Interactive Graphics Sketch-Planning Model for Urban Transportation

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This paper presents a description of an interactive graphics sketch-planning model for urban transportation developed at Princeton University. The model was developed to operate in an IBM 370 VM/CMS environment with functions and subroutines written in both APL and assembler language to improve flexibility and speed in accessing and manipulating large networks and data bases. Benefits of the interactive sketch-planning aspects of the model are described. The sensitivity of sketch planning to spatial aggregation of demand data and remedies for alleviating the inaccuracies resulting from spatial aggregation are discussed.

The need for solutions to the current problems of urban transportation has given a sense of urgency to the transportation planning process. While energy shortages, traffic congestion, and pollution have imperiled the future of the automobile in urban areas, public transportation has been beset by mounting financial difficulties. New, more flexible approaches are required if transportation planners are to accomplish their mission.

In the attempt to improve transportation facilities, attention has been increasingly directed to the use of mathematical models as aids in the planning process. A well-known example is the Urban Transportation Planning System (UTPS) model developed for the Urban Mass Transportation Administration (UMTA). Such models assume that individual decisions by travelers as to when, where, and how to make their trips can be estimated by a set of mathematical equations programmed on a digital computer. Difficulties associated with earlier versions of these transportation planning models were that (a) they were cumbersome to iterate on system design options because output data were difficult to interpret, (b) input data were voluminous and difficult to "digest," and (c) software typically consumed large amounts of time and money.

The transportation planning process is essentially an iterative procedure in which the next move to be made is decided on the basis of the results of the preceding move. This is the approach taken by interactive sketch planning; it allows dialogue between person and computer and enables iterations to be carried out as a continuous process rather than advanced in fits and starts. Moreover, interactive computing is ideally suited to permit the transfer of information between person and computer in easily visualized graphic form rather than in the complicated digital form typified by punched cards.

Interactive sketch planning is not the only valid approach to the transportation planning process, but it does provide a vital link between the coarse types of analysis that indicate basic relations and detailed, microscopically oriented procedures such as real-time simulations. In fact, a sketch-planning model can be used to accept results from a coarse model such as a parametric analysis and then pass on these results as input to a detailed simulation of system operation. One of the most critical tasks that a sketch-planning system can accomplish is the evaluation of a number of network configurations including alternative routings and station locations and the identification of an optimum configuration. This is a difficult problem for which closed-form analytic solutions exist only for the most trivial networks. Given any realistic structure for transportation demand, the analytical problem of specifying the optimum network configuration cannot even be formulated let alone solved because the performance index cannot be made explicit. This is where the planner, the transit system designer, and the policy maker are required to have direct input into the transportation design process. Given data in an easily digestible form, they can weight the various performance measures, determine the impacts of previous iterations, and propose new configurations that would improve the system design. By use of a rapid and inexpensive sketch-planning model that presents results in an easily understood form, designers, planners, and policy makers can experiment with new configurations as a learning process and ultimately fine-tune preferred configurations for final recommendation.

Although several sketch-planning computer models have been developed, it is the premise of this paper that the Princeton sketch-planning model described here, which is more fully documented by Hess and Kornhauser (1), is the only one that begins to meet the interactive graphics user-oriented objectives set forth above. The software itself is rather straightforward. It contains some innovations in that it applies and implements concepts that are only discussed by others. It would be incorrect to imply that the analysis could only be carried out by using an interactive graphics system. In fact, standard UTPS evaluates transit system configurations without use of interactive graphics, and the present interactive graphics model was developed from a batch-process model. But the time-related benefits of the interactive and graphic capabilities are considerable, producing savings in (a) the time necessary to produce the first network and subsequent networks in machine-readable form, (b) the time necessary to ensure the elimination of network coding errors such as tunnel links, and (c) the time to digest and interpret the output of the network analysis process.

Additional benefits include the fact that even a novice user can effectively use the model and learn to appreciate even subtle trade-offs in transit network design. The experienced user can also benefit in that the simplicity of model applications enables the user to probe model performance to greater depths. It was this capability that led to the analysis of the sensitivity of model forecasts of transit ridership to the level of spatial aggregation of base demand data.

DESCRIPTION OF THE SKETCH-PLANNING MODEL

Purpose and Structure

The purpose of the Princeton University project was to design and implement on the computer an interactive transportation planning system. This system was to be fast, inexpensive, and reliable in achieving those answers it set out to achieve. It would combine the facilities necessary for rapid "number-crunching" operations on large data bases with the flexibility required to provide two alternative methods for graphic input, editing, and output of transportation data. That is, it would allow the user to describe, for example, a transportation network in visual terms as he or she sees it on a map. The computer would assume the responsibility for converting graphic constructions and images into their digital representations within the program, analyze the performance of the network, and report its findings by using both graphic and numeric media.

The sketch-planning model was structurally designed so that it could be applied to a wide range of different transportation systems. It was to have the ability to compare the relative merits of two competing transportation modes over a specified geographical area and to allow successive modifications to one mode—the other mode being held constant—in the interest of improving its performance relative to the other mode. This structure would normally be applied to real conditions by holding constant an existing fixed system, such as an urban street network, and varying against it different configurations of a proposed fixed-guideway mass transit system or a new route structure for an existing bus system. However, it would be possible to vary the network originally held constant against a single network from its competitor mode by simply interchanging data bases, if that were desired.

Princeton University Computer System

The program has been developed, and is currently undergoing further development, on Princeton University's IBM 370/158 computing system. The 370 is linked by means of a file spooling system to Princeton's other primary computer, an IBM 360 model 91; these two computers and the various devices attached to them provide the program with great versatility in the areas of input and output. The heart of the program lies in a "workspace" consisting of functions and subroutines written in the APL computer language. APL is particularly well suited to interactive computing because of the ease with which user-oriented input-output structures can be implemented.

In its current version, the workspace operates in the environment of APL/CMS, an implementation of APL written by IBM to run on their VM/370 operating system, which Princeton uses. Although the program is capable of functioning as a self-contained unit within an APL workspace, it presently takes advantage of the external file system provided by the VM/370 system to access large data bases and execute assembled object codes stored outside the workspace for efficiency. This option, which was specially added to the Princeton version of APL, enables the program to overcome the inefficiencies presented by program loops in an interpreted language such as APL (as opposed to an assembled or compiled language) simply through the process of programming the innermost nested loops in assembler language. The program thus benefits concurrently from both the speed of IBM assembler language and the flexibility of a high-level interactive language such as APL.

The model takes advantage of the great variety of input-output devices available at Princeton University. Input to the workspace is accepted primarily from Tektronix model 4013 and 4015 interactive cathode ray tube (CRT) terminals, which use the APL and ASCII character sets and allow both graphic input (via crosshair cursors) and output (via vector lines) on the terminal screen. In addition, graphic input from maps can be entered on a Tektronix model 4954 digitizer, and card images can be sent from a card reader through the 360/91.

Output too goes direct to the user who sits at a Tektronix CRT, and images on the screen can be hard-copied on an attached dry-silver recording copier. Output may also be sent by means of the 360/91 to a variety of other devices including Calcomp 936 and 565 plotters and IBM line printers or card punches. Thus, input and output options are not at all constricting.

The program as applied to a study of Trenton, New Jersey, for engineering laboratories resides in an "active" workspace of approximately 170 kilobytes of dynamic core. Because the capacity of the workspace has yet to be exceeded, it is unclear how large a network may be analyzed within this structure. Networks containing 120 or more stations have been accommodated without incident. The program itself, stored on disk, occupies approximately 45 kilobytes of functions, subprograms, the symbol table for the APL system, and data internal to the workspace. In addition, external files containing the demand data base and assembled object decks fill about 25 to 30 kilobytes of additional disk space.

The following are the capabilities of the sketch-planning model:

1. The network can be input by means of either a CRT or a digitizer tablet.
2. Network editing in terms of station, link, or intersection deletion, addition, or translation can be accomplished by using the CRT (Figure 1).
3. Flexible "windowing" features allow interactive scanning and focusing on specific parts of the network (Figure 2).
4. Pathfinding and network-assignment routines have been written in assembler language to improve computation speed.
5. Complete transit system analysis routines include a choice of several mode-split analysis techniques and route assignment and economic analysis routines.
6. Various levels of formatted output—graphic supported by numeric—are available.

FUNCTIONS OF THE MODEL

A more detailed description of the methods used by the interactive sketch-planning model is presented below.

Initialization of the Data Base

To analyze the performance of a transit network in a given geographical area, the digitizer or CRT screen must first be associated with the coordinate system of the region to be studied. An initialization function called MAPINIT is available for this purpose. MAPINIT also allows the user to input in graphic form a backdrop of political boundaries, streets, or other physical features that can be displayed or generated on maps in conjunction with the interactively designed transit network.

The next step involves initializing the data base, which normally consists of the location of demand points and two matrixes containing origin-destination (O-D) demand information and disutility for automobile travel between each demand point. In addition, if it is desired to make use of the uniform demand distribution option for some or all traffic assignment zones, two additional pieces of information must be supplied for each zone: the size of the zone and its demand characteristics (whether uniform distribution, point source, or a cross between the two). Two functions, DEMAND and EDGE, can be used to perform these tasks. When all this information has been entered into the computer by the most convenient method, it is compressed by using a bit-packing function and stored principally in external data files on an on-line disk by means of the STORE function.

Network Design Procedure

The normal network design process involves sketching an initial network on a map of the study region, placing the map on a digitizer, and tracing over the network with an electronic pen or "bullseye." Transit networks are constructed by means of links interconnecting stations at which passengers are permitted to board and depart from the network, and interchanges, at which three or four links are allowed to come together. The initial input procedure for the digitizer is controlled by a function called TAB3. Alternatively, if the user has provided a geographic background that is sufficiently detailed to obviate the digitizer, he or she may sketch the network directly on the CRT screen by using the CRT3 function, which accepts input through the use of the crosshair cursors.

After the initial network loop has been accepted by the computer, the user may then enter the network editing mode, which permits manipulation of the network

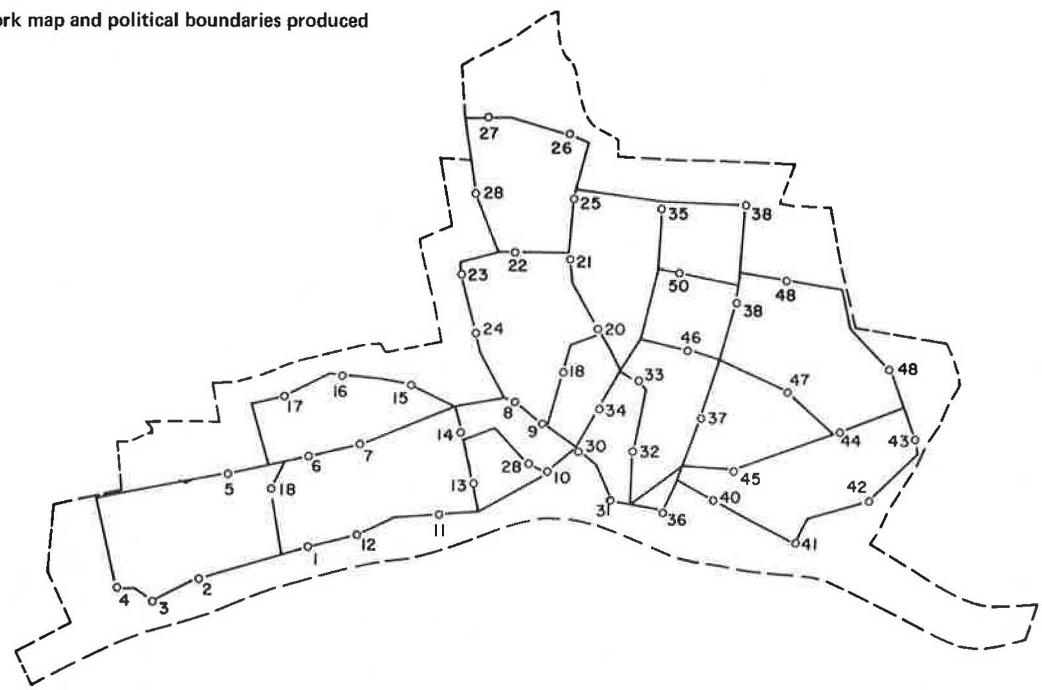


Figure 1. Network map and political boundaries produced by NETMAP.

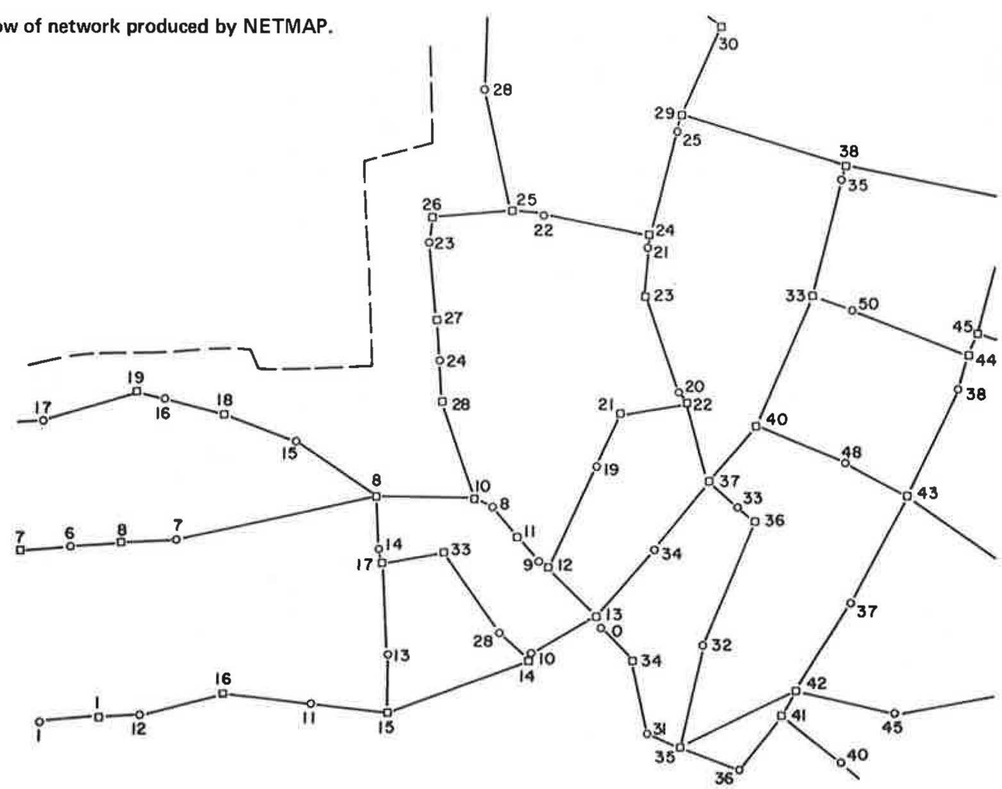


Figure 2. Window of network produced by NETMAP.

by use of the following functions: ADDINT inserts an interchange on an existing link; ADDLINK adds an entirely new link to the network; ADDSTA inserts a station on an existing link; DROPINT deletes an interchange from a link; DROPLINK deletes an entire link from the network; DROPSTA deletes a station from a link; REVERSE changes the direction of flow of a link; and TERMOVE moves a node to a new location.

After having entered a series of modifications, the user can exit from the network editing mode by means of the STREAM function, which updates the network on the basis of the modifications ordered by the user. This function also reassigns node numbers to improve future computational efficiency and creates a buffered set of graphic control characters that contain the image of a network map. These characters may be dumped to the terminal screen at any time along with the NETMAP function to produce a map (Figure 1). NETMAP allows the user to specify exactly which of five sets of graphic information should be displayed in the map: the geographic backdrop, the network itself, station node labels, interchange node labels, or directional arrows on links.

When a map of standard scale produced by NETMAP is on the terminal screen, a selected portion of the map may be expanded to fill the entire screen, a process sometimes referred to as windowing. This process, which is handled by a function called ENLARGE, permits close examination of sections of a compact, detailed network for increased clarity. The process can be repeated in recycled form any number of times until the scale is sufficiently large (Figure 2). Two options for the NETMAP and ENLARGE map-generation functions (referred to as NETMAPC and ENLARGEC) are used to send output to a Calcomp paper-and-ink plotter as well as to the terminal screen.

The next step in the analysis procedure is to compute distances around the interactively designed network for the purpose of determining station-to-station travel time. This is a four-stage process. The first stage involves setting up data on adjacent nodes on which an algorithm for minimum-path calculation can operate. The original approach consisted of using a function called ADJACENT to create an "adjacency matrix" in which all values were infinity except those elements representing direct connections between adjacent nodes. The adjacency matrix was then operated on by the MPATHALL minimum-path function, which took advantage of the extendability of APL operators to multidimensional arrays to achieve unusually efficient execution times for APL. This algorithm also made use of the loop network structure and sequential node numbering to improve efficiency in the generation of a predecessor node matrix. Although this algorithm was designed according to the characteristics of the networks on which it was to operate and is one of the fastest available in APL, when the ability to load and execute assembled object decks from within the APL workspace was added to the Princeton APL system, no APL minimum-path program was able to compete with assembler language. As a result, ADJACINT and MPATHALL were redesigned to make use of an assembler minimum-path program written by Cormen, a Princeton student. For input this program requires, instead of an adjacency matrix, a "link list" that specifies for each link the distance (or travel time) and the number of the node on the downstream end. This link list is indexed with a set of pointers that indicate the identities of the upstream nodes.

When minimum paths among interchanges have been determined, the information must be translated into station-to-station distances. The NERINT function finds the distances between interchanges and adjacent stations and performs this translation.

The final stage in the assembly of travel-time information is the most crucial: the determination of feeder access from travel demand sources to stations on the transportation network. It is at this stage that the effects of aggregation of travel demand manifest themselves in an underestimation of the average access distance between demand point (zone centroid) and transit station.

The original version of NERSTA treated zone centroids as point sources of demand and merely determined the direct walk distance from centroid to station. During the study of aggregation effects, however, this approach was found to be invalid except when it was applied to disaggregate data. The new version of NERSTA makes use of three added features as inputs: (a) the area of each traffic assignment zone; (b) the demand characteristic of each zone (uniform, point, or superposition); and (c) the function CIRDIST, which finds the average distance between the station and the locus of points within a circular zone as a function of the radius of the zone and the distance between its center and the station.

The new NERSTA produces a considerably more realistic approximation of walk access than does the original version. This formula of course cannot hope to replicate exactly the disaggregate characteristics of walk access because of the effects of averaging resulting from aggregation, but it yields access data whose average is much closer to the average across the disaggregate data base.

After the completion of NERSTA, the total transit travel time for every O-D pair can be compiled and a transit disutility calculated. For each trip or group of trips with a common origin and destination, COMPATH examines the 16 possible choices of routings on the transit network represented by the combinations of the four stations nearest to the origin demand point with the four stations nearest to the destination point. After weighting the feeder access (i.e., walk) and ride times by means of the user-specified feeder access speed and transit vehicle speed, the function picks the minimum disutility path of the 16 possible paths and computes a relative disutility value between the transit mode and the automobile mode. It then examines the origin and destination stations to see if they are the same, in which case that trip (like all intrazonal trips) is assigned to the pedestrian model. When all walk trips have been eliminated from further consideration, a logit model is used to calculate the transit ridership between each O-D pair.

In the process of determining mode split, a record is made of transit travel time and feeder access distance for all but the intrazonal trips regardless of the mode to which any trip was assigned. This information is later displayed in a pair of graphs and tables for reference. Meanwhile, now that the function has decided exactly which trips are to be assigned to the user's network, the program loads these trips onto the network so that passenger volumes on links and in stations can be determined.

As it performs these operations, COMPATH accesses two external data files that contain demand data and competing-mode, travel-time disutility and reads them sequentially into the workspace, one record at a time. Thus, only one record of each of these large data files is in the workspace at any time, a feature that results in substantial economies with respect to dynamic core requirements for program execution. Each record, being a single row of a matrix, contains information on all trips that originate at a particular demand point. The records are decored from bit-packed into normal

APL integer format and, when the travel-time differences have been found, APL branches to an assembler program that tabulates time difference, transit travel time, and walk distance and loads transit trips onto the network by tracing each path through the predecessor node matrix. When this process is complete, or if the demand point did not generate any transit trips, the program returns to APL, which reads the next record from each file. Processing continues until the last demand point has been examined, at which time APL outputs the results to the user's terminal.

COMPATH sends information to the terminal on overall mode split based on the logit model; this is followed by a table on travel-time differences for trip ends, differentiated by demand point. This table is perhaps the most important feature because it presents in detail an indication of the level of service that the user's network offers to each demand point. The table not only shows which demand points have the densest concentrations of demand but, more importantly, which demand points exhibit dense concentrations of demand at or near the point of zero utility difference. It is this demand that can frequently be transferred into the transit column by means of minor modifications to the interactively designed network implemented with the aim of improving service to specific demand points.

After the detailed time-difference table has been generated, the time-difference distribution for the entire study area is listed and plotted (Figure 3), to be followed in turn by graphs and tables of transit walk access and travel time and station and link volumes. Once calculated, the link volumes will show up on all enlargements until the network is modified.

Although COMPATH is the "workhorse" of the workspace, it normally does not represent the end of the analysis procedure. Link volumes generated by COMPATH can be used to create a "bandwidth" plot with the function LOADNET in which each link on the network is drawn in a width proportional to the passenger traffic on that link (Figure 4). The option LOADNETC sends a bandwidth diagram to the Calcomp plotter. In addition, MINIPATH, another available function, performs mode-split duties, draws minimum-path trees out of a designated origin demand point, and writes travel-time information for the user's network into an external data file. Finally, a COST model is available to provide a rough economic analysis of the network including total capital cost, annual capital cost (as determined by the capital recovery factor), annual operating and maintenance cost, and total annual cost, both in absolute terms and in terms of expenditures per unit distance of passenger travel.

At this point, the user must make an important decision: (a) decide that he or she has seen enough of the analysis procedure and quit or (b) return to the network editing mode and attempt to improve the network on the basis of what has been learned from the results of the analysis. If the user chooses the second course, he or she enters the iteration process in which the search for the optimum centers on the dual aim of increasing ridership while decreasing average cost. The iteration process continues until the user is satisfied with the network. Typical users working with the Trenton data base have achieved relatively well-optimized networks after, at most, 20 iterations.

By using this program, a network can be created from scratch in as little as 15 min and subsequent iterations can be performed within 5 to 10 min. Because execution time for the current version of the workspace depends primarily on the number of demand points in the data base rather than on the size of the network, execution time for one iteration is relatively constant within the range of 45 to 60 s. In terms of daytime rates on the Princeton 370/158, the typical cost per network iteration on the Trenton data base has run to about $5, including "connect time"; after midnight the charges are half as much, or $2.50. In view of the reasonable cost and the advantages offered by time sharing, it is hoped that this program will see increasingly wide application in the future.

IMPACT OF SPATIAL AGGREGATION

Because the model could be readily executed and modified, several analyses were undertaken to investigate the sensitivity of some of the analytic techniques used in the sketch-planning process. The primary focus of one investigation, which probably would not have been undertaken if it were not for the availability of a flexible and easily implementable sketch-planning model, was to establish the sensitivity of the transit ridership forecasts of the mode-split modeling process to the degree of specificity of O-D location.

It is well-known that the mode-split task of any transit demand forecasting project is the task that is most sensitive and prone to error. Questions arise as to the functional form of the mode-split model and the value of various coefficients. A further question has been raised recently about the impact of spatially aggregating demand data into zones by assuming that all trips within that zone are generated at the zone centroid. Of principal interest here is the spatial aggregation of trip-generation points to the centroids of zones.

Mode-split modeling could be considered an art if it were not founded on the behavioral consumer choice theory of individual utility maximization. Any application of the mode-split models should be done at the level of the individual traveler unless it can be documented that the aggregation of travelers into any group does not bias the quantitative output of the mode-split model. Nonetheless, the first step normally taken in the urban transportation planning process is to aggregate travel demand into traffic assignment zones finite (and often large) in size. This is usually indispensable because raw data do not exist, computer storage facilities are inadequate, or the repetitive process of analyzing each traveler would require excessive computer time. Mode-split estimates are then made without validation of the spatial aggregation of the data; at least the literature does not contain documentation of that validation.

It may be argued that spatial aggregation is acceptable as long as the disutility collection and distribution elements of the transportation system are insignificant as compared with the line-haul disutility of urban trips. This is true for most automobile trips because walk distance at both trip ends is usually small and the street system is ubiquitous. This is not the case for many transit trips and especially those that must depend on the walk mode for collection and distribution. For these systems, the access modes contribute heavily to total trip disutility to such an extent that the disutility of the line-haul portion of the trip may even become insignificant (2).

Travel Demand Data

An analysis of the effects of spatial aggregation on the patronage forecasts of the sketch-planning model made extensive use of data collected by the Princeton University Transportation Program during its study of transportation alternatives for the city of Trenton, New Jersey. Of the data available from this study, the most valuable input was a collection of disaggregate travel demand information compiled from a 1972 home inter-

Figure 3. Travel-time differences presented on the terminal screen.

TIME DIFFERENCE TABLE FOR NON-WALK TRIPS FROM EACH ZONE

(AUTO)6	5	4	3	2	1	0	1	2	3	4	5	6+(PRT)	
753	298	242	428	425	111	281	136	141	8	0	33	0	58
1279	212	94	151	389	88	134	61	0	36	0	0	0	59
389	48	56	152	130	144	175	76	58	44	25	19	0	60
991	152	377	316	647	380	196	89	111	65	125	0	0	61
625	137	44	78	705	157	89	24	24	42	0	47	0	62
305	7	428	390	457	90	291	177	158	97	17	71	14	63
555	127	185	142	479	257	467	48	149	40	20	0	0	64
769	140	189	317	428	136	93	54	88	0	0	0	0	65
998	285	166	128	263	52	66	35	64	0	0	0	0	66
1576	311	582	360	33	82	218	181	0	79	0	0	0	67
1334	239	504	512	227	135	38	61	24	16	16	25	0	68
743	368	151	221	45	170	45	67	60	0	0	0	0	69
573	30	28	14	30	59	0	0	0	0	0	0	0	70
522	0	0	0	0	0	0	0	0	0	0	0	0	71
84	0	0	0	0	0	0	0	0	0	0	0	0	72
371	43	68	12	31	12	0	0	0	0	0	0	0	73
324	32	88	56	54	37	5	48	9	23	0	0	0	74
1683	222	27	153	36	63	132	0	0	0	0	0	0	75

TIME DIFFERENCE DISTRIBUTION

(AUTO)		-2	16154
-15	1260	-1	11852
-14	568	0	11988
-13	772	1	7262
-12	1110	2	7462
-11	2880	3	4138
-10	5074	4	2494
- 9	7108	5	1790
- 8	13284	6	566
- 7	13806	7	332
- 6	12020	8	46
- 5	14724	9	100
- 4	19780	10	0
- 3	17298		
		(TRANSIT)	

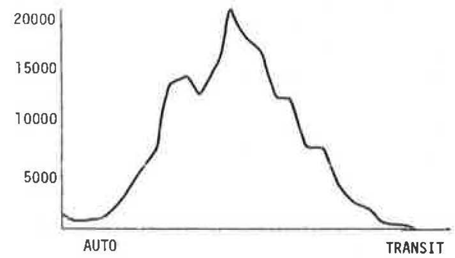
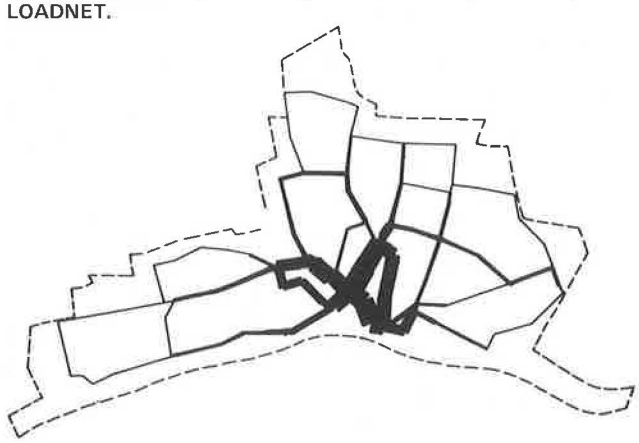


Figure 4. Bandwidth plots of assigned link densities produced by LOADNET.



view survey that covered a 14.7 percent sample of Trenton's population of 105 000. The respondents to this survey reported making approximately 24 800 trips/d, of which slightly more than half, or 12 600, were intracity trips whose origins and destinations were all within the Trenton city limits. The scope of the analysis was limited to those intracity trips and the city of Trenton alone.

O-D geographic locations for these trips were coded in terms of census blocks, which correspond very closely with actual city blocks. Trenton contains 1217 of these census blocks. This implied a geographic resolution of approximately 60.96 m (200 ft). After assembly of the interview data, the trips were "factored"—based on the number of interviews conducted in each section of the city as a proportion of the number of residents in each section—into a total of 99 408 intracity trips estimated to be taken by city residents on a typical day. This information constituted the disaggregate data base.

Accompanying the disaggregate data was an aggregation scheme that clustered the 1217 census blocks into 74 traffic assignment zones for the purpose of simplifying analyses of the various transportation options considered for Trenton during the course of the Princeton University study. Neighboring homogeneous census blocks were grouped to form traffic assignment zones that varied in area from as few as 2 city blocks in the central business district to as many as 33 blocks in residential neighborhoods near the city limits. Average zone size was approximately 0.25 km^2 (0.1 $mile^2$); the geographic location resolution was approximately 243.8 m (800 ft). Each zone in turn was assigned a centroid, which was located at the center of trip-generation activity for the census blocks that comprised each zone. All trips with origins or destinations in one of the census blocks encompassed by a particular zone were then assumed to originate or terminate at the centroid of that zone. Thus, the disaggregate trip data derived from the home interview survey were assembled into a 75-by-75 O-D demand matrix.

Analysis Results

The principal test network—an automated guideway transit (AGT) system with 38.6 km (24 miles) of one-way guideway and 48 stations—was analyzed by using the Trenton demand data first in spatially disaggregate form and then in aggregate zonal form. Overwhelming discrepancies were found between the two analyses. Based on a logit mode-split model that used a weighted travel-time difference between automobile and transit as a measure of utility, the number of daily transit trips assigned by the model rose from 14 811 for the disaggregate case to 31 015 for the aggregate. This represents a difference in the results of 109 percent, attributable solely to the spatial aggregation of demand.

In addition to the disturbingly large shift in mode split resulting from spatial aggregation, there were similar movements in the distributions of transit access distances, travel times, and the time difference between transit and automobile. Compared to the more disaggregate results, the average walk distance involved in a transit trip, as computed by means of the aggregated data, decreased by 45 percent or by nearly half; the average total transit travel time fell by 1.82

min; and the time-difference distribution shifted by an even greater displacement—2.3 min—in favor of the transit system. The discrepancy between the two sets of results in terms of modal split could be eliminated only by holding the logit parameter (α) for the aggregate analysis at the high value of 6 while implementing an extremely drastic reduction in the parameter to 0.198 for the disaggregate:

$$MS = 1/(1 + e^{\alpha \Delta T}) \quad (1)$$

where

- MS = mode split to transit,
- α = logit parameter, and
- ΔT = travel-time difference (transit minus automobile).

Several other networks were designed and subjected to analysis at each of the two spatial aggregation levels. A comparison of the results is given in Table 1 (3).

The inescapable conclusion from these results is that spatially aggregating demand data to point sources introduces significant variability into the bottom-line results of the mode-split procedure. It results in an underestimation of walk access distances to transit routes and a corresponding overestimation of the willingness of travelers to engage in the extra walking necessary to use transit instead of the automobile.

Models for Spatial Distribution of Trips Within Traffic Assignment Zones

It appears that, whenever the number of stations or other access points on the transportation network being modeled is of the same order of magnitude as the number of aggregation zones, a more uniform distribution of trips across the area encompassed by each zone must be assumed. Most urban areas exhibit more of the characteristics of uniform distributions than of a small number of point sources of travel demand; apparently the city of Trenton cannot be modeled as a set of 75 miniature oases in a 19.4-km^2 (7.5-$mile^2$) desert. Although a strictly uniform distribution across each zone was found to produce slightly overstated values for walk distance and somewhat understated predictions of transit travel demand (the principal test network, for example, was assigned only 14 331 daily transit trips based on a strictly uniform model), its output was much closer to the results of the more disaggregate analysis. When aggregation must be done, it appears that the solution that will yield the most satisfactory approximation is to accommodate the two approaches by realizing that most zones will exhibit the characteristics of a uniform demand distribution but some zones will possess centers of activity that result to some extent in the concentration of demand around a centroid. This approach should serve to minimize the negative effects of aggregation, which, in extreme cases and if used without safeguards, could lead to totally meaningless computer output.

The approach taken in this analysis to accommodate spatial aggregation of data was to set up a calculation model for access distance that would allow a flexible accommodation between the uniform demand concept and the point source. As implemented, this flexibility permits the planner to tell the computer, for each aggregation zone, whether its demand distribution should take on the characteristics of a uniform spreading, a point source, or a superposition of the two concepts in which a specified percentage of the travel demand in the zone is assumed to be based at the zone centroid and the other part is allocated uniformly around the centroid in the remainder of the zone. As applied to Trenton, this new model resulted in the categorization of the 75 traffic assignment zones into three groups: 50 zones using the uniform distribution, 6 using a point source, and the remaining 19 modeled according to the superposition approach. The degree of superposition was estimated from the distribution of trip-end density over the census blocks that comprised each zone. The configuration of each zone was assumed to be an equivalent circular zone with a radius equal to half the average distance between the four nearest centroids.

The assumption of any type of area-based distribution of travel demand requires the development of parameters that express the dimensions of the areas involved. One of the simplest models possible, but one that has proven itself to be accurate in the Trenton analysis, views a traffic assignment zone as a circle centered on the zone centroid. If the area of the zone is expressed in terms of πr^2, the parameter of interest in the determination of access distances is the effective zone radius (r). The radius appropriate for each zone can be arrived at in several ways. Two such methods were examined in this study, the fastest of which involves examining the distances from the centroid of the zone of interest to all other zone centroids and to the city limits. In this study, in view of the irregularities with which many of Trenton's traffic assignment zones were created, several different variations on this first method were considered; each was compared in turn with the ideal results as determined by the second method—the direct measurement of the area of each zone.

Because the Trenton city limits existed as a continuum, it was possible to examine only the single point on the city limits closest to each zone centroid. The distance to this point was then multiplied by 2 to take account of the fact that this distance served to estimate the radius of the zone rather than its diameter, which was the parameter estimated by the distances to neighboring zone centroids. This result was then combined with the pool of distances from the centroid of interest to the other 74 centroids to form a set of 75 distances. The study procedure involved taking the three shortest distances from this pool, then the four shortest, and finally the five shortest, averaging them, and multiplying by 0.56 (a circle of a radius of 0.56 units contains the same area as a square of sides 1 unit long).

Table 1. Comparative analysis of three networks at two levels of spatial aggregation of demand data.

Item	Principal Network		Alternate Network 1		Alternate Network 2	
	Aggregate	Disaggregate	Aggregate	Disaggregate	Aggregate	Disaggregate
Transit demand, trips/day	31 015	14 811	28 136	14 491	16 155	9899
Average walk distance, km	0.283	0.511	0.285	0.525	0.430	0.592
Transit travel time, min	8.297	10.117	8.350	10.319	10.027	11.237
Time difference, min (automobile minus personal rapid transit)	1.960	4.263	2.036	4.489	3.730	5.410

Note: 1 km = 0.62 mile.

Table 2. Results of network analysis process using zonal distribution functions.

Item	Principal Network		Alternate Network 1		Alternate Network 2	
	Aggregate[a]	Disaggregate	Aggregate[a]	Disaggregate	Aggregate[a]	Disaggregate
Transit demand, trips/day	15 136	14 811	16 712	14 491	10 345	9899
Average walk distance, km	0.441	0.512	0.449	0.525	0.536	0.592
Transit travel time, min	10.178	10.117	10.112	10.319	11.259	11.237
Time difference, min (automobile minus personal rapid transit)	3.795	4.263	3.767	4.489	4.880	5.410

Note: 1 km = 0.62 mile.
[a]With new access model.

Results of these calculations were compared with data for zone radius derived from measurements of the areas of individual zones by the following formula: $r = \sqrt{area/\pi}$. As it turned out, estimates based on the three shortest distances were significantly lower than data derived from measurements, and estimates based on the five shortest distances were significantly higher than the measurement data; estimates based on the four shortest distances, however, were quite close, exhibiting an average value of 23.67 units versus 24.17 units for the data derived from measurements. The method that used the four shortest distances was therefore adopted for estimating zone radius. However, because the average discrepancy between the measured and estimated data was found to be 2.88 units, it was decided to test the new station access model on the basis of the measured data on zone radii. This final step yielded the closest approximation to the disaggregate results achieved by using an aggregate model. The results for three different networks designed for Trenton are summarized in Table 2 (3).

Even a flexible access model that provides for both uniform and point-source demand distributions cannot hope to match the fineness of a disaggregate model on the microscopic level. The statistical variance of the disaggregate data is diminished by the process of aggregation. The uniform model surpasses the point-source model, however, in that a more acceptable estimate of average walk access distance for a transit system is obtained. There will, of course, be distortions in the model estimations, and in some aspects it cannot be regarded as a completely satisfactory replacement for disaggregate analysis. But what is important is that the distributions it calculates shift much closer to their true form.

USE OF THE MODEL

In addition to being a valuable research tool for the critical evaluation of various modeling procedures used in transportation sketch planning and network analysis, the interactive sketch-planning model is in itself a valuable planning tool. Almost 100 persons have used the software to evaluate many hundreds of AGT network configurations for Trenton and for Philadelphia's South Jersey commuter shed. Some of the networks were studied for academic reasons; others were used in AGT feasibility studies and a proposal for a downtown people mover submitted to UMTA by the city of Trenton.

Although a few users have been computer experts in transportation planning, most users have been freshman students enrolled in a 4-week, 16-h minicourse, Introduction to Urban Transportation. Many of these students were liberal arts majors, and most had no previous computer experience. During the 4-week period, students were taught a few concepts about urban transportation planning; learned how to use the sketch-planning model; designed initial network configurations from socioeconomic and land-use maps of Trenton; established their own implicit design performance indexes that weighed patronage, area served, capital and operating costs, and subsidy; redesigned their network several times to improve on their own performance index; and wrote a final report. The fact that this can be accomplished tends to prove that this sketch-planning tool achieves most of the objectives set forth in this paper.

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REFERENCES

1. J. L. Hess and A. L. Kornhauser. Demand Modeling for Automated Guideway Transit Systems. Transportation Program, Princeton Univ., Rept. 76-TR-13, March 1976.
2. T. Domencich and G. Kraft. Free Transit. Heath, Lexington, 1971.
3. A. L. Kornhauser, S. Strong, and P. Mottola. Computer-Aided Design and Analysis of PRT Systems. In PRT III, Department of Audio-Visual Aids, Univ. of Minnesota, June 1976, pp. 377-384.