USE OF INTERACTIVE GRAPHICS IN BRIDGE ANALYSIS AND DESIGN

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

August 1983
VHTRC 84-R7

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SUMMARY

This study evaluated the role of computer-aided design (CAD), including interactive graphics, in engineering design applications, especially in the design activities of the Virginia Department of Highways and Transportation.

A review of the hardware and software applicable to CAD indicated the availability of technology for performing a variety of tasks in the design process, particularly those involving drafting and the preparation of plans. Almost all computer manufacturers market some form of hardware and software packages; however, some of these have not been tested adequately in real applications within transportation departments.

A survey of the CAD systems, including those used in several transportation departments, revealed that the most satisfactory system is a self-contained, turnkey CAD system consisting of a dedicated computer, one or more graphics terminals with high resolution graphics, and software specifically developed for the desired applications. At present several transportation departments use the turnkey systems and benefit from the convenience and efficiency they provide in a variety of uses. While in bridge design the emphasis is on the graphical output of structural plans and details, the CAD system can be used for road design, mapping, planimetric surveys, and roadway repair, widening, and location.

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INTRODUCTION

Within recent years, an increasing number of engineering activities relating to analysis and design have come to rely heavily on the use of high-speed digital computers. The computational capability for such activities has been available for industrial and engineering use for over two decades; however, only within the past few years has it become almost universally used as a result of the cost effectiveness of computer hardware and the availability of supporting software.

Recent efforts have been concerned with the development and use of computer-aided design (CAD), a computational capability that will synthesize the complete design function of entire structural components and provide a graphical output. In the case of a bridge, for example, automated design would produce an optimum structure in terms of member sizing, girder spacing, deck thickness, and other design parameters while requiring only minimal input information such as span length and vehicle loading. While significant progress is being made, such a complete design capability is not yet available for general use. However, certain elements of CAD, in particular the capability for automated drafting, are available and widely used. In fact CAD, as currently interpreted, does not involve complete interactive design but consists of computational algorithms which, together with an interactive graphics terminal, can be used to effect selected design activities and to manipulate graphical data for final plan drafting.

A number of state departments of transportation have, within the past few years, embarked on ambitious programs of acquiring and incorporating interactive graphics hardware and software for automated design and drafting in their design divisions. Because such systems involve considerable expenditures of funds, at least initially, a careful assessment and evaluation is particularly important when a CAD system is being considered by any state agency. Experience in other departments of transportation has shown, however, that the use of such a system can be not only cost effective in the long run, but can significantly enhance the quality and reliability of work produced. Accordingly, it is appropriate and timely for the Bridge Division and similar design divisions within the Virginia Department of Highways and Transportation to consider the capabilities of the CAD systems available and the experience of interactive graphics and CAD applications in other departments of transportation.

OBJECTIVES

The broad objective of this study was to investigate the feasibility of incorporating an interactive graphics capability into the traditional analysis and design activities of the Bridge Division of the Virginia Department of Highways and Transportation. Toward this end, the following objectives were addressed.

1. The state-of-the-art capability of interactive graphics hardware and software was investigated by identifying vendors that manufacture and market such equipment, determining the types of hardware configurations available and determining the availability and capability of compatible software. Emphasis was placed on hardware/software configurations that seemed to most nearly meet the needs of bridge engineers and that had been used with success in other departments of transportation.

2. The applicability of existing hardware/software capabilities in bridge analysis and design was studied. Specifically, this task was to determine how other departments of transportation were utilizing interactive graphics and CAD, the experience of these departments, and the applications that they had found to be most practical. This information was obtained from the Federal Highway Administration and a number of highway departments known to have used interactive graphics.

3. The final task was to prepare recommendations regarding the feasibility of using interactive graphics in the design activities of the Virginia Department of Highways and Transportation's Bridge Division. These recommendations are presented in a subsequent section.

SCOPE AND METHODOLOGY

This study concentrated primarily on those aspects of CAD and interactive graphics that were seen to pertain directly to the mission of the Department, particularly to the design activities of the Bridge Division. Thus, applications of CAD to other engineering fields were not considered.

In collecting information regarding hardware and software capabilities and in reviewing current applications of interactive graphics in the CAD environment, only those aspects believed to be relevant to the activities of a highway department were considered. Thus, while a few engineering firms were contacted regarding their experience with CAD, and while a limited amount of information relating to industrial applications was gathered, the major effort was given to contacting vendors whose products had been considered by transportation departments, and to contacting and visiting transportation departments currently utilizing such equipment.

One further point should be kept in mind. The speed with which interactive graphics and CAD are being developed and expanded is truly incredible. Thus, what might have been state of the art one or two years ago may well be approaching obsolescence today. This has become clear as this report is being prepared in the fall of 1982 and winter of 1983 while much of the information developed was collected during the latter part of 1981 and in the early part of 1982. Even in this brief interim period, the capabilities in both hardware and software that will be available in the late 1980s are significantly more advanced than those available and described in this report. While the summary and conclusions of this report will imply some urgency in the Bridge Division of the Virginia Department of Highways and Transportation involving itself as soon as possible in utilizing interactive graphics to as large an extent as possible, such urgency is magnified by the tremendous speed at which the interactive graphics and CAD area is progressing.

HARDWARE/SOFTWARE CAPABILITY

Within the general field of interactive graphics and CAD there are a large number of hardware and software vendors, but a discussion of the capabilities in this field must be restricted to the particular area of interest. Thus, a brief discussion will be given of those aspects of hardware and software which would be directly applicable to the design and drafting activities of a bridge division. It is convenient to categorize such elements in three categories; namely (1) hardware, (2) turnkey systems, and (3) software. In the following sections, these categories will be discussed briefly with emphasis on those aspects of each which relate specifically to engineering design.

Hardware

Hardware is the obvious resource when one thinks of computing capability or interactive graphics, and yet is included in this section only for completeness and will be discussed only superficially. This is because most hardware available, whether it be a large-scale computer, a minicomputer, a microcomputer, a terminal, a plotter, or a digitizer, is not uniquely designed for CAD or interactive graphics applications, and so many types are available that a complete discussion is impractical.

Mention will be made of the major component of a computational system, including large-scale computers, which are generally of a type manufactured by such corporations as Control Data Corporation, IBM, Data General, and Digital Equipment. Within the minicomputer field, the two most popular versions seem to be the VAX manufactured by Digital Equipment and the Prime, which are similar in terms of capability and are designed for interactive use. Microcomputers are available everywhere and include common names such as Apple, Atari, Commodore, Northstar, and IBM. Within the context of this study, the microcomputers that seem most appropriate for consideration include the Northstar, IBM, or similar models since both graphics and communications capabilities are available and thus could be used in either a stand-alone mode or as a terminal connected to a larger system. Such applications will be discussed in a subsequent section under recommendations.

Other types of hardware that are of interest include terminals themselves, specifically those that have graphics capabilities. The major supplier of graphics terminals is Tektronix, which can provide almost any type desired. These have very high resolution suitable for engineering applications and a variety of other features that can make the price vary from approximately $3,000 to perhaps as much as $50,000 each. A number of other available graphics terminals are capable of communicating directly with the host computer for software availability and memory access, and also can interface directly with plotters, printers, or other hard copy devices.

Extensive peripheral equipment is available in the form of light pens, digitizing tablets, external keyboards, plotters, etc., which are of particular rather than general interest. Detailed information on a particular piece of hardware can be conveniently obtained by directly contacting the vendor.

Turnkey Systems

It is in this area category of equipment that most of the growth and activity have occurred. Within the context of this report, a turnkey system includes a dedicated computer, usually a minicomputer such as a VAX or a Prime; peripheral and interconnected work stations, generally consisting of one or more graphics terminals with high resolution graphics and detailed keyboard and menu input; output devices, which generally include at least a printer and high quality electrostatic or pen and ink plotter; and, most importantly, the associated software, which is developed specifically for the hardware components and will perform the particular design and drafting tasks desired by the user. In addition to the hardware and software components of the system, turnkey vendors will always provide a training program, for professionals, that can consist of anywhere from 2 to 6 weeks of intensive instruction. Thus, most purchasers of a turnkey system acquire it for a particular application and, in general, will be quoted a price under a proposal in which the elements of the software, and frequently elements of the hardware, are to be designed to meet the client's requirements. Thus, turnkey systems are hardware/software configurations developed to provide a particular service for a particular industry. In the case of transportation departments, the service provided consists primarily of mapping and drafting activities, but in other industries, as will be discussed subsequently, modelling analysis and design, as well as reanalysis and design capabilities, can be provided.

While there are a number of turnkey vendors who can provide the services just described, only the major ones generally have the expertise and software development capability to bid on the type of system required by large firms or agencies, and these are the ones that will be considered here. The major vendors are Applicon Corporation, Computer Vision, Calma, Intergraph, and Auto-Trol Corporation. There are a number of other vendors, including Gerber Scientific, Genisco, and Bendix Corporation, but these service a relatively small part of the market and the capabilities they provide are limited.

An example of a turnkey system is that provided by the Applicon Corporation. One major component -- the central processing facility -- consists of two computers, a PDP11, with an excess of 200 kilobytes of main memory to handle input-output processing and data base management, and a special purpose computer, which is a 32-bit graphics computer with almost 200 kilobytes of its own memory, that is utilized for rapid display drawing and command processing. While this dual configuration is not necessary, in this particular case it provides for very fast response to user input and output requests. Associated with this central processor are one or more disk drives used for general purpose data storage and, in particular, for the data base containing the model data or the table of data to be used in subsequent drafting. In this case the 200 megabyte disk drive can provide on-line storage for several thousand complete drawings. Magnetic tape drives are also available for peripheral storage.

The second major component of the system is the work station, or interactive graphics terminal. With Applicon, as with most other vendors, graphics work stations can be selected from a number of color or black and white video displays with various tablets and keyboards for direct input. The particular raster scan video display provided permits selective erasing of specified portions of the screen, which provides considerable time savings. Each graphics work station includes either a small data tablet for interactive drawing construction and editing or a larger drafting-table-sized tablet for digitizing existing source drawings and data. With the Applicon configuration, the central processing facility can accommodate up to four graphics work stations.

The range of peripheral devices that can be attached to the central processor includes, in this case, a flatbed, drum, or electrostatic plotter ; card reader; paper tape reader and punch; a variety of line printers, both slow and fast speed; and synchronous communications links to other computer and peripheral equipment.

Comprenhensive software is the key to the productivity of any CAD system. The software available for most turnkey systems, including that offered by Applicon, addresses most phases of engineering and manufacturing including modelling, design, analysis, drafting, documentation, and manufacturing. Every turnkey system possesses some type of graphics application system that will permit and support the creation, editing, and output of either two-dimensional or three-dimensional graphics activities. Specialized packages and components are available in all systems for particular production oriented tasks such as finite element analysis, placement and routing of printed circuit boards, facilities layout, and numerical control programming, as well as for standard routine drafting. Graphics packages are facilitated by system-specific and graphics-programming languages that access graphics and engineering data bases and facilitate routine kinds of drafting activities.

Some sort of data base is also common to most software systems and each is configured to permit easy imput and access for any data as well as internal manipulating, ordering, and operation on various pieces of data. These data bases are also configured so as to permit access by different functional organizations; for example, a data base consisting of coordinates and elevations of the terrain and centerline of a particular highway system could be accessed by a mapping division through its terminal and simultaneously through a bridge division to examine the alignment of a bridge structure.

Typical graphics systems also contain peripheral software tools to perform a variety of design checks and validations. This is particularly useful in machine design where interferences and overlaps can be easily identified by the graphical display. In addition, once a model is developed for either finite element modelling or otherwise, and the final geometry defined, the graphics system automatically will generate geometric properties such as area, volume, weight, center of gravity, and moment of inertia for each component or for each combination of components. Certain of the packages permit finite element modelling in which the final output from the modelling system is designed to interface as input to whatever mainframe finite element analysis package is desired. Within the next few years, it is expected that most turnkey systems will incorporate a finite element analysis capability consistent with that presently available on large, separate mainframe systems.

While some vendors develop their own modelling software, many of them, such as Applicon, utilize software developed by other companies. This is probably a more efficient option since different companies specialize in different types of activity. For example, Applicon utilizes a software package called "Supertab" developed by the Structural Dynamics Research Corporation. This package permits easy development and modelling of two-dimensional or three-dimensional finite element models. Such modelling packages permit the user to specify loading parameters and support conditions directly to a graphically displayed model as well as to edit model data and element connectivity listings. This type of model building permits visual verification of the model and quick interpretation of the resulting response analysis with a graphical display of stress and displacement data.

The preparation of working drawings, including details, assemblies, sections, and material lists, represents a major portion of any CAD effort. Using drafting features with software provided by Applicon and other turnkey vendors, the professional draftsman can retrieve previously developed design information, isolate components for detailing, scale and rotate, check tolerances, and automatically dimension parts. In addition, the software permits immediate section generation and automatic cross hatching and it displays lists, notes, and specifications from previously developed libraries. Final drawings can be developed to meet the most exacting drafting standards using the aid of software features such as multiple text fonts, the ability to condense and expand letters, proportional spacing, and an almost unlimited variety of user-defined line types and surface patterns. The editing capability for drafting is also extremely efficient, and it provides significant time savings in that it permits revisions to complex drawings by changing definitions of a component with a single command in which the change is progressively produced throughout the library system wherever that particular component appears. Because final drawings are generated from modules, subsequent drawings can be quickly and efficiently generated by selecting the modules from a library table and placing them where desired on the final drawing layout. For example, graphics libraries can contain a variety of complex line shapes such as divided highways, railroads and boundary lines, and these shapes can be immediately reproduced on a subsequent drawing by merely digitizing the centerline and entering a single command. The same is true for intersections, interchanges, and other complicated configurations that require many man-hours of manual work.

An appreciation of the flexibility, generality, and capability of CAD packages with their associated software can be gained only by direct observation and working with installed systems.

Software

Briefly considered next are some of the software packages that can either be obtained through a time-shared system or be purchased from vendors. These are of interest because in the event an agency cannot afford initial capital expenditures for a complete turnkey system, it might well be possible for it to utilize part of the capability of CAD by getting a less expensive graphics terminal and, through time-sharing or otherwise, utilize individual software components.

Many of the software packages deal specifically with finite element modelling and structural analysis. Included in these are general purpose codes such as ANSYS, STRUDL, NASTRAN, SAP, and MARC, and a number of other more specialized programs. Most of these packages may be either purchased or leased and some have limited interactive graphics capability. There are several programs that offer certain elements of drafting. Among these is AD2000, which was developed as an automated drafting package and is available in a number of versions on different pieces of hardware. Also, there are a number of pre-and post-processors for structural modelling, including some that are inherent in programs such as ANSYS and others that are independent but accept data and interact with analysis programs. The interactive graphics capability that will display models, geometry, and other features are an aid to the engineer and a substantial enhancement to the analysis capability. None of these individual software elements, however, will perform the automated drafting functions available on turnkey systems and output a finished pen and ink drawing.

INTERACTIVE GRAPHICS IN DEPARTMENTS OF TRANSPORTATION

This section is devoted to a consideration of the applications of interactive graphics in state departments of transportation, a description of the hardware and software already acquired by such agencies, an evaluation of such equipment, and plans these agencies have for expansion.

Most applications of interactive graphics, particularly in state agencies, have been related to automated drafting in roadway and bridge design. This is not a significant restriction, however, since a major portion of labor costs and time involved in the design process is, in fact, dedicated to the generation of plans and drawings.

Before describing a typical system configuration and applications for which it has been used successfully in transportation department activities, it is worth noting that relatively few departments have acquired, installed, and fully utilized the interactive graphics capability. In fact, as of 1982, only roughly a dozen transportation departments claimed to have an interactive graphics capability, and of those by far the majority were using the capability only for drafting, and in this context primarily for mapping. Certain of the departments contacted noted that while they did have such equipment, and that while certain claims might be made for the sophistication of this equipment, there was actually no utilization of interactive graphics and CAD for bridge analysis and design. Of the states that have made some attempt, those that seem to be the farthest along and have the most experience are Michigan, Florida, New York, and Texas. A number of others, such as Oklahoma, Illinois, and Wisconsin, have made modest attempts to get started.

Only one state seems to have completely embraced the concept of interactive graphics and to be utilizing it essentially to full capacity. The Michigan Department of Transportation has established a unique unit within its organization, called the automated drafting unit, which services and is a part of the Design Division. They are, in fact, utilizing it so fully that the system operates twenty-four hours a day, five days a week, and is completely booked up. The manner in which this system is being utilized will be discussed in detail subsequently.

The remainder of this section of the report will discuss typical system configurations and representative applications of them within transportation departments. The detailed description of the most widely utilized system will be described in the context of the Michigan Department of Transportation's activities.

Typical Interactive Graphics System

As noted earlier, a computerized interactive graphics system is a stand alone system which primarily is used to improve productivity in the drafting and design areas.

Based on the experience of a number of transportation departments, the Intergraph Corporation of Huntsville, Alabama, apparently has the most appropriate interactive graphics system for use in these agencies. Accordingly, almost all of the interactive graphics sytems in use in those transportation departments that have these facilities are those produced by Intergraph. This section provides a brief description of the Intergraph hardware/software systems currently used by states such as Michigan and Texas.

Hardware

Intergraph offers a number of graphics systems based on different combinations of central processor units (CPU), graphics work stations, plotters, and other peripherals. Currently, it offers three different CPU's that are essentially minicomputers, namely, the PDP11 or VAX11/751, the VAX11/780, and a new 11/23 miniprocessor. These processors are all made by the Digital Equipment Corporation, and different models of these are available depending on the requirements of the user.

The 11/23 minicomputer is the bottom of the line, economical minicomputer, but will serve as a full capability, stand alone, interactive graphics system for relatively small firms or agencies, or as a node in a larger distributed network. This system runs under a modified version of the RSX-11M operating system and has a 16-bit word size.

The VAX11/751 CPU is the mid-range member of the VAX family of minicomputer systems. The 11/751 processor is a 32-bit virtual memory computer with four bytes of address space allowing extremely large program handling. The operating system is the VAX/VMS (virtual memory system) which is a general purpose, multi-programming operating system with a capability of simultaneously handling multi-user real time and multi-stream batch applications plus on-line program development. This particular data processing system can handle up to eight work stations, whereas the 11/23 data processing system could handle a maximum of four through its CPU.

The VAX11/780 CPU is the top of the line minicomputer and is a 32-bit extension to the PDP11 family. The operating system for this CPU is also the VAX/VMS. The VAX11/780 data processing system can handle up to sixteen independent work stations and is the top of the line interactive graphics system offered by the Intergraph Corporation.

In addition to the CPU's described, the data processing system (DPS), the heart of any Intergraph system, also includes basic elements of a file processor, a data concentrator, and software. Disc drives, tape drives, consoles, and work stations, as well as other peripherals are, of course, added to the data processing system to complete the graphics system.

The graphics work stations use a high-speed concentrator which is a microprocessor-based communications controller. It handles all communication functions with graphics work stations and remote devices. This high-speed device provides communications for up to sixteen local graphics work stations and also serves to interface remotely located stations over modems and telephone lines provided by the user.

Each work station consists of a display system and an input system. Stations are classified as either design/digitizing stations or design stations, depending on whether or not they include a digitizing table. All stations communicate with the CPU through the high-speed concentrator. Every Intergraph work station includes an LSI-11, 16-bit microprocessor with 64K bytes of memory that is used for communicating with the concentrator and interfacing with all other devices at the station. The Intergraph approach to interactive graphics uses dual graphics display screens as the focal point for inputing and constructing graphic files. Digitized files are displayed in real time and can be edited as work proceeds.

The dual display configuration of the Intergraph graphics station provides the maximum amount of graphic information to the user. Each screen is a 19" (480-mm) diagonal with 1280 x 1024 resolution and will support either a full-screen display load or a four-view quadrant display load. In the latter case, each of the quadrants is independently addressable so that the software can provide eight views related to a particular drawing or to a number of different drawings. The operator has full control over the views he wishes displayed.

All Intergraph work stations, with the exception of the stereodigitizer, include an input system which typically consists of a menu tablet, a digitizing table, keyboard, and cursor. Command menus, generally attached to a menu tablet, are the primary means by which a user communicates with the software. Most of the input systems use a floating menu in conjunction with a digitizer. The floating menu is a 15"x 18" (380 x 455 mm) sheet of heavy plastic with two flat positional coils. When it is placed on top of the digitizer, the digitizer interface continuously senses the relative location of the two coils and the cursor coil, and the software can then determine the exact position of the cursor on the menu. Input systems are also provided with a digitizer, keyboard, and cursor mode for additional input capability. The keyboard is a full-function keyboard that provides a 96-character set consisting of upper and lower case.

A number of additional hardware components are supplied with Intergraph, including a stereodigitizer station, quick copiers, plotters of various types, card readers, line printers, and alpha and numeric terminals.

Software

All Intergraph software, including that for graphics, data management, and prescribed applications, is designed to run under the standard operating systems furnished by the Digital Equipment Corporation with its respective computers. In addition to the assembly, the operating systems include a wide range of utility programs which enable the user to develop and easily interface his own application software. With the interactive graphics systems supplied by Intergraph come the appropriate operating systems for the particular CPU selection. The VAX/VMS is the standard operating system for all of the VAX11 series systems. It includes an extensive file and record management system to aid in file maintenance and includes graphic design and manipulation utilities that are application independent.

The software used for interactive graphics is a general purpose, modularized set of programs tailored to meet user needs. The IGDS (Intergraphics Design System) programs may be addressed through the menu tablet or the keyboard, or under program control. The open-ended IGDS data structure allows the user to create complex drawings with size limited only by the storage capacity available. Security features are included in the software to prevent unauthorized access to previously generated user drawings. IGDS supports both two-dimensional and three-dimensional capabilities, with the operator choosing the mode.

IDGS drawings are stored on either a disk or magnetic tape as files. Two files available on the disk and used for design purposes are called the design file and the cell file. The user may select a design file containing the results of the previous design effort and use this as the basis for further activity or he can begin with a blank design file for a new design activity. The cell file is simply a file of standard design elements which permits the user to create and store, by name, frequently used, complex sets of design elements called cells. During a design session, the engineer can place, delete, move, modify, or otherwise operate on various drawing elements using the multi-level display capabilities of the dual screen to increase effectiveness. When a design session is completed, the user stores the results of his work for that particular session in the design file.

The IGDS graphics software also includes a variety of capabilities to facilitate the generation and editing of drawings. The system supports features to automatically insert hidden lines, dimension lines with arrowheads, and dimensional text in a variety of modes. The user has the option to have the dimensioned text placed either manually or automatically.

There frequently exists non-graphic data which augment the graphic design system produced by IGDS. Accordingly there is also provided a capability for storing and manipulating non-graphic data.

The data management and retrieval system (DMRS) is a high-level data base system which allows the user who is not interested at a particular time in design and graphics system to manipulate the non-graphic portion of the total corporate data base. The DMRS also supports attribute data bases which have no association with a particular IGDS. Thus, the user can maintain personnel or payroll data bases with the Intergraph system using DMRS.

In addition to the hardware and software components of the Intergraph system described previously, there are additional peripheral components which provide linkage communication, maintenance, and other services for the system. In addition, Intergraph provides software for particular job uses. These components are not described in this report but may be found in appropriate references provided by the Intergraph Corporation.

Typical Applications in Transportation Departments

Interactive graphics systems have been applied in transportation departments for county mapping, land use and vegetation inventory, planimetric surveys, topographic mapping from field notes, urban area mapping, coastal zone mapping, land use mapping, signing plan production, signalization plans, collision diagrams, terrain modelling, plan mapping, bridge and road plan production, contract plans and right-of-way plats, bridge plans, standard detail drawings, and special maps.

As may be noted, most of these applications are in the photogrammetric, mapping, and drafting operations of a transportation department, and very few have a design orientation. Those applications relating to design will be described in more detail in the following section.

Highway Plans

Typically, transportation departments produce four major types of plans -- roadway, bridge, right-of-way and traffic -- where most of the drafting is done by the conventional pen-and ink-method. An interactive graphics system could provide more applications and produce a greater impact in the production of plans than probably any other task. This is because the major drafting effort and the widest variety of drafting functions are expended in this activity.

Using an interactive graphics system, the draftsman could draw lines and curves by simply defining end points and the control characters. The computer would then act as the straightedge for the lines and the curve template, and erasing could be done electronically with a light pen. Dimensioning and bearings could be done automatically, and all of these preliminary activities could be done prior to the drafting of the final document.

Title sheet formats along with all the standard title work, notes, etc., could be stored as individual modules. Thus, to produce a title sheet, the operator would simply call up the title sheet base drawing, merge it with whatever other portions of the drawing he desires, and then add whatever information that is unique to the project before finally plotting the combined final drawing.

Several typical section drawings could be stored in the system more or less as standard drawings. Only information unique to a particular project would need to be added or revised and could be created quickly using the interactive graphics system.

Plan and profile sheets could make extensive use of the layering capabilities of the system and could result in others utilizing much of the drafted items created by a particular group. For example, the survey centerline, existing right-of-way lines, and topography need only be drawn one time compared to multiple times as is presently done. With the menu capabilities of the system, much of the tedious drafting work can be eliminated by defining and storing symbols for such things as right-of-way markers, fences, and power poles.

When plans and plats are finalized in districts, for example, all data could be retrieved via the CAD system by the central office for checking. Changes, if any, could easily be made on the system, final plots and drawings could be produced, and as many copies as required could easily be generated.

A set of highway plans typically is made up of from 30% to 50% of standard drawing sheets. The sheets cover construction details etc., that are standard from project to project and normally show several methods or layouts of the various items on each sheet. Since the standards may have been developed for a wide range of applications, there may be only one or two items on a sheet that actually pertain to a specific project. In order to include the applicable parts, the entire sheet must be included. With an interactive graphics system, all of the standard drawings could be placed in computer storage modules and the operator could then simply call up the required sheets as desired to be plotted for inclusion in the final project plan.

Bridge Plans

In Virginia, the Bridge Division in the Central Office currently produces plans for various types of bridges, box culverts, etc. Considerable original drafting goes into these plans, including the repetitive work of drafting standard details, standard notes, and typical views.

With interactive graphics and CAD capabilities, bridge plans would form a standard data base for future drawings. The capability to use previous drawings or elements of previous drawings as well as standards would greatly reduce the time required for plan preparation and for the final complete pen-and-ink drawing. As an example, a bridge girder cross section view could be called from a previous drawing or from a stored module rather than having to be redrawn. The real efficiency is realized when a cell library is created wherein a cell can be defined to be a component or any combination of elements.

The full potential for CAD in the design activities of a state transportation department has yet to be realized. Present production efficiencies can be increased an order of magnitude over the next few years.

FINDINGS AND RECOMMENDATIONS

This brief review of computerized interactive graphics, including a review of state of the art in hardware and software, a summary of applications of such technology, and an evaluation of the experience of other transportation departments in their use of CAD and drafting, shows conclusively that --

1. the necessary technology exists for the successful use of CAD in design applications;

2. it is being used extensively and effectively by other industries and engineering disciplines;

3. those transportation departments that have effectively implemented computerized design and drafting techniques are unanimous and enthusiastic regarding the benefits to their design activities;

4. the use of computerized interactive graphics has proven to be cost effective, to improve the reliability, accuracy, and quality of work, and to significantly increase the productivity of a group; and

5. the use of computerized interactive graphics is expected to continue its rapid growth over the next few years, and there appears to be no reason to defer a decision on its adoption and use.

Based on these and other factors, the following general recommendation is provided. The use of computerized interactive graphics in bridge design and other related activities is feasible and cost effective, and the Virginia Department of Highways and Transportation should undertake a detailed study directed toward the use, justification, and acquisition of such a system. As part of this general recommendation, specific recommendations include the following:

1. Within design divisions such as the Bridge, and Location and Design Divisions, appropriate personnel should identify those design and drafting activities which would be candidates for implementation on a CAD system.

2. A detailed feasibility study should be undertaken to ensure the degree of cost-effectiveness expected.

3. To gain an understanding and appreciation of the extent and manner in which computerized graphics is being utilized in other state transportation departments, appropriate personnel from the design divisions and the Research Council should visit one or more states to observe the operation of their automated design groups.

4. Consideration should be given to the type of hardware desired and the optimum configuration of such equipment (e.g. central location or remote stations).

5. After the needs within the design divisions have been identified, consideration should be given to the development of criteria and specifications unique to these needs.

6. A plan should be developed for the optimum system configuration, the location, and the use of this equipment and the corresponding organizational arrangement for its operation.

7. Other states should be contacted to learn of their experience and of prior studies, so as to prevent duplicative effort.