THE GCARS SYSTEM: A COMPUTER-ASSISTED METHOD OF REGIONAL ROUTE LOCATION

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The generalized computer-aided route selection (GCARS) system is designed to fulfill the need for improved regional planning methods. Computer-aided planning systems, such as GCARS, combine the engineer's judgment with the computer's data-handling and logical capabilities. This makes possible the rapid generation and objective assessment of larger numbers of alternative corridors in terms of many conflicting location factors. The GCARS system builds and stores within the computer specific cost models, termed "value surfaces." Several value surfaces may be combined in various proportions to form a "utility surface." Repeated minimum-path analysis of these surfaces generates a series of ranked alternatives between any desired termini in response to selected factors alone or in combination. The effects of changes in the importance of any factor or in the locations of termini can be quickly determined. The sensitivity of each situation is measured by comparing the subsequent choices to the first. The operation of the GCARS system is demonstrated by examples from an Indiana study. Two bypass locations near a town of 60,000 population are examined in terms of earthwork, pavement construction, right-of-way acquisition costs, trip distributions, and present road network. Experiments have shown that these techniques become increasingly attractive as the number of factors to be considered increases and when the engineer has interactive control of the process through a teletype or similar device.

•AN IDEAL HIGHWAY LOCATION has been defined as "a path of maximum social benefit at least social cost" (7). Although difficulties arise in the practical definition of "social costs and benefits," it is recognized that engineers must be able to defend their proposals not only in terms of traditional cost-benefit analyses but also in terms of aesthetics and environmental effects.

Time and manpower limitations dictate that the traditional planning procedures be revised and improved. Graphical procedures have been utilized to determine optimal locations in terms of several factors (1, 7). However, the procedures are liable to bias. They do not necessarily increase the speed of the planning process, because the drafting of the required gray-scale overlays is slow. It is rarely practical to revise the overlays and test the effects of these changes on the selection of the corridors.

The digital computer offers, in contrast, an ideal method of storing, manipulating, and retrieving information. This paper describes a method of utilizing the digital computer in regional planning. The generalized computer-aided route selection (GCARS) system allows the engineer to store, manipulate, and retrieve information on any location factor and to analyze these data to determine a series of ranked alternative corridors for any factor or combination of factors. Changes in the importance of any factor

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or modifications to the route termini are easily made, and new corridors are determined within minutes. The GCARS system has been applied to two areas in Indiana and is currently being used on an experimental basis in Illinois and Ontario.

REGIONAL PLANNING PROCESS

Data Preparation, Search, and Selection

Planning involves three activities (10): The data-preparation activity concerns the collection of suitable information for all pertinent factors, the search activity evaluates the data and generates alternatives, and the selection activity chooses among the alternatives generated. In large projects planning becomes a hierarchically structured process (4, 10). The location is defined in a series of steps, each forming a level in the hierarchy. Each level involves the same three activities, so that, once the suitable procedures for these activities have been defined, these procedures can be applied repetitively until a solution is found. Thus, the techniques incorporated in the GCARS system are independent of scale. The GCARS system can be applied equally to regional studies in rural or developing areas and to detailed studies in suburban areas, provided that the data represent the pertinent location factors with appropriate detail.

Classification of Highway Location Factors

Highway location factors include those natural and man-made conditions that affect the location of highway facilities. Two groups of factors can be distinguished.

The first group includes factors such as topography, soils and geology, land use, and population distribution. Because these factors can be studied without reference to any preselected alternative, they are termed "route-independent factors." These factors may be used to define a preliminary set of alternatives.

The second group of factors is used to refine the preliminary alternatives to produce a final set of alternatives. Factors such as user costs, maintenance costs, structure costs, aesthetics, and disruption of previously existing communities or facilities can only be defined with reference to a preselected alternative. Such factors are therefore called "route-dependent factors."

From the preceding descriptions, it becomes clear that certain location factors, the route-independent factors, are associated with the search activity, while the route-dependent factors are associated with the selection activity.

Rationale for Computer-Aided Planning Systems

Computers have no intelligence and therefore no judgment capability. They are capable of some logic, because they can identify positive, negative, or zero values. Many routine procedures are logical and do not involve judgment. These can be programmed. For example, computers are commonly used to calculate earthwork volumes and design geometry. Automating the planning process through use of Bayesian decision theory has been suggested (4). However, our inexact knowledge of the awards and penalties in the planning process prevents us from easily programming such techniques.

Man has judgment capabilities because he has intelligence. In fact, man is at his best when making judgments based on ill-defined criteria. He is inefficient at dull, routine work, often doing more or less than he is supposed to do. He is poor at handling large volumes of data, becoming confused and forgetful. The judgment ability of man contrasts with the data manipulation ability of the machine; they are complementary.

The capabilities of currently available computers and our knowledge of the highway-planning functions make automated planning systems, in which the computer does all the work, impractical. In contrast, computer-aided planning systems are feasible.

THE GCARS SYSTEM

System Organization

The GCARS system is a computer-aided regional planning system. During regional planning the data-preparation and search activities involve logical routine operations as well as some judgment. The selection activity involves considerable judgment, because it evaluates and chooses the "best" of the generated alternatives.

As a result of these considerations, the GCARS system uses the computer only in the data-preparation and search activities. During data preparation, the computer develops and evaluates quantitative models of selected route-independent factors. During the search activity, it manipulates these models and generates a series of alternatives between designated termini for one or more factors.

Such a computer-aided system is effective only if convenient man-to-machine dialogs are possible. At each stage the engineer must initiate an analysis and then be informed of the results. Graphical and statistical displays are the best forms of machine-to-man dialogs, because they allow the engineer to extract the important information quickly and easily. The GCARS system incorporates such displays.

Programs

The GCARS system is written in FORTRAN IV. The programs have been run on Control Data Corporation 6000 series and IBM 360 computers. The programs are fully documented in a users manual (12) and in a three-part programmers manual (11). Eight main programs and 20 subroutines form an interconnected system. The engineer may select those programs and sequence of operations suitable for his analysis.

Basic Concept

The GCARS system incorporates a general concept proposed by Roberts (9). Figure 1 shows this concept. Appropriate mathematical and statistical methods are applied to some basic information for each factor to develop numerical cost models. The cost models may be visualized as solid surfaces, as shown in Figure 1. In actual practice they are stored as matrices within the computer.

Desirable routes will follow the valleys across such cost models. The most desirable route combines directness and low elevations so as to obtain the lowest total cost. Less desirable routes follow other valleys and passes over the intervening high-cost areas. Sometimes such alternatives 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 overall length and total cost.

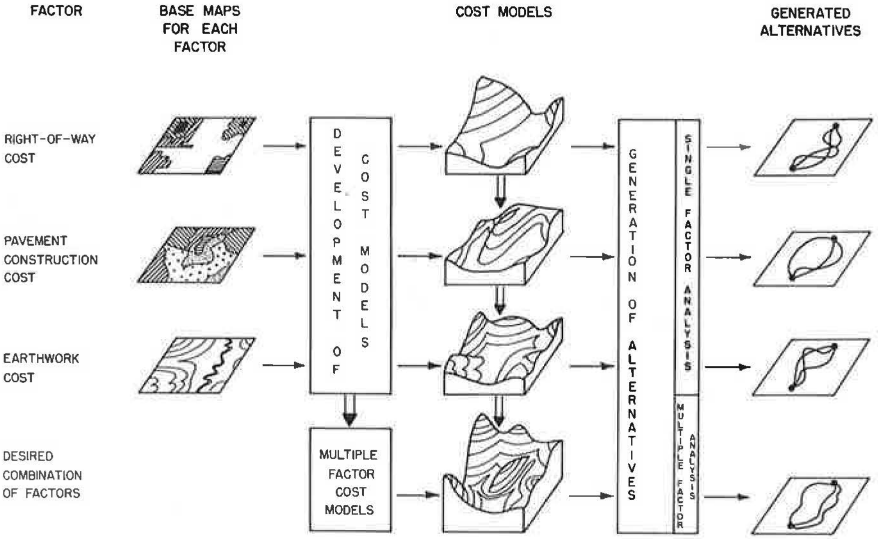


Figure 1. Basic concept of the GCARS system.

If a grid network is laid on such cost models such that each link in the network is assigned the cost of traversing it, minimum-path analysis will discover the optimal path. Preventing the further use of the links forming central portions of the chosen path and reanalyzing the revised network will produce a second minimum—a second-best alternative. Repeating the process will allow the generation of a ranked series of alternatives.

Figure 1 also shows that models for several factors can be superimposed and summed to produce cost models for any desired combination of factors. Before summation each model can be multiplied by a weighting factor, allowing it to be enhanced to any desired degree. Repeated minimum-path analysis on networks derived from such combined models will generate a series of ranked alternatives in terms of combinations of factors.

Computational Procedures

The GCARS system uses two broad classes of computational procedures. During data preparation, various "numerical surface analysis procedures" are used to construct a cost model for each factor (10). During the search activity, minimum-path analysis procedures have been adapted to generate a series of ranked alternatives.

Data-Preparation Activity Computations

The GCARS system includes a number of procedures for building and checking the value and utility models. Many of these methods have been borrowed from geography and geology, sciences in which there is considerable experience with handling spatial data. Full descriptions of these methods are given by Turner (10). Only the use of trend-surface analysis for determining cut-and-fill costs will be mentioned here.

Trend-surface analysis is a specialized form of regression analysis much used in the earth sciences to separate regional from local effects for any spatial data (3, 8). The application of trend surfaces to the estimation of cut-and-fill costs is shown in Figure 2. Roberts suggested a similar concept (9).

Trend surfaces are calculated to approximate the terrain in varying degrees of complexity. If one such surface is assumed to approximate possible grade lines, then the residuals, measuring the lack of fit of this surface to the elevation data, represent the magnitudes of cut and fill required to build a highway having a grade line following the trend surface. In general, the trend surfaces are much less steep than actual highway grade lines. However, the relative volumes of cut or fill would be similar to the

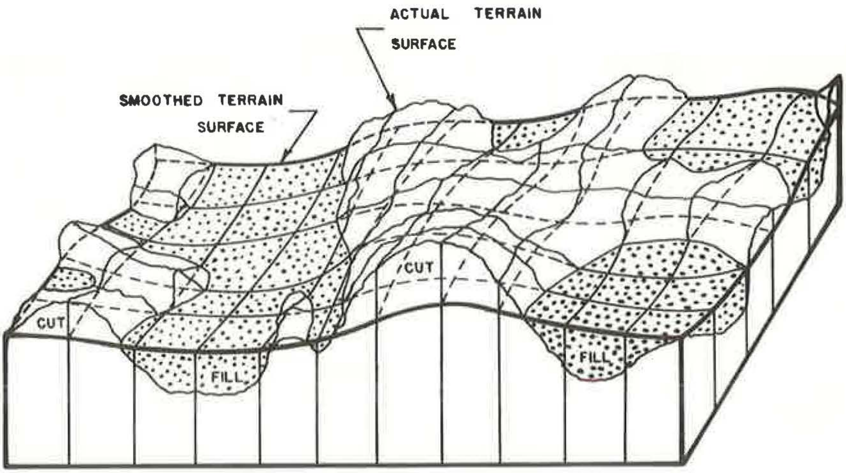


Figure 2. Terrain smoothing to simulate cut-and-fill costs.

residuals, and so the topographic residuals are suitable values of the earthwork cost factor.

In cases where the terrain is too complex to be satisfactorily approximated by a single trend surface, trend surfaces can be fitted to overlapping subareas. A trend mosaic can be assembled from these various parts, much as a photomosaic is assembled from individual aerial photographs.

Search Activity Computations

The GCARS system uses a modified version of the Road Research Laboratory (RRL) minimum-path algorithm developed in Great Britain (15). This algorithm involves no iterations, in contrast to the Moore algorithm used by the Federal Highway Administration (5, 6). Because the RRL algorithm can be stopped as soon as it has found a path between the required origin-destination pair, it allows considerable savings in computational time.

All rows and columns in the utility matrices are joined to form a square grid network having a link-to-node ratio of almost four. The link costs are computed as the average of the utilities of their end nodes. It is assumed that travel can occur on them in either direction.

Alternative minimum paths are generated according to the procedures defined by Ayad (2). After the first path has been found, its central lines are reassigned very high values and so removed from consideration. The revised network is then reanalyzed and a new minimum found. This process is repeated either until a specified number of alternatives, up to a maximum of seven, is generated or until the latest alternative has a path total greater than twice that of the first choice. The choices will become constrained if all links in a path are given high values. Based on Ayad's recommendations, 7 percent of the links—3½ percent of each end—retain their original values. This value is rounded upward to the nearest link and never is less than one link at each end.

The RRL algorithm coding presented by Martin (5) has been extensively revised to improve its efficiency and to incorporate Ayad's concepts. A routine to produce maps of the alternatives has been added. The generation of five alternatives and the development of a map of the paths takes about 1½ min of computation time.

DEVELOPMENT OF VALUE SURFACES USING GCARS SYSTEM ANALYSES

To demonstrate the capabilities of the GCARS system, examples of analyses from a test area in Northern Indiana are presented. The following discussion is by no means exhaustive; the interested reader is referred to Turner (10) for a more detailed analysis.

The GCARS system generates a series of preliminary alternatives by analyzing route-independent location factors. A total of seven measures representing five route-independent factors were studied.

Earthwork Cost Factor

Figure 3 shows the general topographic conditions within the 12- by 15-mile test area. Trend surfaces were fitted to 2,521 spot elevations. The trend surface shown in Figure 4 explains 53 percent of the variability in the data and was selected as a suitable smoothed grade-line surface. Figure 5 shows the residuals to this surface that were used as the earthwork cost model.

Pavement Construction Cost Factor

Ten soil types are mapped within the test area. Each soil type was given a code, and the map was digitized. Soil ratings developed by Ulbricht (14) for Indiana soils were used to convert the soil codes to values for the pavement construction cost factor. Ulbricht was able to develop soil ratings and demonstrate that they were proportional to the soil-support factors required by the AASHO design equations. A simple inversion of these ratings produced values that are large for poor soils and small for good ones. Figure 6 shows the resulting value surface.

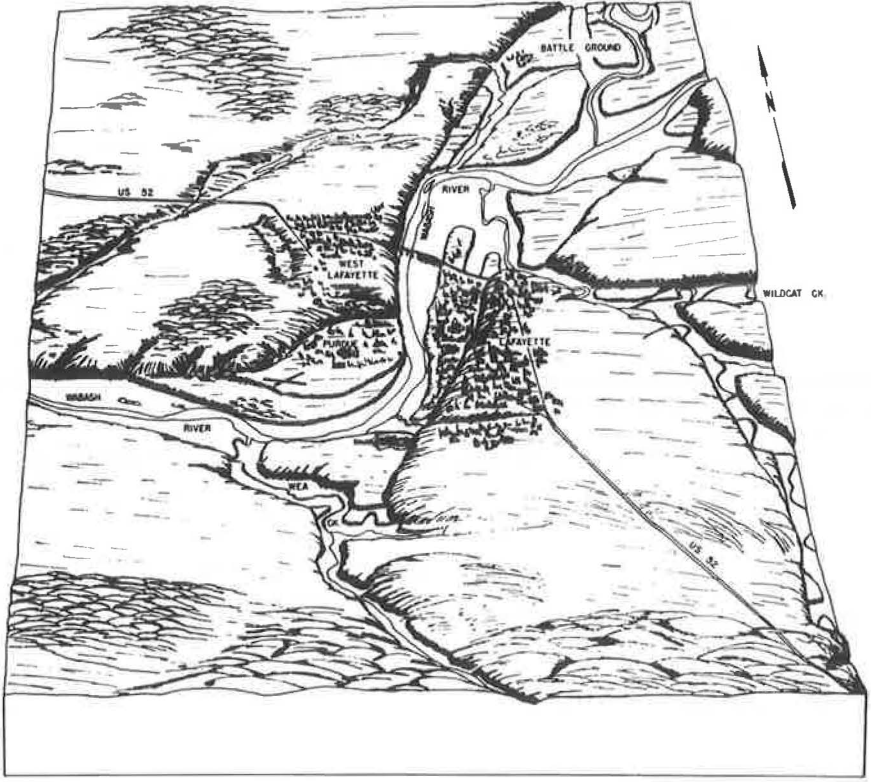


Figure 3. Physiographic diagram of northern test area.

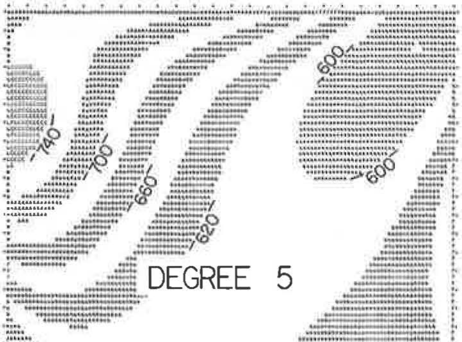


Figure 4. Contours of fifth-degree trend surface fitted to topographic elevations.

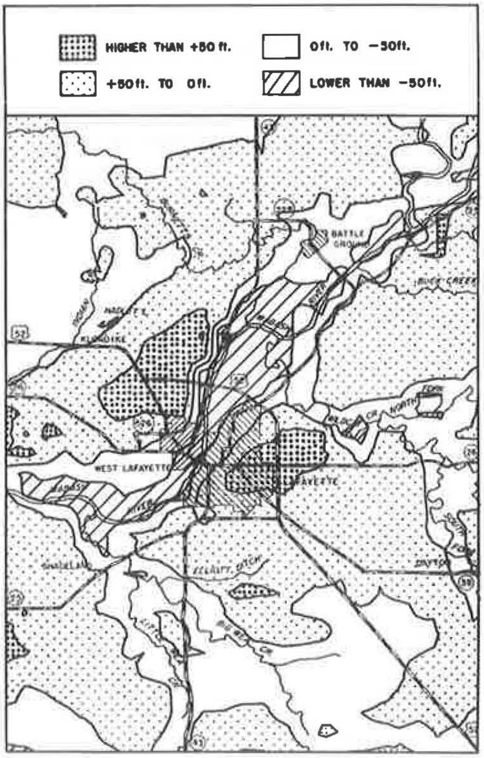


Figure 5. Contours of earthwork cost model.

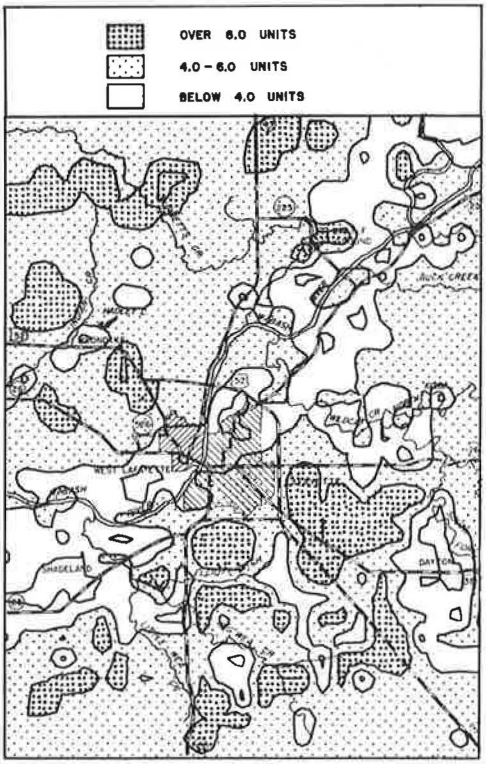


Figure 6. Contours of pavement construction cost model.

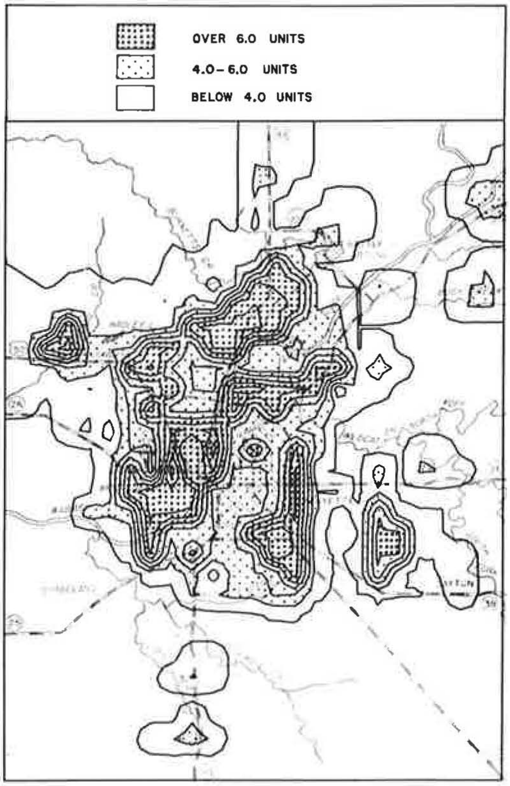


Figure 7. Contours of right-of-way acquisition cost model.

Right-of-Way Acquisition Cost Factor

The test area was divided into 213 origin-destination zones. Zones in the urban areas had been defined during an earlier transportation study. Additional zones were defined by air-photograph analysis. Each zone was assigned to one of six land use classes. A rating scale was devised to convert the land use classes to right-of-way acquisition costs. The ratings were chosen in consultation with a panel of qualified persons and were intended to reflect dollar costs tempered by an appreciation of social and aesthetic considerations.

The authors recognize that such a rating scheme is at best a rough approximation of costs. A series of weighted interpolations were made from zone centroids to compute the gridded value matrix. This tends to adjust the assigned costs to reflect the presence of nearby higher or lower valued land uses. Thus, the surface shown in Figure 7 is believed to be a reasonably valid right-of-way acquisition cost model.

Service Benefit Factors

Four measures were tested to represent practical service benefits of new facilities. Three measures were measured for the same origin-destination zones. Zone population totals and densities were derived partly from data from the previous transportation study and partly from the 1960 census forms. Zone trip ends were obtained from the transportation study for the urban areas. Rural zone trip ends were estimated from the population data by a simple regression equation. The resulting models were quite similar. Figure 8 shows the trip end model.

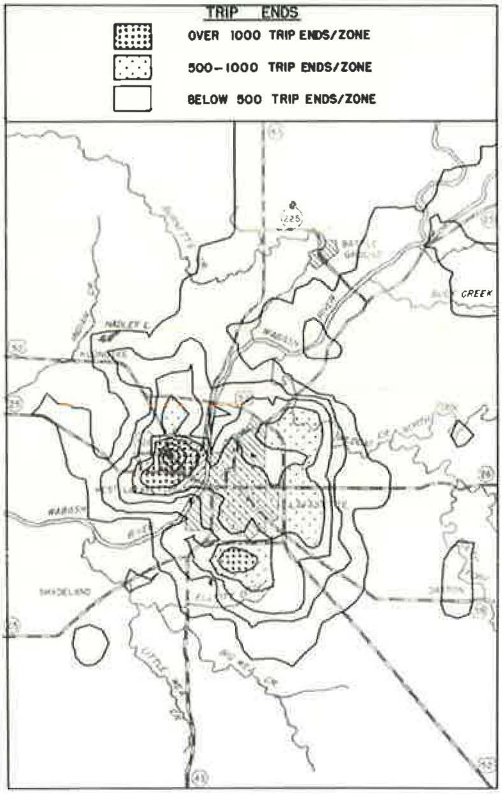


Figure 8. Contours of trip end model.

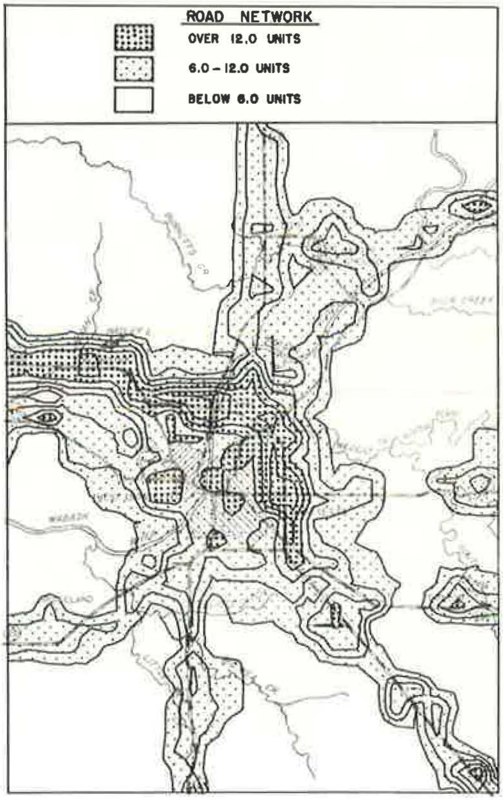


Figure 9. Contours of road network model.

The quality of the present road network was also analyzed. Other things being equal, a new facility should not duplicate existing facilities. Each road class shown on the Tippecanoe County highway map was given a rating ranging from 1 for a gravel road to 6 for a four-lane, divided highway. Each road intersection was given a rating equal to the sum of the ratings of the roads constituting it. These values and the locations of the intersections were used to build the model shown in Figure 9. This model shows high values where there are good high-class roads and low values where road capacities are low.

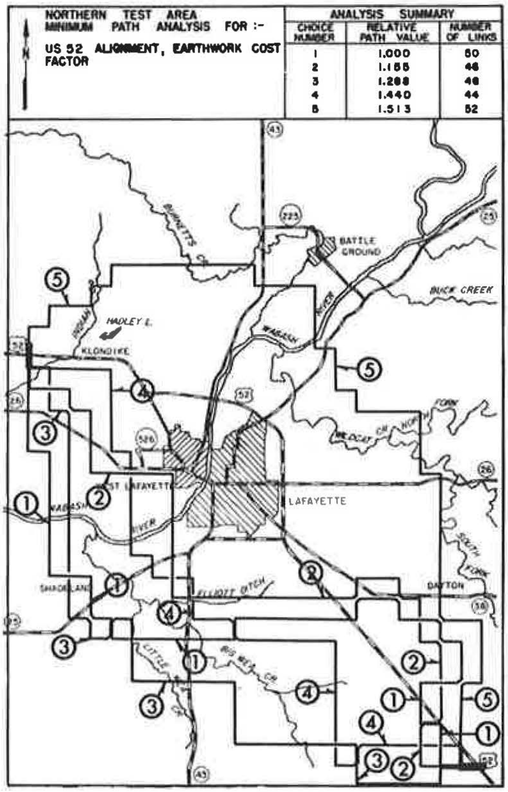
US-52 BYPASS STUDY

The most heavily traveled highway in the area is US-52 that connects Chicago and Indianapolis. The present route includes an old bypass through the eastern and northern portions of Lafayette that is now being improved. It was decided to analyze the data to discover the best location for a new bypass to carry US-52 traffic.

Analysis of Individual Location Factors

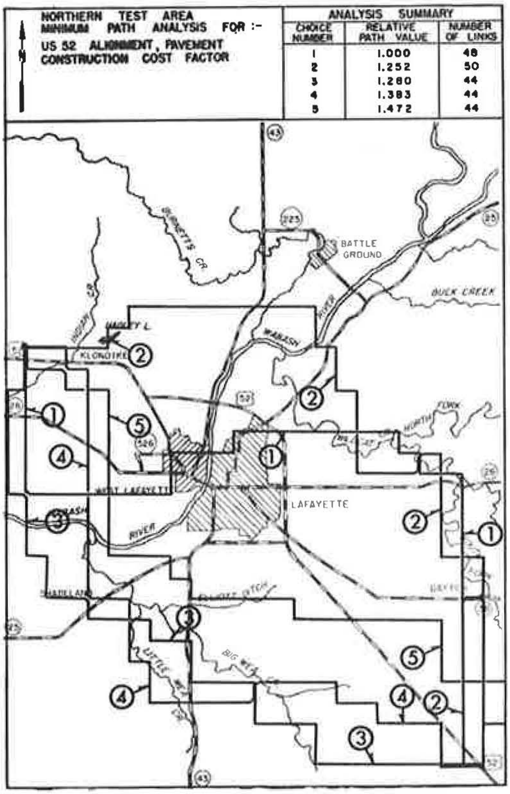
Based on their experiences, the authors believe that the first step in any study should be the analysis of individual location factors. These analyses give the engineer an opportunity to discover the best locations for each factor alone and thus gain an appreciation of the conflicts among the factors.

Most alternatives generated to minimize earthwork costs (Fig. 10) lie south and west of the urban area. The competing eastern route is not chosen until the fifth choice and costs over 50 percent more than the first choice. All alternatives tend to follow natural depressions when approaching the Wabash River Valley. The alternatives generated to



ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.155	46
3	1.268	46
4	1.440	44
5	1.513	52

Figure 10. US-52 alignments for earthwork factor.



ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	48
2	1.252	50
3	1.280	44
4	1.383	44
5	1.472	44

Figure 11. US-52 alignments for pavement construction factor.

minimize the pavement construction costs (Fig. 11) quite faithfully reflect the distribution of granular materials. The right-of-way acquisition cost-factor analysis (Fig. 12) demonstrates marked preference for the southwestern portions of the area, which are primarily agricultural and have low population densities.

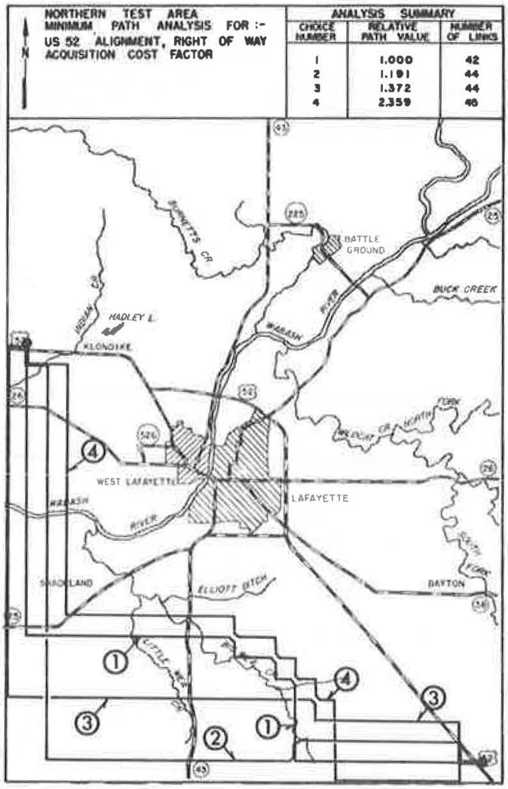
Analyses of population and trip end data produced a series of alternatives passing directly through urbanized areas. Figure 13 shows the results for the trip end data.

Analysis of Combined Location Factors

Over 20 combinations of factors and factor weightings were studied (10). Figure 14 shows the alternatives generated for the combination of the earthwork and pavement construction cost factors. The alternatives continue to reflect the distribution of granular soils, and the ease of crossing the Wabash River Valley. When the right-of-way cost factor is included (Fig. 15), the routes are shifted as the southwesterly alternatives become the most desirable.

Figures 16 and 17 show the effects of changing the importance of factors. When pavement costs are emphasized by being given a higher weight (Fig. 16), the generated alternatives tend to follow the coarse-textured materials. Figures 11, 14, and 16 show similar general patterns; however, careful examination reveals changes in the placement of sections of the alternatives and in their rankings that reflect the interactions among the factors.

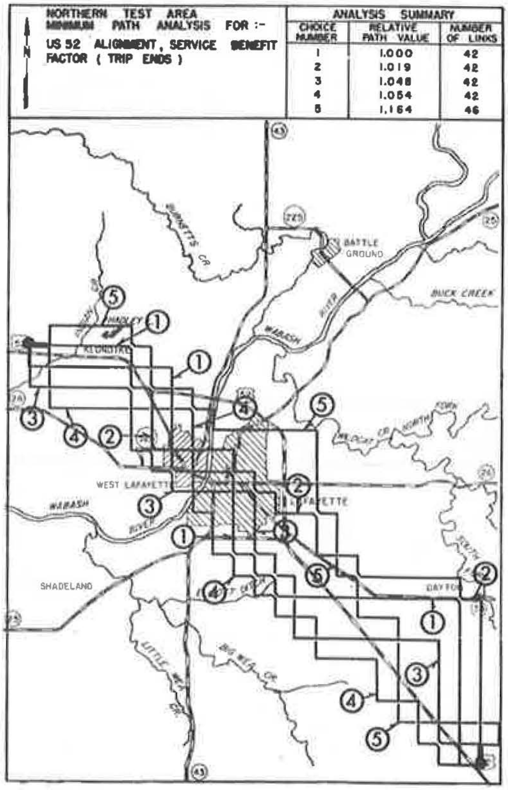
Figure 17 shows that the southwestern locations become dominant when the right-of-way costs are emphasized. Figures 18 and 19 show the final model developed. A combination of five weighted factors produces a well-defined southwestern corridor.



NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR :- US 52 ALIGNMENT, RIGHT OF WAY ACQUISITION COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.191	44
3	1.372	44
4	2.359	46

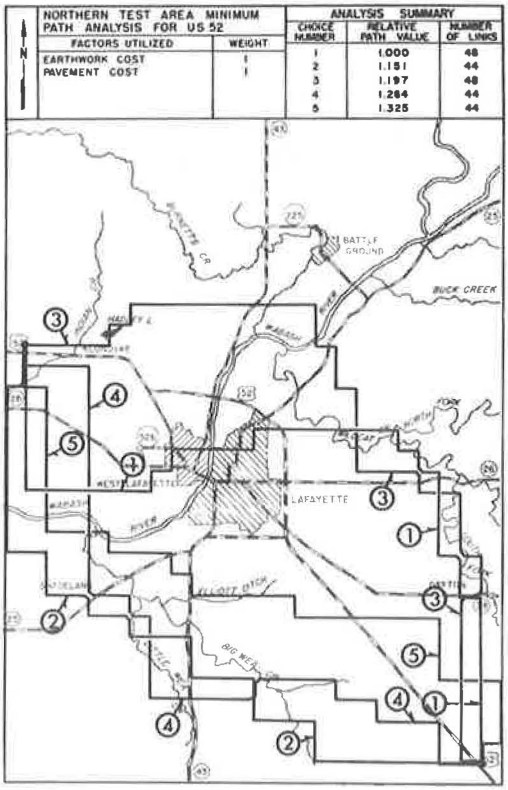
Figure 12. US-52 alignments for right-of-way factor.



NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR :- US 52 ALIGNMENT, SERVICE BENEFIT FACTOR (TRIP ENDS)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.019	42
3	1.048	42
4	1.054	42
5	1.164	46

Figure 13. US-52 alignments for trip end factor.

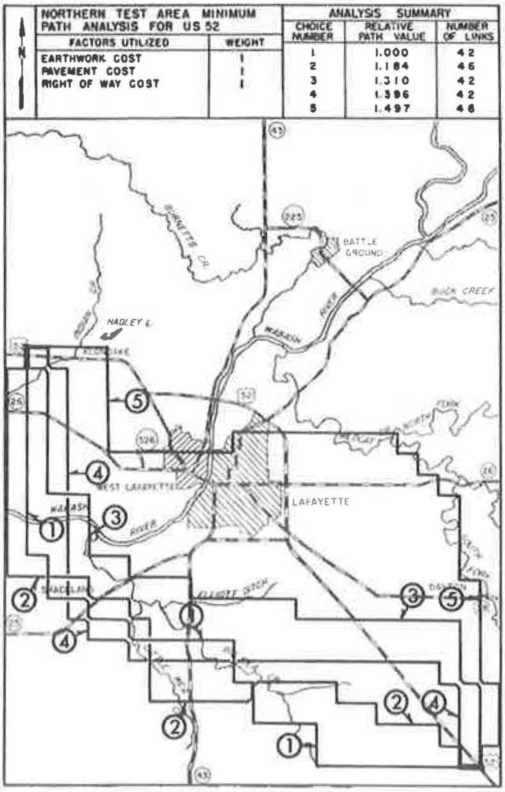


NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	46
2	1.151	44
3	1.197	46
4	1.264	44
5	1.325	44

Figure 14. US-52 alignments for earthwork and pavement construction factors.

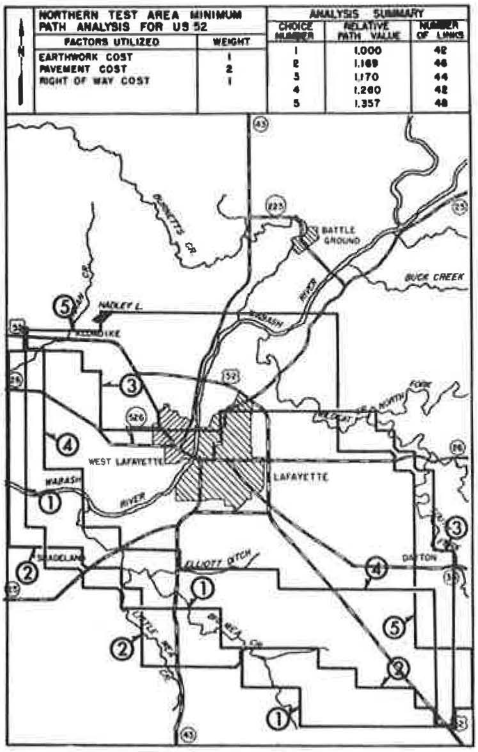


NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.184	46
3	1.310	42
4	1.396	42
5	1.497	46

Figure 15. US-52 alignments for earthwork, pavement construction, and right-of-way factors.



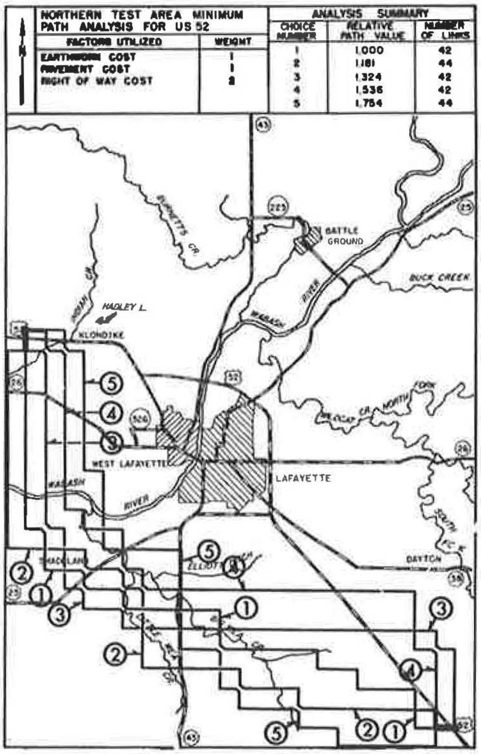
NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	2
RIGHT OF WAY COST	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.169	46
3	1.170	44
4	1.260	42
5	1.357	48

Figure 16. US-52 bypass analysis–effect of emphasizing pavement construction factor.



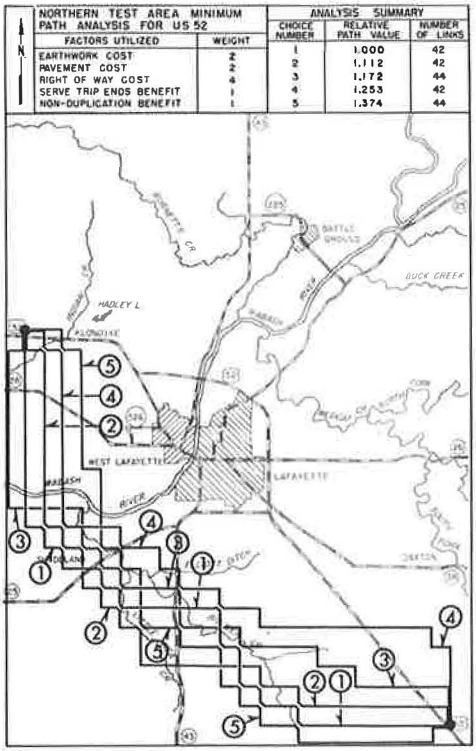
NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	2

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.181	44
3	1.324	42
4	1.536	42
5	1.754	44

Figure 17. US-52 bypass analysis–effect of emphasizing right-of-way factor.



NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	2
PAVEMENT COST	2
RIGHT OF WAY COST	4
SERVE TRIP ENDS BENEFIT	1
NON-DUPLICATION BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.112	42
3	1.172	44
4	1.253	42
5	1.374	44

Figure 18. US-52 alignments generated for five weighted factors.

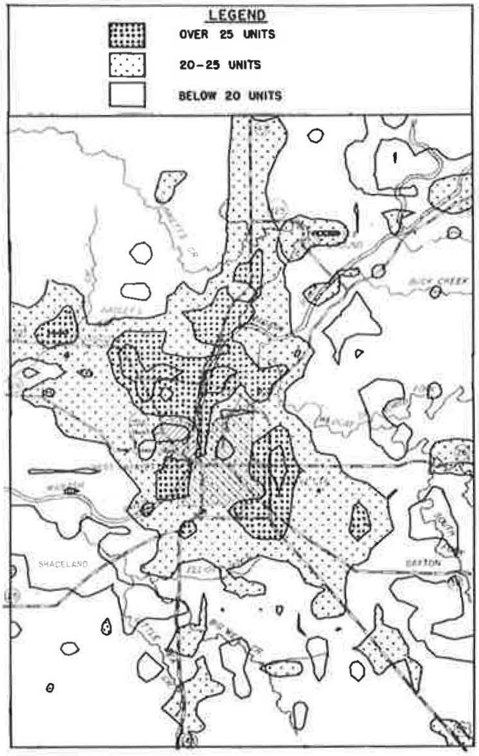
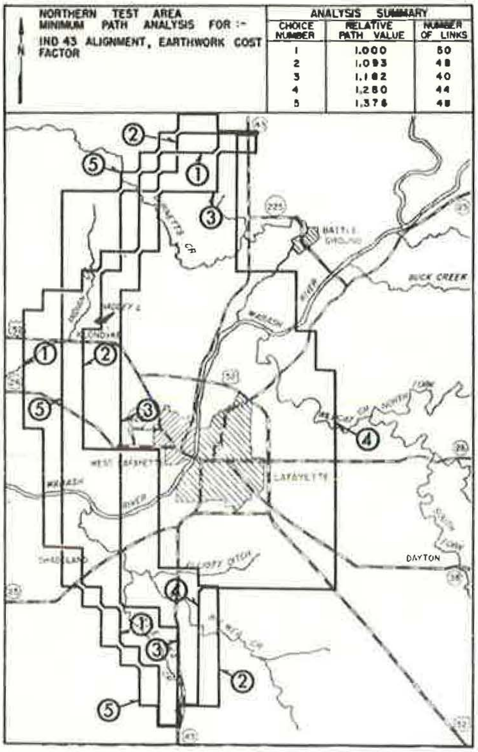


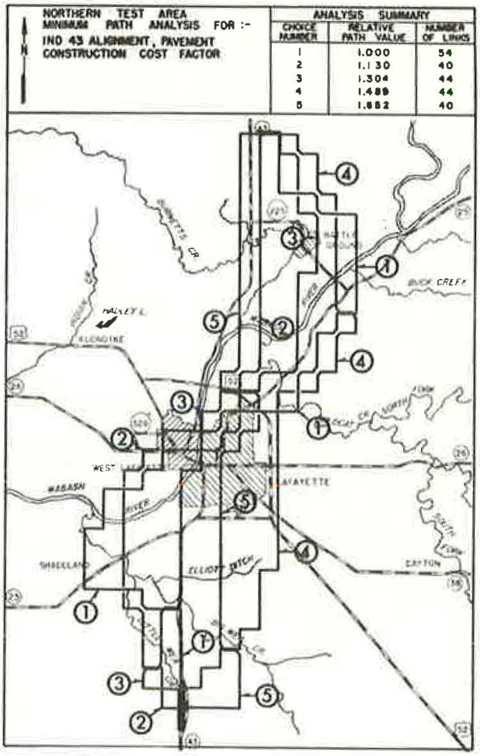
Figure 19. Contours of cost model of utility surface corresponding to Figure 18.



NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
IND 43 ALIGNMENT, EARTHWORK COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.093	48
3	1.182	40
4	1.280	44
5	1.376	48

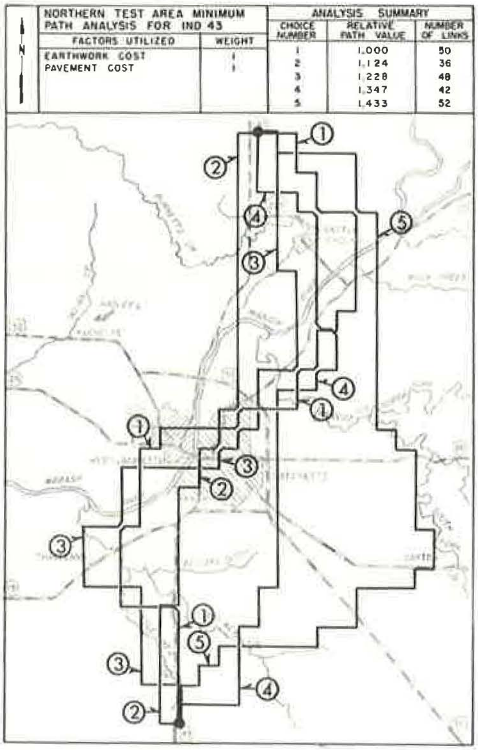
Figure 20. Ind-43 alignments for earthwork factor.



NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
IND 43 ALIGNMENT, PAVEMENT CONSTRUCTION COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	54
2	1.130	40
3	1.304	44
4	1.489	44
5	1.882	40

Figure 21. Ind-43 alignments for pavement construction factor.

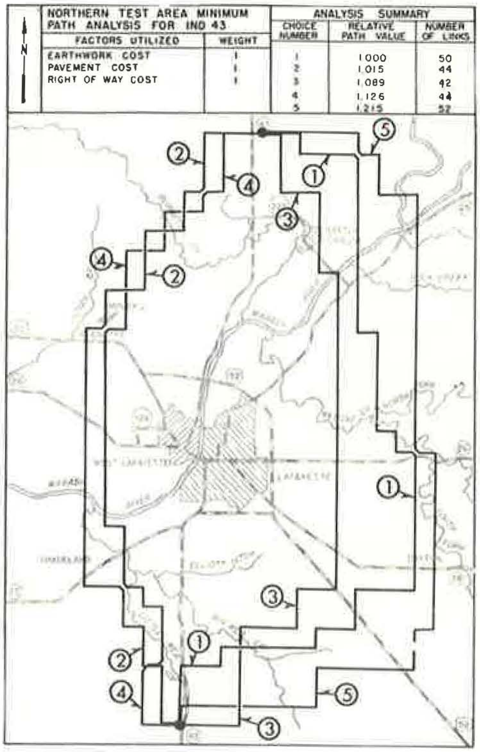


NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.124	36
3	1.228	48
4	1.347	42
5	1.433	52

Figure 22. Ind-43 alignments for earthwork and pavement construction factors.



NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.015	44
3	1.089	42
4	1.126	44
5	1.215	52

Figure 23. Ind-43 alignments for earthwork, pavement construction, and right-of-way factors.

IND-43 BYPASS STUDY

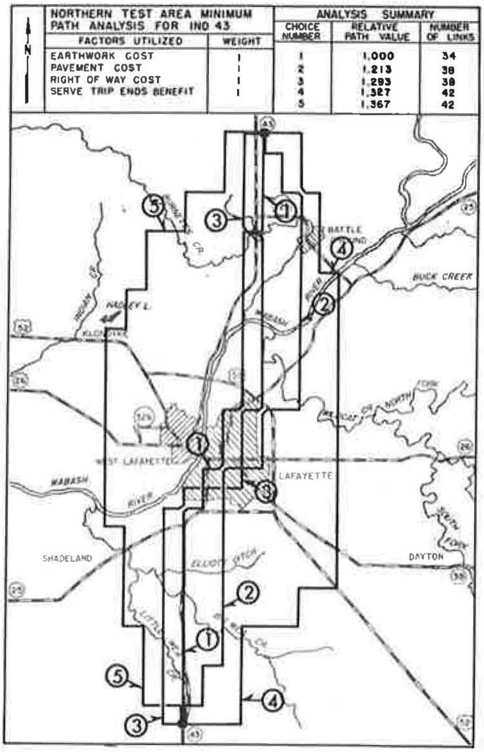
One of the advantages of using the GCARS system is the convenience with which any origin-destination combination can be analyzed. Analyses have also been made for bypasses for other roads in the area. Ind-43 is the main north-south route through the area.

Analysis of Individual Location Factors

Figure 20 shows the alignments for the earthwork cost factor. The western portions of the area offer better conditions for crossing the Wabash River Valley. It is more open, and the sides are lower. Figure 21 shows the alignments generated for the pavement construction cost factor. The strong attraction of the granular soils is evident. Analyses of right-of-way costs produced circuitous routes avoiding all populated areas, whereas the population and trip end data generated routes that closely follow the present route of Ind-43.

Analysis of Combined Location Factors

Figure 22 shows the alternatives generated when earthwork and pavement construction costs are combined with equal weights. The locations are affected by the presence of granular soils. Figure 23 shows the effect of adding the right-of-way cost factor. Changing the weightings of these factors causes marked changes in the alignments, indicating that, for this origin-destination combination, the optimal alignment is sensitive to factor rankings. Addition of the trip end factor (Fig. 24) results in the first three choices passing through the urban area. Figure 25 shows the choices generated for



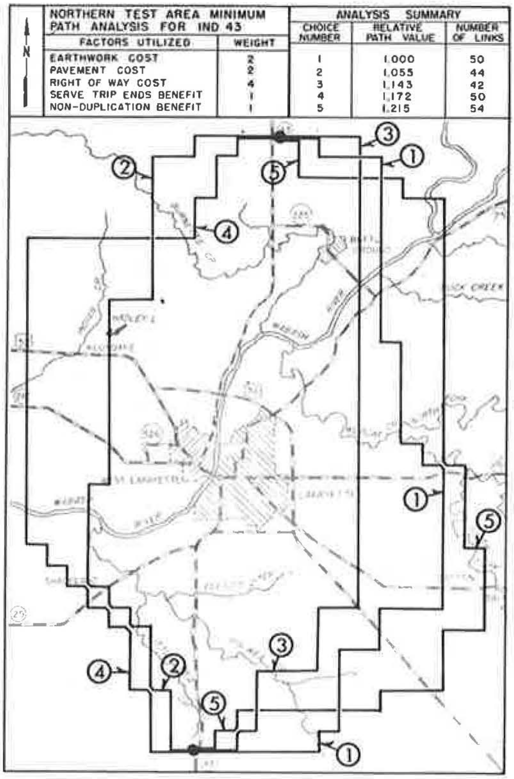
NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1
SERVE TRIP ENDS BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	34
2	1.213	38
3	1.293	38
4	1.327	42
5	1.367	42

Figure 24. Ind-43 alignments generated for four factors.



NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	2
PAVEMENT COST	2
RIGHT OF WAY COST	4
SERVE TRIP ENDS BENEFIT	1
NON-DUPLICATION BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.055	44
3	1.143	42
4	1.172	50
5	1.215	54

Figure 25. Ind-43 alignments generated for five weighted factors.

the model shown in Figure 19. This is believed to represent a reasonable weighting of the factors for this area. Each choice represents a distinct alternative. The second and third alternatives are considerably shorter than the others.

CONCLUSIONS

The GCARS system is a viable method of computer-aided regional route planning. The system gives realistic answers and has a sensitive response to small changes in the location factors. The authors believe that this type of system is superior to graphical methods when complex or ambiguous factor interactions are encountered.

The chief advantages of the GCARS system are (a) its speed in generating alternatives once the models are built; (b) its ability to rank the alternatives generated; (c) the ease with which factors can be changed, substituted, or weighted; and (d) its capability of analyzing any origin-destination pair. This last factor has not been thoroughly exploited, but it would be possible to rapidly evaluate alternative destinations. The effects of alternative intermediate control points can also be studied.

An experimental interactive system, GCARS 11, has also been developed (13). In this system the engineer monitors the alternative generation at a teletype terminal. After only a few minutes of instruction, a number of engineers with no programming experience were able to use the system. Such developments and the continued increase in the number of data banks for urban areas will enhance the utility of a GCARS system. However, further work is required in these areas.

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