

1. Survey: a. traverse closure, b. triangulation net adjustment, and c. coordinate conversion.
2. Highway plan and profile design: a earthwork volume, b land value, and c. grade and curve layout.
3. Bridge design: a. stress analysis, b. beam and bent design, and c. span length.
4. Traffic analysis: a. origin and destination and b. demand forecast
5. Drainage design: a runoff and b. drainage structures.
6. Traffic engineering: a. intersections and b. urban traffic movement control.
7. Drafting: a. cross-section, b. plan and profile, and c. mass diagram.

Each of these represents a great deal of manual effort. A single intermediate speed computer could handle the majority of them for a large engineering outfit.

Despite the ability to solve more than one problem on a single computer, the committee will see that some jobs do not easily fall into the same pattern as the rest. For instance, the data for all the above jobs can be punched into cards for direct entry into a digital computer; but the amount of computing per punched card varies from practically none for drafting of various charts, to a vast amount for traffic analysis Obviously, all of the best features of a computer could not be used all of the time for such different jobs.

The committee should separate these problems into three categories.

1. The mechanical jobs requiring little computing, such as drafting, should be considered for analog plotting machines and standard electronic accounting machines. The plotting machines interpret holes in punched cards (or other input media) as coordinates of the point to be plotted. The result can take the form of a graph, a contour map, or a scatter diagram. Standard card operated accounting machines, normally used for preparing tabulated lists, can also be programmed to draw a chart Since their output is very rough, they are preferred only if they are already installed for accounting purposes. After all other jobs have been accommodated, a digital computer could perform such jobs in its spare time.

2. The very bulky computing jobs such as traffic analysis should be considered for high speed digital computers. The detailed programming and operation of the computer

can be performed by the service bureau from which computer time is purchased.

3. All other jobs, which represent the bulk of daily computations should be considered for an intermediate (or slow) speed digital computer installed in the organization.

After breaking down the categories, the committee must compare the cost of existing procedures to the cost of computer methods. In the case of existing methods, the factors involved are cost of personnel (man-hours), cost of equipment (hourly rate), and cost of limited data handling capacity (lost contracts, missed deadline penalties).

For the computer, the same factors are considered although different personnel grades and equipment are used. An additional factor—cost of conversion to new methods—can be estimated. If the total computer costs, including intangibles, are less than present costs, the computer should be installed. If the computer costs more but does a great deal of desired work beyond present capacity, the computer is still justified. Otherwise, a computer will merely increase costs, and the committee should investigate sharing a machine with another group, or purchasing computer services from a commercial services bureau.

The above list of engineering applications was presented as an example of the types of job facing the computer committee. They are also concerned with the mechanization of research and administrative problems. Research wanders all over the lot as far as computation is concerned. Many projects are concerned with devices; here, analog computers, small enough to fit into a field test or experiment, are useful. Other projects are based on mathematical theory and statistical analysis. The latter can be handled by a digital computer, the speed of which depends on the scope of the problem. It is convenient for a small research group to plan on using their organization's intermediate speed computer except for the occasional problem that may call for a high speed service bureau machine. There should be no reluctance on the part of the scientists to put even small computing jobs on a digital computer. The more arithmetic he farms out, the more time the researcher leaves for thought.

For the administrator, there is no need to explain that electronic computers can do his payroll, cost accounting, budget preparation, fiscal accounting, personnel accounting, supply and inventory control, equipment and maintenance reporting, sales analysis, profit and loss statement, and bid evaluation. In every case, machine accounting is a proven advantage over manual accounting. The speedup available in an electronic computer is that much more desirable. Less obvious to the non-professionals in an engineering organization is the tremendous saving possible by letting the computer do operations programming. The assignment of vehicles and earthmoving equipment can be correlated with various material stockpile locations to arrive at minimum haul distances and a reduced number of trips. The computer can assign equipment daily as a direct assistant to the dispatcher. The procedure used is called "linear programming" and can be applied to the optimization of any definable system of linear inequalities. In addition, statistical analysis of operational data can be readily processed by the computer to yield correlation coefficients and variance in a fraction of the time formerly taken by the statistician.

## COMPUTER PERSONNEL

Rough estimates of benefits from electronic methods will lead the computer committee to recommend detailed studies of a selected computer. The computer committee should select a small staff to study computer programming in order to work out exact cost figures on the most important problems. The staff should consist of two or three of the best men in the organization at an operational level. They must devote full time to their computer work to turn out the desired results. Since these same men would logically organize and run the computer installation, their assignment to the computer committee must be a permanent relocation and calls for a new job description. The prestige and pay associated with this job must be attractive enough to hold a good man. The cost of any computer is so high that it would be foolish to economize on supervisors at the expense of an efficient installation.

A training course of from 1 to 6 weeks is adequate preparation for the staff members. The courses given by manufacturers teach the students programming and data handling techniques. After training, and with the help of manufacturers' personnel, the staff will prepare programs that take advantage of machine features not obvious to the computer committee. For instance, in IBM's earthwork volume computation, the mass diagram is a by-product of the computation. The simplicity of such a combination of results was not clear until much of the program had been written. The staff must be familiar with all aspects of the organization's operations so that they can reduce the work necessary to provide data for computation. For example, in any problems involving survey data, no processing should be required before computation other than the punching of cards directly from the field notes. Or, as in Ohio, certain stages of survey can be eliminated when equivalent terrain data can be obtained from aerial photos. In design of structures, ground rules calling for 4 repetitions of a moment distribution or comparisons of 6 alternate designs for pricing can be replaced by more desirable computer methods. Iterative methods can be carried out until no further improvement is obtained by successive trials. Price comparisons can be made in detail for all feasible alternate designs regardless of their number. Perhaps speed is more important than quantity of computations. The staff can set up a schedule for routine computations so that results can be returned to the field the day after data are received at the computer site.

When the major problems have been laid out for the computer, it is time to build up the permanent computer staff. From 4 to 15 full time programmers and machine operators will be required some 12 to 18 months before the computer is to be delivered. Before the date of installation, they must receive training and then proceed to program new jobs, revise earlier programs, test programs, and teach the organization how the computer will serve it. The most efficient computer installation is a relatively large closed shop where all programming is done by professional programmers only. Such an arrangement is not always possible. As an alternate, selected people outside the installation learn to program part time in order to augment a small permanent staff.

The closed shop is not to be construed as preventing outside engineers from originating problems. They should be encouraged to bring problems in for solution, but they should not be asked to spend a couple of weeks of valuable engineering time writing a program that could probably be written better by a programmer.

All people using the computer will have to reorient themselves with respect to mathematics and logic. Unfortunately, the effort to reduce computation time has, over the years, substituted simple form solutions for algebraic or geometric problems. Engineers who can calculate double meridian distance areas flawlessly would be hard put to find the area of a combination cut and fill section by trigonometry. Lack of practice prevents the engineer from remembering how a given method was derived—what equations apply. Since an equation is generally more efficient than any procedure substituted for it, the computer should be programmed to solve equations. This means that engineers as a group will have to relearn the fundamentals of their trade. Fortunately, such a reversion, not only is an aid to computations, but it is also a stimulant to the development of new and improved engineering methods.

## INSTALLATION

The planning and preparation for a computer installation takes a considerable amount of time. Depending on the variety of jobs to be assigned to the computer, from 6 to 24 months should be allowed for detailed planning after the computer has been ordered and before it is installed. As stated earlier, there are only two general classes of jobs to be done on the computer—daily routine data processing jobs, such as earthwork calculations, and recurring jobs, such as bridge design, have the characteristic that the computer program used in their solution is written once and used endlessly; one-shot jobs, such as traffic analysis, which occur with random frequency but are too big for hand calculation, may require a different program for each occurrence. But neither class can be done without a completely tested program. All programs for recurrent jobs and foreseeable occasional jobs must be finished prior to machine installation so that useful work can be done the day the computer is turned over to the organization. For large engineering organizations, routine data processing is the bread and butter paying for the computer. Experience of one manufacturer which has installed some 500 intermediate-speed computers primarily for data processing, indicates that the most successful installations were those allowing from 15 to 24 months for preparatory planning.

The location of the computer must be recommended by the computer committee. In engineering organizations where a single intermediate-speed computer can handle all computations, the machine should be centrally located at the organization headquarters. Data from the field can be funneled to the center (via mail, messenger, radio, teletype, transceiver, etc.), processed, and returned immediately. If the communication lag offsets the advantages of centralization as it might in international operations, smaller computers would be appropriate at each sub-headquarters. A more common reason for decentralizing occurs in a completely decentralized organization. When sub-headquarters do all their own work and merely send reports to the super-headquarters, a computer would be assigned to each group that has a work load justifying electronic methods. In this case, it is often important to have a similar or, at least, compatible machine at super-headquarters to process the field reports and to present data for management decisions.

## NEED FOR COMPUTERS

Computers are needed to solve engineering computations presently done by professional personnel or not done at all. They provide additional benefits in accuracy, speed and ease of operation, as well as research and development possibilities. Results become available in minutes rather than weeks and they represent a more complete analysis of the data than was ever possible with manual methods. So far the most urgent projects have come under attack from the computer planners. Survey and earthwork problems have been solved in programs which are available from manufacturers' libraries and computer user groups. Bridge design is rapidly being adapted for electronic methods. So are the other problems listed earlier.

For example, an organization which is faced with extensive culvert construction may wish to take advantage of the benefits of a computer. The engineer would examine his problem and see that the size and gage of each culvert can be based on such field data as rainfall intensity, drainage area, etc. But the solution of Manning's formula which involves fractional exponents is not easy. By collecting all the field data for a culvert in a punched card, the engineer can write a computer program to solve Manning's formula for a single culvert. Then, by repetition all the culverts can be designed using the same program. As he writes his program, the engineer will see that it is practical to place a table of pipe sizes, gages, and standard culvert areas in the memory of the computer. As the quantity of runoff to be handled by each culvert is calculated, it can be used to find the exact area of culvert required. This area, when compared to the table of standards, will determine the particular type of culvert to use. The time to run through the entire process would take only a few seconds on an intermediate speed computer (after the data have been prepared). Therefore, this job would easily fit on a machine originally procured to do other types of calculations.

The drainage example illustrates how many distasteful or difficult manual computations can be converted to electronic methods. Another important area is the initiation of jobs not now done. Today, it is assumed that aggregate should be hauled from the nearest yard or borrow pit to the destination When there are many aggregate sources with different capacities, the assumption does not always result in the least cost of hauling But no one has time to compute what source should supply each destination on a large contract. There is a method, called the "transportation problem," for mathematically minimizing the cost of hauling. All that is required is a list of aggregate available from each source along with requirements at each destination and the distance between each source and each destination. The data all arranged into a set of simultaneous equations which are solved by a repetitive process. At each stage of the process there are sufficient clues to indicate how to make the next try better than the last. At the end, a simple clue shows that no further reduction in hauling cost is possible. The results tell exactly how many yards to ship from each source to each destination to fill the requirements at the lowest cost.

Such a transportation computation is very time consuming when more than a few sources are considered. Even on a computer, a day's hauling assignments might take half an hour to solve. But there is this advantage—using a program available today in program libraries, the best hauling assignments for each day's operations can be made as soon as all the requirements are submitted. By processing phone reports from the aggregate sources against radio, phone, or written requisitions from the road gangs, daily programming of haul trucks can become an efficient, economical procedure.

The transportation problem and its more general parent "linear programming" optimize more than just aggregate hauling costs. They will compute maximum profit or minimum cost for any operation which can be adequately described. It would be desirable to optimize, the dispatching of earth moving equipment for an entire organization as a unit. But those who have tried know that the task is impossible without the aid of electronic computers. On the other hand, an electronic computer can speed through the repetitive arithmetic at a rate inconceivable by other means. So the organization which uses a computer to take the burden of daily engineering calculation from the engineers' shoulders automatically has a tool capable of improving management efficiency by programming all organizational operations.

## CONCLUSION

The immensity of the new Federal highway programs has highlighted the need for increasing engineering productivity. New earthmoving equipment will increase speed of building. New prefab and surface laying techniques will also contribute to the "doing" end of highway construction. New instruments, better surveying methods, new techniques of reproduction will speed up the "collecting" phase of design. But none of these changes affect the "thinking" phase. The only way to improve "thinking" output is to put more brain cells to work. That doesn't mean waiting until a new generation graduates from college. It means trying for 100 percent use of the trained, experienced brains now available. Electronic computers will do this in two ways: (1) the computers will do the back work now occupying a major portion of each engineer's time; (2) the computer will amplify the output of each engineer by giving him improved analyses of the facts on which he bases his decisions.

For these reasons, each manager must investigate electronic computing methods as they pertain to him, and he must bear in mind that he is studying equipment which is so powerful that it must be operated by his best men lest it become a hindrance instead of a help. He must realize too that the computer will not think for him but will merely provide him with better information, sooner, and in more quantity than he ever had before. Properly used, the computer will be a tool contributing to his more effective leadership.