

# Design and Analysis of Advanced Transit Systems Using Interactive Computer Animation

ALAN L. ERERA AND ALAIN L. KORNHAUSER

The Princeton Intelligent Transit Visualization System (PITVS) is described. The PITVS is software designed to provide transit planners, engineers, and the general public with an interactive three-dimensional transportation system design and analysis tool. The software provides the functionality to (a) build transit networks, positioning guideway, intersections, and stations while specifying guideway cross-section characteristics and station demand characteristics using a graphical user interface; (b) view these networks in a three-dimensional representation of the planning area with fully interactive user control over viewing positions; and (c) view randomly generated simulated operations on a transit network design based on demand characteristics and a system operations strategy. Both the methods of and the motivations behind the PITVS are explained, and the positive enhancement that interactive three-dimensional graphics will give to the transit systems design process is affirmed.

Mass transit is a public service: researchers, planners, and engineers do not create a transit system for colleagues to study in a laboratory—they build the system for the public. The design of any mass transportation system must take into account the desires of the community and its public officials as well as the engineer's assessment of the community's transit needs. Any proposal for a new transit system will meet with public scrutiny in many areas; a design that is not amenable to the public will probably never gain enough social and political acceptance to be built. It is up to planners, therefore, to prove to the public both the necessity of the transit system and the adequacy of the proposed system for solving the transportation problem.

It is usually not an easy task to convince community members that a proposed transit system is an acceptable solution to their transportation problems. Questions almost always arise over the costs of a transit system: the financial costs of a system and the impact costs that a system may inflict on the environmental and socioeconomic conditions in a planning area are crucial issues. Today's planning efforts are systematic approaches that take considerable pains to relay important information about such costs and effects to the community for which a system is being planned. The more information that is available to planners, decision makers, and the public, the more successful any planning effort is likely to be. One of the most exciting new forms of information that can be

made available for transit planning is three-dimensional computer visualization.

The state of current computer hardware and software technology offers the opportunity for the analysis of much crucial visual information concerning proposed transit systems far before any physical construction takes place. The powerful graphical capabilities of the personal workstation make possible the three-dimensional viewing of transit system designs in a modeled planning world. The processing power of the workstation furthermore offers the possibility to view this visual information dynamically; users are not limited to a "fixed view" of the modeled world, but they can look at the state of the system at any instant in time from an almost infinite number of perspectives.

The Princeton Intelligent Transit Visualization System (PITVS) is an initial attempt to provide this new level of planning information to designers, engineers, decision makers, and the public. Using the power of user-interactive three-dimensional graphics, the software system provides an advanced visualization tool that can aid both planners and the public in sorting out many of the complex visual impact issues posed by any fixed mass transit design. Thanks to the speed of the modern personal workstation, the PITVS can readily provide on-screen visual comparisons of a variety of user-specified system layout designs and give the user a peek at what a true implementation of a transit system may look like before it is built.

## PITVS DESIGN CONSIDERATIONS

The PITVS began as a term project for Princeton University's introductory transportation systems course and has since been enhanced and retooled. Major enhancements intend to improve the both the visualizations provided and the flexibility of the system. Developed with the philosophy of using the latest technology in personal workstation computing, the PITVS is designed to enhance the transportation planner's design task in a way not previously available: through the use of interactive three-dimensional computer graphics. Earlier efforts in the use of interactive computer graphics for the analysis of transportation problems are documented by Kornhauser (1). These efforts typically focused on problems in transportation data analysis, but the PITVS is a step forward in the use of graphics for transportation design visualization.

The system model in its current implementation has been written in the C programming language under the Unix op-

A. Erera, ALK Associates, Inc., 1000 Herrontown Road, Princeton, N.J. 08540. A. L. Kornhauser, E319 Engineering Quad, Princeton University, Princeton, N.J., 08544.

erating system for use on Silicon Graphics personal workstations. These workstations are especially powerful for graphics because of their use of specialized graphics hardware engines and support for a large software library of graphics routines. Although the processing and graphical power of such machines is great, it is not without limit, and therefore reasonable constraints are placed on the realism of the PITVS visualization.

The background environment in which the transit system is placed and visualized by the user is designed with the goal of providing reasonable realism without overburdening the system hardware. Since user-controlled, dynamically changing views are considered essential to the system, the realism of the background is somewhat limited to allow for instantaneous screen refreshes. Of course, modeling a real-world setting could be infinitely complex; limiting the realism of this background environment model entails drawing only the components of the modeled world that are necessary for an adequate visual analysis.

Currently, the system requires as input three-dimensional geometric descriptions of buildings, roadways, and any other prominent natural and physical structures necessary for the adequate modeling of a planning environment. The time spent on forming this geometric background representation should be on the order of tens of man-hours for an average-size planning area. The geometric data are currently required as a sequence of vertex coordinates for use in polygon drawing routines; future improvements will allow users to create and modify such data through an interface and possibly support importing such data from popular computer-aided design (CAD) packages. The background views offered by the PITVS provide a sufficient representation of reality without detracting from the performance of the system. With the development of faster computer hardware, the realism of the background view can be enhanced to create an even more useful visualization tool; currently, the authors let the user's mind fill in the gaps. It is also important to note that the PITVS does not support modeling ground elevation data in its planning world; this feature is being explored as an enhancement to the system.

To render three-dimensional visualizations of transit system hardware, the PITVS requires a three-dimensional geometric description of the guideway cross section as well as support column and station designs. Fairly simple geometries are required for performance reasons. Whereas the cross section of the three-dimensional guideway is simple, the guideway is allowed to curve between user-defined placement locations (hereafter called nodes). Curving guideway was considered essential to represent turns and intersections adequately. The representation of the transit stations could also be fairly basic in order to limit the number of polygon draws that the system must execute. A simple platform and shed structure next to the guideway and a shaft structure extending to the ground representing an elevator shaft or stairwell are used to represent graphically the stations in our demonstration system. The PITVS also allows the visualization of transit vehicles on the guideway. Once again, the geometric descriptions of the vehicles are kept simple. On the demonstration system, for example, each vehicle consists of only a few polygons pieced together to form a box-like car representation.

The relatively simple geometric design of the three-dimensional modeling world is intended to enable the system to refresh the screen in real time as the user views the transit system design from many viewpoints. Viewing a single transit design from multiple points is not enough, however. The PITVS can also change quickly between different network layouts in the visualization, and thus it easily allows comparable analysis. Another common situation would be one in which the planner decides that a guideway alignment may look better if it were altered slightly. Easy-to-use network editing functionality for creating and altering network designs is therefore also provided as one of the key tools of the software. Thus, the PITVS provides an adequate platform for the visual comparison of alternative transit networks, and any changes to a network created with the network editor can also be visualized quickly.

Finally, the PITVS allows users to view a transit system design not only at a single point in time but also as a dynamically changing system in a three-dimensional visualization of simulated operations. Again, flexibility in controlling the visualization was a paramount design criterion. The PITVS lets the user view operations on the same system with different user-specified demand situations. Special viewing perspectives are offered for viewing a transit design with simulated operations. Once again, excessive detail is spared in the simulation to allow for flexibility and user control over simulated operations; although the demand information is generated fairly simply and the control algorithms for the vehicles are not incredibly sophisticated, the simulation provides yet another bank of visual information for the user to analyze.

## PITVS SOFTWARE COMPONENTS

### Overview

The PITVS software model provides three main areas of functionality, shown graphically in Figure 1. The first set of functions allows the user to create, modify, store, and retrieve

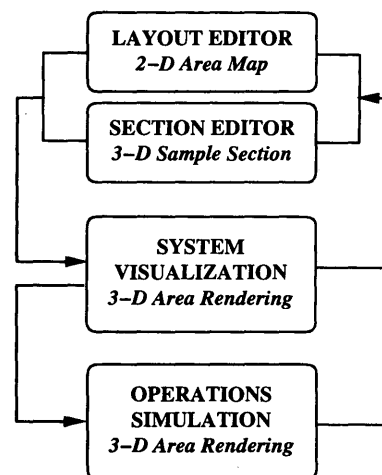


FIGURE 1 PITVS functionality flow chart.

transit networks to be used in the visualization. Next, the main group of functions allows the user to visualize a transit network design at a fixed point in time as part of a three-dimensional world. The third area of functionality allows the user to set up a variety of simulation parameters and then view simulated operations over a network design in what is essentially a dynamic, real-time visualization of the state of the transit network.

The PITVS can provide three-dimensional visual information for any fixed-guideway mass transit system. As a demonstration of the software, the authors chose to model the system characteristics of personal rapid transit (PRT) and to attempt to visualize several system designs for the Princeton University campus. Advanced mass transit system design is seen as one of the potential applications of the PITVS software. An advanced visualization system such as the PITVS offers a fairly detailed preimplementation view of any transit system design; this can be especially useful for advanced transit that may have questionable visual impacts and misunderstood operational characteristics due to the lack of existing example systems. Public acceptance of the visual impacts of elevated guideway has long been a problem for PRT; almost 20 years ago, Lutin wrote that "the major considerations in determining the guideway route arise from aesthetic and environmental conditions" (2,p.36). Certain operational characteristics of PRT systems also transfer well to this demonstration of the animated viewing of simulated operations. Automated service means, of course, that in an actual implementation computers would be controlling the movements

of vehicles; such a situation lends itself nicely to a computer simulation of operations.

The Princeton campus and PRT having been chosen for demonstration, the first step in using the PITVS is to generate a geometric description of the planning world as well as the general guideway cross sections, support structures, and station structures. Currently, this information is read from file at run time and not altered during the operation of the software; this is simply the current implementation and is by no means a necessary constraint. Once these geometric data have been processed, the user can begin a planning and visualization session.

### Visualization Functionality

The user-interactive visualization functionality is the true power of the PITVS. After retrieving a transit network from disk or creating a network using the network editor (to be discussed shortly), the user clicks a single button on the on-screen control panel to transform the view from a flat two-dimensional editing tablet into a window on a three-dimensional world. Figure 2 gives an example of a view created with the PITVS. The sample depicts an elevated monorail-type guideway weaving among buildings of the Princeton campus. Users can now activate the zoom feature on the control panel and use the mouse to "fly" anywhere in this world, watching the view dynamically changing as they move the mouse in different directions. The flexibility is available for the users to position

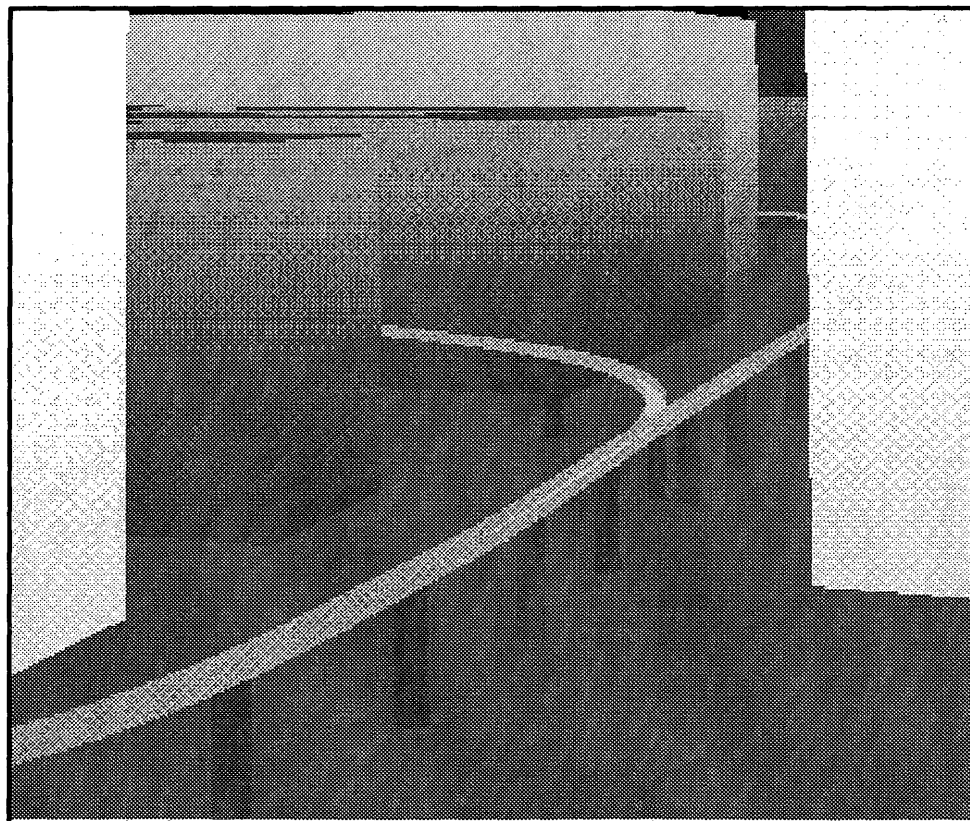


FIGURE 2 Sample PITVS visualization.

themselves virtually anywhere in, around, or above the world that they have just created. To view this world effectively without noticeable delay between redraws, several advanced features of the graphics workstations are used. The Silicon Graphics machines support a drawing method known as double buffering in which an entire scene is drawn into an invisible buffer that is then made visible by "swapping" buffers. Using this method, the PITVS can create smoothly changing views as the user zooms throughout the three-dimensional scene.

The view itself is created by a series of multicolored polygon draws. The background environment of buildings, roads, and other features is drawn first. Once the background is drawn, the software renders the user-defined transit network. To create a smoothly curving guideway, a mathematical splining algorithm is used; Figure 3 illustrates the Cardinal spline curve. The position of the guideway is defined by a number of nodes (the numbered circles in Figure 3), and the curving guideway is created by generating a number of sequential control points (the gray squares) through the use of this mathematical algorithm. The guideway is then rendered as straight segments between these control points. A forward difference algorithm is used to create the control points for the parametrized curve (3). To improve the PITVS, work is under way to allow the user to specify minimum curve radii for the guideway design and provide constant radius curves as guideway options. The current implementation uses curve fitting only for simplicity; more advanced alignment modeling techniques are being explored.

Once the control points for the guideway have been determined, they are stored with the other transit network information and are not recalculated unless a change in the network is made. The three-dimensional guideway segments are drawn between these control points. Although each segment is straight between control points, the guideway image truly appears to curve; a greater number of control points will produce a more smoothly curving guideway. When the user has specified elevated guideway, support columns are drawn to the ground underneath the guideway at evenly spaced intervals. After drawing the guideway and columns, the program renders the stations. Since the demonstration system is currently oriented toward PRT, the stations are drawn off-line, paralleling the guideway at the same height. Station

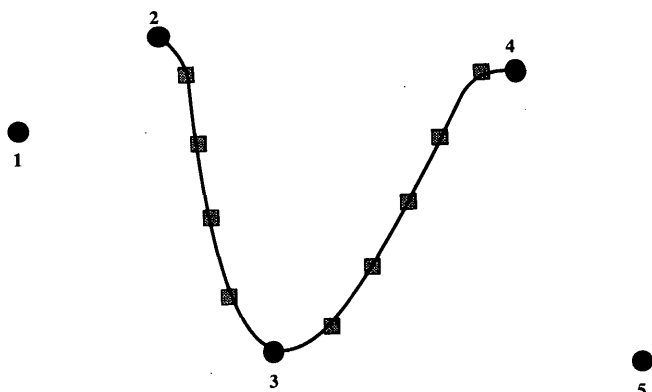


FIGURE 3 Generation of control points using cardinal splines.

platforms and housings are then drawn next to the guideway. To model a PRT system accurately, the length of the off-line segment used to represent a station is made a function of the station's vehicle berthing capacity.

After the completion of the polygon draws for the background, guideway, and stations, the buffers are swapped and the three-dimensional image appears on the screen. It is important to realize that almost every polygon must be redrawn each time the user changes viewpoint in order to account for the new perspective attained on the scene; more detail, therefore, creates slower redraw speeds and hence less flexible software operation.

**Network Editing Functionality**

Graphical CAD software packages are readily available for the design of everything from automobile engines to skyscrapers. Although the PITVS does not support many of the advanced design tools that a typical CAD package offers, the software includes tools for graphically laying out a network of transit guideway on a two-dimensional map representation of the design area. Using a palette of on-screen push buttons partially depicted in Figure 4, the user can set and change the guideway position quickly and easily. The guideway is positioned by running a curving line segment through a series of positioning nodes. These node locations can be quickly changed by clicking on them with the mouse and dragging them to new locations. To create a connected network of transit guideway, intersections can be added with guideway segments branching off in other directions. Stations are added at points along the guideway and are given size and use characteristics to be used during the operations simulation. The system assumes certain basic characteristics of the transit guideway, but it does allow the user to edit some of the scaling attributes

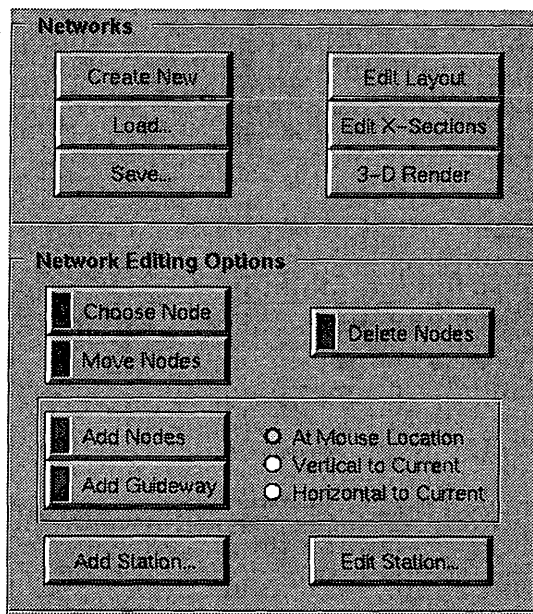


FIGURE 4 Portion of main network editing control pad.

of the guideway cross sections using the push-button palette shown in Figure 5. Simple controls can be used to change the height and width of the guideway deck as well as the height of the support columns; thus the visual impact of a 3-ft-wide guideway and a 6-ft-wide guideway can be compared.

The PITVS software uses the FORMS library of graphical user interface tools as its primary means of interaction with the user (4). The FORMS library is public domain software that provides functions for the creation of the control panels and dialogue boxes used in the PITVS. A main control panel is fixed on one side of the screen while the system runs. Nearly all network editing functionality is invoked by clicking with the mouse on buttons on this main control panel and then pointing and clicking over the main program window to add nodes, move locations, and so forth. Certain functions such as adding or editing stations open additional dialogue box areas in which the user inputs information on station capacity and demand characteristics. A status bar area on the main control form is used to give instruction to the user while editing networks.

Designs created with the network editor of the PITVS can be saved to disk and later retrieved and worked on again; the guideway information is stored in text files in a simple format so that any transit network design created using a different system can easily be converted to a form readable by the PITVS. And, any time during the editing process the user can switch to the three-dimensional visualization mode to view the design. By switching back and forth between the editing tablet and the viewing mode, the network designer can fine tune the positions of the guideway, stations, and intersections in the transit design. The network design functionality of the PITVS is not meant as a replacement for detailed alignment sketches or guideway engineering plans. It is intended to be an easy-to-use network editor, however, that allows fairly simple translation of alignment sketches into the PITVS format while also allowing those who are experimenting with the design of guideway layouts to do so in an interactive computer graphics environment.

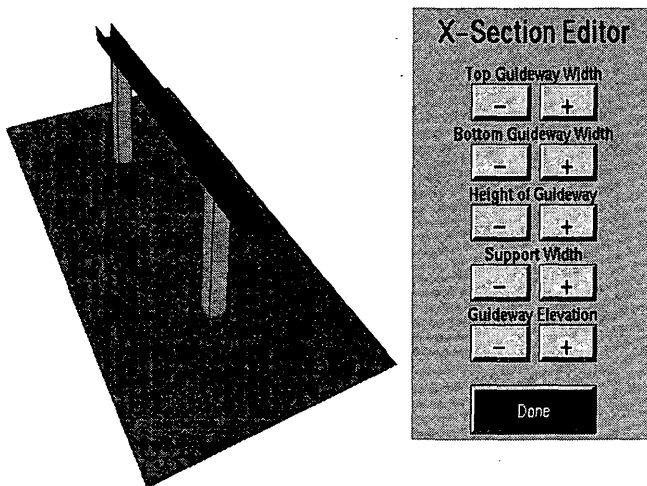


FIGURE 5 Cross section editing.

### Simulated Operations Functionality

The final area of functionality provided by the PITVS deals with simulating operations over the user-designed transit network. After editing a proposed transit design on a two-dimensional map and visualizing it at a static time frame in three dimensions, the user has the option of watching a three-dimensional real-time simulation of transit operations once again from a virtually limitless number of viewing points.

The operations simulation has several components. First, an array of patron arrival information is created through a simplified method that assigns a fixed exponential interarrival rate to each station. When building a network, the user is asked to specify estimates of the number of daily vehicle arrivals and departures for each station. This estimate of vehicle departures from each station is then used to determine an average patron arrival rate for that station over a 16-hr operational day. Each station's patron arrival rate is used as the parameter of a Poisson process to generate patron arrivals throughout the day. Because Poisson processes have exponentially distributed interarrival times, an inverse transformation of the exponential cumulative distribution is used for the simulation (5). After generating a uniform random number  $U$  on  $[0,1]$ , the exponential interarrival time  $X$  is determined by the following equation:

$$X = -1/q \log(U)$$

where  $q$  is the exponential arrival rate.

Each arrival patron (or group of patrons) is then assigned a station destination. This destination is generated simply by calculating a relative attraction factor for each station on the basis of the user-supplied information about the daily number of vehicle arrivals and, from these attraction factors, forming a cumulative distribution function for station destinations. Each arriving party is then randomly assigned a destination station using this derived cumulative distribution.

Currently, the generation of patron arrivals and destinations is not time dependent; each station's patron arrival rate remains constant throughout the simulation. Adding sophistication to the demand scenario simulation would probably add value to the operations simulation. Since the simulation is designed to be viewed in real time, however, there may be no need to further refine the calculation of the demand scenario; demand probably remains constant over the 5- to 10-min window that the average planner spends watching the simulation.

Once the patron arrival information has been determined, transit vehicles are assigned to the stations on the network on the basis of user specifications, and then the simulated operations begin. At each time step during the simulation, a system state update occurs in which a number of tasks are executed. First, all of the new patron arrivals are determined for each station in the network on the basis of information in the patron arrival array generated earlier. Queues of patrons waiting for vehicles are updated with this information. Next, passengers are unloaded from occupied vehicles now berthed at their destination stations. Third, patrons waiting in station arrival queues are loaded into berthed empty vehicles that have destinations equal to the patrons' destinations.

The demonstration created for PRT uses some control strategies specific to automated transit design. For example, in PRT operations simulation an empty-vehicle dispatchment algorithm is implemented that attempts to redistribute empty vehicles in a logical way around the network. Destinations for the empty vehicles are determined by an algorithm that calculates excess capacity at each of the stations by subtracting the vehicles berthed at that station and the number of vehicles en route to that station from the station's berth capacity. The empty vehicle shuttling algorithm sends the vehicle to the station with the largest positive excess capacity in an attempt to rebalance the transit vehicles dynamically.

Other control strategies are also implemented for PRT simulations. Vehicles that have been berthed at stations or are waiting in the arriving or departing vehicle queues are moved into open station slots ahead of them or out onto the guideway. Any vehicle in the farthest position in the departing vehicle queue is moved out onto the guideway, if possible; all trailing vehicles in the departure queue are subsequently moved forward one slot, if possible. Once all of the station movements have been completed, the control strategy algorithm turns finally to vehicles moving on the guideway. Each vehicle traveling between stations has been assigned a station destination determined either by the station destination of the passengers riding in the vehicle or by the empty vehicle shuttling algorithm. When the simulated operations are initiated for PRT simulation, the PITVS computes network-spanning shortest-path trees for each station using a label-setting algorithm. The result of this computation is an  $(S \times N)$  array of "next-node" information where  $S$  is the number of stations and  $N$  is the number of nodes on the network. For each station destination and node location of a vehicle, this array tells the vehicle the next node to which it should proceed in order to reach the destination along the shortest path. To control systems other than direct origin-to-destination systems such as PRT, this array of next-node information will no longer be acceptable. To generalize operations simulation, enhancements will include encoding such information specifically for each simulated vehicle so that vehicles having different routes can be used.

Although the current demonstration PITVS simulation algorithms give the user an interesting visualization of a PRT system in action, it is important to note that the goal of the simulated operations was not to provide transit planners with key performance information. Currently, the demand generation and control algorithms are far too infantile for this purpose. Instead, the authors wanted a reasonable approximation of actual operations with calculations simple enough to be performed by a personal workstation in real time. The results have been promising; all of the system state update algorithms are performed along with an entire screen refresh many times each second, providing a smoothly changing view of real-time simulated operations.

## PERFORMANCE ENVELOPE

To determine if the PITVS provides a useful visualization tool, it is essential to discuss performance issues. As has been emphasized, any visualization tool must be able to provide

access to its visual information with a speed that does not leave the user frustrated and unwilling to continue to use the tool. How fast is fast enough? The PITVS lets the user dynamically change viewpoints with the mouse, essentially flying around the modeled world, and this action requires that the entire screen be redrawn several times every second. Additionally, to update the view of the system state during simulated operations in real time, the scene must again be redrawn at least once a second to be useful.

The PITVS attempts to limit the number of polygons drawn in order to keep the draw speed at a satisfactory level; even these attempts, however, cannot prevent some performance limitations. Performance of the PITVS in terms of redraw speed is a function of the hardware, the size of the user's network design, and the detail of the geometric representations. Most system development was done using a Silicon Graphics 4D/210 workstation configured with VGX graphics. The 4D/210 uses a single RISC 25 MHz processor rated at 3.3 MFLOPS, and the VGX graphics board renders 180,000 polygons per second. Also used were an IRIS 4D/35G with a faster processor rated at 6 MFLOPS but slower graphics, rendering only 6,000 polygons, and a 4D/35 with an Elan graphics board capable of 100,000 polygons. The best performance of the PITVS software was realized during a demonstration on an IRIS with VGXT graphics. Fast redraw speeds provided excellent user control while changing viewing positions in the visualization. As a testimony to the usefulness of the system, several transportation engineers attending the discussion inquired about using the system for visualizing roadway and parking designs for airports.

One exciting hardware development that would greatly enhance the PITVS is Silicon Graphics' newest graphics hardware configuration, the Reality Engine. This powerful system offers real-time texture mapping, a feature that would allow the PITVS to increase its level of realism dramatically. Texture mapping in real time means that images scanned into the computer from color photographs can be displayed on polygons drawn on the graphics screen and can be updated almost instantaneously as the user changes viewing positions. Hence, photographic images of buildings and natural features could be incorporated into the PITVS display to further enhance the visual information that the system provides. Current system development is being done on a Silicon Graphics Indigo2 configured with Extreme graphics.

It is important to comment on the practical size of a three-dimensional world to be modeled with the PITVS. Although completely dependent on the detail of the geometric representations and the configuration of the hardware, the PITVS should be able to render on the order of  $10^5$  visible polygons on most systems without considerable delay. Visible polygons refer to those that actually need to be drawn on the screen, not those that lie behind the current viewpoint. This threshold should allow adequate visualization of on the order of 1 to 10 mi<sup>2</sup> of a planning area at a time.

## CONCLUSIONS AND RECOMMENDATIONS

The state of personal workstation computing today provides the opportunity for advanced three-dimensional visualiza-

tions; the PITVS takes advantage of this power to give transit planners, engineers, and the general public a three-dimensional view of proposed transit systems far before implementation. The PITVS provides visual information rarely if ever before available to transit planners and does so with some degree of flexibility. More important, however, the PITVS software may serve as a base platform from which even more advanced visualization systems can be built. What is state of the art in terms of computer hardware today is often commonplace tomorrow; soon, therefore, may be available the necessary processing and graphics power to more closely approximate reality in the PITVS model. An example of a possible enhancement envisioned would be a so-called texture-mapped background environment in which the polygons representing structures in the PITVS scene would be overlaid with actual photographic images. Any reality-enhancing improvements that do not detract from the system speed and flexibility will increase the value of the PITVS. As a stand-alone system in its current state and as a platform for future development, the PITVS provides powerful new information that will help professionals and the public alike in sorting out complicated visual impact issues as well as enhance the transit designer's task.

## ACKNOWLEDGMENTS

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