Increasing Productivity in Engineering

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In planning for a further acceleration in highway construction it is evident that it will not be possible to provide the additional engineering capacity required simply by employing more engineers. Even with more intensive recruitment, it appears unlikely that additional engineers can be brought into the highway field from the colleges and from other segments of civil engineering in numbers much larger than those required to offset losses.

Consequently, the larger capacity needed will have to be provided by increasing the productivity of the engineering force available, both engineers and supporting personnel, to the extent necessary to bring production into balance with program needs. Furthermore, this will have to be done without any significant impairment of the quality of engineering performance.

There are a number of ways in which engineering productivity might be increased, all of which appear to offer promise. However, the discussion in this paper is limited specifically to ways and means of increasing productivity through improved engineering operations, particularly in location, road design, bridge design, and the preparation of plans and estimates. It is this series of processes which frequently controls the speed with which programmed projects can be placed under contract.

●IN 1955, the Highway Research Board conducted a survey to determine the progress made by the state and territorial highway departments in improving their operations and in adapting to their needs the time-and labor-saving methods, procedures, and devices made available by recent technological developments. A progress report was issued in July 1955 (1) and the complete findings are now being published.

This survey, together with information from other sources, reveals that considerable progress has already been made in one highway department or another in increasing engineering productivity through the adoption of improvements in engineering operations. The progress has been spotty however, and the procedures, methods, and devices used in much of our highway engineering work are essentially the same today as they were years ago.

The reductions in time and manpower requirements achieved in the individual highway departments which have developed improved practices indicate that a very substantial increase in over-all productivity can be attained simply through the general adoption of such practices. They also indicate the further advantage to be gained through continued investigation and development.

NEW DEVELOPMENTS AND FURTHER POSSIBILITIES

Some of the improvements in engineering operations in the highway departments are the result of a more advantageous utilization of procedures, methods, and devices which have been used to a lesser extent for a number of years. Others consist of entirely new methods which have been developed within the highway agencies. Still others are devices or adaptations of methods which originated outside the highway field. In some cases, further possibilities, not yet fully explored, are indicated.

Use of Aerial Surveys and Photogrammetry

Most of the highway departments use aerial photographs in preliminary location studies and to some extent in final location. A lesser number use topographic maps prepared by photogrammetric methods in lieu of ground surveys and maps prepared manually. Photogrammetry has developed rapidly in the last few years and the highway departments which use it report savings in time up to about 75 percent of the time required by ground methods. The saving in manpower is even greater. Where the work is done by contract, aerial photographs and preliminary location topographic maps are obtained without using any highway department personnel. A very considerable added advantage

of the aerial survey method is the wider coverage and the complete information provided which tend to permit better engineering analysis and a more economic location.

In many cases, by using aerial photographs and maps made from them, the necessary reconnaissance studies can be completed, the final line and grade established, the construction plans and specifications completed, the engineer's estimate made, and right-of-way negotiations either completed or at least begun without placing a survey party in the field except for checks on unusual conditions.

Further increases in productivity are available through the use of aerial photographs in the determination of drainage areas, drainage conditions, structure requirements, and property damage; in access studies for limited access facilities; in the identification of soil types along the route including areas where rock or unstable material occurs and of possible sources of aggregate; and for detailed layouts of interchanges, grade-separations, and bridges.

Used to maximum advantage, aerial surveys and photogrammetry offer a means of very substantially increasing productivity not only through manpower savings but also through reductions in over-all time requirements for advancing projects to the construction stage.

Mechanization of Survey Computations

Survey computations for location traverses and property boundaries are tedious and time-consuming. In recent months, the California Division of Highways (2) in collaboration with the International Business Machines Corporation, and independently, the Corps of Engineers' Research and Development Laboratories (3) in collaboration with the Monroe Calculating Machine Company, have both developed methods for computing coordinates, error of closure, and area on electronic computers. Attention is now being directed to the solution of other surveying and engineering problems on the computers. The Corps of Engineers has under contract the development of an electronic computer housed in a van-type vehicle which is to be used for all types of survey computations in the field.

New Surveying Instruments

Surveying instruments of improved design have been developed which make possible substantial savings in time with equal or better precision than the usual instruments. For traverse work, compact, lightweight transits with optical plummets, direct micrometer reading of circles, and other time-saving features are available. For leveling, a new self-leveling level is reported to reduce by 50 percent the time required to run levels. At the same time it produces results of first order accuracy. It is a small, ruggedly constructed instrument with a circular plate level which is centered approximately in setting up the instrument. A pendulum and prism device inside the telescope then levels the line of sight automatically and keeps it level no matter which way the telescope is pointed. California and Virginia are using this level and both report good results.

For distance measurement, an electronic instrument called a "geodimeter" has been developed in Sweden. This instrument is easily portable and operates by projecting an almost invisible red light beam which is reflected from a plane mirror target. For distances up to 10 miles, an accuracy of 1 in 300,000 is obtainable. The time required to set up the equipment and take the observations is about 2 hours with an additional hour or two required for computation. While this device is not appropriate for ordinary highway work, it is interesting as an example of the progress being made in this area and as a possible forerunner of electronic distance measuring instruments suitable for highway and property surveys.

Use of State Plane Coordinate Systems

In the past, much wasted effort has resulted from failure to "tie in" traverse points and property corners to state plane coordinate systems. The immediate advantage in using the coordinate system lies in the elimination of the return traverse for closure, but of much more importance is the elimination of the need for complete new surveys

when change or reconstruction becomes necessary. In a number of highway departments, it is now standard practice to reference surveys to the state system of plane coordinates and to monument traverses and property boundaries. In these states an increasingly dense network of monumented control points is being developed through this practice. In addition to preserving the survey, the monumented points provide a convenient means of closure for other surveys and can be used for ground control in aerial mapping projects.

Aids in Soil Surveys

The use of aerial photographs in identifying soil types has been mentioned previously. In combination with agricultural soil maps, geological maps, and where appropriate the refraction-seismic or earth-resistivity methods of subsurface exploration, their use permits obtaining desired information with a minimum of sampling and testing. The use of engineering soil maps where available is particularly helpful not only in soil surveys but also in tending to improve the utilization of local materials in road construction.

Road Design Standards and Standard Designs

In road design, standards for various elements of geometric design have been developed by a number of highway departments. Others rely on the design values and details recommended by the American Association of State Highway Officials in "A Policy on Geometric Design of Rural Highways" published in 1954. A companion treatise, "A Policy on Arterial Highways in Urban Areas" is in preparation. Design methods and standards for the structural design of the roadway have also been developed in a number of highway departments.

While these data are intended to serve as guides and criteria in assuring adequate design, they incidentally contribute to improved productivity.

Standard designs for culverts, endwalls, underdrains, inlets, catch basins, manholes, slope protection, cribbing, retaining walls, and other appurtenances are used in varying degrees by many of the highway departments. Charts and nomographs for rainfall intensities, runoff for small drainage areas, and culvert size determinations are used to some extent.

A few of the highway departments include all design material of this kind in a manual together with other data in tabular and chart form needed for day-to-day reference. This is not only effective in saving time for the experienced designer but it is invaluable for the young engineer newly assigned to design.

Bridge Design Aids and Standard Designs

In bridge design, many aids are available and are used in varying degrees in a number of highway departments to increase the designer's productivity. These include influence lines for reactions, shears and moments, tables and charts for reinforced concrete factors, slab thickness and reinforcement, fixed-end moments, carryover and stiffness coefficients, deflections, direct stress and bending, retaining wall design, pile footings, rainfall intensities, runoff, open channel flow, and other similar data.

In addition, a number of highway departments use standard designs for bridge superstructures. In two or three states standard designs are used for simply supported spans up to about 60 feet and for continuous spans up to about 250 feet, for various roadway widths and skews. In California, standard plans have been developed for multiple span, longitudinally reinforced, concrete slab superstructures which are complete to such an extent that a detailer can produce a complete set of finished plans even though he is not familiar with structural analysis and design procedures. In Georgia and New Mexico, standard designs using precast deck units have been developed.

Standard substructure designs including various types of bents, piers, and abutments are also used but to a lesser extent.

The potential increase in engineering productivity through maximum utilization of design aids and standard designs appears to be quite large and to warrant further development. A common objection to the use of standard bridge designs has been that the skew is different in practically every crossing. In this connection, is it necessary to use

skews measured to the nearest minute of angle or even to the nearest degree? Would it not be possible to use skews to the nearest five degrees particularly for stream crossings where the banks are not normally aligned precisely. If so, it might be practicable to use standard supersturcture designs for many of the bridges to be constructed in the expanded programs.

Standard designs are obviously not practicable for the larger, more complex structures, but even there some advantage may be gained by the greater use of standard details.

Another device of value in increasing productivity is used in Nebraska and possibly in other states. As many design procedures as possible are outlined and detailed by steps to minimize errors and to permit designers with limited experience to make adequate designs expeditiously. Procedures of this kind would appear to be effective in adapting standard designs to individual situations as well as in original design.

While high-speed electronic computers have been used only to a very slight extent in bridge design up to now, their potential value in design computation, particularly for indeterminate structures, appears to be quite considerable and to warrant further investigation. Very substantial increases in productivity may be possible.

Preparation of Plans

There is considerable variation among the highway departments in the amount of detail shown on construction plans and in their format. Modifications have been made in a number of states to eliminate duplication and unnecessary detail. The principal developments include the placing of information relative to drainage structures, guardrail, fencing, and other miscellaneous items in consolidated lists or schedules instead of on the individual plan sheets; the elimination of notes that are covered in the specifications; the inclusion in the general notes of many of the notes previously shown on plan-profile sheets; and the increased use of standard sheets covering typical sections, incidental construction, general notes and tables, quantity tabulations, small bridges, and culverts and other drainage structures and facilities.

A number of highway departments have substituted typing for hand lettering for the index of sheets, the tabulation of quantities, various schedules and tables, and the general notes. One or two departments use printed adhesive acetate sheets which are affixed to the tracings in place of hand lettering.

In a few highway departments, tracing has been almost entirely eliminated. Plans are prepared in pencil only and cloth reproductions equivalent to ink tracings are made by photographic reproduction processes.

Michigan and also Kansas are investigating the possibility of making plan and profile sheets by photogrammetric methods direct from aerial photographs. It is estimated that this process, if proven practicable, will reduce the cost of preparing plan and profile sheets by about 60 percent. At the same time, it would make possible very considerable reductions in time and manpower requirements.

In developing construction plans for bridges, the photographic reproduction method of producing "tracings" is also used to good advantage in few of the highway departments. By this method a tracing is produced in a matter of minutes where several days might be required in the ordinary manual method. In addition, this method provides considerable flexibility in the development of new plans from parts of plans for previously designed structures and from standard details. In this connection, it is interesting to note that the General Electric Company, by the use of a similar process recently adopted, is reported to have reduced the time required for producing engineering drawings by 95 percent. The engineer prepares a coded order to the reproduction department where a composite film transparency comprising reusable positive film overlays is used to print a translucent positive photo-mechanically which then becomes the original "tracing."

In addition to saving the designer's time, eliminating tracing and reducing over-all time requirements, this process eliminates errors which are bound to occur in manual copying and tracing.

Mechanization of Earthwork Computation

In computing earthwork quantities by the traditional method, weeks and even months

are spent in plotting, checking, inking, templating, and planimetering cross sections. One highway department, in preparing work schedules, allows an average of 17 engineering aid man-days per mile for this work including the computation of volumes. While this may be a liberal allowance, it will serve for comparison. Oregon has developed and is using a method (4) in which earthwork quantities are computed on IBM business machines at an average rate of one mile in 7 hours without plotting cross sections at all.

In an entirely independent study, the Bureau of Public Roads, in collaboration with the International Business Machines Corporation, and also with the Bendix Aviation Company, has developed a method for computing earthwork quantities on high-speed electronic computers at the rate of about 3 hours per mile also without plotting cross sections. Where the cross sections are taken by ground methods, the rod readings and offsets as shown in the field notes are fed into the computer together with design data and the answer is delivered in cubic yards of cut and fill for each station length or partial station length and also cumulatively to any desired point or for the entire project. Where the cross section data are taken from aerial photographs or topographic maps made from them, elevations and offsets are fed into the computer instead of rod readings and offsets, otherwise the process is the same.

California has also been working on this problem and has very recently developed a solution for use with an IBM computer.

Elimination of Field Cross Sectioning

Where aerial photographs or topographic maps made from them are available at appropriate scales, adequate cross section data can be obtained from them thus eliminating the need for field cross sectioning. Considering that complete cross sections normally are taken at least twice on each project and in many cases, three times, the productivity increase available from the elimination of field cross sectioning is appreciable. Comparisons which have been made show that earthwork quantities obtained by using cross-section data taken from aerial photographs or maps agree within 3 to 5 percent with quantities obtained by using cross-section data taken by ground methods. There is, of course, no reason to assume that either method is more accurate than the other.

Two or three highway departments recently have used this new method for computing final pay quantities as well as quantities for bidding purposes. In order to obtain specific comparisons of the two methods and also to explore more fully the advantage of using electronic computation in combination with photogrammetric methods in highway location the Bureau of Public Roads is planning time, cost, manpower, and quality studies on selected forest road projects in the west. The studies will also include comparisons with the method being investigated by California which it calls the "contour-grading" plan (5). In this method, volumes are obtained by multiplying areas lying in horizontal planes by vertical distances in contrast to the conventional method of multiplying areas lying in vertical planes by horizontal distances. The areas enclosed by the original and final contours at each contour level are planimetered, averaged, and multiplied by the contour interval. This method has served well in other fields of civil engineering and California is exploring its suitability for highway work.

Where grading is light, it is often feasible to make payment for grading on a mileage basis thus eliminating earthwork computations for roadway excavation entirely. In some states excavation for pipe culverts and other drainage facilities is not paid for separately, but is included in the payment for construction of the facility. A detailed study of bid items may reveal other cases in which computation can be eliminated by using a mileage or lump sum basis, or by covering incidental work in the basic item.

Centralization of Estimating and Pricing

In some states, there is an estimating and pricing section in the design department which is responsible for analyzing bids, maintaining current price data for all parts of the state, and preparing and pricing estimates. All work of this kind is centered in the section thus tending to develop a high degree of efficiency.

Increasing Length of Projects Let to Contract

Increasing the length of projects let to contract eliminates repetition and duplication all along the line and thus contributes substantially to increased productivity. The advantage carries over into construction where better utilization of field personnel is made possible. This has been done in a number of highway departments with good results.

CONCLUSIONS

In conclusion it appears from this discussion that if each highway department were to adopt the improvements developed in each of the other highway departments and if, in addition, they were to use aerial surveys and photogrammetry, photographic reproduction processes, electronic computers, standard designs, and other time-saving methods and devices to maximum advantage, much of the increased productivity needed to meet new program demands might very well be attained by these means alone and in a relatively short time.

If this were done, field surveys would be considerably reduced, manual plotting of topography and cross sections would be practically eliminated, survey and earthwork computations as well as other lengthy computations would be done by electronic computers manned by trained operators, structural design and drafting for drainage structures and other appurtenances would be limited to unusual situations, bridge design would be limited largely to complex structures and the adaptation of standard designs to special conditions, detailing and drafting would be reduced considerably, and tracing would be eliminated entirely.

Corresponding adjustments in organizational and operational arrangements based on an optimum combination of machines, operators, clerks, technicians, engineering aids, and engineers would produce still further gains in productivity. Routine operations could be performed by trained machine operators and engineering clerks supervised by technicians skilled in photogrammetric methods, electronic computer programming and operation, photographic reporduction processes, estimating and pricing, and other specializations. The supervising technician positions could well be career service positions carrying considerable responsibility with attractive salaries. Under these conditions, it should be possible to recruit and hold individuals of high competence capable of sustained production with a minimum of direction.

The engineers would thus be relieved of time-consuming routine tasks and direct supervision of production leaving them free for analysis, evaluation, design, and development in a truly professional way.

These accomplishments and potentialities demonstrate the value of the kind of investigation and development which has led to the improved procedures, methods, and devices cited, not only in improving engineering productivity, but also in lowering costs and in reducing the time required to advance projects to the construction stage. They emphasize the importance of continuing and extending such investigation and development, at an accelerated rate and on a coordinated basis if possible, to achieve still further increases in engineering productivity and still further reductions in lead time and cost.

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