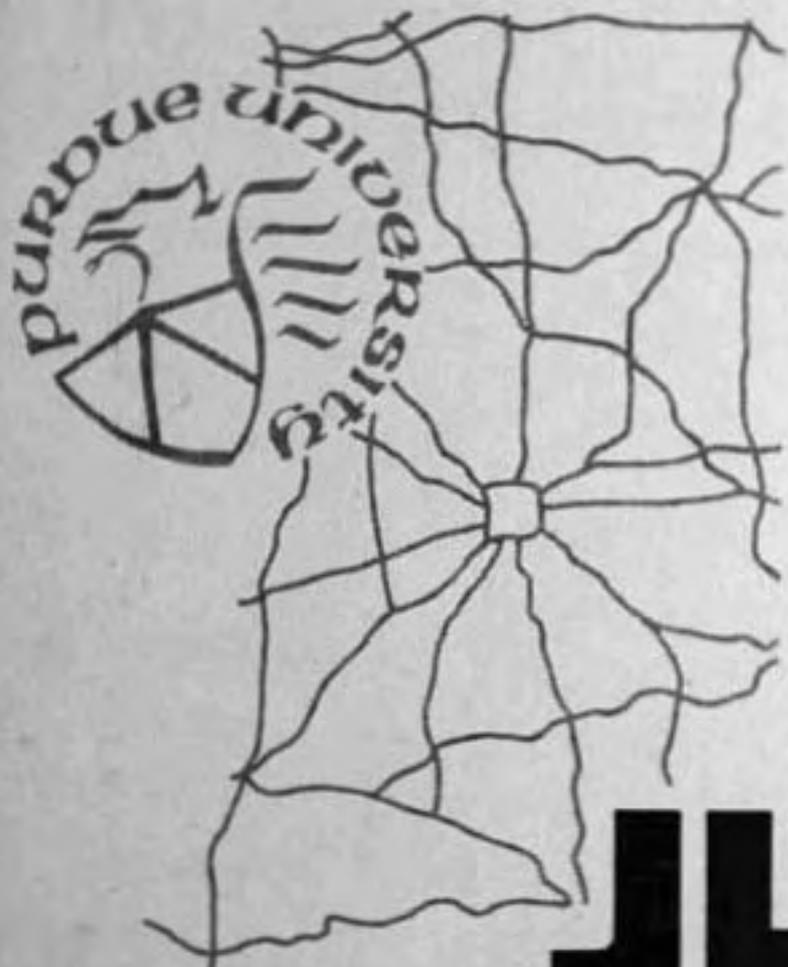


COMPUTER-AIDED REGIONAL HIGHWAY
LOCATION STUDIES

MAY 1969 - NUMBER 12



BY

A. K. TURNER

R. D. MILES

JHRP

JOINT HIGHWAY RESEARCH PROJECT

PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION

Technical Paper

COMPUTER-AIDED REGIONAL
HIGHWAY LOCATION STUDIES

by

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Joint Highway Research Project

Project: C-36-72A

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Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana State Highway Commission

and the

U.S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

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Bureau of Public Roads

Purdue University
Lafayette, Indiana
May 6, 1969



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Technical Paper

COMPUTER-AIDED REGIONAL HIGHWAY LOCATION STUDIES

TO: J. F. McLaughlin, Director
Joint Highway Research Project

May 6, 1969

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File No: 1-6-1

Project No: C-36-72A

The attached Technical Paper "Computer-Aided Regional Highway Location Studies" is being presented by the authors, Dr. A. Keith Turner and Professor Robert D. Miles, at the National Conference of the AASHO Committee on Electronics on May 6, 1969 in Seattle, Washington. Approval for this presentation was granted by the Bureau of Public Roads on submission of the Abstract.

The material in this paper was developed from the current HPR-1(5) research on "Evaluation of Numerical Surface Techniques Applied to Highway Location Analysis."

The paper is now presented to the Board for approval for publication in the AASHO Proceedings. It will also be submitted to the ISHC and the BPR for their review, comments, and approval.

Respectfully submitted.

Harold L. Michael

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"Computer-Aided Regional Highway Location Studies"

by

A. Keith Turner and Robert D. Miles

A paper to be presented at the 1969 Annual Conference of the Committee on Electronics, AASHO, Seattle, Washington, May 6-7.

ABSTRACT

Present highway location procedures concentrate on the geometric and economic aspects of only a few alternatives. New techniques are required to assist the design engineer in rapidly generating and objectively assessing larger numbers of alternatives, particularly during the initial planning phases when regional studies are undertaken and generalized corridors determined.

A prototype model of a "Generalized Computer-Aided Route Selection (GCARS) System" has been designed and tested at two Indiana test sites. The GCARS System utilizes the man and machine according to their capabilities; the man controls the analysis and makes assessments of alternatives on the basis of data storage, retrieval, and manipulation functions undertaken by the computer. Information exchanges are facilitated through the use of statistical and graphical displays.

The system processes suitable measures of each highway location factor selected by the engineer to produce a series of utility surfaces. These surfaces may be combined in various proportions to produce multiple factor utility surfaces. Repeated minimum path analysis of these utility surfaces generates a series of alternative locations between any origin and destination, in terms of selected location factors alone or in combination. The sensitivity of the locations to the various factors and combinations is measured by comparing subsequent choices to the first choice.

These procedures are illustrated by examples from the test area studies. The results show how the selection of new highway corridors is affected by the various location factors reflecting either construction costs or service benefits.

COMPUTER-AIDED REGIONAL HIGHWAY
LOCATION STUDIES

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INTRODUCTION

In general, the "best" highway location represents a path of maximum social benefit at least social cost in terms of many conflicting criteria. The necessity for a broader analysis of the social and economic consequences of proposed highway developments has become increasingly apparent in recent years.

Due to time and man-power limitations, presently utilized location procedures concentrate on detailed geometric and economic analysis of comparatively few alternatives. Improved designs can result only when adequate analysis is undertaken at all stages in the planning process; therefore, new methods are required to rapidly and selectively generate and evaluate regional highway alternatives.

This paper describes the underlying logic and computational procedures of the prototype Generalized Computer-Aided Route Selection (GCARS) System. The GCARS System has been developed to aid the design engineer during the initial stages of the highway planning process through use of the computer for data storage and manipulation functions.

The development of this system was sponsored by the Indiana State Highway Commission and the Bureau of Public Roads; however this paper has not had the benefit of their review. The opinions, findings and conclusions expressed in this report are those of the authors and do not necessarily represent those of the sponsoring agencies.

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THE HIGHWAY PLANNING PROCESS

The Highway Planning Hierarchy

The identification of the best highway location involves a hierarchically-structured sequential decision process. The location is defined with greater and greater precision in a series of steps, each forming a level in the hierarchy. Table 1 shows this relationship and defines five standard levels.

The steps, termed "actions" by Manheim (14), contain three "activities". The data preparation activity concerns the collection and sampling of suitable information for all factors believed pertinent; the search activity includes evaluation of the data, and generation of alternatives; the selection activity involves choosing among the alternatives generated.

Figure 1 represents a map of a hypothetical route location problem and shows the spatial relationships of the various actions and activities. These are lettered in the order they were generated and evaluated. The selection of the corridor is of major importance in highway location investigations.

Classification of Highway Location Factors

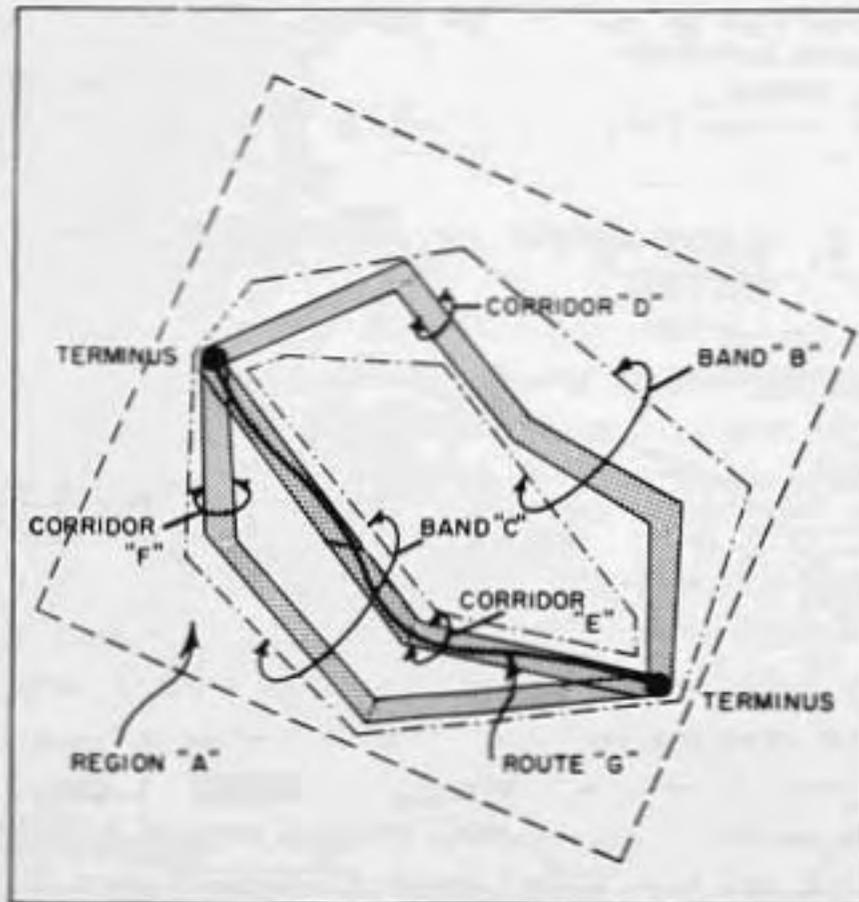
Highway location factors include those natural and man-made conditions which affect the selection of highway bands, corridors, routes, and alignments. At any level in the highway planning hierarchy, two groups of location factors can be distinguished. These are shown in Figure 2.

The first group includes those factors which may be used to define a preliminary set of alternatives. Since they can be studied without reference to any preselected alternative, these factors are termed "route-independent factors".

The second group of highway location factors is used to define the preliminary alternatives to produce a final set of alternatives. These factors cannot be defined except with reference to a pre-selected alternative, and are therefore called "route-dependent factors". Many route dependent factors can only be described at the lower levels of the highway planning hierarchy. For instance, it is very difficult, if not impossible, to quantitatively evaluate the

TABLE 1
THE HIGHWAY PLANNING HIERARCHY

	ACTION	ACTIVITIES
LEVELS	Region	Search for and select a large area containing all conceivable feasible solutions.
	Band	Search for and select one or more "bands" five to ten miles wide.
	Corridor	Search for and select one or more "corridors", two to five miles wide.
	Routes	Search for and select one or more "routes" one half to one mile wide.
lowest	Alignment	Search for and select one or more trial alignments, prepare final plans for facility.



(adapted from Manheim)

FIGURE 1. A HYPOTHETICAL ROUTE LOCATION PROBLEM SHOWING THE SPATIAL RELATIONSHIPS OF VARIOUS ACTIONS GENERATED AND EVALUATED.

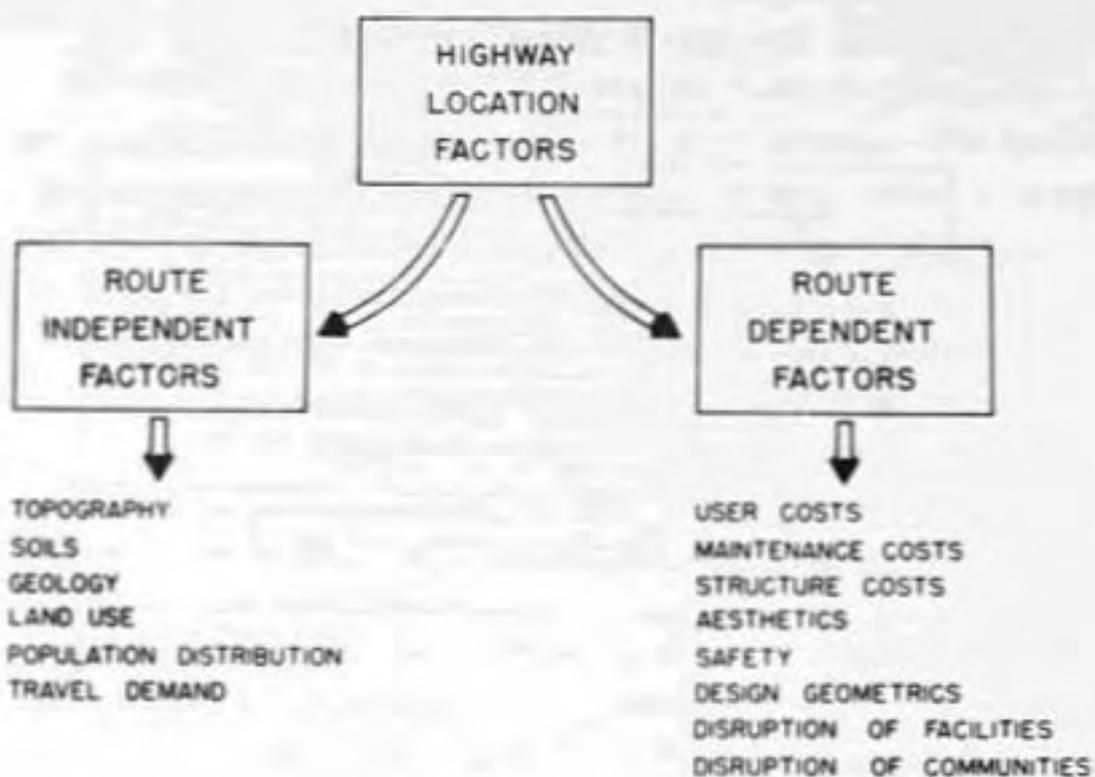
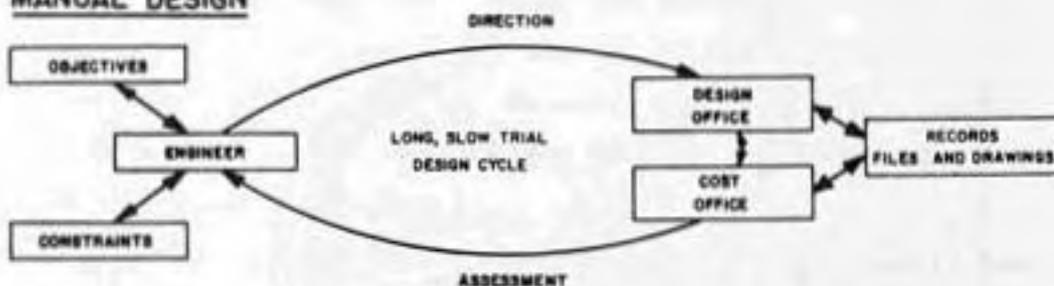


FIGURE 2. CLASSIFICATION OF HIGHWAY LOCATION FACTORS.

MANUAL DESIGN



COMPUTER-AIDED DESIGN

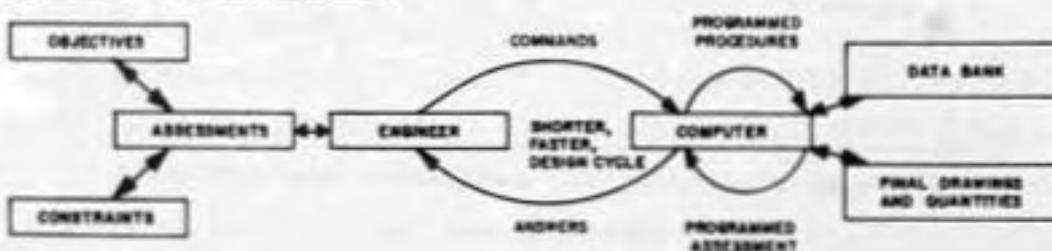


FIGURE 3. ALTERNATIVE DESIGN PROCEDURES.

disruptive costs or aesthetic values associated with a corridor. Consequently, in the upper levels of the highway planning hierarchy, where the GCARS System is expected to be used, only generalized values can be assigned to most route-dependent factors.

Alternative Highway Location Analysis Procedures

At least two approaches have been utilized to select a "best" plan for a new transportation facility in terms of a number of conflicting criteria. These are (1) Graphical route selection procedures, and (2) Computer-assisted design procedures.

Graphical Route Selection Procedures

Many engineers have utilized graphical procedures to determine optimal route locations (1,18). Although there is little standardization among the various systems, they all may be reduced to the following steps:

- 1) identification of the pertinent highway location factors,
- 2) development of maps at a consistent scale, showing each factor,
- 3) preparation of overlays for each factor showing by a series of gray scales the levels of utility for highway locations associated with each map location, in terms of that factor,
- 4) the combination of these overlays in some fashion to determine the "best route" for all factors, as shown by zones of coincidence of gray scales.

The authors believe that graphical procedures are particularly liable to operator bias. Subjectivity is bound to enter the analysis either during the construction of the individual factor overlays or in the extraction of the essential patterns from the combined overlays. Elimination of such bias appears difficult.

Also, the use of graphical procedures does not automatically lead to more efficient analysis procedures. The development of gray-scale overlays is a time consuming manual process. Thus it is rarely practical to revise these overlays and test the effects of these changes on the selection of alternatives.

Computer-Assisted Design Procedures

The rapid development of digital computers naturally resulted in attempts to utilize this new tool in highway location. The computer was found useful in two areas: in the detailed geometric analysis of roadway alignments for which several systems have been developed (4,13,22), and in the production of "driver's-eye" movies used to simulate a trip along a proposed facility (8,9,13,20). The use of the computer has lagged in the more generalized analyses required in the upper levels of the highway planning hierarchy (23).

Computers have no intelligence; they compute according to programmed instructions. Programming a computer so that it can automatically generate correct decisions by analyzing data is a most formidable task. Linear programming techniques, including Bayesian decision theory, have been suggested (14). The present lack of knowledge concerning appropriate "awards" and "penalties" associated with trade-offs among conflicting factors has restricted the implementation of such procedures.

As a consequence, computer-aided design systems, in which the computer is used as a design aid, rather than as the designer, have been suggested (13,23). In such a system man and machine are complementary partners; both perform those functions for which they are best suited. Generally this means that the machine performs laborious, repetitive data manipulation, storage, and retrieval functions, while the man controls the analysis by interpreting the results of the machine procedure and by planning subsequent steps. The concept of a computer-aided design scheme, as opposed to an entirely manual one, is shown in Figure 3.

A computer-aided system can only be effective if rapid and convenient "man-machine information interchanges", or "dialogs" are possible. Data must first be reduced to machine usable form, generally by sampling and digitization. Graphical and statistical output shortens the machine-to-man dialog and allows the design engineer to extract the important information quickly and easily.

Use of a computer-aided scheme involves the four basic steps

used in graphical route selection procedures. Numerical representations stored within the computer replace the graphical representations. These allow more objective assessment of alternatives and can be more readily modified to reflect changes in the relative importance of factors, or in the characteristics measured for any particular factor.

THE GCARS SYSTEM

The GCARS System Design Standards

The GCARS System was developed on the basis of the following seven design standards:

- 1) The system shall be a computer-aided design system, with the computer used for data storage, retrieval and manipulation procedures.
- 2) Effective man-machine dialog procedures will be incorporated into the system.
- 3) The system shall be capable of incorporating suitable quantitative measures of all pertinent factors.
- 4) The system shall generate and order regional highway alternatives by analysis of location factors alone or in combination.
- 5) The system shall be programmed in FORTRAN-IV.
- 6) The system shall be capable of operation on medium-sized computers.
- 7) The system shall have general compatibility with available lower-level design systems, such as the Digital Terrain Model, in the terms of resolution and data collection.

The Basic Concept

Roberts proposed a similar concept in 1957 (21). The prototype GCARS System represents the first attempt to actually develop the concept. Figure 4 represents the GCARS System in graphical analog form.

It is assumed that some form of basic information for each factor is available on maps. By appropriate mathematical and statistical procedures these maps are transformed to numerical cost

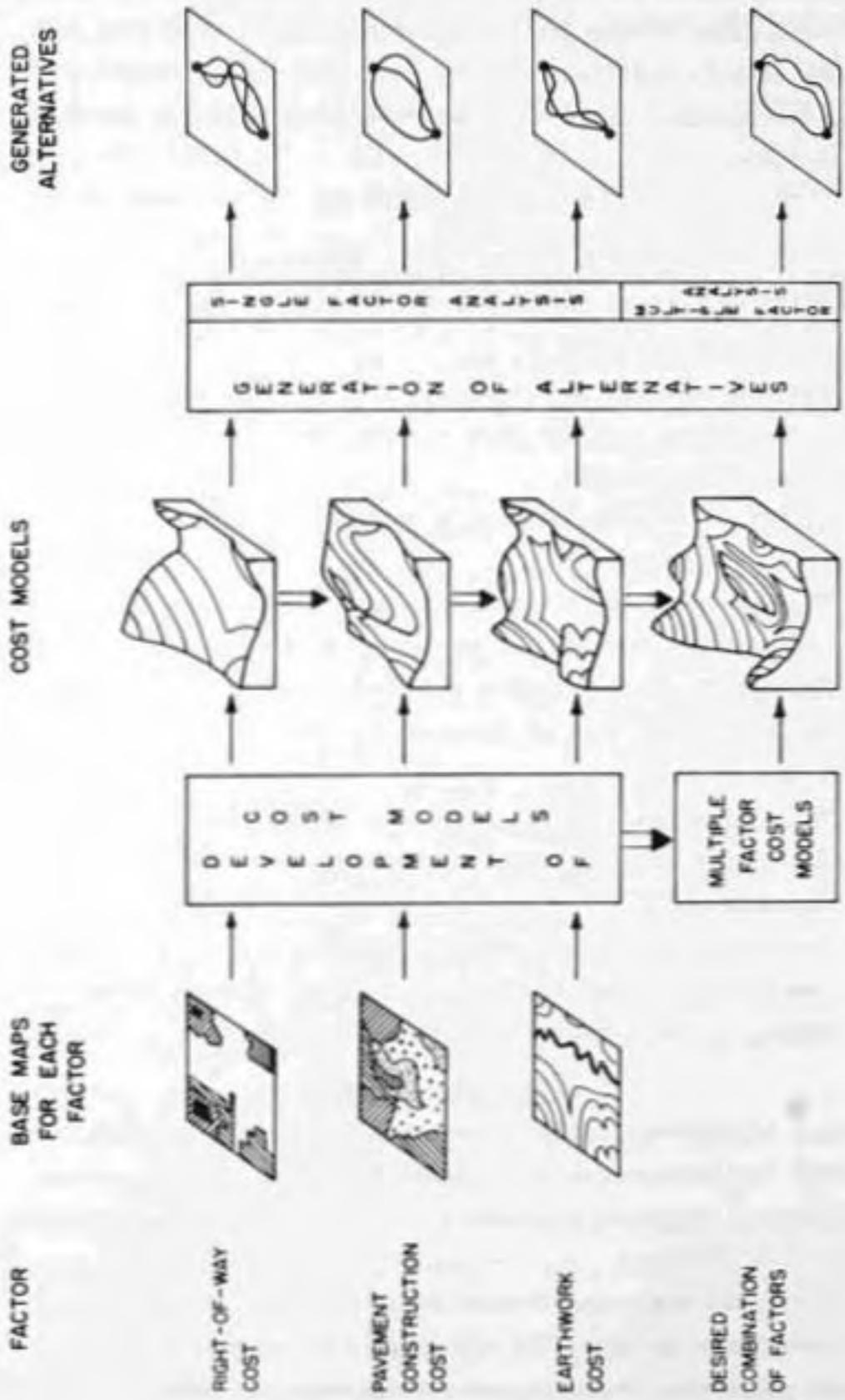


FIGURE 4. THE BASIC CONCEPT OF THE GCARS SYSTEM.

models and stored within the computer, one cost model for each factor. The cost models shown as three dimensional solid surfaces in Figure 4; in actual practice they are stored as matrices within the computer.

Desirable routes follow the "valleys" across these models. The most desirable route combines directness and low cost ("elevations") to obtain the lowest total cost. More costly routes can be found following other valleys and "passes" over the intervening high cost areas. Sometimes such alternative routes are shorter than the first choice, and, although having a higher cost per unit length, may be more desirable. Thus, the various choices should be compared in terms of both their total costs and their overall lengths.

Figure 4 also shows that models for several factors can be superimposed and summed to produce cost models for any desired combination of factors. Valleys on these models represent the desirable routes in terms of several location factors. Before summation each model can be multiplied by a weighting factor, allowing any location factor to be enhanced to any desired degree.

Figure 5 shows a flow chart of the prototype GCARS System. The data preparation activity concerns the conversion of the maps for each factor into machine usable numerical data. The search activity converts these data to numerical equivalents of the cost models and then generates a series of alternatives by finding the valleys on these models for any desired factors alone or in combination.

The computer is only dominant in the search activity. The selection activity is the responsibility of the design engineer. Since he is best qualified to make the right decision given all the necessary facts. Man is also dominant in the data preparation activity, although he is aided by the computer, or other machinery, in the computations required to design the sampling methods and in the actual data digitization. The GCARS System is thus seen to be a computer-aided design system. The extensive use of graphical and statistical information to aid in the machine-to-man information dialogs is shown in Figure 5.

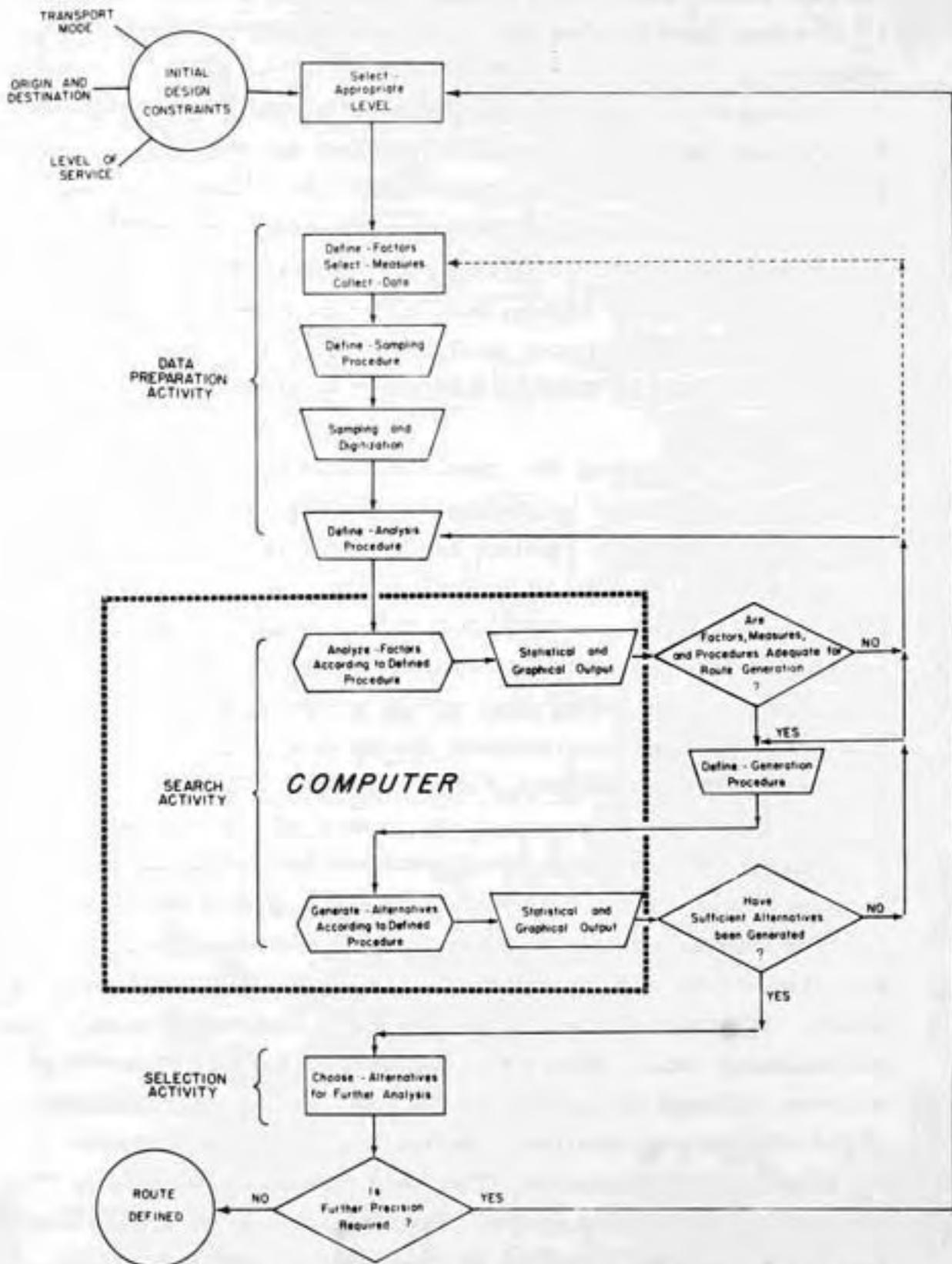


FIGURE 5. FLOWCHART FOR THE GCARS SYSTEM.

COMPUTATIONAL PROCEDURES

The GCARS System utilizes two broad classes of computational procedures. Numerical surface analysis procedures are used to transform maps representing data for each highway location factor into cost models stored within the computer. Minimum path analysis procedures generate a series of alternatives by analyzing these cost models.

The use of the system at any level in the highway planning hierarchy follows the data preparation, search, and selection activities shown in Figure 5. These activities can be further subdivided into eight steps as shown in Table 2. To simplify the discussions, certain stages in the development of the cost models have been defined as "measures", "values" and "utilities".

Measures, Values and Utilities

A suitable source of information for a factor is called a "measure". For example, an engineering soils map contains basic information needed to evaluate the pavement construction cost factor, and thus is a measure for that factor. It is but one form of a soils map, however, and other maps are also measures of the same factor. There are two types of measures; graphical measures (maps) and numerical measures. Map digitization, the reduction of graphical measures to numerical measures, is required before computer analysis is possible.

Numerical measures are strictly numerical analogs of the original maps. Generally they do not supply all the information on the factors that is required by the GCARS System. Measures thus have to be transformed so as to reflect either the costs which will be incurred or the benefits which will accrue in terms of particular factors. Such transformed measures are termed "values". A "value" may be defined as "a function of a factor reflecting either costs or benefits according to some quantitative or semi-quantitative scale." Values may be defined without direct reference to either dollar costs or dollar benefits. Values are a spatial phenomenon; thus it is possible to discuss and graphically portray "value surfaces."

TABLE 2
THE METHOD OF INVESTIGATION

Activities	Procedures	
Data Preparation	Step Number	Description
	1	Define route-independent factors and select or prepare graphical measures of each factor.
	2	Define sampling procedures.
Search	3	"Digitize the data" - convert graphical measures to numerical measures.
	4	Transform numerical measures to values by applying a suitable value function or rating scale.
	5	Check values for accuracy and lack of bias through the use of trend surface analysis procedures.
	6	Transform values to utilities, and construct utility networks on single or combined utility surfaces.
Selection	7	Generate single and multiple factor alternatives by repeated application of minimum path analysis procedures.
	8	Evaluate generated alternatives and reorder if necessary to reflect route-dependent factors.

A value surface may be either a cost surface or a benefit surface. Each value surface has a unique vertical scale representing the particular value function or rating system used to derive it. Values are not always suitable for minimum path analysis and in the general case a further transformation is required.

Transformed values are termed "utilities." A utility is defined as:- "a function of a factor reflecting either costs or benefits in a form suitable for minimum path analysis and having a standardized range of values so that addition with other utilities is possible in known ratios." Utilities are also spatial phenomena, and thus form utility surfaces.

Values representing costs can be transformed to utilities by merely standardizing the range of values. Values representing benefits must be inverted as well as standardized, so that areas of high benefit values on the value surfaces become low areas on the utility surfaces. Minimum path analysis of the utility surfaces will result in maximization of the benefits. Figure 6 summarizes the inter-relationships among factors, measures, values, and utilities.

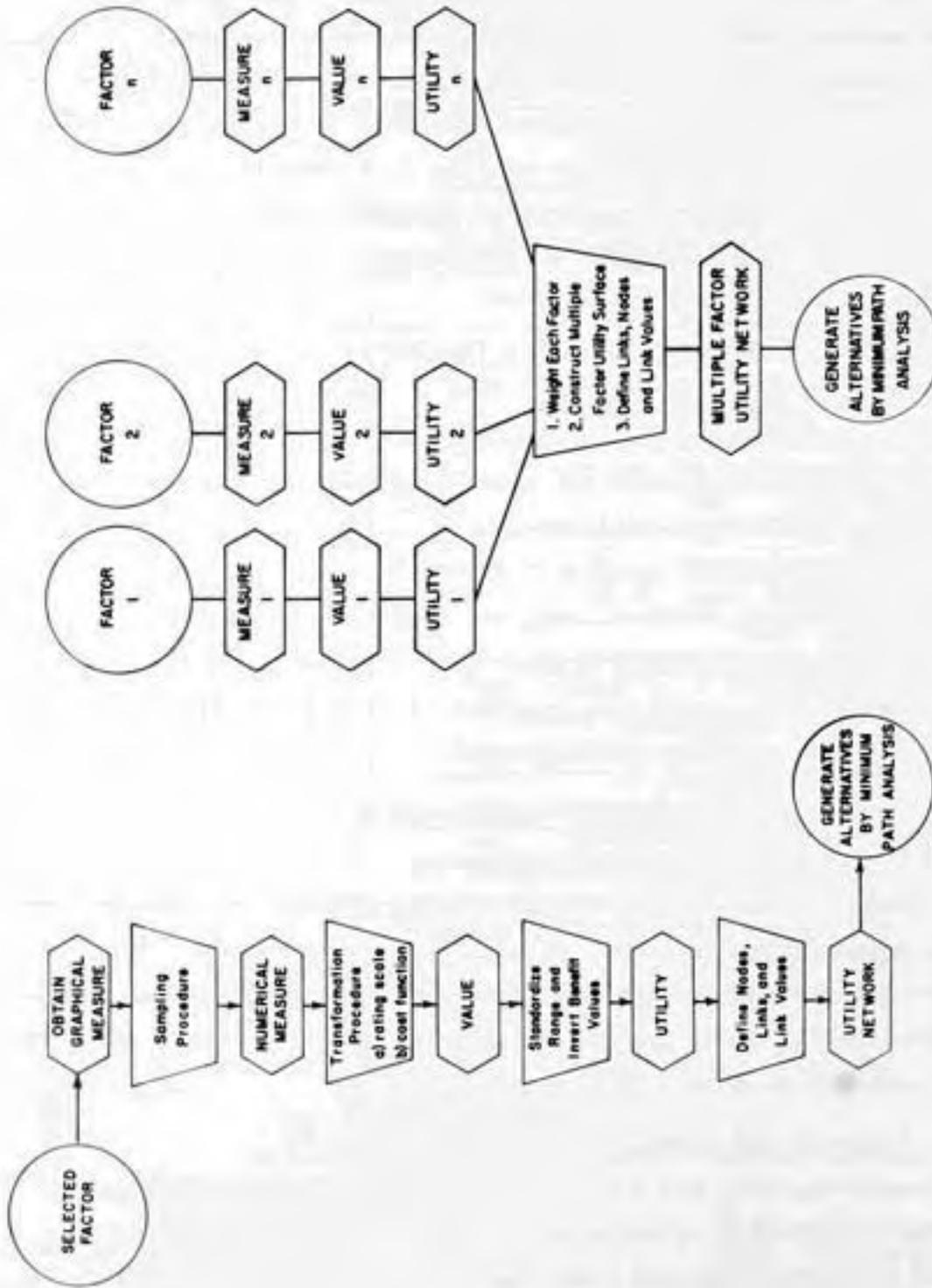
In the prototype GCARS System, measures, values, and utilities are stored in the computer as matrices. The transformations described involve simple matrix algebra.

Numerical Surface Analysis Procedures

Numerical surface analysis procedures include a diverse group of mathematical and statistical procedures designed to analyze spatially related observations (28). Figure 7 shows the inter-relationships among the included procedures. The techniques actually used by GCARS are shown connected by heavy lines. All these techniques are described by Turner (28).

Vector Analysis and Surface Comparison Procedures

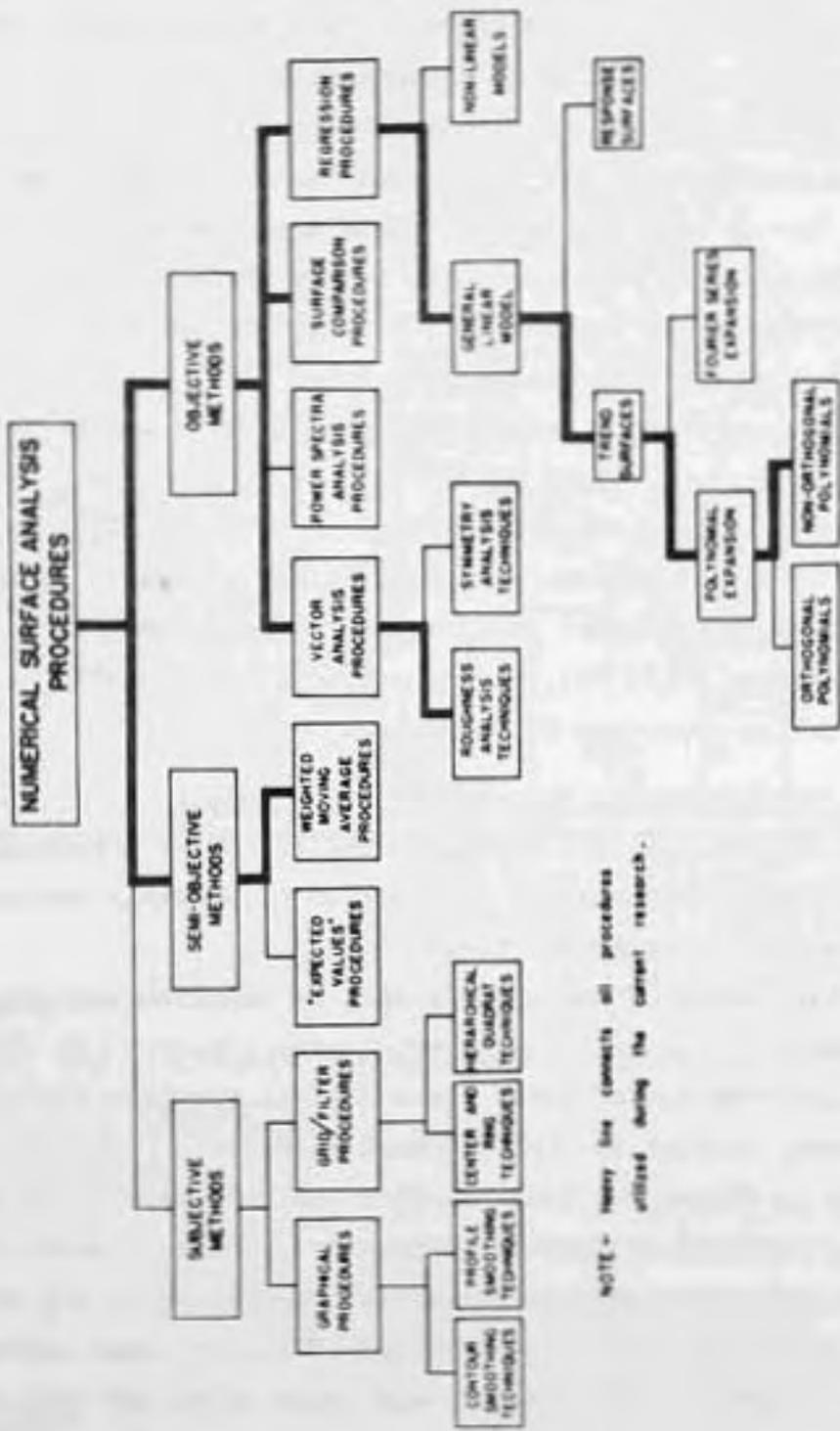
Vector analysis and surface comparison procedures are used in the data preparation activity to design reproducible sampling procedures for topography and other factors. The vector analysis techniques are based on the theoretical work of Fisher (7) as amplified by Hobson (11). The surface comparison procedures used were suggested by Tobler (24). The applications of these procedures are fully described elsewhere, and are beyond the scope of



A) SINGLE FACTOR ANALYSIS

B) MULTIPLE FACTOR ANALYSIS

FIGURE 6. THE DATA ANALYSIS SEQUENCE.



NOTE - Heavy line connects all procedures utilized during the current research.

FIGURE 7. CLASSIFICATION OF NUMERICAL SURFACE ANALYSIS PROCEDURES.

this paper (27,28).

Trend Surface Analysis

Trend surface analysis, a variety of regression analysis, is used in the analysis phase of the search activity (see Figure 5) to test value surfaces for adequacy and lack of bias. Trend surface analysis is widely used in the earth sciences to separate regional from local effects for any type of spatial phenomenon. The technique involves the fitting of comparatively simple trend surfaces to data, according to the least-squares criterion. Statistical measures, such as partial and total F-tests (6,12) and the simple correlation coefficient, are used to estimate the significance of the surfaces. One or more of these surfaces are selected to represent the regional effects. The residuals to the surfaces, representing the lack of fit of the surface to the data, are plotted as contour maps and studied for information concerning local anomalies. This technique is described in detail by Turner (28) and in the geological literature (12,16,19).

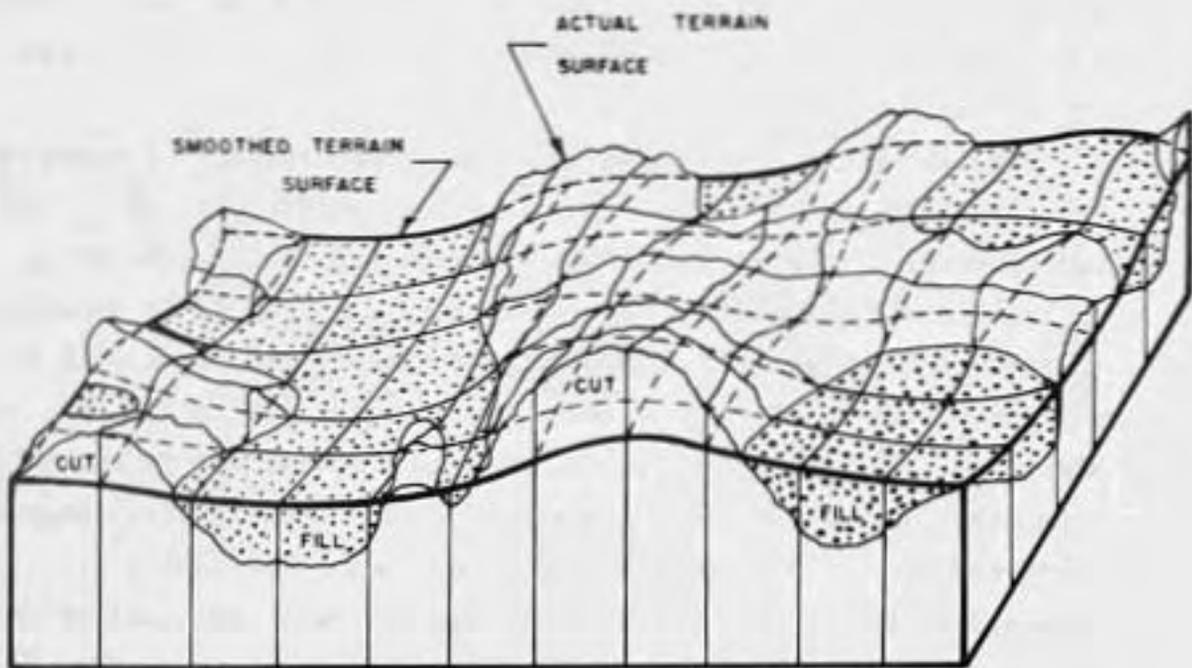
The trend surface analysis program used in the GCARS System was especially developed for the purpose. An early version is documented by Turner (26). Current versions are being documented and will be released shortly (29,30). Trend surfaces up to the fifth degree were used in the prototype GCARS System.

Conversion of Topographic Data to Earthwork Values

Trend surface analysis was also used to convert topographic data to earthwork cost values. Estimation of probable earthwork costs throughout an area requires:-

- 1) development of topographic data by sampling topographic maps,
- 2) approximation of grade lines for all possible highway routes.

The procedure, similar to that proposed by Roberts (21), is shown graphically in Figure 8. Trend surface analysis develops a series of smoothed surfaces of varying complexity. These trend surfaces are assumed to approximate all possible grade lines in the area while the residuals, measuring the lack of fit of these surfaces to the elevation data, represent the magnitudes of cut or fill required



(after Roberts)

FIGURE 8. TERRAIN SMOOTHING TO SIMULATE CUT AND FILL COSTS.

to build a highway having a grade-line following the trend surfaces. Because the trend surfaces are least squares regression surfaces, the volumes of cut and fill over the entire area should nearly balance, therefore the volumes encountered along a random line across the area should approximately balance.

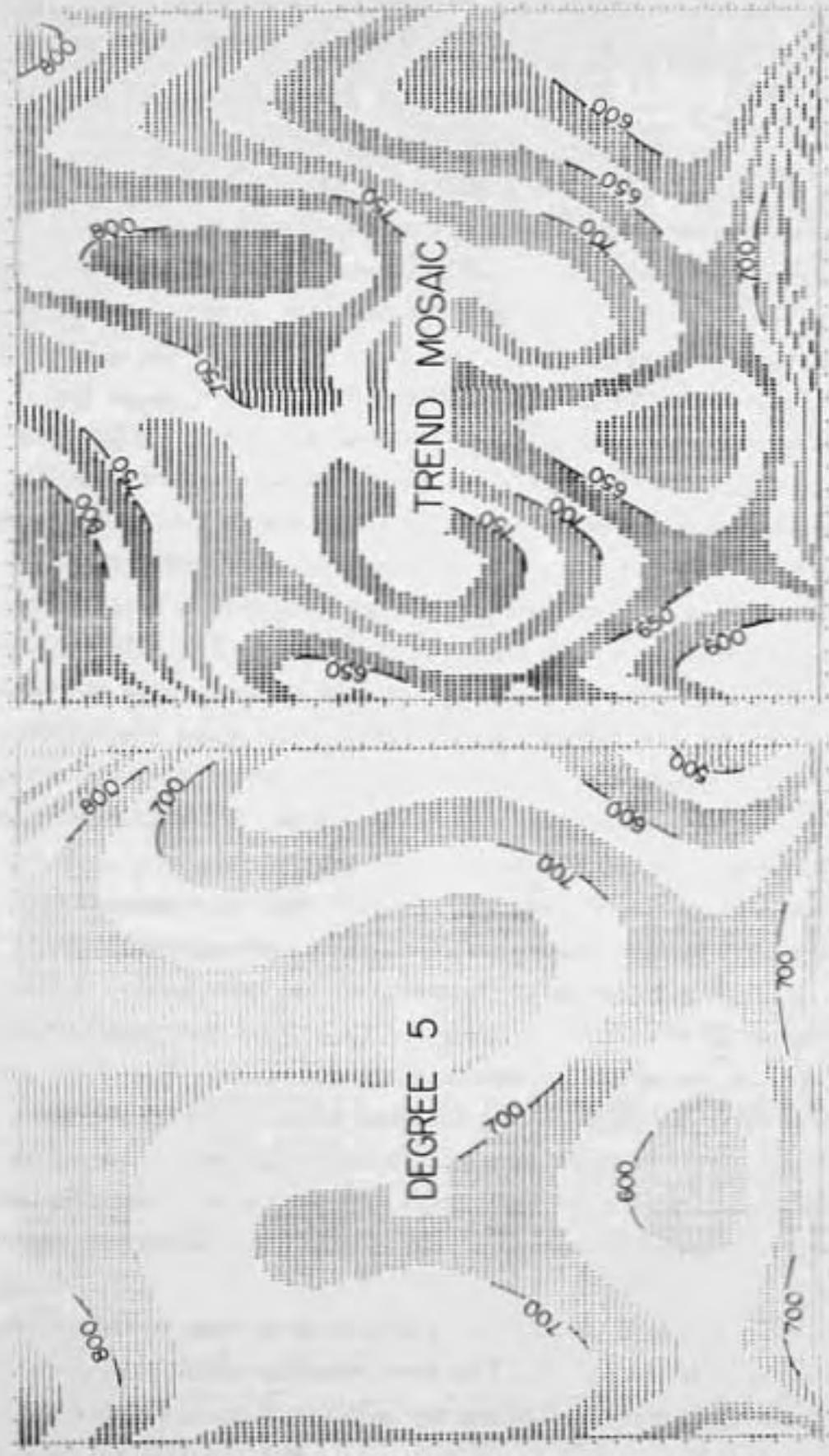
Obviously the grade-line defined by a trend surface is frequently much less steep than an actual highway grade line. In most cases however, the relative magnitudes of the cut or fill costs along a highway would remain approximately the same as those shown by the residuals, although the actual volumes might be less. The residuals define those areas lying far above or far below the local mean elevation. Thus, topographic residuals are a suitable value of the earthwork cost factor.

The elevation data can be obtained from a variety of maps, while the residuals can be obtained for any trend surface fitted to each set of data. In cases where the topography is too complex to be satisfactorily explained by a single trend surface, it is possible to fit trend surfaces to overlapping sections of the area. After such "piece-wise" fitting of trend surfaces, a trend mosaic can be assembled from the various parts, much as a mosaic map is assembled from individual aerial photographs. Figure 9 shows a fifth degree trend map and a fifth degree trend mosaic map. The latter is composed of four fifth degree trend maps fitted to portions of the same area. The greater complexity of the trend mosaic surface is evident.

Weighted Moving Average Procedures

Weighted moving averages are used in the GCARS System to interpolate irregularly spaced observations onto a regular (square) grid of a desired spacing. The method used is based on an algorithm developed by Tobler (25). The value of each grid point is determined from the values of a set number of nearby original observations, each being weighted according to its relative distance from the grid point.

While the algorithm utilized is efficient, the interpolation of large data arrays is very time-consuming. The computer has to



CONTOUR INTERVAL = 50 FEET
CONTOUR INTERVAL = 25 FEET
FIGURE 9. COMPARISON OF TREND SURFACE AND TREND MOSAIC SURFACE.

sort through the entire set of observations to find those closest to each grid point. For efficiency in computation, arrays larger than 1000 observations are pre-sorted into a series of smaller overlapping arrays.

Minimum Path Analysis Procedures

The prototype GCARS System utilizes a modified version of the Road Research Laboratory (RRL) minimum path algorithm developed for the British Government (32). This algorithm is described in detail by Martin (15). Hillier and Lieberman (10) summarize the basic algorithm as:-

- 1) Connect source node to nearest node
- 2) Identify the unconnected node that is closest to any connected node. Repeat until all nodes have been connected.

This procedure automatically generates a minimum path tree connecting the specified source node to all other nodes. No iterations are required. This is in contrast to the Bureau of Public Roads Moore Algorithm which does require some iterations (15,17). This direct solution characteristic of the RRL algorithm makes it most attractive for finding a minimum path between a single origin and destination. Testing each entering node to see if it is the required destination allows the computation to be stopped as soon as the minimum path is found, often at considerable savings in computation time.

Minimum path analysis can only be performed on a network of inter-connected links. Accordingly, all rows and columns in the utility matrices are joined to form a square network having a link to node ratio of almost four. The link capacities are computed as the average of the utilities of their two end nodes. The links are assumed to be undirected, having the same capacity for travel in either direction. On this basis a link table is constructed which describes each link, in each direction, by origin node, destination node and its associated capacity. These networks are termed utility networks.

The RRL algorithm was further modified according to the procedures defined by Ayad (3) so that a series of alternative routes could be generated. After the network is analyzed for the

first minimum path between the designated origin and destination, the central links of the path are reassigned arbitrarily very high values and removed from further consideration. The revised network is reanalyzed to find a new minimum path which becomes the second choice and the process is repeated until a limiting criterion is met. In the prototype system generation of alternatives continued until either the latest path total equalled or exceeded twice the first choice path value, or until seven choices were evaluated.

Not all the links in the chosen paths are reassigned high values; those near the ends are allowed to retain their true values and thus may form part of several alternatives. This is necessary if the choices are not to become unduly constrained. Based on Ayad's studies, seven percent of the links in the path-three and one half percent at each end-were allowed to retain their original values. This value was rounded to the nearest link and was never allowed to drop below one link at each end.

Additional computation is necessary to generate alternatives for a combination of factors. First, a suitable combined utility matrix must be developed; second, a network must be derived from this matrix; third, minimum path analysis must be applied to this network.

As an aid in the analysis of the alternatives, a subroutine has been written which produces a map of the various alternatives on the line printer. Figure 10 shows an example of this output.

In common with most minimum path routines, the RRL algorithm requires considerable storage. The original version utilized three arrays to store the basic link table information; one for the origin nodes, one for the destination nodes, and one for the link values. This restricted the size of the networks that could be handled to about 1200 nodes and 4800 links, corresponding to a 30 by 40 utility matrix. In an attempt to increase this maximum size, the origin and destination node arrays were packed into a single array. This saved 4800 core locations, but required frequent "unpacking" of origin and destination node values. Some increase in computation time was thus inevitable. With present modifications, the generation of five alternatives, and the development of a printer display of their locations can be accomplished in about three minutes.

THE GENERATED ALTERNATIVES

ALTERNATIVE	DATA TYPE	RELATIONSHIP	STATUS
1	CONCRETE	CONCRETE	OK
2	CONCRETE	CONCRETE	OK
3	CONCRETE	CONCRETE	OK
4	CONCRETE	CONCRETE	OK
5	CONCRETE	CONCRETE	OK

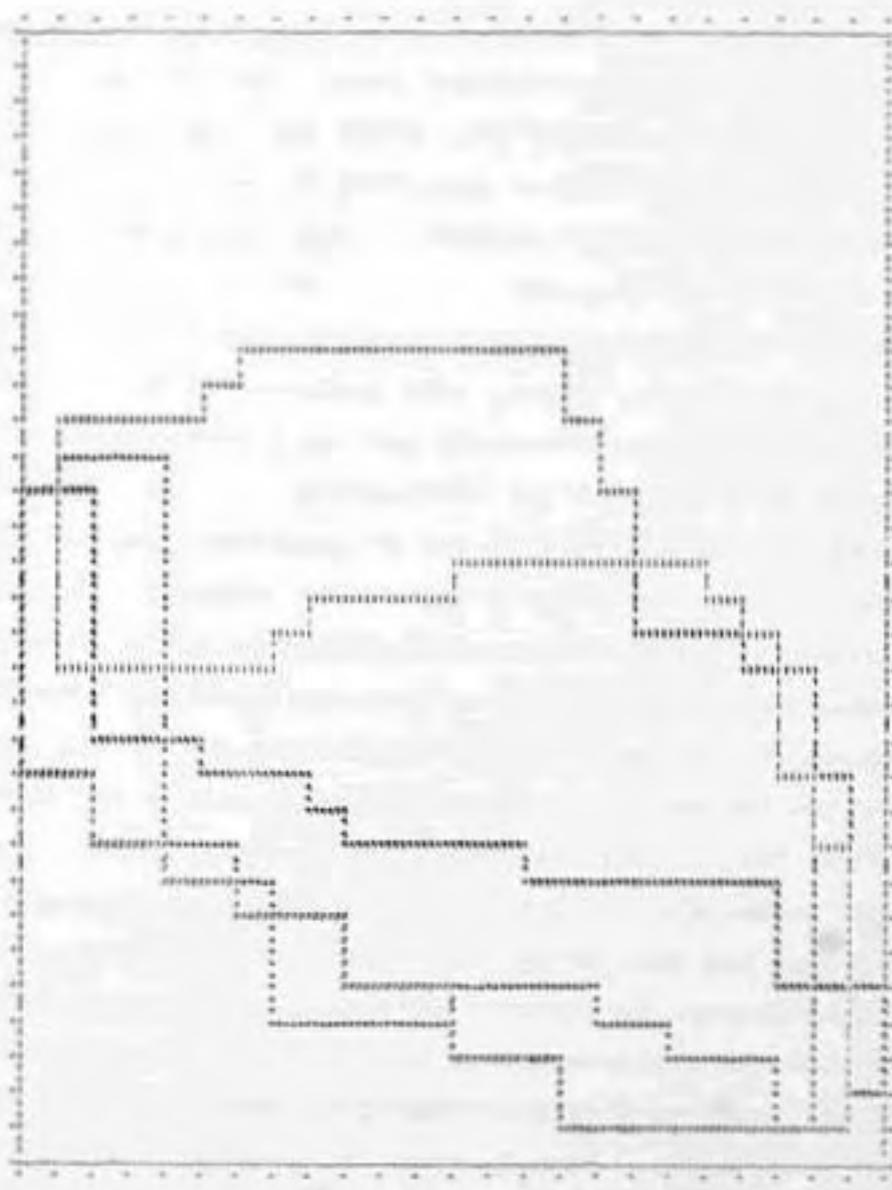


FIGURE 10. COMPUTER-GENERATED MAP OF FIVE ALTERNATIVES.

This time is data dependent however.

APPLICATIONS OF THE GCARS SYSTEM

Test Areas

The prototype GCARS System was tested at two Indiana test areas, as shown in Figure 11. The large southern test area was selected for regional studies, typical of the Band or Corridor levels of the highway planning hierarchy. The smaller northern test area utilized the GCARS System for locating new bypasses near a medium sized urban area.

Factors Studied

The GCARS System generates a preliminary set of alternatives by analyzing route-independent location factors. The following factors were studied at both test sites:- 1) an Earthwork Cost Factor

- 2) a Pavement Construction Cost Factor
- 3) a Right-of-Way Acquisition Cost Factor
- 4) and Service Benefit factors.

Table 3 shows the measures and transformations investigated for each factor at each test area.

The GCARS System does not ignore the route-dependent location factors. During the selection activity generalized values of these factors are used to re-order the preliminary set of alternatives generated by the computer through analysis of the route-independent factors.

Selected Analyses in the Northern Test Area

The capabilities of the GCARS System can be best described with the aid of a few examples. These are by no means exhaustive, and the interested reader is referred to Turner (28) for a more complete analysis.

Derivation of the Earthwork Cost Factor Value Surface

Figure 12 shows the general topographic conditions of the northern test area. A total of 2521 spot elevations measured from 1:24000 scale topographic maps formed the numerical measure. First through fifth degree trend surfaces were fitted to these elevations.



FIGURE II. LOCATION OF TEST AREAS.

TABLE 3
THE HIGHWAY LOCATION FACTORS STUDIED

Northern Test Area					
Factor	Earthwork Costs	Pavement Construction Cost	Right of Way Acquisition Cost	Service Benefits	
Measure transformed to Value by	1:24,000 Scale topographic maps	Tippacano County Engineering Soils Map	Land use categories for origin-destination zones	(a) Census data from 1960 National Census by census tracts. (b) Tippacano County Highway Maps	
Measure transformed to Value by	Residuals to fifth degree trend surface fitted to topographic data.	Rating scale based on soil ratings determined by Ulbricht.	Rating scale devised by author.	(a) Population totals determined for each zone (b) Population densities for each zone (c) Trip ends for each zone (d) Road intersection rating scale devised by author	
Southern Test Area					
Factor	Earthwork Cost	Pavement Construction Cost	Right of Way Acquisition Cost	Service Benefits	
Measure transformed to Value by	(a) 1:250,000 scale topographic maps (b) 1:24,000 scale topographic maps	State of Indiana Engineering Soils Map.	Land use map prepared by interpretation of airphoto mosaics.	(a) Census data from 1960 National Census (b) 1:250,000 scale topographic maps	
Measure transformed to Value by	Residuals to - (a) fifth degree trend surface fitted to elevations from 1:250,000 scale maps. (b) fifth degree trend surface fitted to elevations from 1:24,000 scale maps (c) fifth degree trend mosaic	Rating scale based on soil ratings determined by Ulbricht.	Rating scale devised by author.	(a) Populations of all incorporated towns and cities. (b) Population densities for approximately 20 square mile zones. (c) Road intersection rating scale devised by author.	

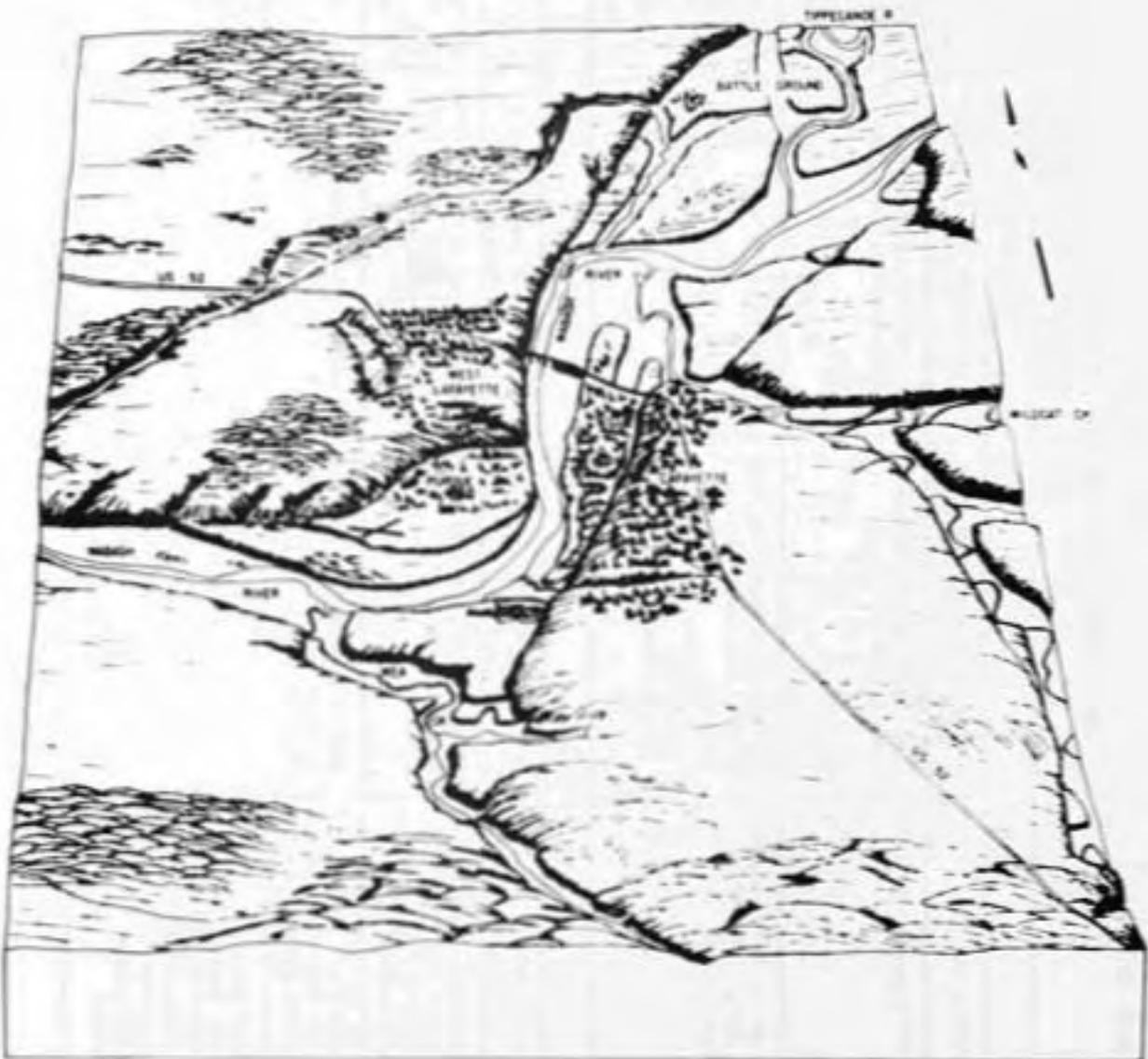


FIGURE 12 . PHYSIOGRAPHIC DIAGRAM OF THE NORTHERN TEST AREA.

These surfaces are shown by computer-generated contour maps in Figure 13.

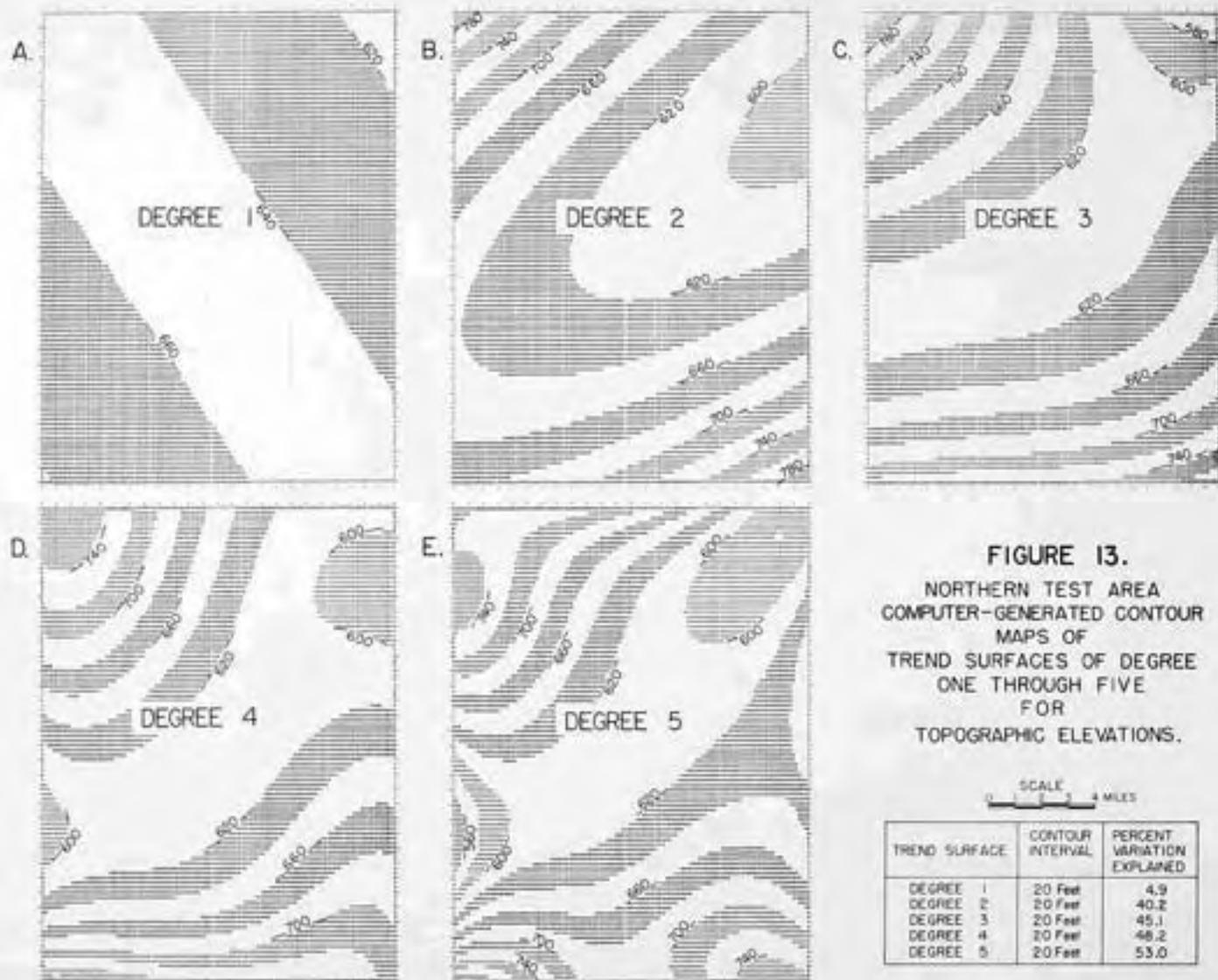
The first degree surface forms a plane dipping gently toward the northeast. It explains less than five percent of the variability of the original elevation data. However the total and partial F-tests show its coefficients to be highly significant. In other words it shows a true regional dip. This tendency to lower elevations in the northeast probably reflects the greater width of the Wabash valley northeast of Lafayette, and the presence of low elevations along Wildcat Creek in the eastern part of the area.

The second degree trend surface has a central low zone, conforming to the presence of the Wabash valley. The percent variation explained has increased to over forty percent, while the partial and total F-tests leave no doubt as to the significance of these coefficients.

The third degree trend surface shows the curve of the Wabash Valley. The statistics show an increase of about five percent in the percent variation explained by this surface over the second degree. The coefficients remain significant.

The fourth and fifth degree trend surfaces continue to add refinements to this basic pattern. The fourth degree surface shows some response to the presence of Wildcat Creek along the eastern border. The fifth degree surface carries this effect further and adds a low in the south central part of the map area which reflects the presence of Wea Creek. A widening of the low zone in the western part of the map may possibly reflect the presence of Indian Creek. These surfaces retain a high significance in their coefficients and add a few percentage points to the percent variation explained.

Of all the surfaces, the fifth degree surface expresses the regional topography in the most satisfactory manner. Over 53 percent of the variability in the original elevation values is explained by this surface. Accordingly, a piece-wise analysis and construction of a trend mosaic surface, as performed in the southern test area, was believed unnecessary. The fifth degree trend surface was selected as the best smoothed gradeline surface. A weighted



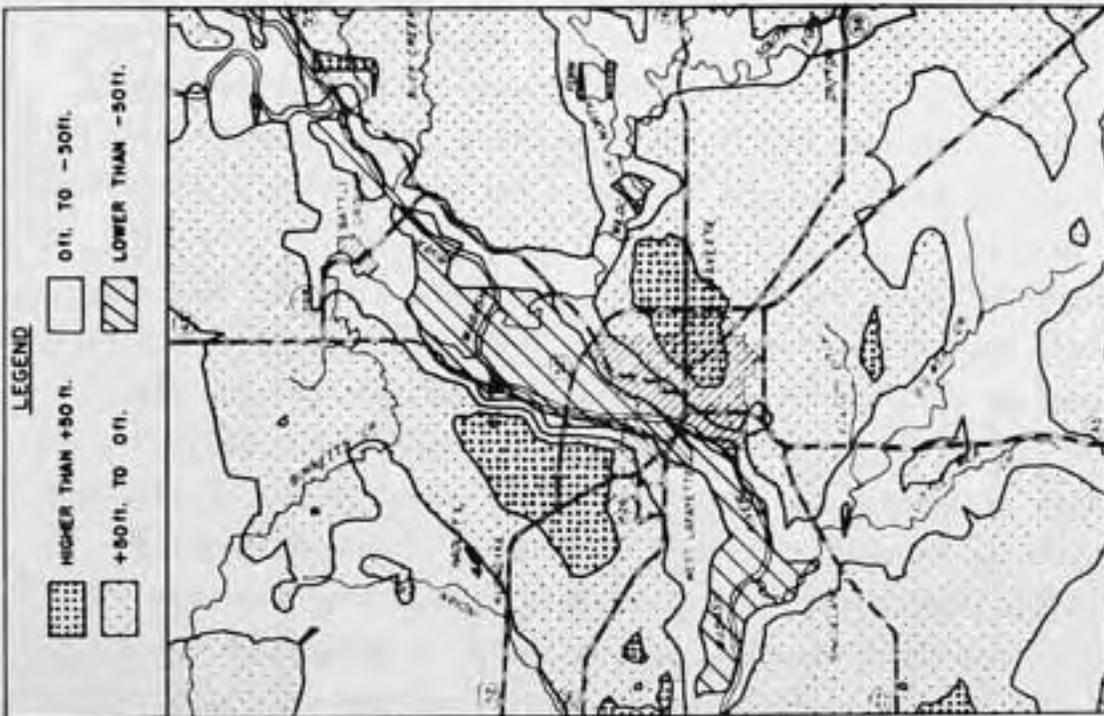


FIGURE 14. EARTH WORK COST FACTOR VALUE SURFACE

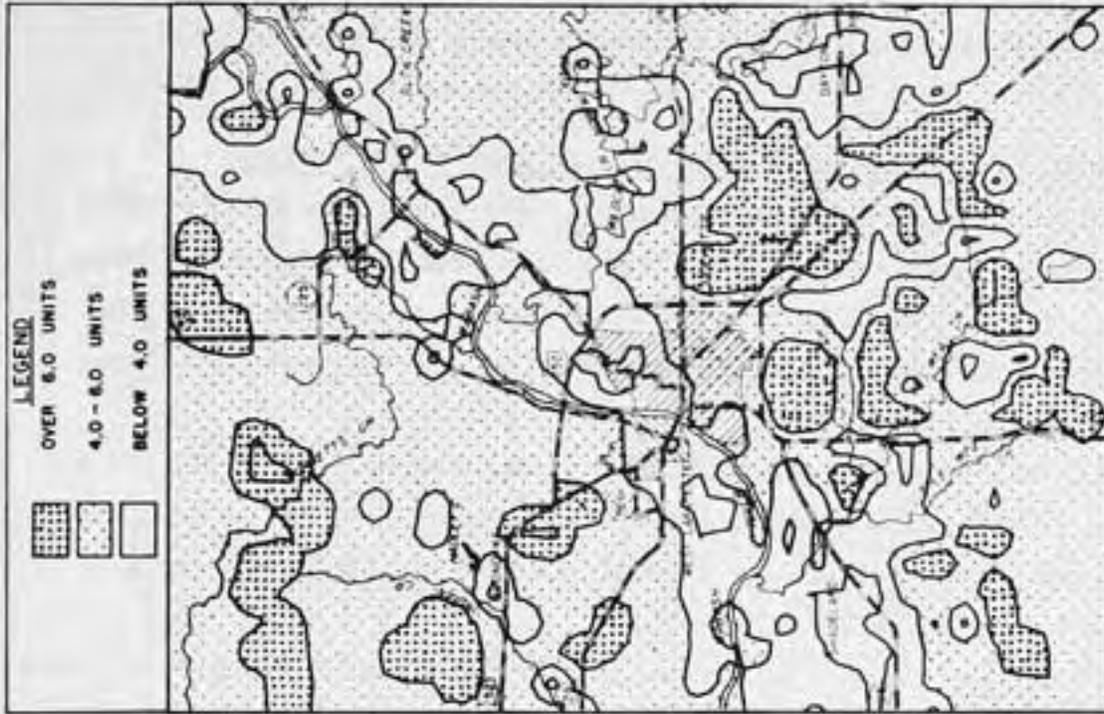


FIGURE 15. PAVEMENT CONSTRUCTION COST FACTOR VALUE SURFACE

moving average procedure was applied to the residuals to this surface. The resulting interpolated grid values were utilized to form the value surface for the earthwork cost factor. Figure 14 shows a computer generated map of the residuals based on these interpolated values.

Derivation of the Pavement Construction Cost Value Surface

Information on the distribution of soil types for the northern test area was obtained from the Tippecanoe County Engineering Soils Map prepared by Yeh (33). Ten soil types are mapped within the test area. Each was given a code number and the map was digitized, a total of 609 sample points being required.

The code numbers representing the engineering soil types are a measure. Conversion of this measure to a value for the pavement construction cost factor was accomplished by the use of the soil ratings developed by Ulbricht (31).

By using a panel of six experienced engineers, Ulbricht developed a mean soil rating for each soil type shown on a statewide engineering soil map (5). Ulbricht was able to show that these mean soil ratings were proportional to the soil support factors required by the AASHO design equations. Thus larger ratings meant larger soil support factors, greater equivalent pavement thicknesses, and longer pavement life for any pavement design under a given traffic condition. Alternatively, if a standardized useful pavement life is desired, cheaper, thinner, pavements can be built on soils having higher ratings.

Ulbricht's mean ratings are on a ten point scale in which high values are assigned to desirable soils. It is necessary to subtract these ratings from ten to obtain pavement construction cost values that are large for poor soils and small for good ones. Table 4 gives the values utilized. Two engineering soil units, ground moraine and ground moraine covered with thin loess, were judged essentially identical in pavement construction costs in this area and thus were given identical weights. Ulbricht did not separately classify terraces or organic topsoils so appropriate ratings were selected by the authors.

TABLE 4
NORTHERN TEST AREA PAVEMENT CONSTRUCTION COST VALUES

Engineering Soil Type	Soil Code Number	Ulbricht Mean Rating	Ulbricht quality description	Pavement construction cost-value*
Terrace	02	8.7**	very good	1.3
Outwash	03	8.5	very good	1.5
Dune Sands	06	7.0	good	3.0
Ridge Moraine	09	4.8	average	5.2
Ground Moraine	07	4.7	average	5.3
Ground Moraine with thin loess	08	4.7	average	5.3
Sandstone and shale	04	4.5	average	5.5
Recent Alluvium	01	4.1	average	5.9
Organic Topsoil and Clay	05	2.0**	poor	8.0
Muck	10	0.3	very poor	9.7

*Pavement Construction Value Cost = 10.0 - Ulbricht Mean Rating.

**Rating not defined by Ulbricht.

The data were then checked for adequacy and lack of bias by trend surface analysis, and then a value surface was developed by weighted moving average procedures. This surface is shown in Figure 15.

Generation of Alternatives

A series of value surfaces were developed for all the other factors according to the procedures listed in Table 3. Generation of alternatives was then undertaken. Two sets of analyses were run. Figure 16 shows the alternatives generated for four single route-independent factors, for one of these location problems. Such analyses should be run first, to give the design engineer an opportunity to discover the optimal locations in terms of each factor alone.

A large number of multiple factor analyses were performed. These are summarized in Table 5. Figures 17 and 18 show a selection of the results obtained.

CONCLUSIONS

The GCARS System can assist design engineers in analyzing a larger number of alternatives. The combination of numerical surface analysis and minimum path analysis procedures forms a suitable basis for a computer-aided design procedure of use in the highway planning process.

FURTHER WORK

Currently the authors are experimenting with an interactive system using teletype terminals to allow the design engineers to more easily control the system. It is hoped that this experimental GCARS II System will make the system more useful to the design engineers, and lead to improved formats for data presentation.

The GCARS System has considerable appeal to developing regions and also to metropolitan areas which are now developing "data banks". The availability of data in such "data banks" will enhance the capabilities of the GCARS System, making it feasible to investigate the location of urban arterials. Field testing of the concept for either or both these applications is required.

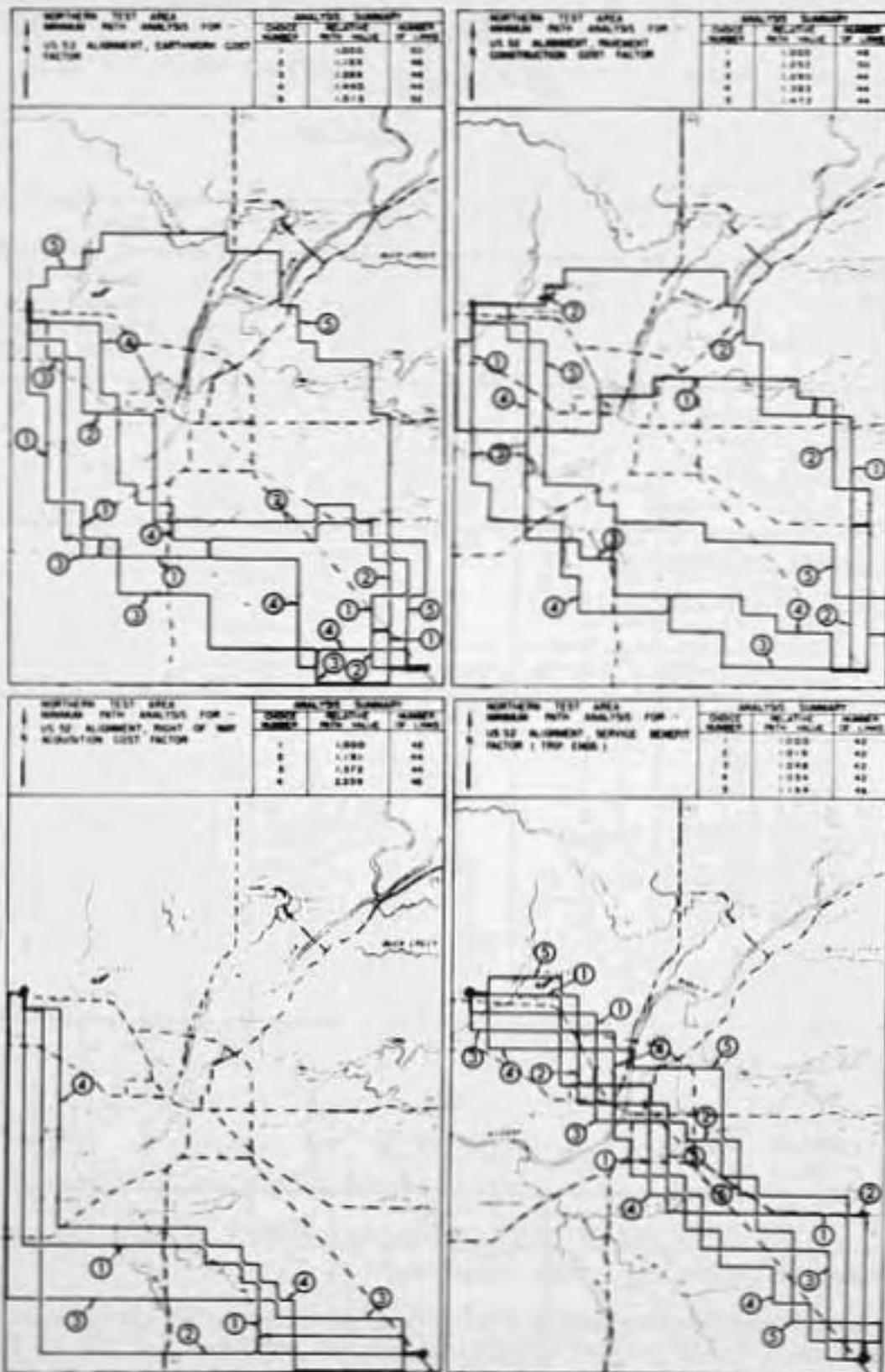


FIGURE 16. GENERATED ALTERNATIVES FOR FOUR DIFFERENT FACTORS

TABLE 5
NORTHERN TEST AREA
MULTIPLE FACTOR ANALYSES

Category of Analysis	Factor Weights Used in Each Analysis*				
	Earthwork Cost	Pavement Cost	Right of Way Cost	Service Benefits**	
				Trip Ends	Non-duplication of facilities
<u>Two Factor Analyses</u>					
Trial (a)	1	1			
Trial (b)	1	2			
Trial (c)	2	1			
<u>Three Factor Analyses</u>					
Trial (d)	1	1	1		
Trial (e)	1	1	2		
Trial (f)	1	2	1		
Trial (g)	2	1	1		
<u>Four Factor Analyses</u>					
Trial (h)	1	1	1	1	
Trial (i)	2	1	1	1	
Trial (j)	1	2	1	1	
Trial (k)	1	1	2	1	
Trial (l)	1	1	1	2	
Trial (m)	2	2	1	1	
Trial (n)	1	1	4	1	
Trial (o)	2	2	4	1	
Trial (p)	1	1	2	4	
Trial (q)	1	1	1	4	
<u>Five Factor Analyses</u>					
Trial (r)	1	1	1	1	1
Trial (s)	1	1	1	1	2
Trial (t)	1	1	1	4	1
Trial (u)	2	2	4	1	1

* Each analysis was performed twice; once for the US 52 Route and once for the State Road 43 Route.

** One special four factor analysis utilizing maximization of the present road network as the only service benefit measure was performed for the US 52 route.

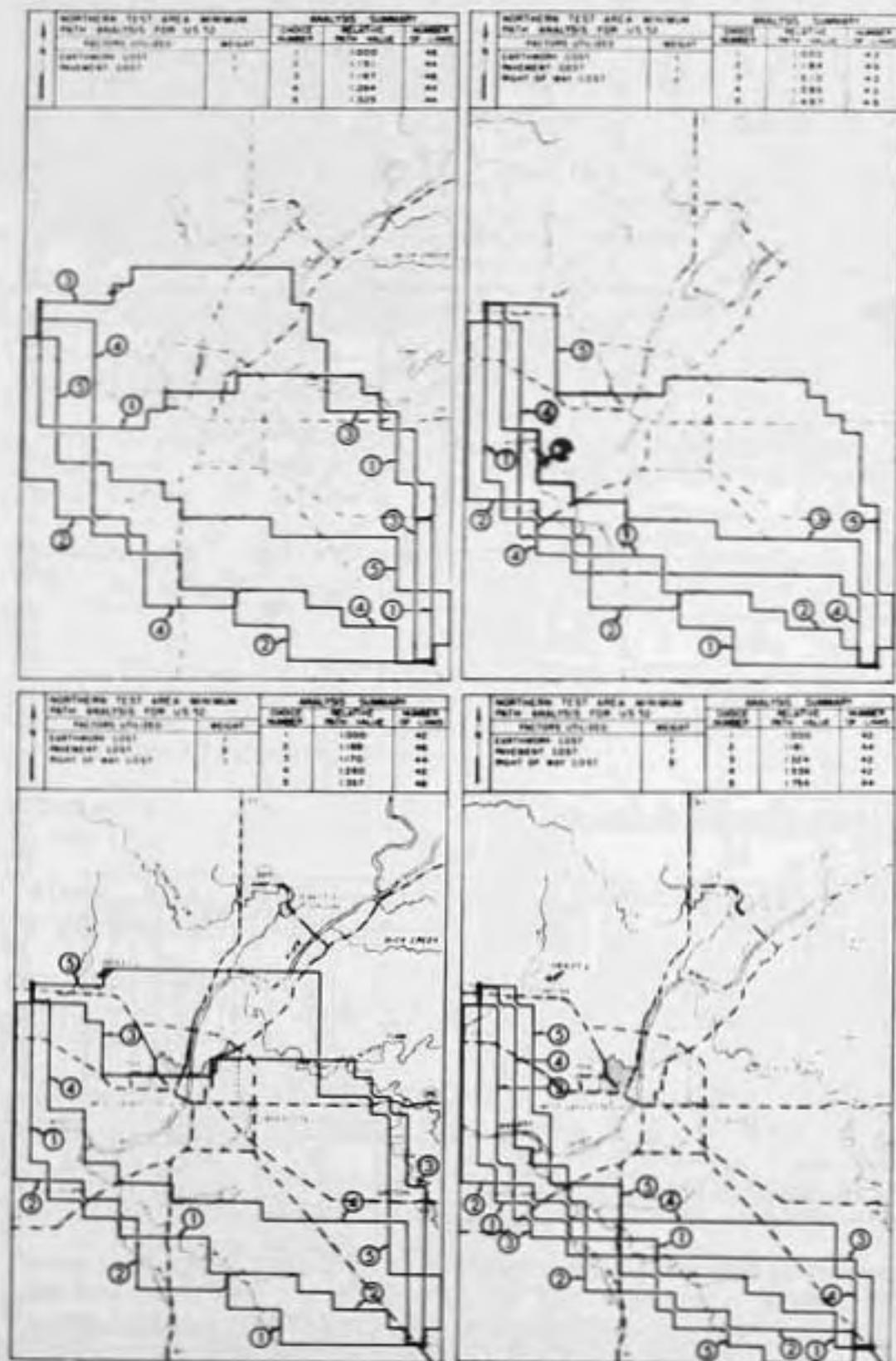


FIGURE 17. GENERATED ALTERNATIVES FOR FOUR COMBINATIONS OF FACTORS

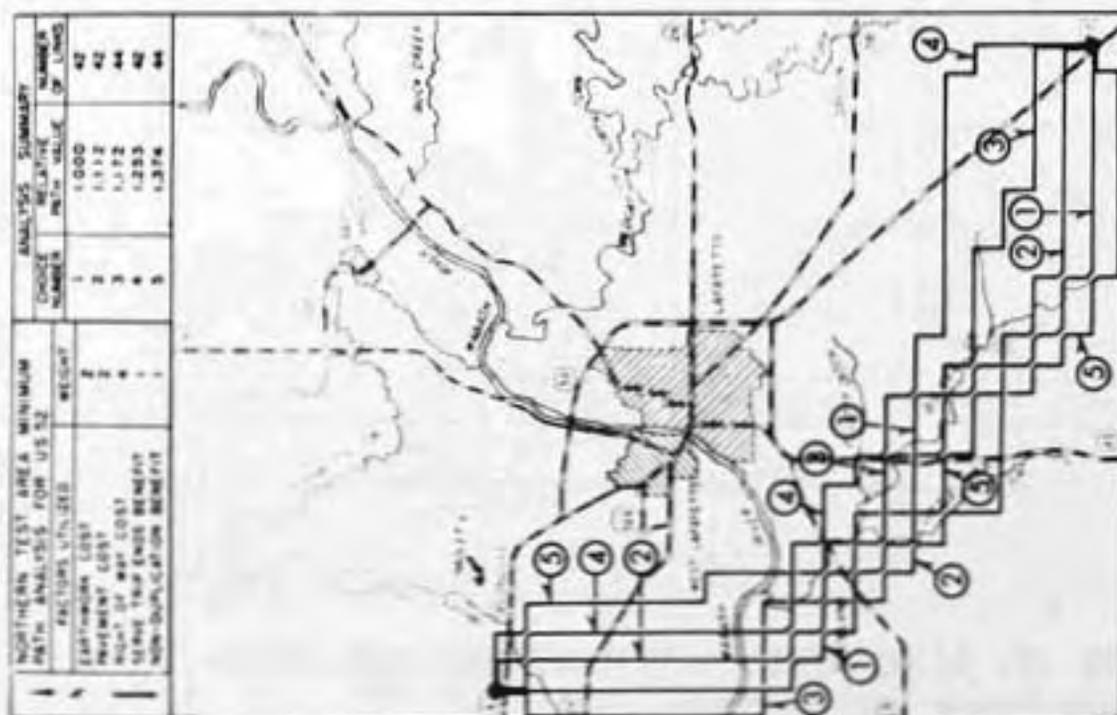
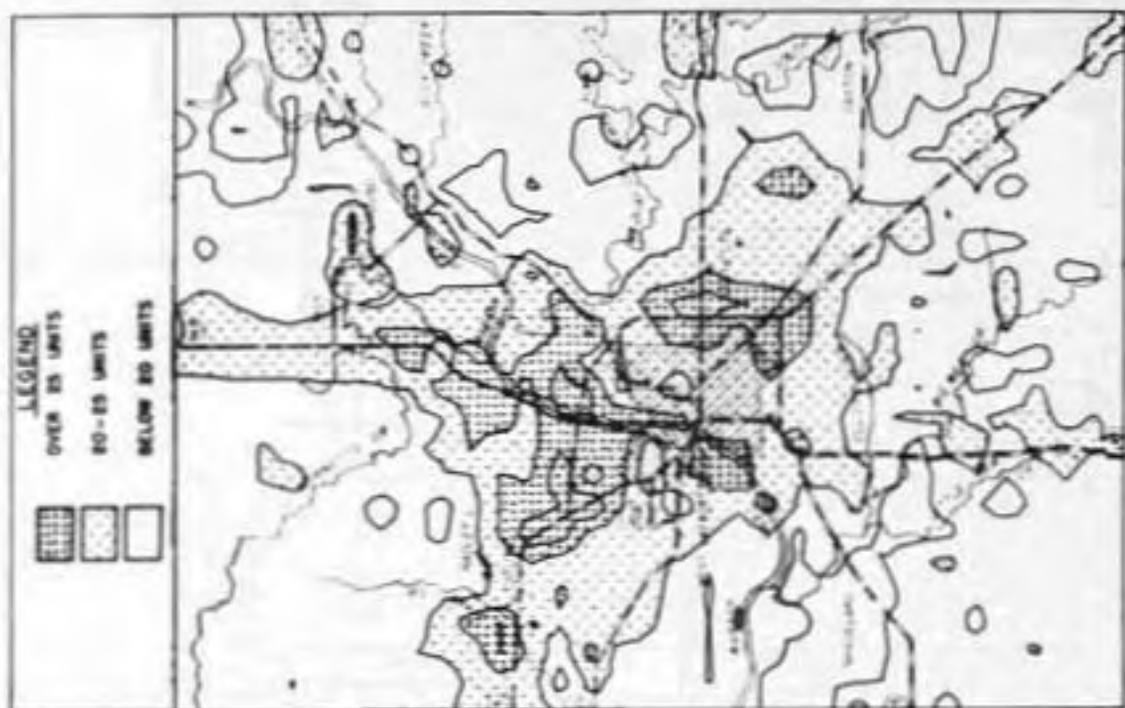


FIGURE 18. NORTHERN TEST AREA - FINAL GENERATED MULTIPLE FACTOR ALTERNATIVES AND MAP OF CORRESPONDING UTILITY SURFACE.

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