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NEW LEVEL OF HIERARCHY

THE USE OF DIAGRAMS IN HIGHWAY ROUTE LOCATION: AN EXPERIMENT

Christopher Alexander
Marvin L. Manheim

RESEARCH REPORT R62-3

DEPARTMENT OF CIVIL ENGINEERING

CIVIL ENGINEERING SYSTEMS LABORATORY

THE USE OF DIAGRAMS IN HIGHWAY ROUTE LOCATION: AN EXPERIMENT

by

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The work described here was performed at the Civil Engineering Systems Laboratory at M.I.T. The authors gratefully acknowledge the suggestions and criticism freely offered by Professors A. Scheffer Lang, Charles L. Miller, and Paul O. Roberts, and by Richard M. Soberman; however, the authors are fully responsible for the remarks made herein.

This work would not have been possible without the enthusiastic cooperation and advice of Alexander Adams, of AD-LINK Inc., commercial photographers and processors, 37 West 47th Street, New York 36, New York.

This method for analysing engineering design problems was first applied to the problem of highway route location by William Litle and Brian V. Martin, in a term paper for a course at M.I.T. (see references). The research described in this report grew directly out of the consultations of the authors with Litle and Martin, in the development of their paper, and is an extension of that paper.

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LIST OF FIGURES

All figures appear with the summary in Chapter I. The individual diagrams shown in Figure 3 also appear in Chapter III, accompanying the verbal descriptions of the requirements.

I. ABSTRACT AND INTRODUCTION

Figure 1 is a photograph of a U.S. Geological Survey map for an area in Western Massachusetts. The area, about twenty miles by ten, stretches north-south along the Connecticut River valley. A section of the Interstate Highway System, Route I-91, is to run roughly north-south in this area, along an axis through Northampton and Springfield.

We chose the problem of determining the location of this highway as a demonstration project, to illustrate certain aspects of a new approach to physical design problems. The location of this section of highway has, in fact, already been determined by the Massachusetts Department of Public Works and the Bureau of Public Roads of the U.S. Department of Commerce. However, we deliberately refrained from consulting the official plan until we had finished the analysis described here.

Figure 2 is a list of requirements which the location has to meet. Their numbering is arbitrary.

The 26 diagrams shown in Figure 3 are utility maps for the 26 requirements, each keyed to the survey map in the obvious way.

The tree in Figure 4 is a design program, derived from a mathematical analysis of the interactions among the 26 requirements. It specifies that order of combination of the diagrams which minimizes the difficulty of resolving conflicts between the requirements. (The lettering is again arbitrary.)

Figure 5 shows the stages in the process of combination. Each combination of several diagrams into one has two stages; the first stage is marked by a round cell, the second by a square cell, in the tree of Figure 4.

Figure 6 shows the location determined by this process of combination, overlaid on the map of the region it refers to. The light lines are possible, but weaker, alternatives.

This paper outlines, step by step, the nature of the problem, the process, and the reasons for adopting a process of this kind in solving the problem.

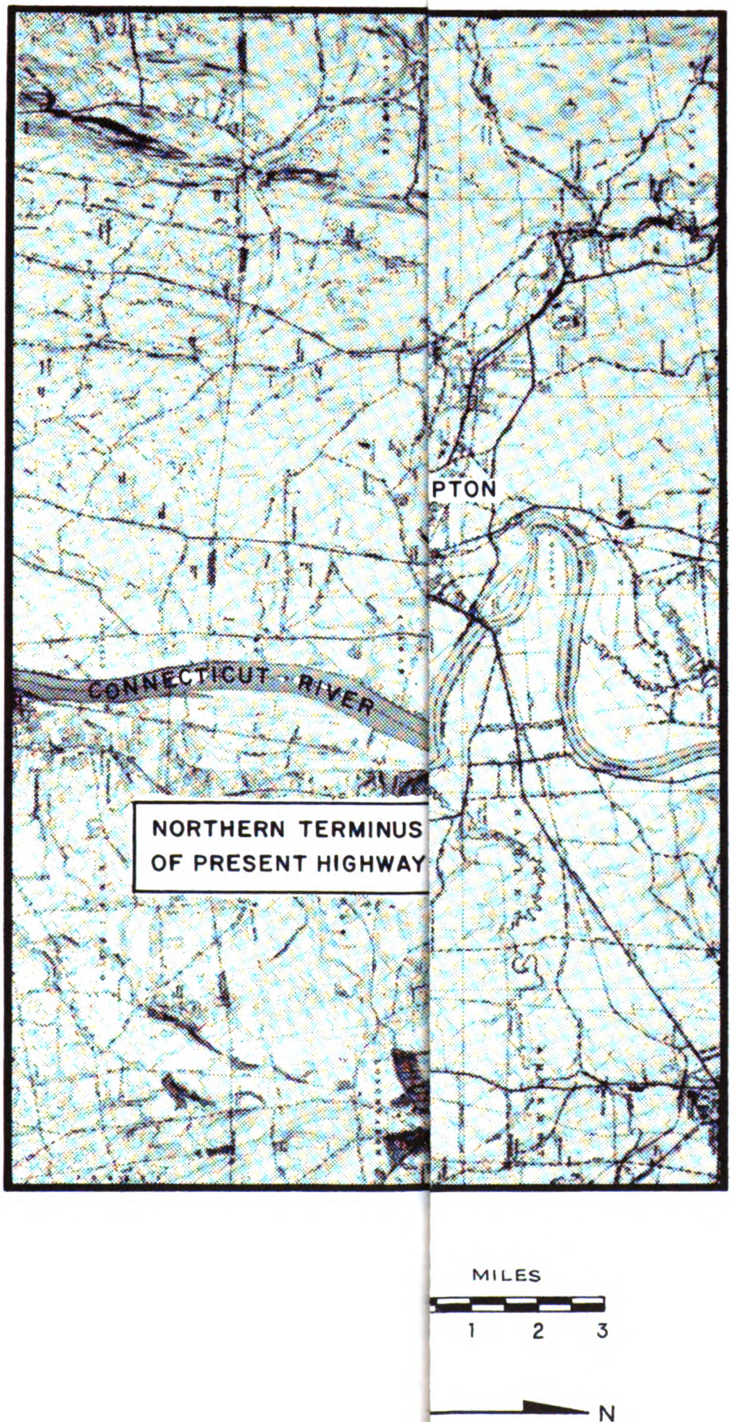
PTON
CONNECTICUT RIVER
NORTHERN TERMINUS
OF PRESENT HIGHWAY
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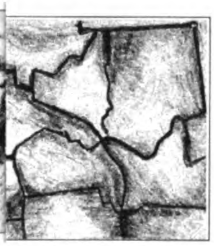
Figure 2. Requirements

1. Earthwork Costs.
2. Comfort and Safety.
3. Regional Development.
4. Local Land Development.
5. Obsolescence.
6. Interference During Construction.
7. User Costs.
8. Services.
9. Travel Time.
10. Pavement and Subgrade Costs.
11. Drainage Patterns.
12. Bridge Costs.
13. Land Costs.
14. Eyesores.
15. Noise.
16. Air Pollution.
17. Weather Effects.
18. Non-Recompensable Public and Private Losses.
19. Public Financial Losses.
20. Major Current Traffic Desires.
21. Catchment Areas.
22. Local Accessibility and Integrity.
23. Future Transportation Systems.
24. Existing Transportation Systems.
25. Duplication of Facilities.
26. Self-Induced Congestion.

I. EARTHWORK COSTS



NT AREAS

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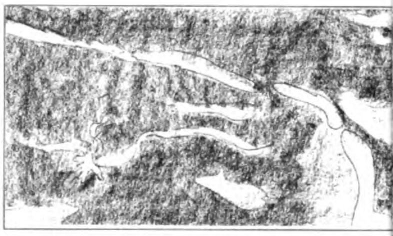
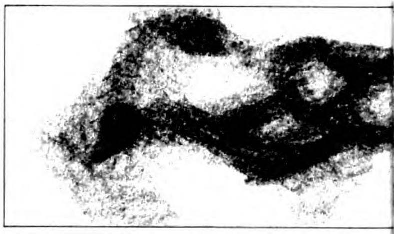


2. COMFORT AND SAFETY

ITY AND INTEGRITY



3. REGIONAL DEVELOPMENT

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4. LOCAL LAND DEVELOPMENT

RTATION SYSTEMS

5. OBSOLESENCE

OF FACILITIES

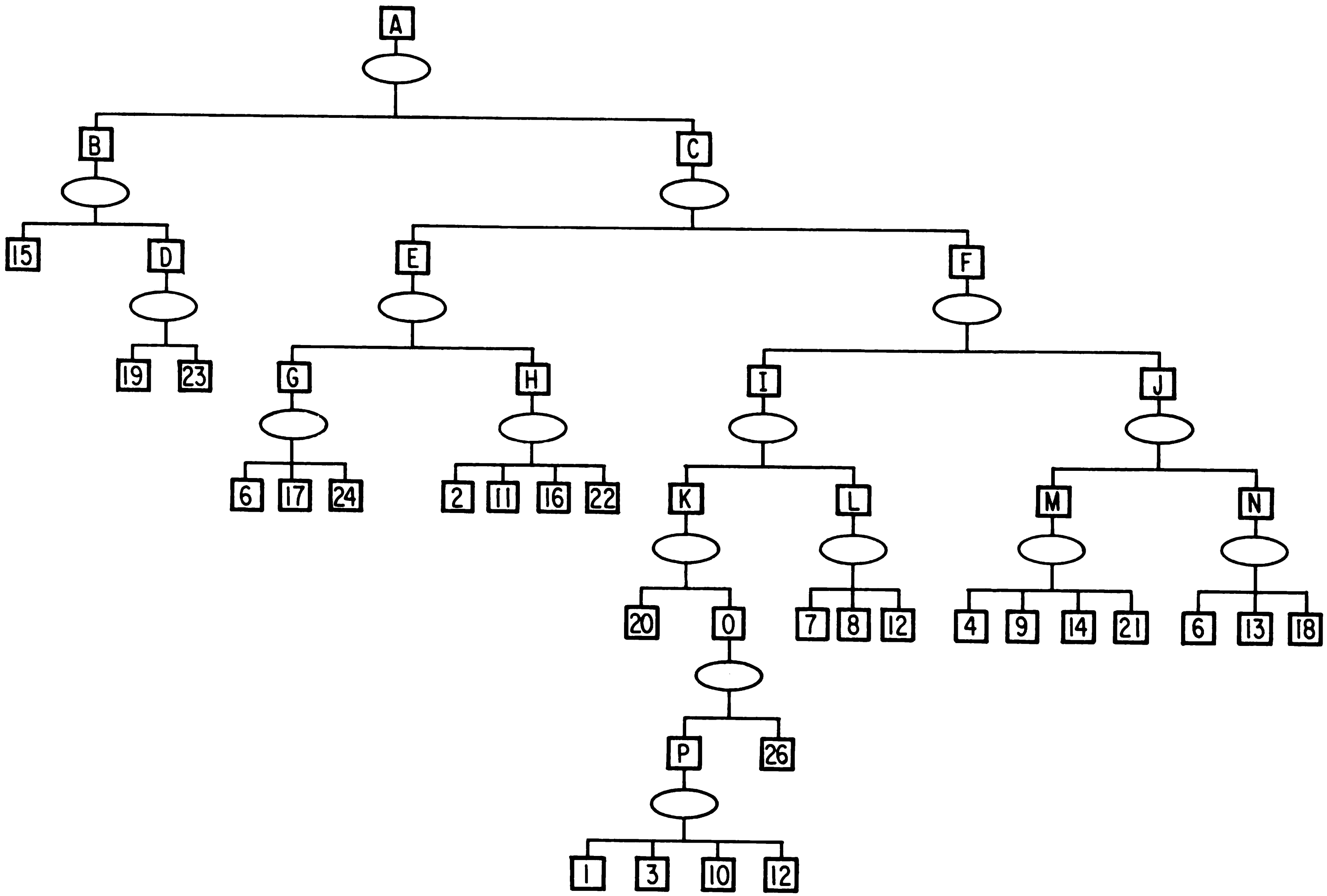
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FIG. 4

FIGURE 5.1

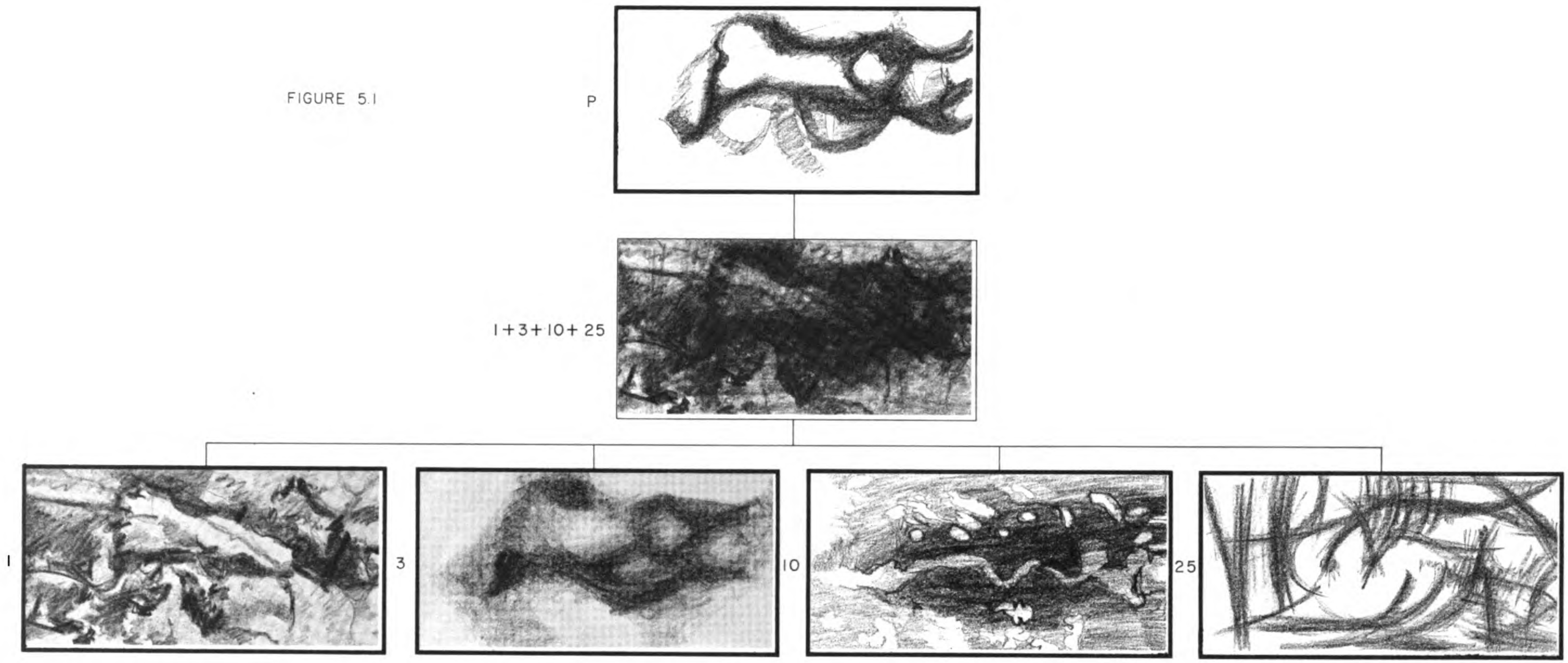


FIGURE 52

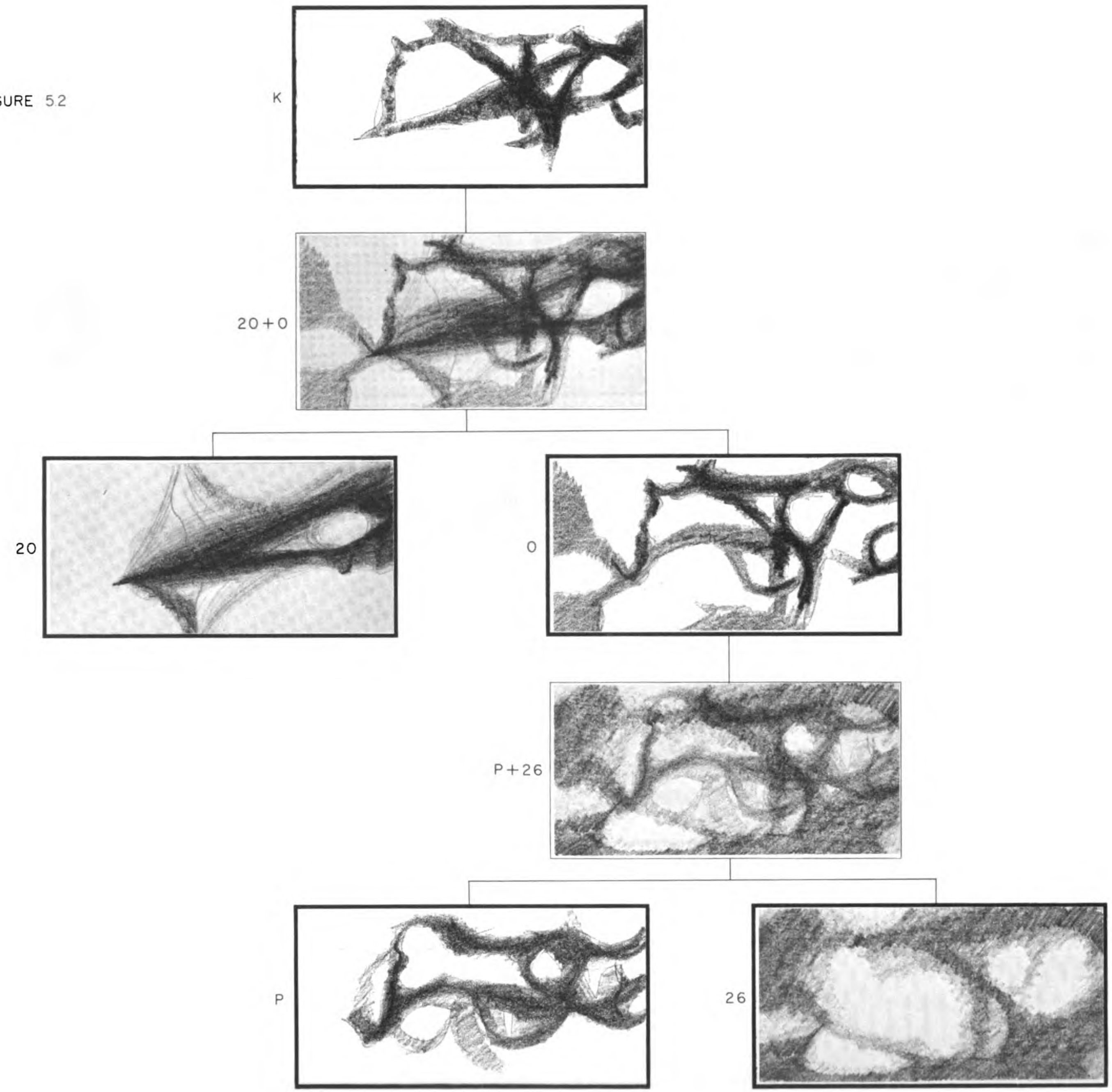


FIGURE 5.3

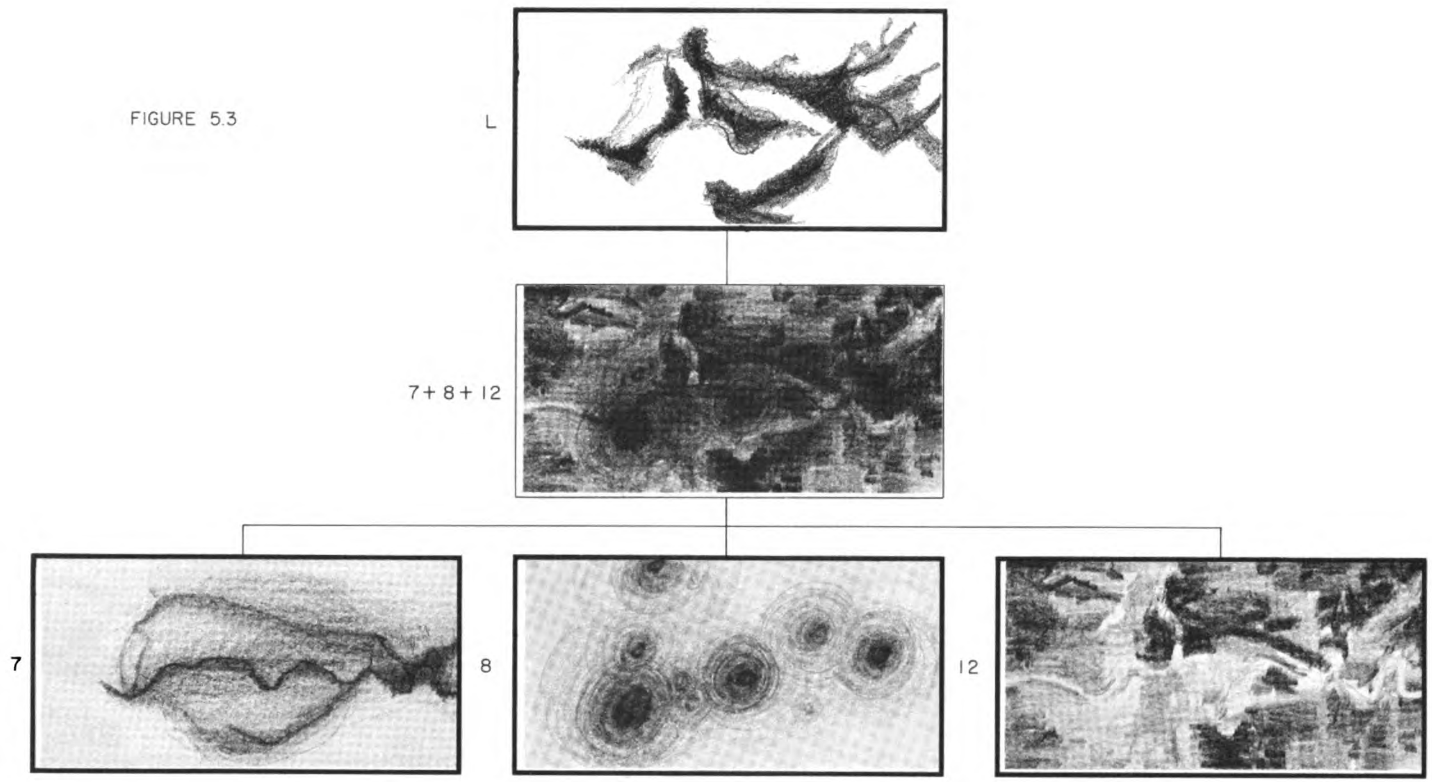


FIGURE 54

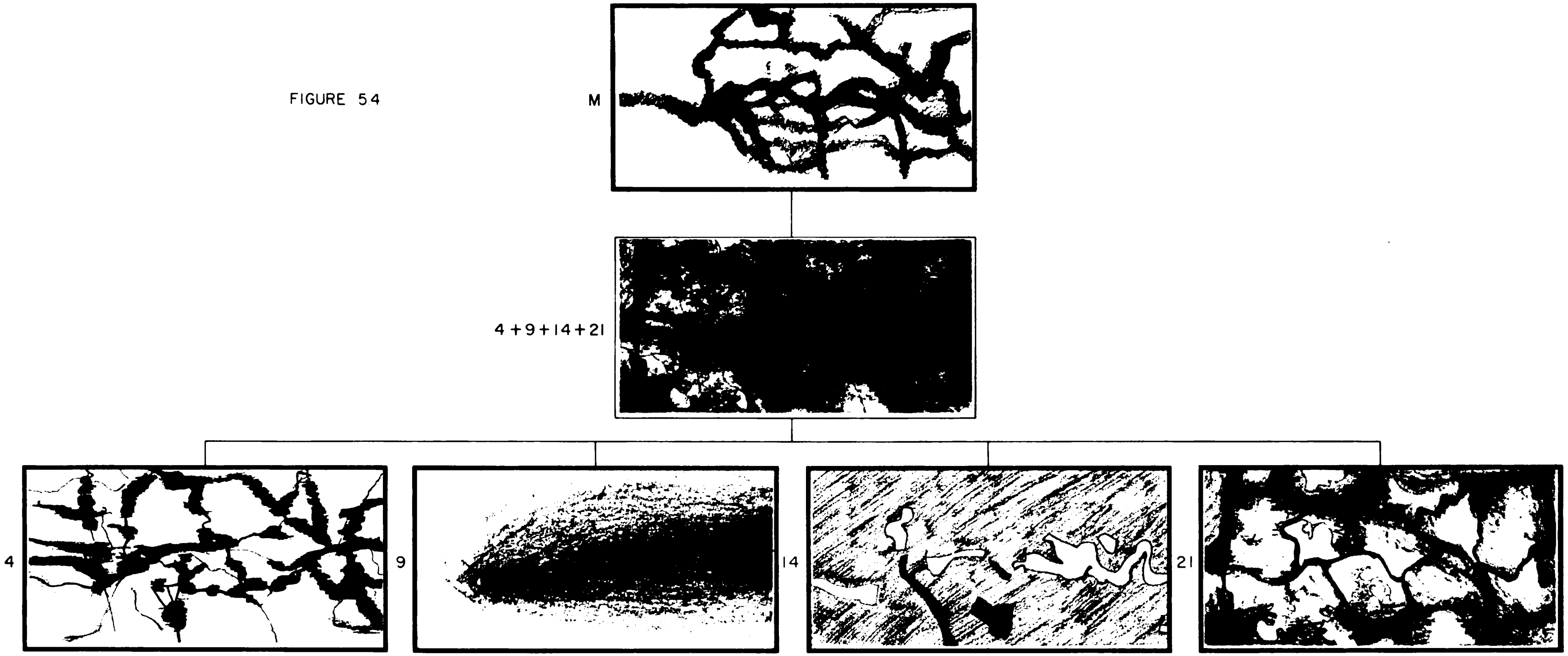
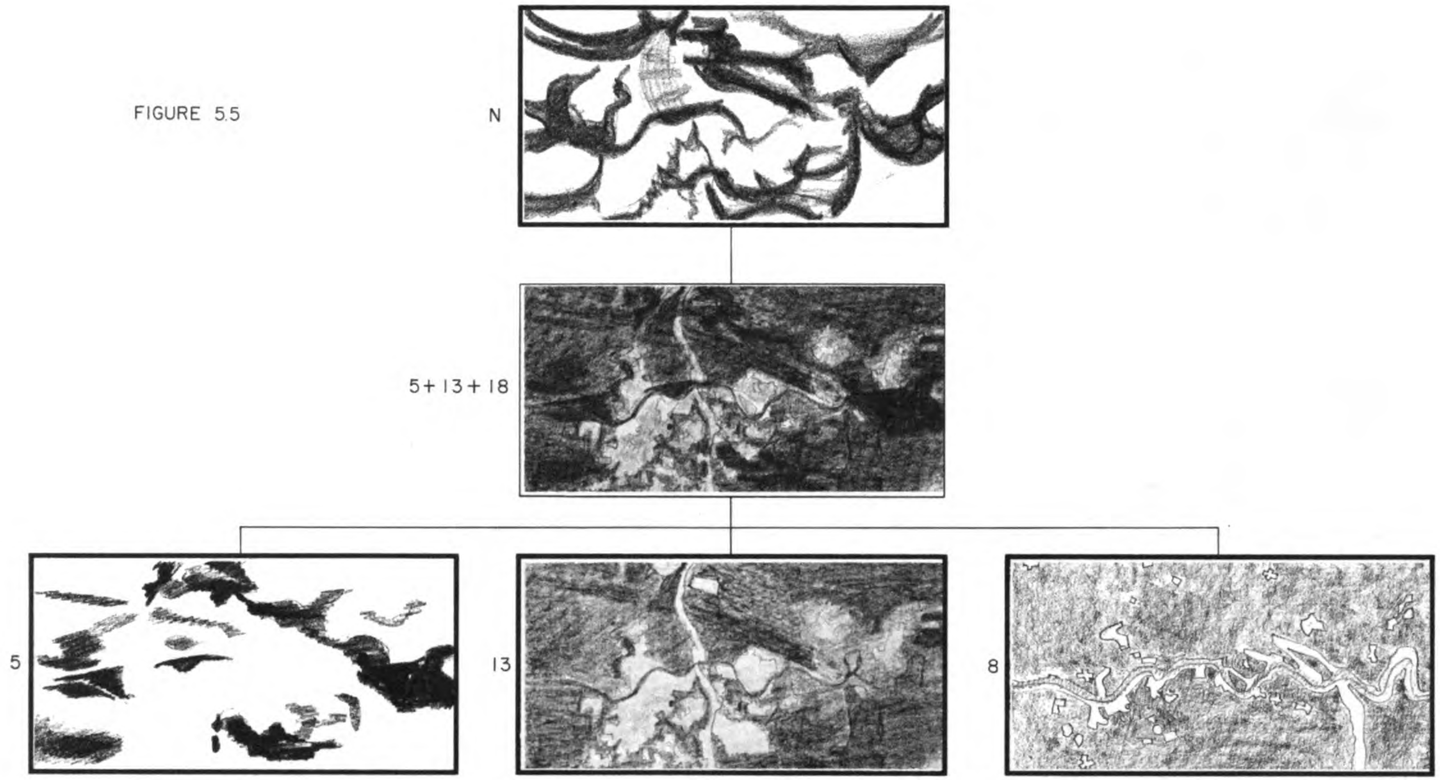


FIGURE 5.5



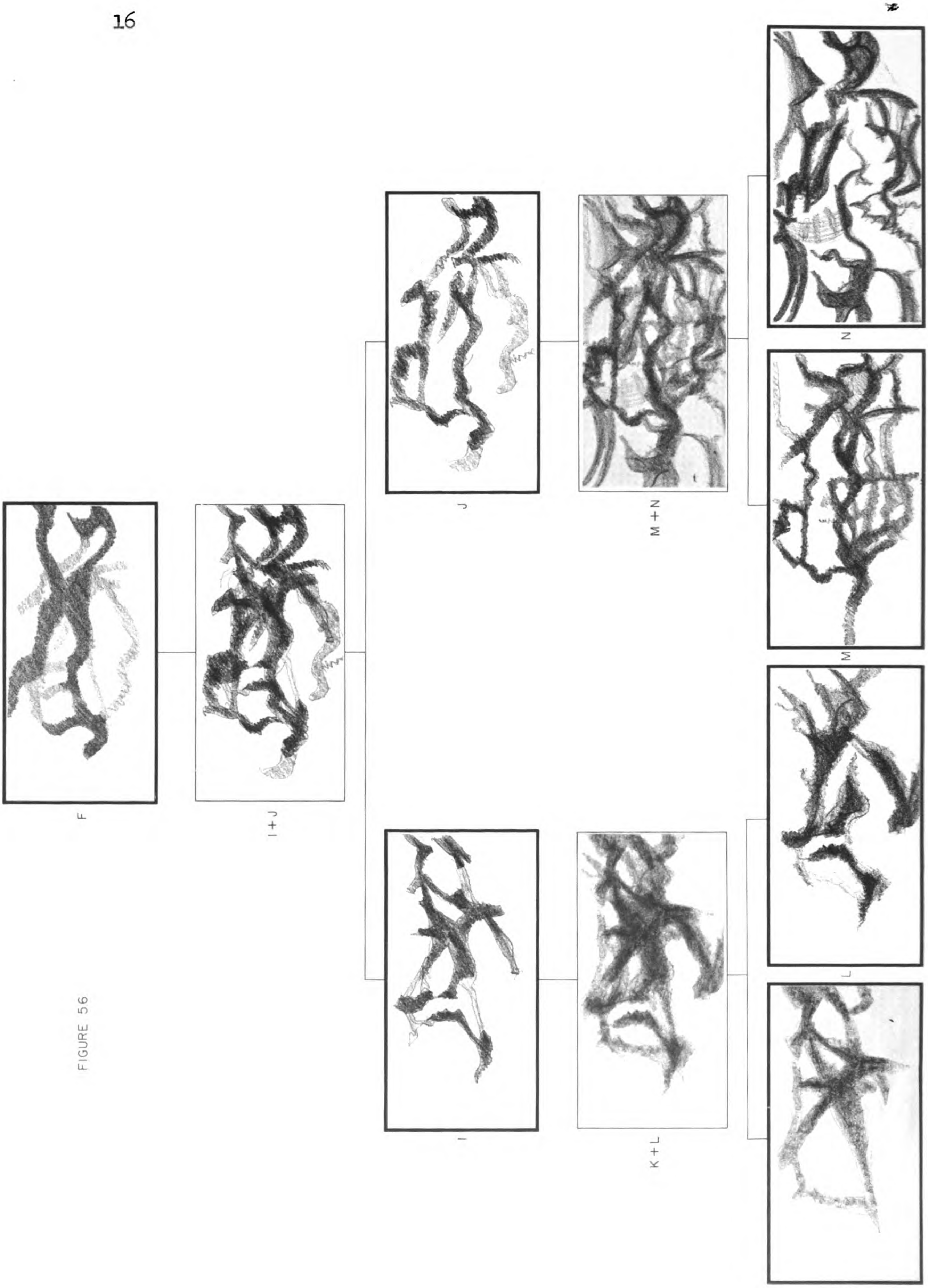


FIGURE 56

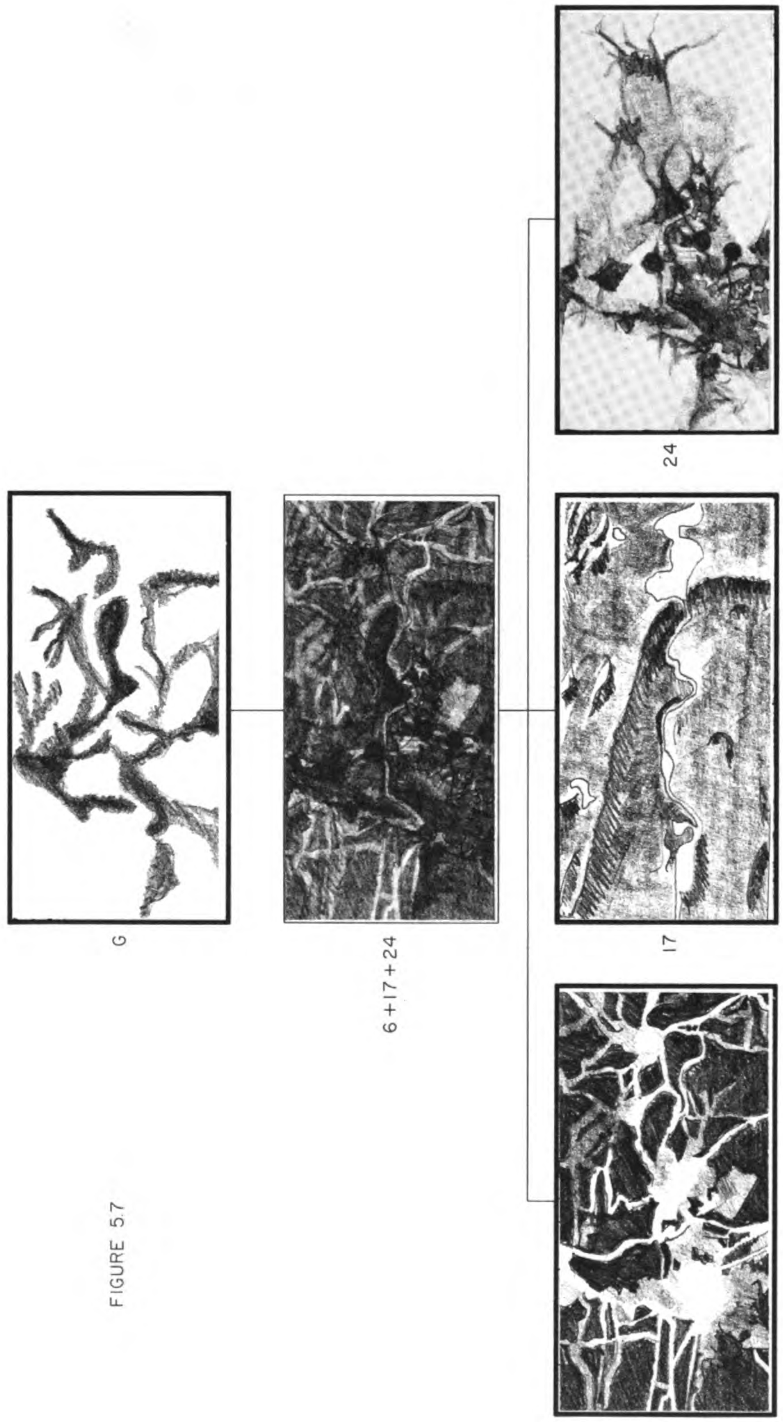


FIGURE 5.7

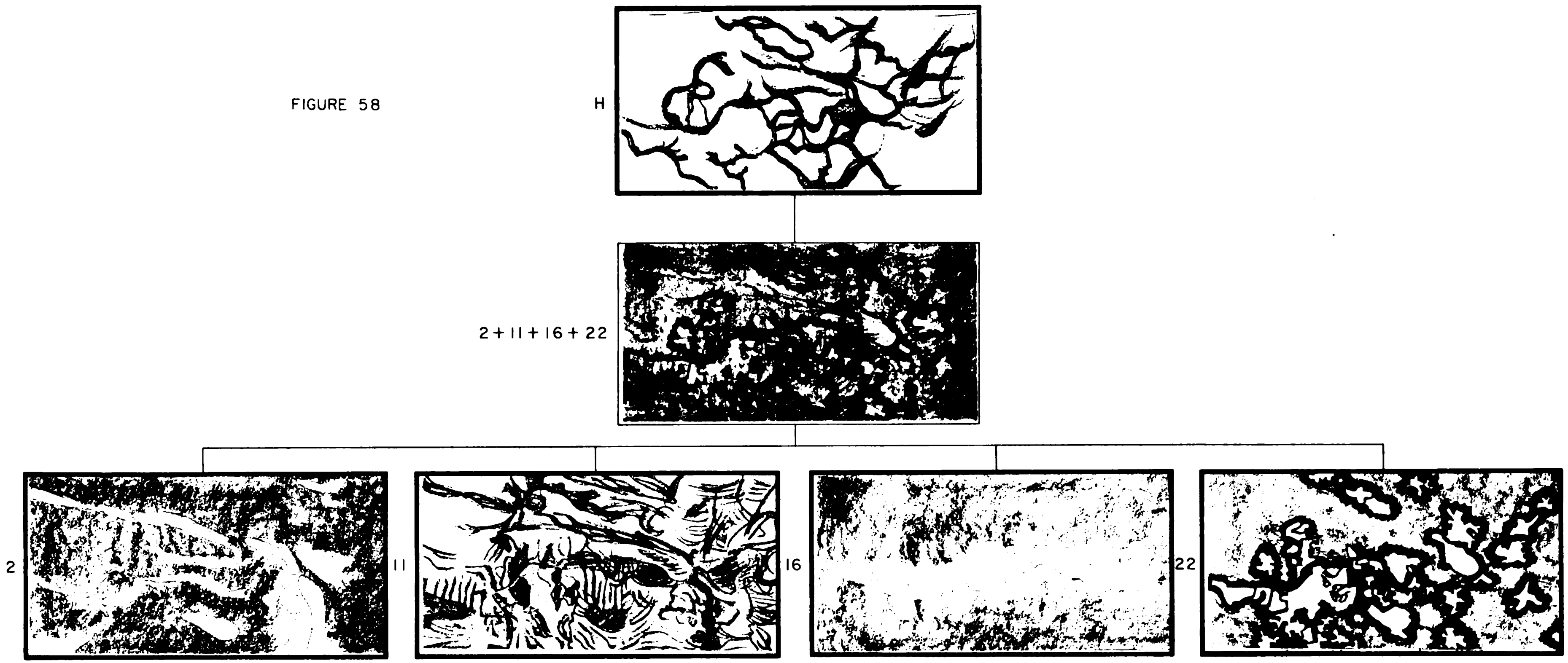
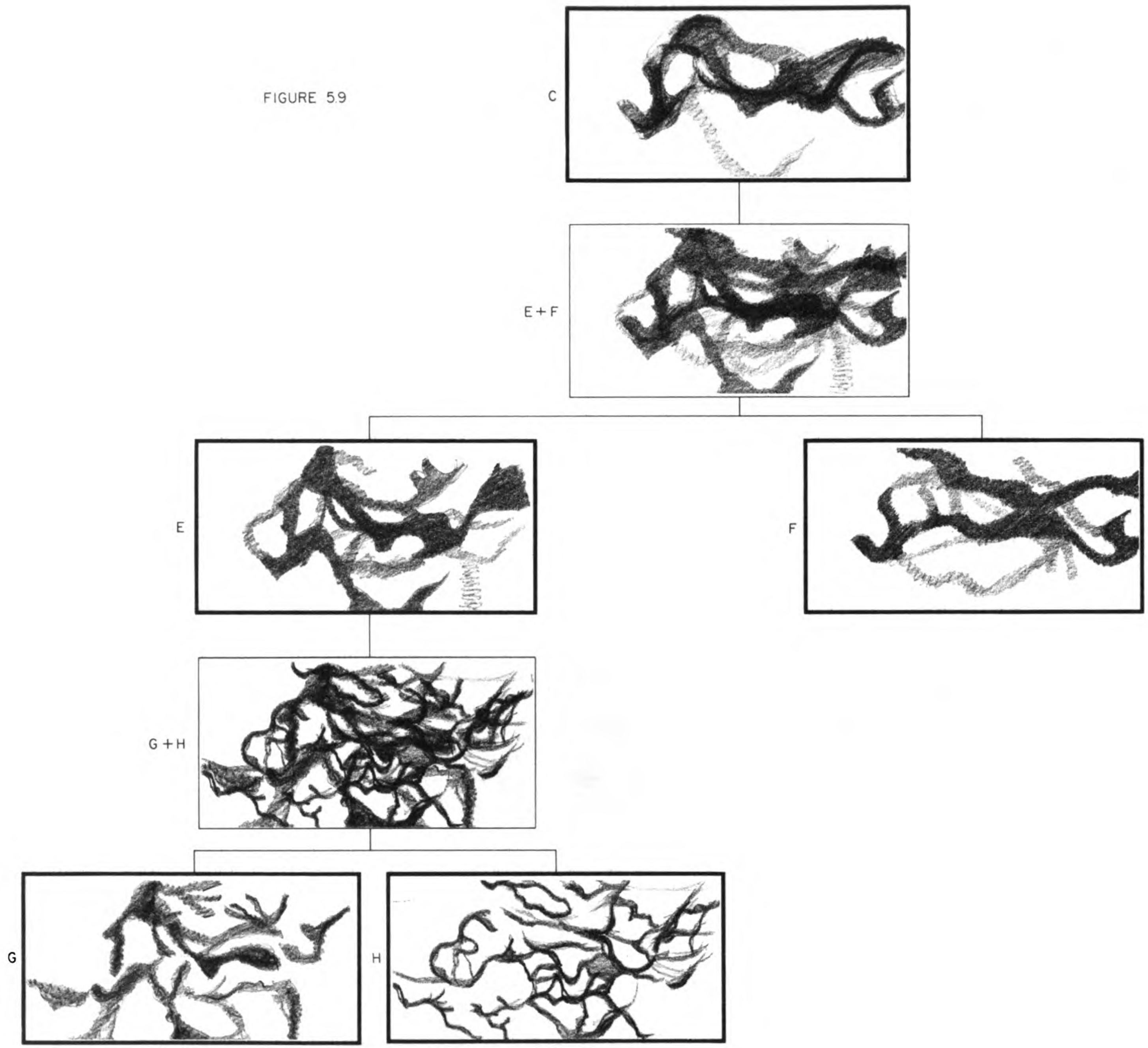


FIGURE 58

FIGURE 59



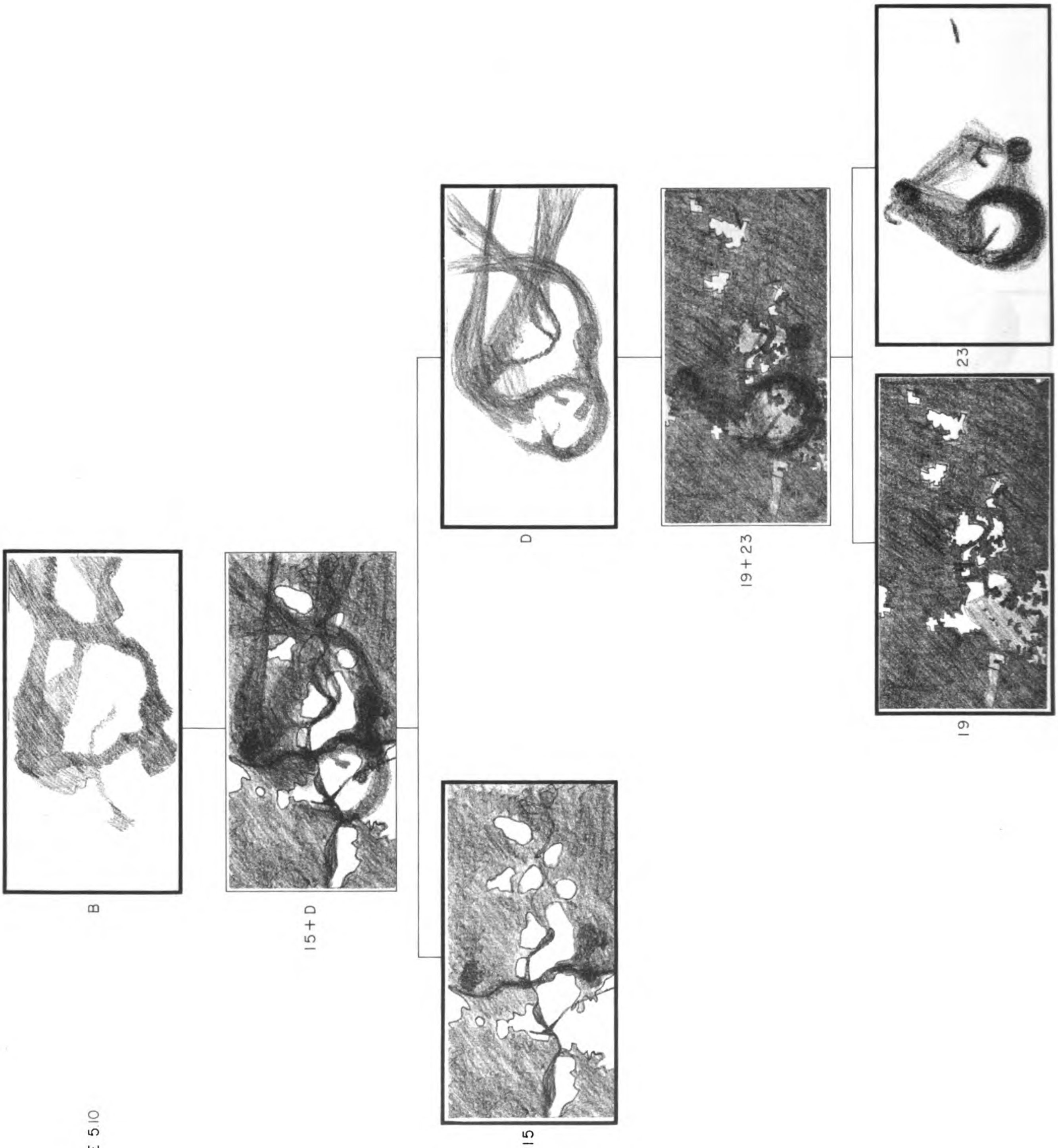


FIGURE 5.10

FIGURE 5.11

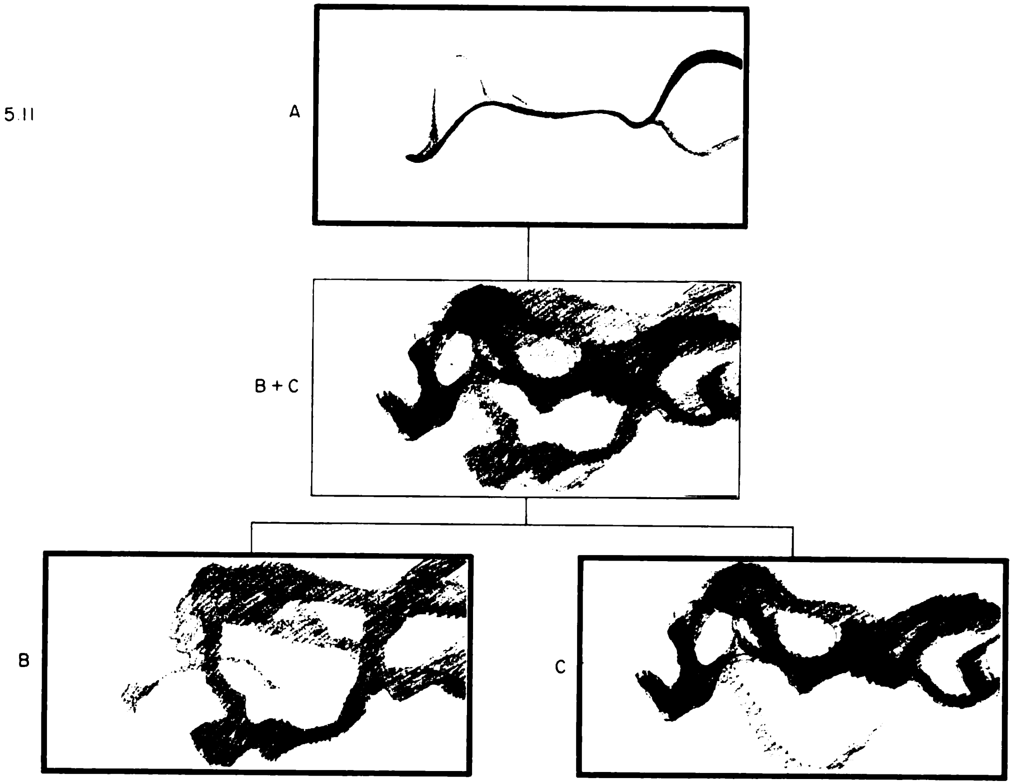


FIGURE 6

II. THE GENERAL PROBLEM

The location problem

The area shown in the map of Figure 1 contains a major river, the Connecticut. The City of Springfield lies on the east bank of this river, and the smaller city of Holyoke and the town of Northhampton lie along the west bank. Running north and east through this valley, and cut by the Connecticut, is the strongly-outcropping Mount Tom-Holyoke Range. The Westfield River runs east from the town of Westfield to join the Connecticut at Springfield - West Springfield. The land in this region includes flood plains along the river (especially near Northampton), low and high ridges, and moderately rolling upland.

For the purposes of this demonstration, the location of I-91 is considered determined to the extent known publicly in 1960-61, with two sections already built. The first of these sections runs north from Hartford, Connecticut, terminating on the southern boundary of Springfield at the bridge by which Route 5, the older image of I-91, is carried across the Connecticut to the west bank before turning north to Holyoke. The second section starts north from Greenfield, Mass., about 35 miles north of Springfield. The problem, then, is the locate I-91, from its present terminus at the Route 5 bridge, northward through the vicinity of Northampton, along an axis roughly including Greenfield. It is assumed that the highway should bypass Northampton (with access to that town), but also be on the west side of the Connecticut as it leaves this area.

Standard procedure

Some of the considerations which bear upon this problem are discussed in the following quotation:

> "The selection of (route) alignment and the extent to which it may be chosen to fit the ground economically, depends upon the geometric design standards adopted for the construction. These standards in turn depend upon the amount and type of transportation usage expected.../In this case since I-91 is part of the Interstate System, the geometric standards for design are fixed by law/...With the classification of service established and the appropriate standards of alignment fixed thereby, ordinarily the combination of tangents and horizontal curvature is sought that will best fit the surface of the ground. At the same time consideration must be given to factors other than the ground fit. In many cases, right-of-way requirements may force a compromise in the alignment, so as to avoid the following: costly or undesirable property severances; the necessity of taking high-priced property where lower prices may be obtainable on another location; the destruction or removal of buildings; the location of the right-of-way through, or too close to cemeteries, churches, and schools...While consideration of right-of-way problems may be the principal influence modifying the best choice of alignment, there are several other factors to be taken into account as well. The alignment of the road with reference to other roads, railroads, stream crossings or utilities may bear importantly upon the location...The requirements for drainage of the highway may have considerable influence upon its alignment...the fit-to-ground consideration prevails, but the best fit may be unattainable under the modifications made necessary by the influence of the other factors...
>
> "Most of the factors mentioned in the previous paragraph also influence the study of grade lines. Alignments and grade lines have mutual dependence

on each other, such that the best alignment does not necessarily permit economical grades to be selected nor vice versa.

"The purpose, of course, of preliminary surveys is to select the line and grade which satisfies the geometric design criteria at the least cost for the transportation benefit sought."*

This quotation says many things about the problem of locating a highway. It draws attention to the fact that the location must meet certain specified requirements. And it also draws attention to the fact that these requirements often conflict, and force compromises. Thus take the statement "consideration must be given to factors other than the ground fit... right of way requirements may force a compromise in the alignment." The need to achieve good ground fit, and the need to satisfy certain right of way conditions, are requirements; the fact that these two requirements call for a compromise indicates that they conflict.

The task of a design process is to offer ways of approaching a set of requirements so as to make it as easy as possible to resolve the conflicts among them. While the ASCE quotation does mention the existence of requirements and of conflicts among the requirements, it does not tell us how to pick a location which meets the requirements. In other words, this quotation does not suggest a design process.

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*William Litle and Brian V. Martin, AN ATTEMPT TO APPLY A SUGGESTED SET-THEORETIC DECISION METHOD TO THE DEFINIATION AND STRUCTURAL ANALYSIS OF A ROUTE LOCATION PROBLEM. Term paper for the course, 1.25-Transportation Route Location (Dept. of Civil Engineering, M.I.T.), May, 1961, unpublished. pp. 2-3. The source of this quotation is "Highway and Bridge Surveys: Preliminary Survey", PROGRESS REPORT OF THE COMMITTEE ON HIGHWAY AND BRIDGE SURVEYS OF THE SURVEYING AND MAPPING DIVISION, Journal of the Surveying and Mapping Division, American Society of Civil Engineers (July 1958).

Method of Analysis

It can be shown that if a design problem is taken to consist of two sets of elements, namely

(1) a set of requirements which the design must meet, and

(2) a set of conflicts which restrict the possible ways in which these requirements can be met simultaneously,

then these two sets can be made to determine a design process for a particular problem.* Such a design process is specified by grouping the requirements into subsets, and ordering the subsets hierarchically into a "tree." (Cf. figure 4) The implication of the tree structure is that the designer starts with the groups of requirements at the lowest levels of the tree, and then proceeds upwards, gradually considering each of the other groups at higher levels. We call this tree of requirements a "program," because it shows a designer the best order in which to tackle the requirements in a design problem.

This program is not always easy to understand. Although the individual requirements of a problem are often statements about familiar facts, the way in which these requirements become grouped in the tree does not, in general, have similarly clear intuitive meaning. Typically, it is hard to find a

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*Alexander, Christopher, NOTES ON THE SYNTHESIS OF FORM, Ph.D. Dissertation, Harvard University (unpublished).

standard label like "economics," "safety," "ground fit," and so forth to characterize the requirements in any given group. Because of this, the implications of each particular group of requirements are hard to grasp, and so it is not necessarily clear how the use of such a tree must lead to a good solution of the design task. This present paper is not concerned with the way in which such a tree is generated for a particular problem,*but with this question about the meaning and use of such grouped sets of requirements.

Diagrams

In order to use the tree effectively as a design program, we must describe each of the subsets of requirements in some clear, meaningful way. We call such a description a "diagram," because in practice, we actually do try to understand the significance of a group of requirements by considering its implications in diagram form. For instance, the first attempt to design a bridge (after the initial calculations have been made) is a rough sketch indicating the broad features of the bridge; the first attempts to locate a highway are pencil lines on a map of the terrain. These examples are such simple diagrams that they give us little sense of the way they might fit into the whole design process.

*Cf. Alexander, NOTES, and Alexander and Manheim, HIDECS 2: A COMPUTER PROGRAM FOR THE HIERARCHICAL DECOMPOSITION OF A SET WHICH HAS AN ASSOCIATED LINEAR GRAPH. Cambridge, Mass.: Civil Engineering Systems Laboratory, M.I.T. (1962).

This paper describes an experiment in the use of diagrams in design. We are concerned with such questions as: what kinds of diagrams are useful in describing groups of requirements? how are the diagrams at one level of the tree related to those at a higher level? The highway route location problem is a good example with which to begin a discussion of these issues, because the diagrams in this case can be expressed very simply, as lines and areas on a map.

III. THE REQUIREMENTS

Requirements and diagrams

In order to develop a tree for a particular design problem we must first identify the requirements which describe that problem. The list of 26 requirements presented in figure 2 contains all the factors we can think of, which are liable to influence the location of a highway. This list is the fourth or fifth we made. In each revision, we tried to make the new list more comprehensive and less redundant than the last.* The important feature of the list is that each requirement is on it only because it has physical implications for location.

---

*Thus, take for instance the requirement "Financial loss in the private sector, direct or indirect, should be as small as possible." This was included in the list until the very end. However, when we came to make diagrams, we found that the diagram for this requirement coincided almost exactly with the diagram for requirement 18, as it then was: "Non-monetary loss in the private sector." It was also confused with the other requirements, "Financial loss in the public sector", and "Non-monetary loss in the public sector." The fact that two diagrams coincide as they did in this case means that the two requirements have identical physical implications for the location, and hence that as far as the problem of finding a location is concerned, there is nothing to be gained by keeping them separate. We therefore fused these several requirements in the present requirement 18. In other words, we use the diagrams to obtain a set of requirements whose physical implications are reasonably independent of one another, so that we have a base set to work on.

Each of the 26 requirements is a criterion for evaluating any possible location that might be proposed. For instance, one location which is a straight north-south line might be good from the point of view of requirement number nine, travel time, but bad for earthworks cost, number one, because it cuts through a ridge. Another location might be undesirable for as many as 20 of the 26 requirements. What we wish to do is to construct some way of distinguishing locations which are bad from the point of view of any particular requirement, from those which are good in terms of that requirement.

Ideally, we should like to have a notation capable of expressing the utility, or desirability, of every possible location, from the point of view of each of the twenty-six requirements. However, there does not seem to be any workable method of assigning a utility to the locations directly: the number of possible paths is far too large to be listed and evaluated, and each point in the geographic area of interest lies on a very large number of paths, making the enumeration of all the paths very difficult.

Utility maps

To avoid these difficulties, we assign a utility to the points of the terrain, instead of to the paths. The particular terrain with which we are concerned in this route location problem is an area about 20 miles by 10 miles* : we construct

*Described in detail in a previous section.

a diagram, for each requirement, by assigning a utility to each point on a map of this terrain. Each diagram is a pattern of greys whose density varies over the complete range from white to black. This pattern is keyed to the base map of the terrain in such a way that a point marked black in the diagram for a particular requirement is a very good point for a highway location to pass through (from the point of view of that requirement). Any point marked white is very bad as far as that requirement is concerned. For example, the diagram for travel time (requirement nine) is a series of concentric ellipses, dark in the center, lighter toward the edge. This expresses the fact that as far as travel time is concerned, the more direct a location path can be, the better; while, conversely, the further that the location is from the Northampton-Springfield axis, the less desirable from the point of view of travel time.

Replacing paths by terrain points simplifies the problem of describing and evaluating alternatives, but raises its own sticky issues. For some requirements, like "land cost," there is a definite utility which can be associated with each point of the terrain. But, for many other requirements - "earthwork costs," for example, - the utility of any one point depends on the utility of other points in its neighborhood. In other words, the cost of putting the road through A is closely related to what is done at point B 100 feet away: a place on a mountain may itself be flat, and therefore very good from the point of view of earthwork costs; but if it is surrounded on all sides by precipices, then we know that it is going to cost a great deal more to get a highway there than the purely local utility suggests. Or, take a point by a river's edge. From the point of view of bridge building, this spot may be cheap if the highway runs parallel to the river, but very expensive if the highway runs at right angles to the river, necessitating an expensive bridge.

In principle, then, to get a utility map defined on a point basis, we examine the totality of all possible paths through a given point, bearing in mind that paths in some directions are more likely and more sensible than paths in other directions. For instance, take a narrow strip of land lying between a steep bluff and a river. It is very unlikely, because of the bluff, that a road would run at right angles to the river, but very likely that a road would run parallel to the river's edge. This means that the chances of having to put in a bridge are less in such a situation, than in a situation where the terrain is flat for a couple of miles from the river. We therefore give this point a better rating, on the bridge costs diagram, than we would give it if it lay in a flat terrain.*

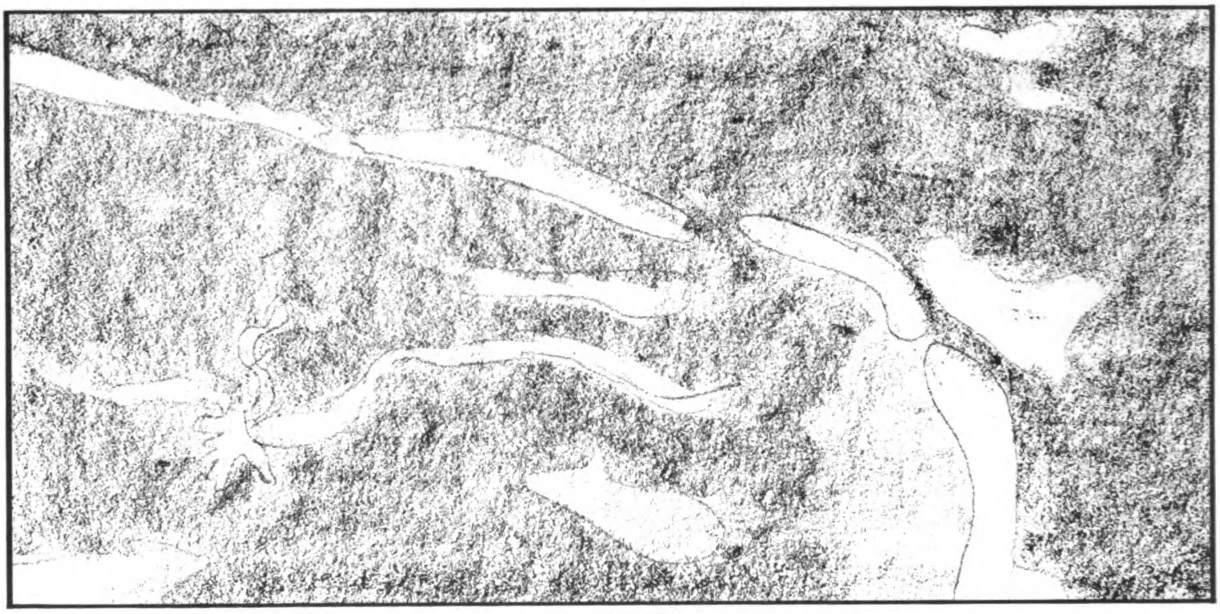
*This does not resolve the dilemma completely, for the moment that any particular path is under discussion, the weighted-average values assigned to each point along the path become incorrect. Thus a path along the river's edge ought to be much blacker than indicated by summing all the local utilities of all the included points, because the utilities of those points have been made lighter to account for the small probability of crossing the river perpendicular to the edge in this area. If the entire design process is repeated more than once (for the same problem), then these utility diagrams are revised at each iteration by taking into account the information about the most probable (desirable) location paths discovered in the previous design attempt.

The twenty-six requirements

1. EARTHWORK COSTS

High expenditures for earthwork arise from the amount and type of earth to be moved for cut and fill. Earthwork costs are low where the terrain is relatively smooth, and are high where the terrain is uneven, or the subsurface is rock.

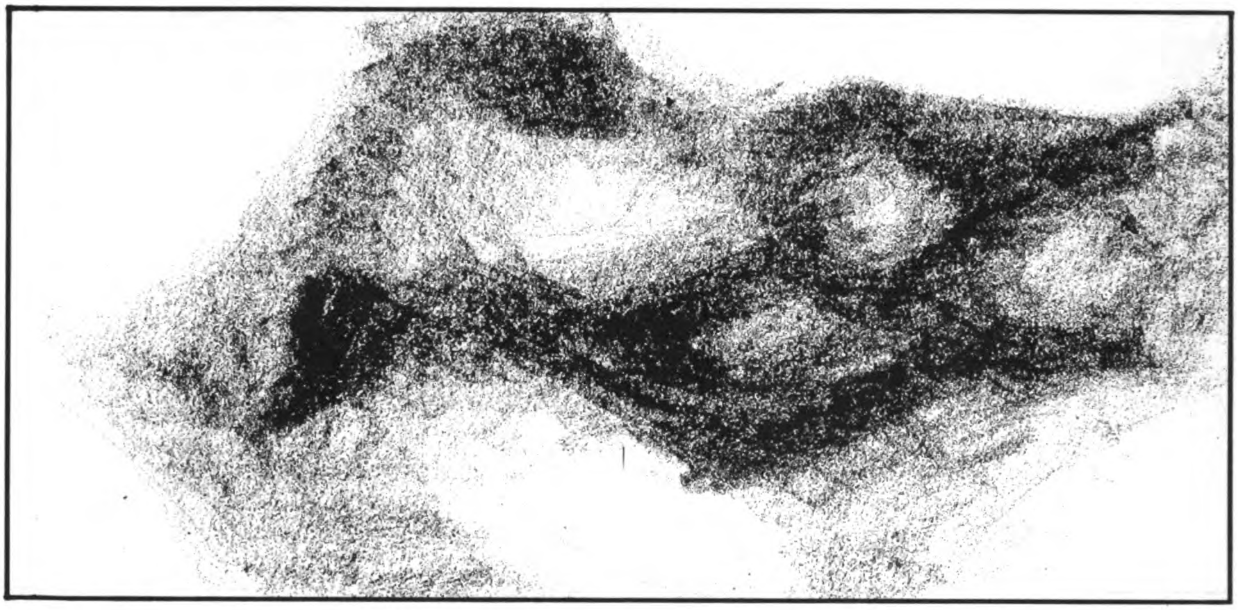
In the diagram, the low-lying land near the river, the level areas between ridges, and the level ridge tops are desirable, while sides of the ridges are not.



2. COMFORT AND SAFETY

From the point of view of this requirement, it is undesirable to have a road which twists and turns so abruptly that it is uncomfortable or unsafe; at the same time, a perfectly level, straight road, because of its monotony, is also uncomfortable and even unsafe. Therefore, both very hilly and very flat areas are undesirable. Gently rolling terrain, which requires smooth grades and curves, is desirable.

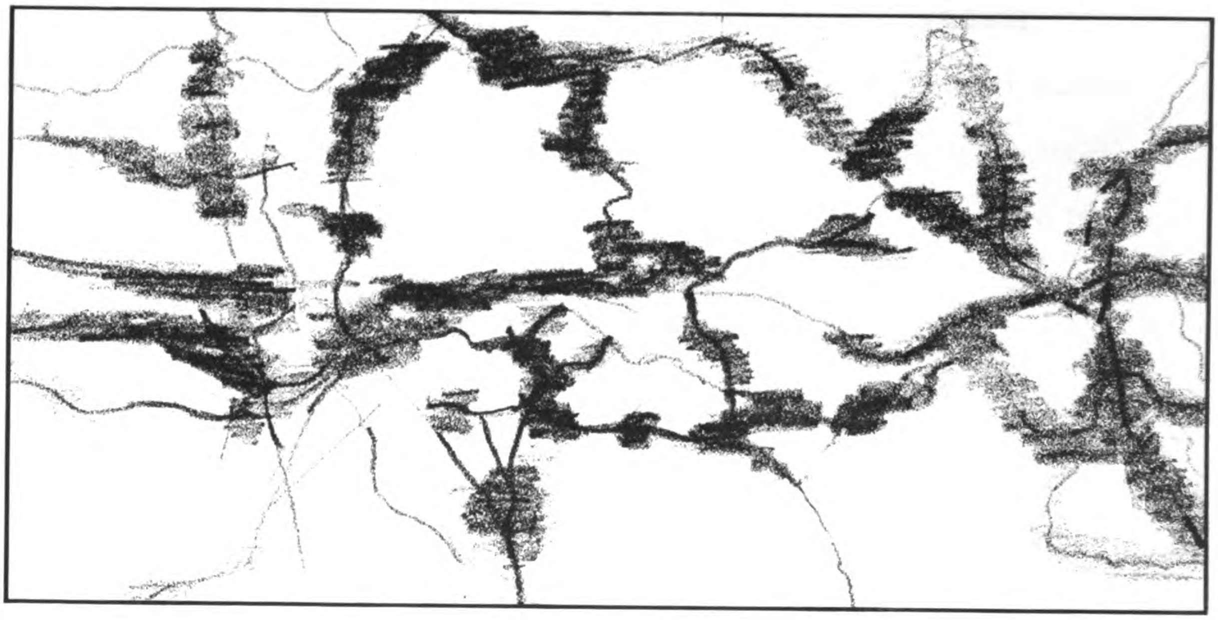
In drawing this diagram, it was very difficult to make decisions about desirable locations. Therefore, only two tones, of very similar densities, were used.



3. REGIONAL DEVELOPMENT

Ideally, the best locations from this point of view would be specified in some regional master plan. Since there is no master plan for this region, we assumed that regional development will work best if the highway goes near as many towns as possible, but stays on the outskirts of each one, so that these outskirts grow.

Also, public facilities, such as the Exposition Grounds and the Air Force base at Westover Field should be served by the highway. Other kinds of potential growth, such as at Westfield Airport, at industrial sites served by railroads, or at residential sites along the ridges, would be restricted by highway encroachments, so these are places to avoid. Also, the highway should not invade local agricultural land, and should not destroy railroad marshalling yards which might help the revitalization of railroad freight traffic.



4. LOCAL LAND DEVELOPMENT

Assuming that every intersection of the highway with a secondary road is going to stimulate a small area of commercial or industrial development, we want to be sure that the intersections go at places which can support such development: on secondary roads with capacity to accommodate stimulated traffic, at locations where services are needed and would be economical, and where land is available for new development or expansion of existing facilities.

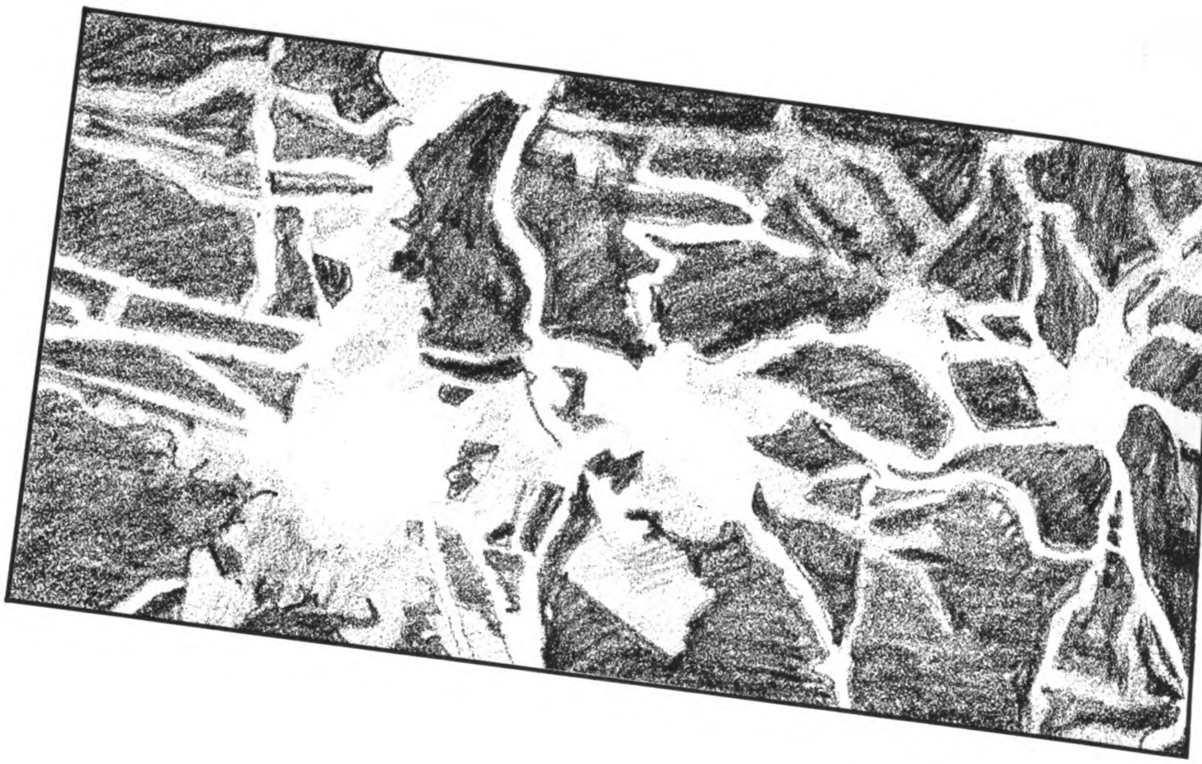
At first glance, the diagram suggests that the new road should follow the existing ones. However, we try to suggest, by the way the diagram is shaded, that it is desirable to serve possible sites by <u>crossing</u> these roads roughly at right angles.

5. OBSOLESCENCE

This requirement states that the location of the highway must be capable of adapting to future developments in transportation technology.

The possibility of electronic highways affects only pavements, not location. However, ground-effect machines need low grades, wide roadways, etc. There is also the possibility of rail or express bus rapid transit, which implies the preservation of wide median strips, and wide right-of-way.

As the diagram indicates, we interpreted this to recommend moderately flat terrain in undeveloped areas.

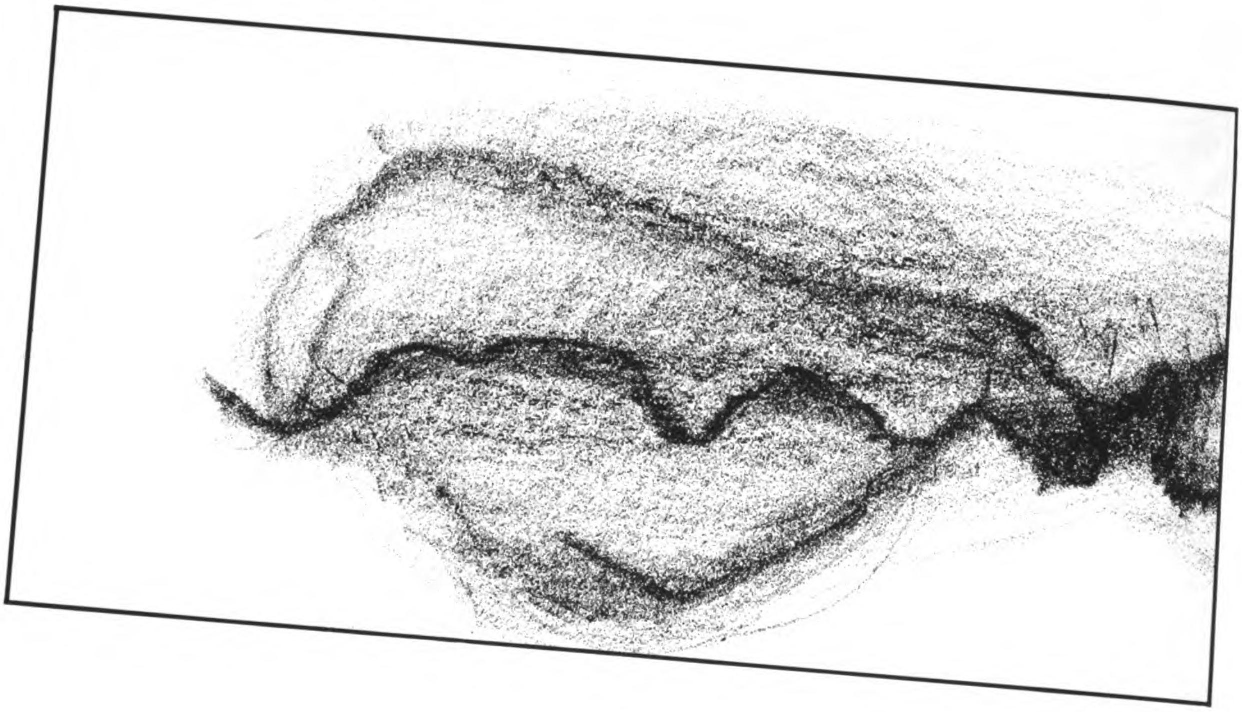


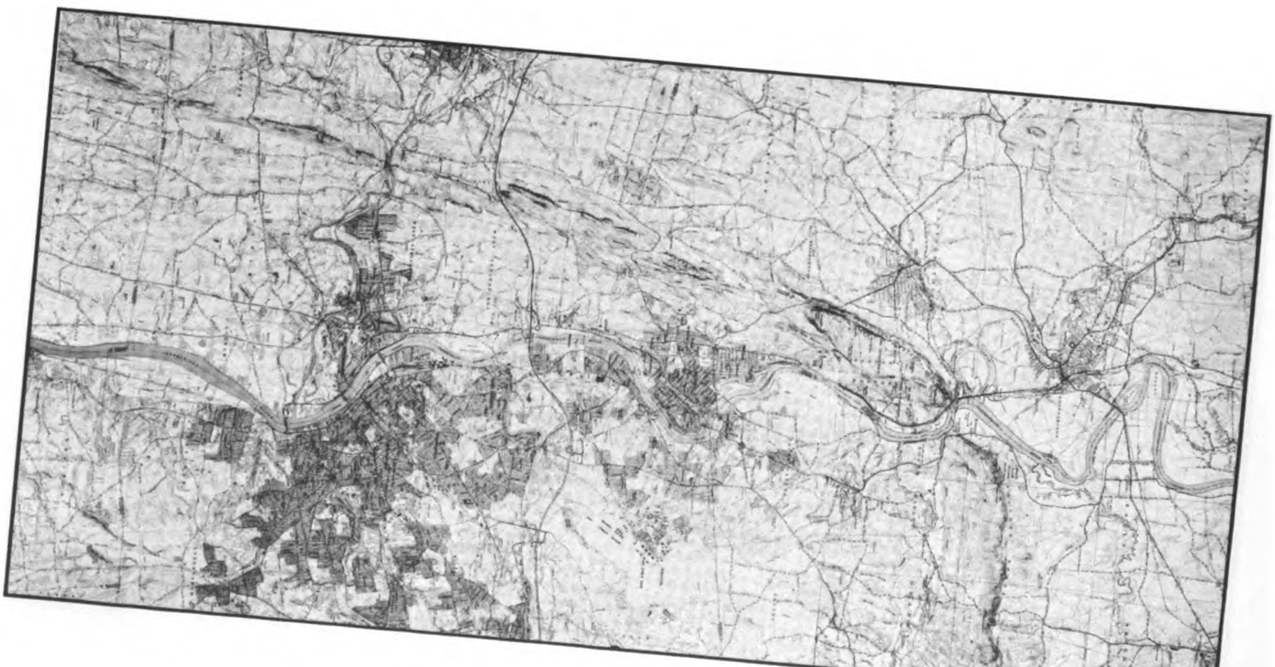
6. INTERFERENCE DURING CONSTRUCTION

This concerns the effect of construction of the highway on the other activities in its immediate environment: disruption of traffic over existing roads while bridges are built, disruption of utility services during relocation, creation of unpleasant conditions in residential or commercial neighborhoods, interference with airports or railroads at crossings, etc.

In the diagram, main roads, community centers, and railroads are to be avoided (white); secondary roads, commercial and densely populated built-up areas are light grey. Sparsely populated built-up areas are grey, and everything else is desirable.

This diagram, like (4), also urges perpendicular crossings of roads.

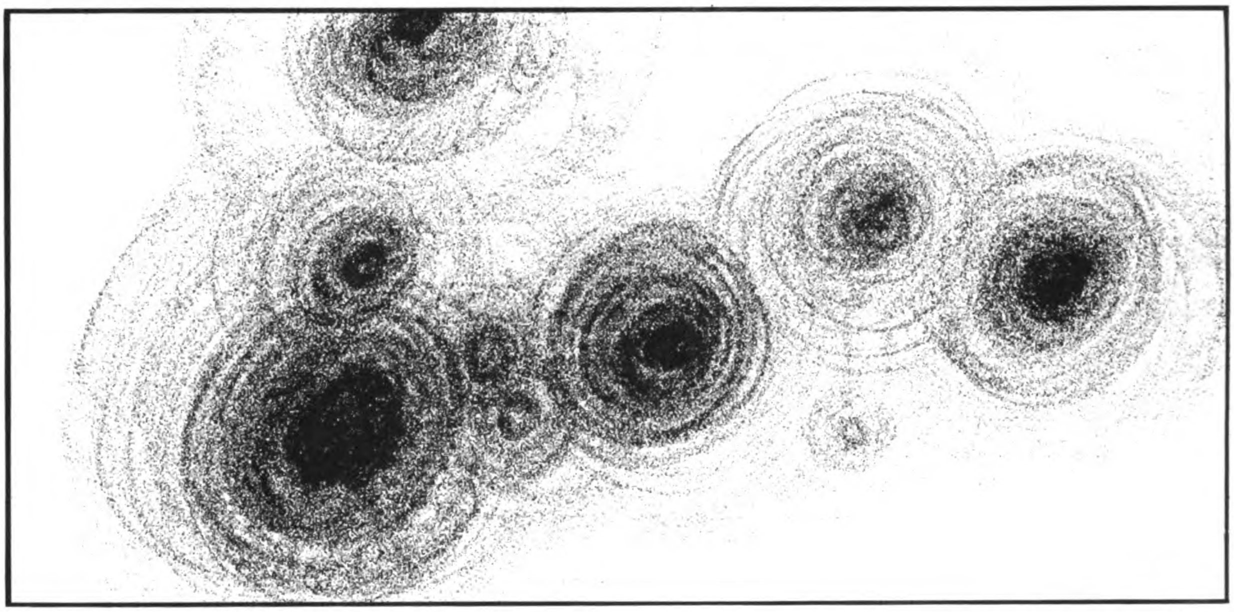




7. USER COSTS

User costs are the direct expenses of operating a motor vehicle. Smooth, straight roadways are desirable from this point of view, with as few grades as possible.

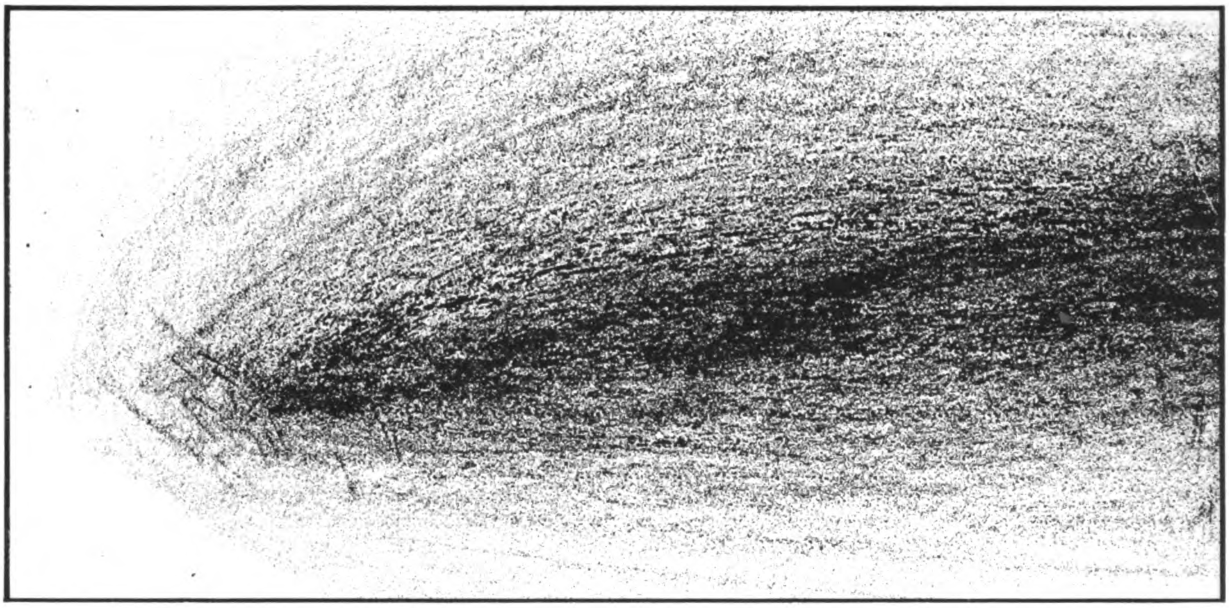
The emphasis in this diagram is upon the total route alignment, so we base it on the most likely alignment for different terrains: in moderately rolling country, where earthwork costs would be low (if the road followed the surface contours), user costs would be high; in very rough country, cut by ravines, say, while smoothing the surface might cause high earthwork costs, the road would be approximately level, with low user costs.



8. SERVICES

No part of the road should be too far from the source of major emergency services like fire engines, ambulances, police, tow trucks, etc. When breakdowns do occur, the driver should preferably not find himself on a dismal deserted stretch of road, out in the open country.

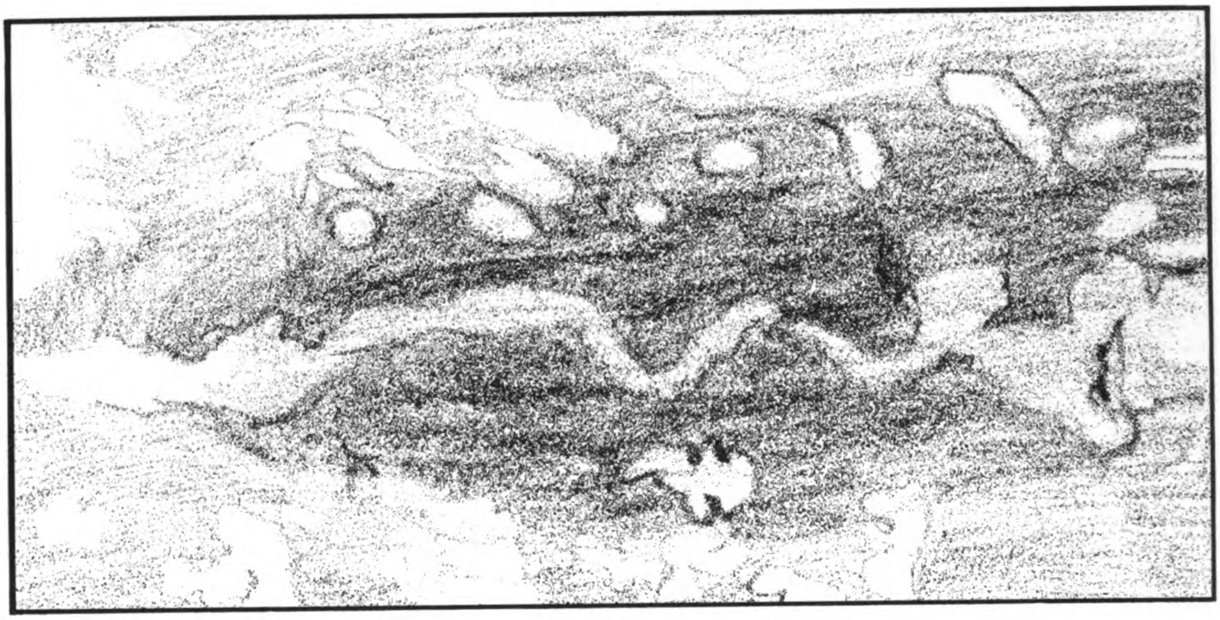
The diagram consists of concentric circles centered on the urban centers where the fire-stations, hospitals, and garages are located.



9. TRAVEL TIME

From the point of view of travel time, the road should be as short as possible.

This is expressed in the diagram by constructing concentric ellipses of decreasing density, whose foci are at the control points through which the road must pass (Springfield and Northampton). (An ellipse is the locus of a point such that the sum of its distances from two foci is constant.)



10. PAVEMENT AND SUBGRADE COSTS

Earthwork costs are concerned with volumes of earth to be moved (the mass-haul diagram); this requirement deals with the <u>kinds</u> of material and their effects upon the costs of preparing adequate subgrade and laying appropriate pavements. Subsoil type is the dominant element, but distance from possible borrow pits is also likely to cause expense.

In constructing the diagram, it was assumed that sources of aggregate were uniformly distributed over the area. Since we did not have complete subsoil information, the major element described by this diagram is the presence or absence of marsh-land. It is assumed that marsh areas were historically larger than at present; white and grey denote the (expanded) areas of present marshes, as well as river bottom lands.

11. DRAINAGE PATTERNS

This requirement is not concerned with the costs of bridging streams, but with the effects of disturbing the natural surface and subsurface flow of water. From this point of view, highway paths cutting across watercourses or bisecting low-lying regions should be avoided.

The diagram represents this symbolically by emphasizing the directions of satisfactory alignments, but not necessarily their locations.

12. BRIDGE COSTS

This requirement is concerned with the length and height of bridge structures. From this point of view, it is desirable to avoid crossing major roads, railroads, water, and ravines.

The diagram was constructed by estimating the bridging likely to be needed in each major section of the terrain.

13. LAND COSTS

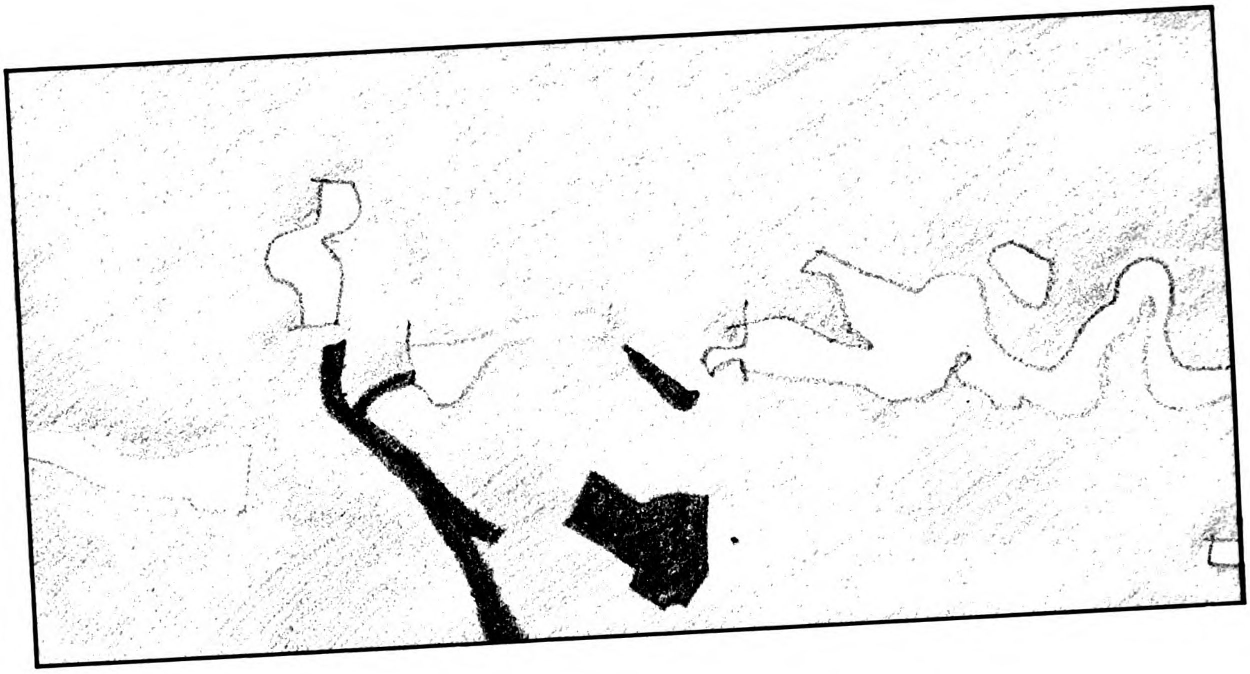
The concern of this requirement is with the direct costs of acquisition of land for the right-of-way of the highway.

To construct the diagram, the following cost classes were developed, readily identifiable on the Geological Survey base map:

(most expensive)

- high-density urban centers and industrial areas
- all other land indicated as built up
- residential and other properties where buildings are shown separately; includes recreation areas, high-value tobacco land, river frontage and accessible hilltop sites for residences
- land not built up, but cleared, as indicated by absence of woodland overlay
- unused land, indicated by woodland overlay

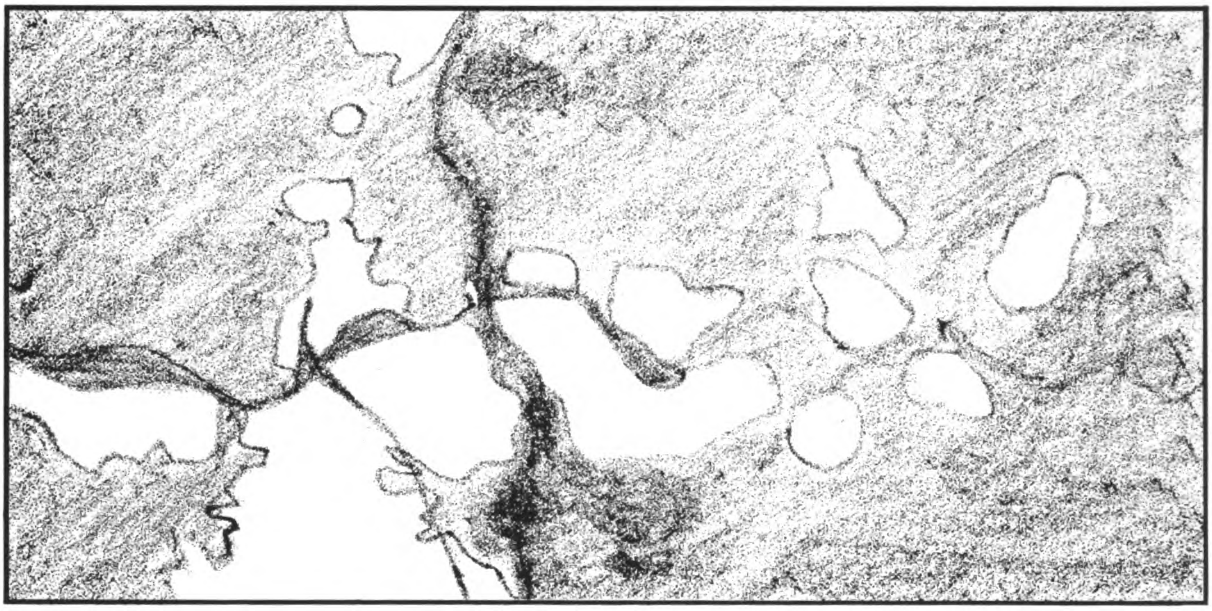
(least expensive)



14. EYESORES

This requirement expresses the desire that the highway should not be placed where it would destroy the character of a bit of pleasant country, or the beauty of the river front.

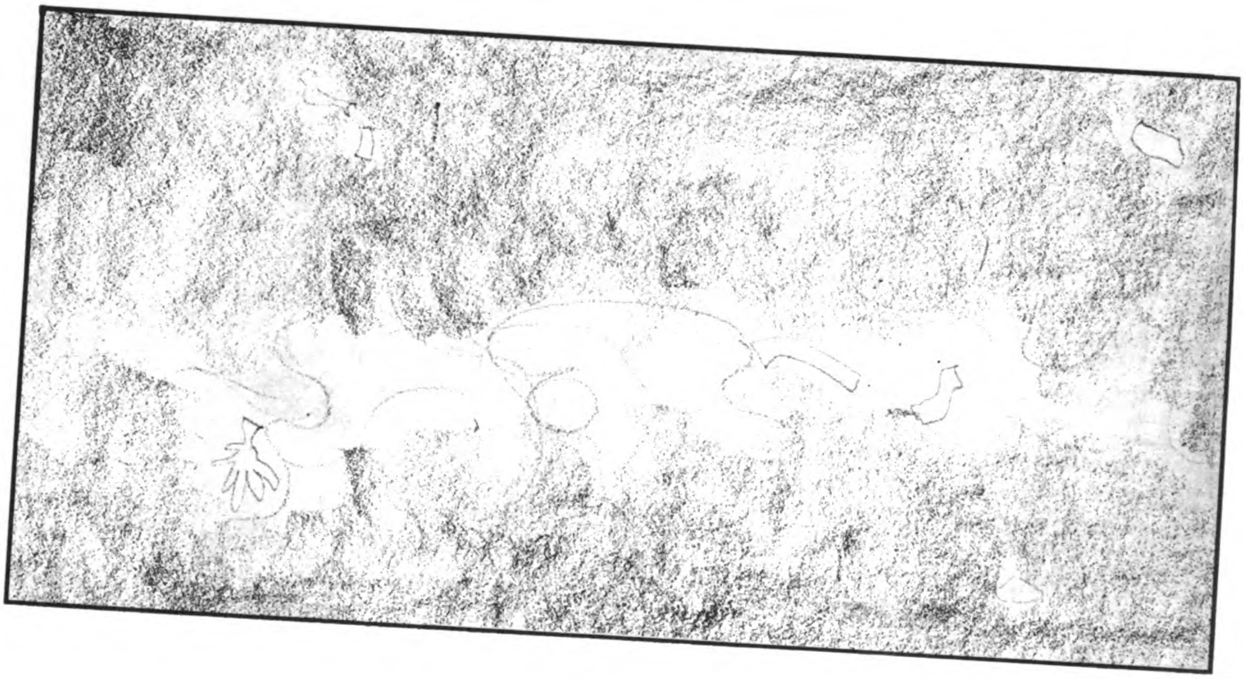
The actual construction of the diagram was difficult, so that only a few major areas are delineated. Definitely bad are the undeveloped stretches of the rivers; definitely permissible are the industrialized stretch along one river, and the built-up area of the air force base.



15. NOISE

Highways generate noise; no stretch of the highway should raise the noise level of its environment beyond that which is locally acceptable.

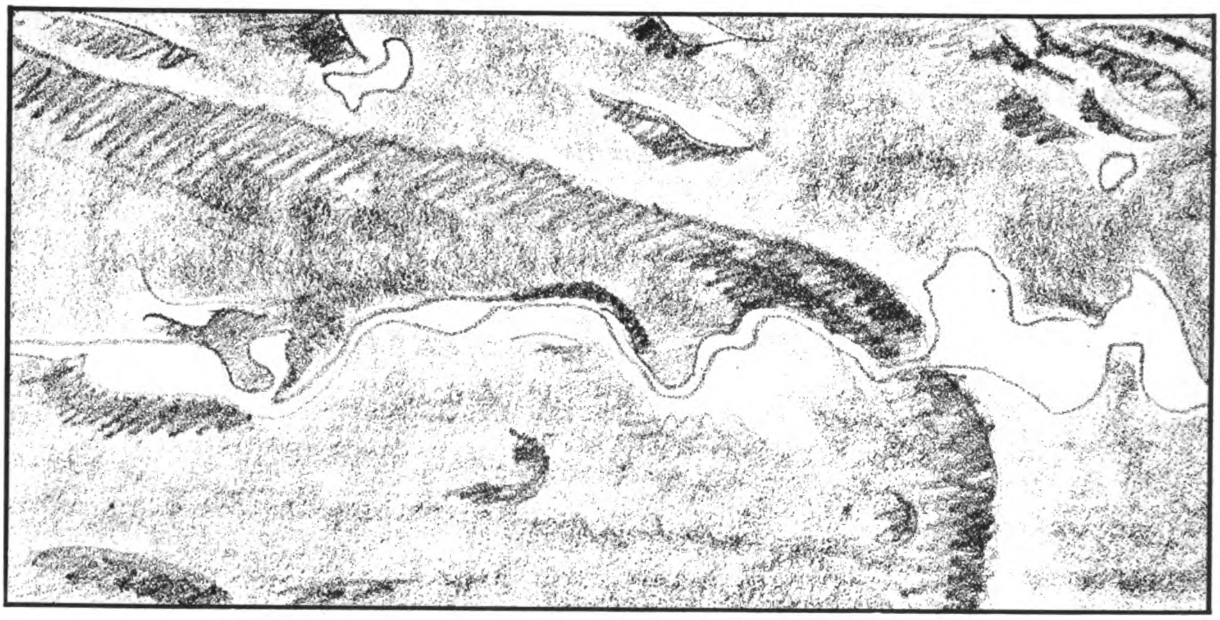
Acceptable locations are along major railroads, and through commercial and industrial districts. In the open country, the noise impact is moderate. Locations near residential areas, hospitals, scenic sites and recreation facilities are bad.



16. AIR POLLUTION

Vehicular traffic affects the purity of the air near a highway; dead air spots are particularly to be avoided.

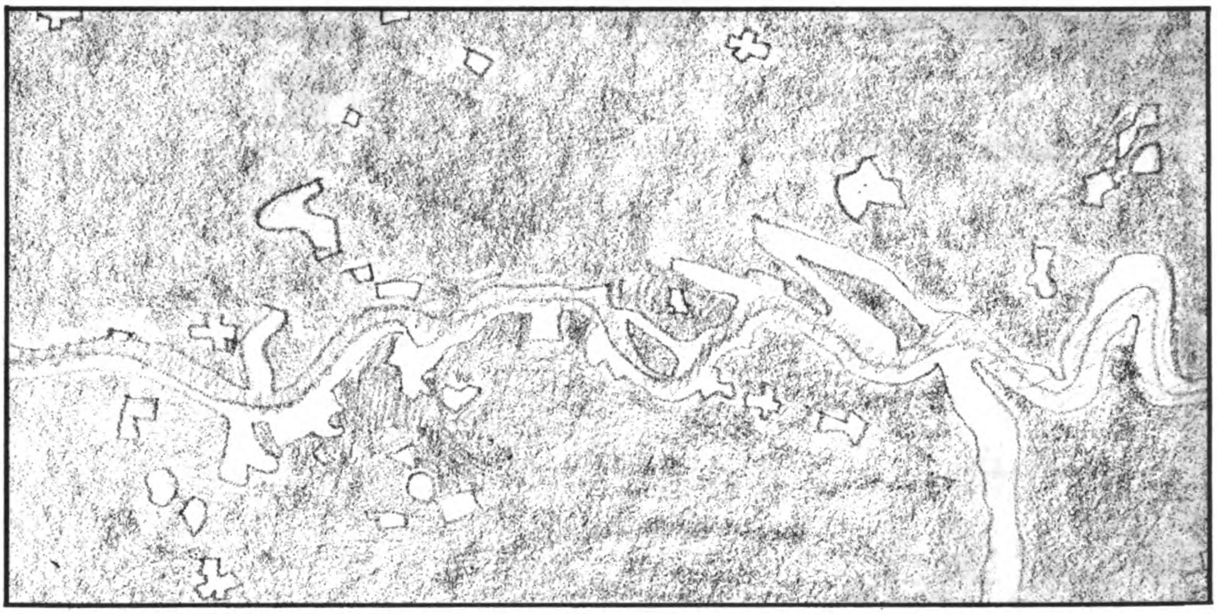
We know so little about microclimatology that this diagram is very hard to construct (hence its almost uniform greyness).



17. WEATHER EFFECTS

This requirements is concerned with the vulnerability of the highway to the effects of weather conditions: floods, snowdrifts on the windward sides of hills, ice on the pavement in the shadows of cuts and underpasses, fog in dips of the road into marshy hollows, unbroken crosswinds, smoke from local conditions, etc.

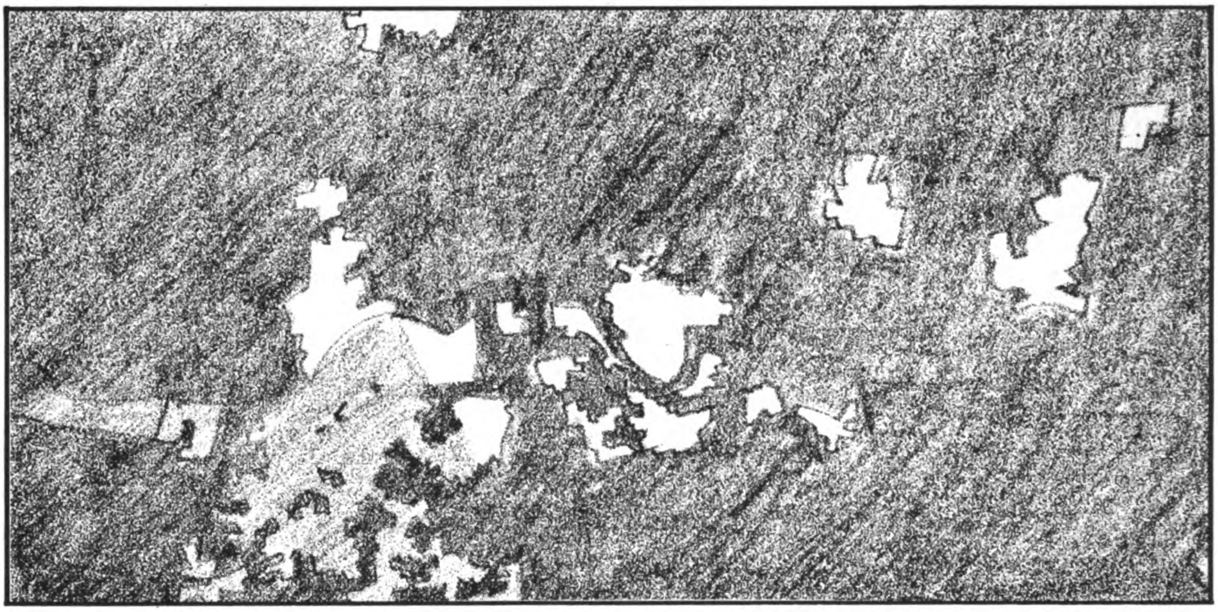
For the purpose of constructing this diagram, it was assumed that the prevailing direction of the wind is from the northwest, so that the sheltered southeast side of hills is the best place for the highway.



18. NON-RECOMPENSABLE PUBLIC AND PRIVATE LOSSES

This requirement is concerned with losses of land or facilities for which adequate financial compensation cannot possibly be provided. (Both public and private losses are considered.) For instance, the loss of landmarks, vistas, waterfront, access points to important sites, cemeteries, colleges, centers of small communities, parks, and destruction of socio-cultural communities and of low-rent housing in good condition.

The greyness of the diagram shows that the construction of this diagram requires detailed information which was not available.



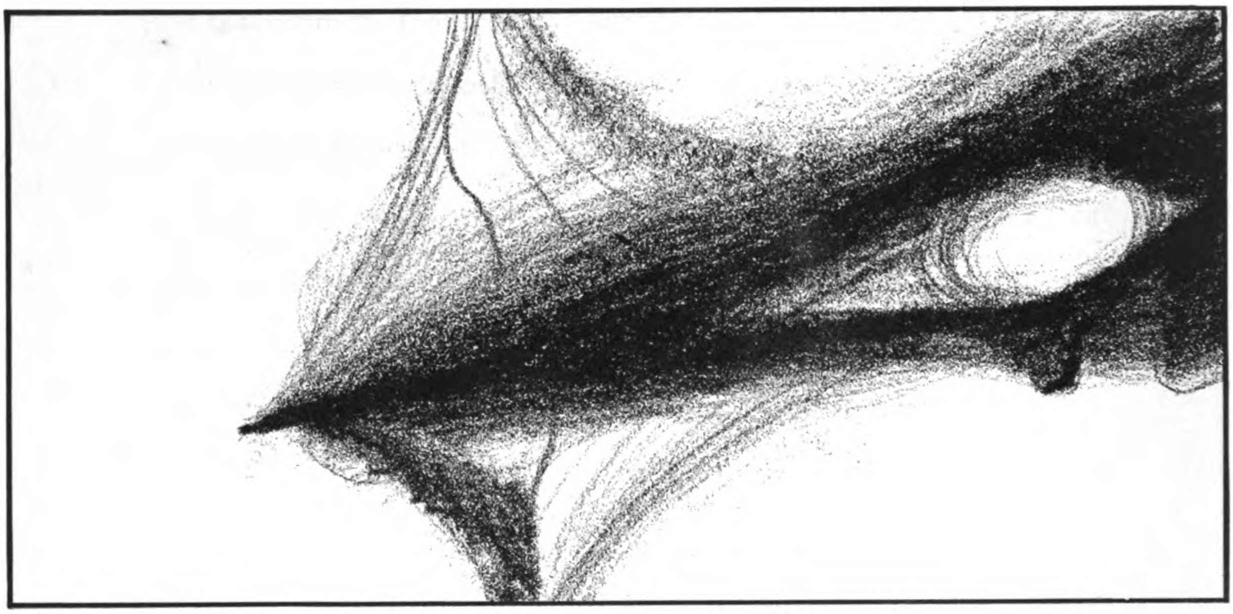
19. PUBLIC FINANCIAL LOSSES

This requirement is concerned with the loss of public revenues to all levels of government through direct and indirect taxes, resulting from removal of property and jobs. This is distinct from 13, since the acquisition cost of a site is not always related to the value of that site to the community.

To construct the diagram, property values were divided into three classes:

- industrial and commercial (city center)
- high-value residential
- other residential, including rural and agricultural

Values assigned to land in the larger towns were modified by the following analysis: total tax revenues are proportional to R^2, where R is the radius of the town. The length of any path through the town (and so the amount of taxable land eaten up by that path) is proportional to R. Therefore, the relative tax loss caused by a highway through a town is proportional to 1/R: hence, the larger the community, the less significant the tax loss is.



20. MAJOR CURRENT TRAFFIC DESIRES

The location should be oriented to satisfy major current unsatisfied travel desires. (This includes the relief of existing congestion, but not congestion caused by induced traffic, Cf. 26.)

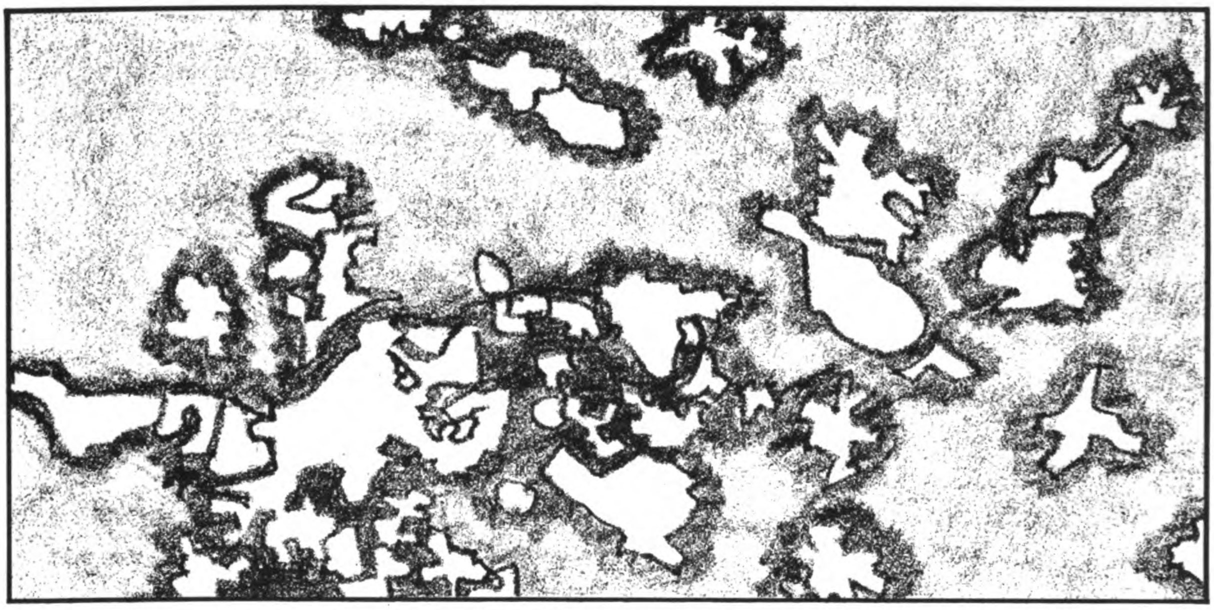
As the diagram indicates, the interstate route is to serve primarily a north-south function. However, a connection to the Massachusetts Turnpike north of Springfield would also serve to satisfy desires for travel between the south and the east.

21. CATCHMENT AREAS

There are many kinds of focal points for the activities in a region; for each of these focal points, there is identifiable a tributary area serviced by the activity. This is called a catchment area. The highway should not separate such foci from their catchment areas.

For instance, schools serve school districts, fire houses have fire districts, shopping centers have market areas, churches and other community facilities have their tributary areas.

In constructing the diagram, it was assumed that each community was serviced by that built-up area which seemed to be the center of the community. This assumption leads immediately to the dictum that the best alignment for a road is along the boundaries between towns given on the map by town-lines.

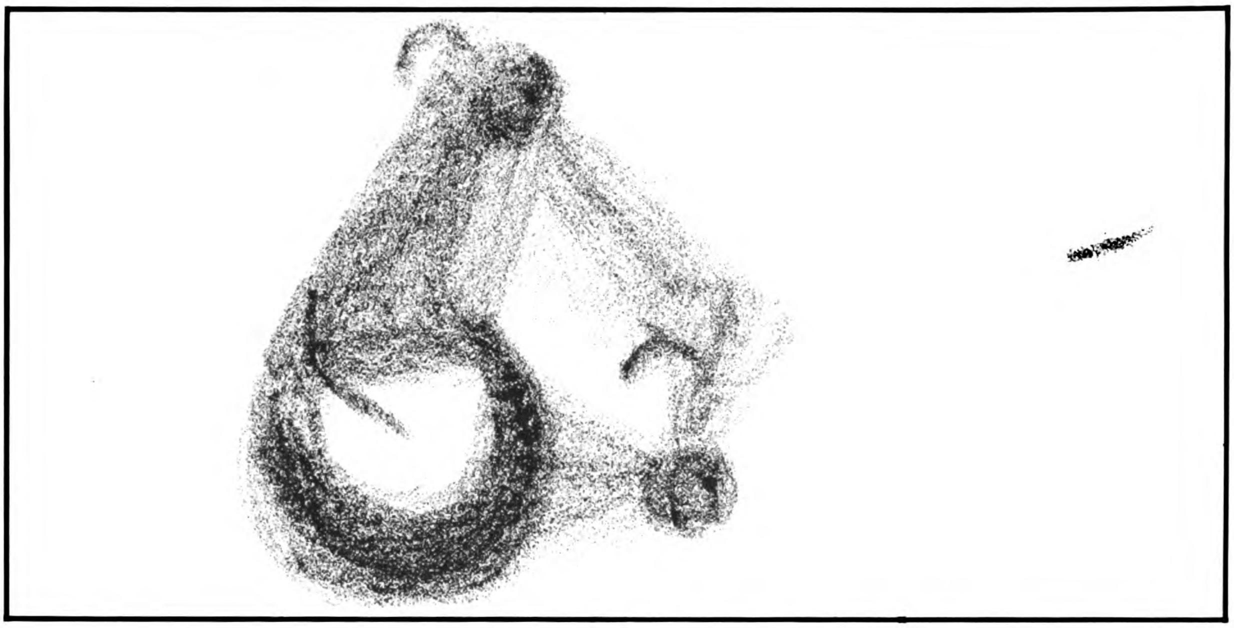


22. LOCAL ACCESSIBILITY AND INTEGRITY

This requirement is concerned with maintaining the integrity of small communities. Since a highway always acts as a physical barrier, we must be careful to ensure that no highway should cut off part of a tight cluster of development from the rest of that cluster.

On the other hand, a highway at the edge of a developed area can be an instrument of effective action to contain development, prevent sprawl, and maintain the unity of existing communities.

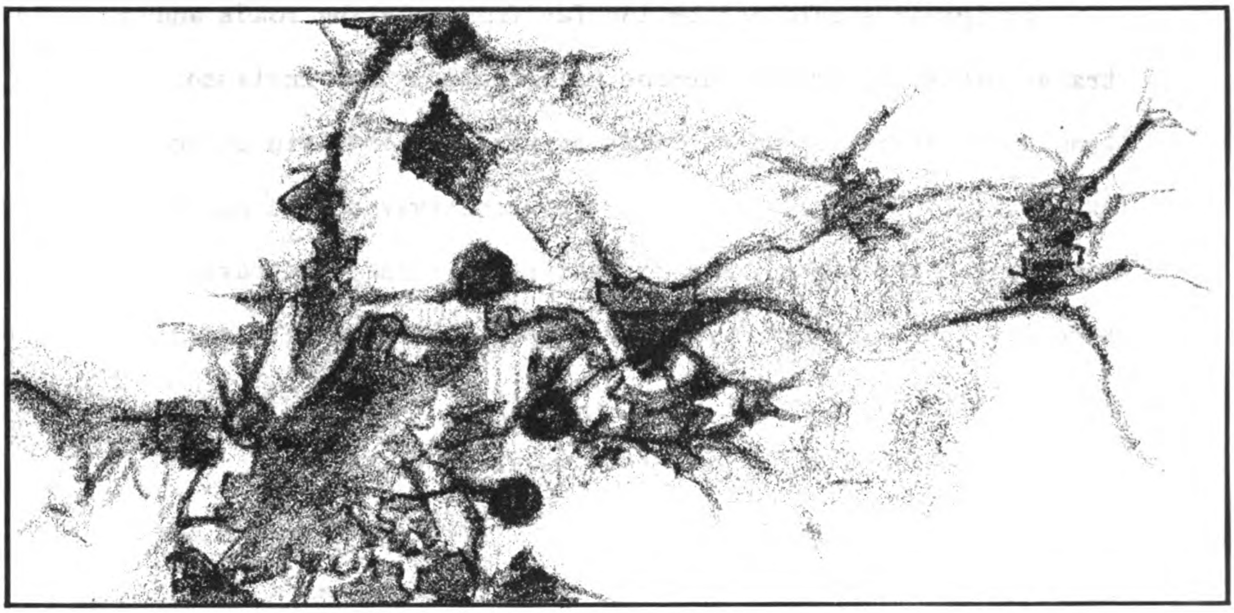
As the diagram shows, the best locations from the point of view of this requirement are those just at the borders of existing development clusters; the land between clusters, though not quite so ideal, is also better (and hence shown darker) than the clusters themselves.



23. FUTURE TRANSPORTATION SYSTEMS

The location of the highway should fit, as far as possible, into announced plans for planned future transportation facilities in the area. It also should be flexible with regard to locations for unannounced but possible future facilities, especially those using new technologies. (This requirement expresses the integration of the highway with other facilities; 5, OBSOLESCENCE, is concerned with the adaptability of the highway location itself to changes in equipment, control, etc.)

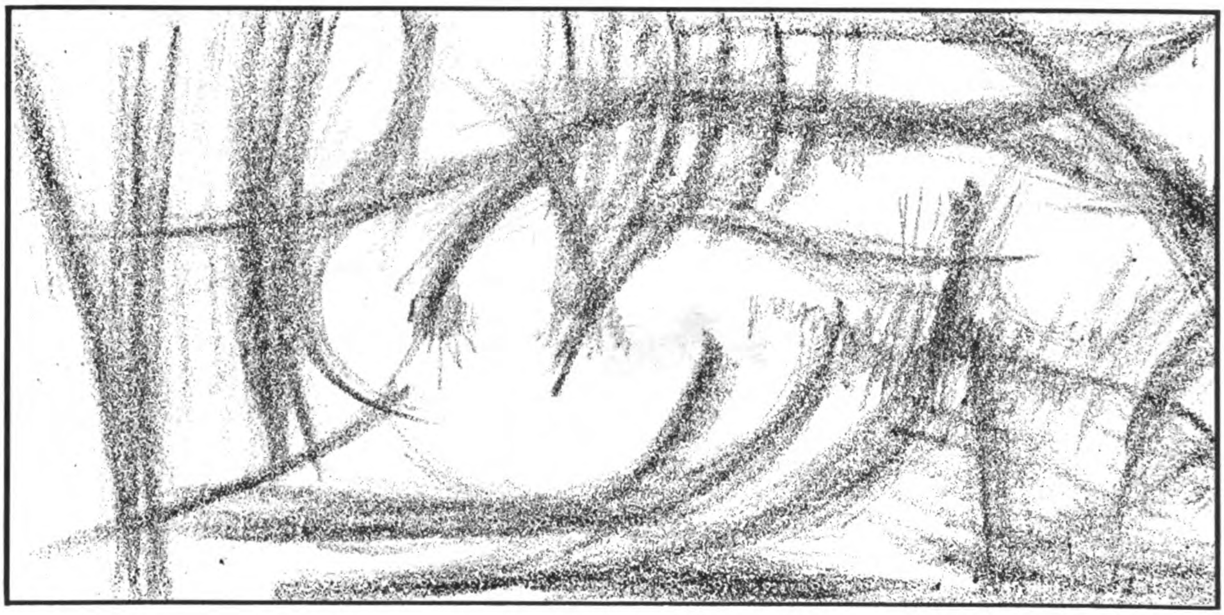
It is very possible that a belt-road may be built around Springfield. The highway should be able to connect with this road, and even serve its function until it is actually built. It should also connect with possible locations for transfer of passengers between the highway and rail, air (Westover Field and Westfield Airport), monorail operating over the existing railroad right-of-way, or for transfer of freight between truck and rail. It should also connect with possible new interchanges with the Turnpike or with improved local roads.



24. EXISTING TRANSPORTATION SYSTEMS

A highway should not be too far from existing roads and travel patterns, or its purpose is defeated. For instance, long trips along secondary roads to make a short trip on an expressway are unsatisfactory: the expressway should carry the larger part of the trip so that it improves the travel time for a significant number of trips which reach it over other roads.

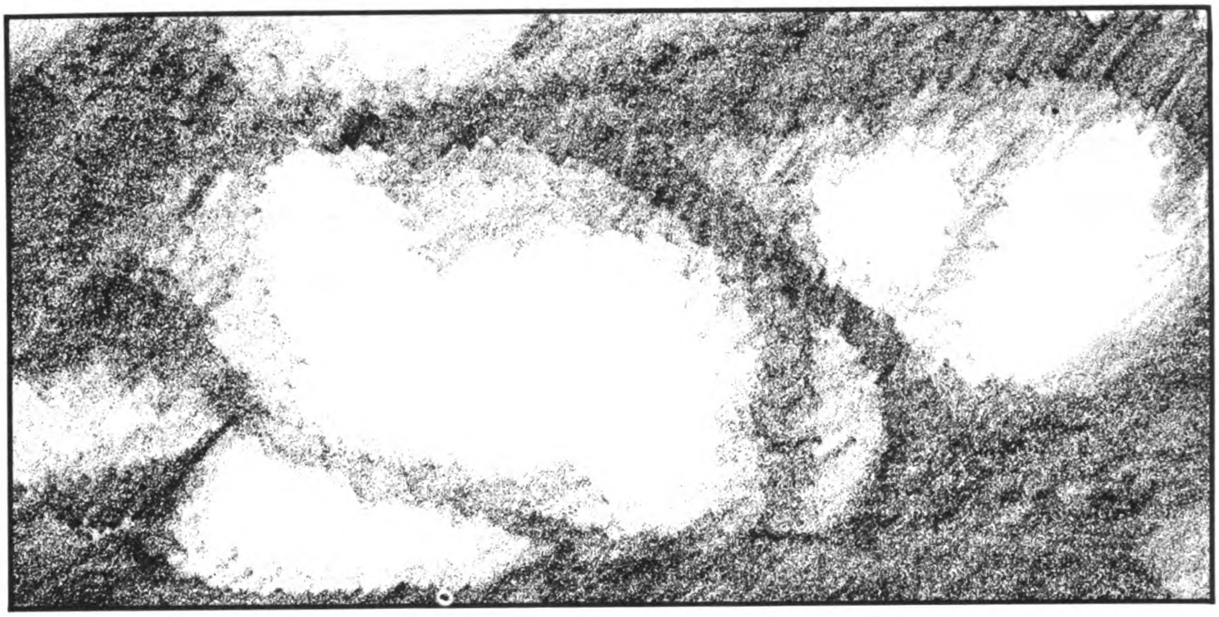
This requirement expresses the desire to have trip ends close, in terms of access over secondary roads, to the highway. Therefore, areas with high density of trip ends and points of connection to important secondary roads are shown as black in the diagram.



25. DUPLICATION OF FACILITIES

Duplication of any part of the existing road system is desirable only if that part is already overloaded. The new highway should fit into the existing transportation system, but preferably in a role not yet fulfilled by any other road.

The diagram indicates symbolically the places and directions where there is, as yet, no facility.



26. SELF-INDUCED CONGESTION

The highway is designed primarily to serve interstate travel. However, it will also attract existing local trips, as well as inducing new local and interstate trips. The generation of new interstate trips cannot be avoided, and should not be; however, in terms of maintaining the ability of the road to serve interstate travel, the highway must not draw existing local trips to itself, or generate new ones.

As the diagram indicates, this can be satisfied by locating the highway at some distance from large areas of existing development (where there is a high density of local trip ends).

IV. AMALGAMATION OF REQUIREMENTS: ISSUES

We now have a diagram, or utility map, for each requirement. Our next objective is to combine the information contained in these diagrams in some manner that will lead us to resolution of the design problem: the selection of a highway path which satisfies all 26 requirements to the greatest extent possible.

Properties of a combination process

There are two kinds of things which a process for combining these diagrams must achieve:

1. At present there are twenty-six distinct utility diagrams; the process must tell us how to combine these diagrams in such a way that we get a single utility diagram.
2. The utility diagrams, in their present form, give us information about the comparative utilities of points in the terrain. Given this information, the combining process must define a way of picking a best path.

The process which suggests itself most naturally is the following:

a. first, superimpose the twenty-six diagrams;

b. then, pick the best path from the resulting composite utility map.

Such a process has in fact been suggested by Roberts.*

Roberts suggests that we get the utility of each point in the composite diagram by adding together the individual

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*Paul O. Roberts, "Using new methods in highway location," PHOTOGRAMMETRIC ENGINEERING (June, 1957), pp. 563-569.

utilities of that point from each separate diagram. He suggests that we then pick a path through the resulting single utility "surface" which runs along the highest "ridge" of that surface (in our notation, a dark line). (Cf. Figure 2, in the paper by Roberts.) To do this, Roberts proposes a common cardinal unit of utility for all his requirements -- the dollar. Because he uses this common unit of utility, he is first of all able to add utilities; and secondly able to evaluate paths by integrating the composite utility along the path.

This process seems simple. However, it fails to account for a most important aspect of the route location problem -- namely, the fact that a highway is an organised entity, and must be treated as such during its design. It also relies on an unacceptable assumption about the comparability of different utility functions.

<u>Configurational properties of a highway</u>

The first objection can be summarized simply: the utility of a path is never just the sum of the utilities of the points along its length, but depends also upon the configuration of these points. A highway, no matter how simple it is, is an organized unit which must have certain properties, because it is a path. For example:

1. A highway is linearly continuous, in that there are neither vertical nor horizontal gaps in it.
2. It is a strip, in that, although its width may fluctuate over a small range, its linear dimension is many times its width: it is a path, not an area.

3. A highway is essentially a <u>single</u> path (as opposed to a system of paths). Even though it may consist of separate roadways, in the large it is one entity, with one path.
4. Since it is a way of getting from one place to another, the highway ought not to roam too much backwards and forwards across the countryside.
5. A highway has a consistent direction, a broad general course, and its twists and turns must be minor relative to this direction.
6. A highway has some kind of "second-order" continuity: neither horizontal nor vertical changes of direction must occur too often along its length.
7. Those changes that do occur must not be too sharp; the rate of change of direction - transition between tangent and curve, between opposite curves, between upgrade and downgrade - must be relatively small.

These properties of the highway as an organised entity are, in a sense, also requirements which the design of a route location must meet. But there is an important distinction between these properties and those we explicitly included in our list of twenty-six requirements. Simply: if the physical entity we design does not have these configurational properties, we can no longer call it a highway, for they are essential to our concept of a highway. The twenty-six requirements, on the other hand, are only ways in which a highway can be more or less desirable - even if a highway is located badly with respect to these requirements, it still has the basic properties which make it a highway.

These configuration properties must therefore enter into the analysis and choice of a location. Any process which picks paths from a utility map must take them into account. In principle, Roberts could use these properties as criteria for picking a path from the composite utility map. However, the properties are complex; and at present, not well enough worked out to use as a practical basis for selection.

Comparability of utility scales

We turn now to our second objection to Roberts' procedure: the assumption that the utilities associated with various requirements are comparable. The problem of comparing different utility scales is a recurrent one in civil engineering. In highway decisions, it is most dramatic in cases where lives saved are balanced against monies expended for safer facilities.*

Suppose, for example, that an engineer has to choose between two alternative route locations, A and B. A will save two more lives per annum than B, but costs $10,000 more than B. An engineer might reason as follows: "In practice, I actually do have to decide between these two alternatives. Inevitably, therefore, I must balance the disadvantages of one alternative against those of the other in making my decision. Whatever decision I make contains an implicit

*See, for example: Highway Research Board, ECONOMIC COST OF TRAFFIC ACCIDENTS. Bulletin 263, Washington, D.C.: Highway Research Board (September 1960).

statement about the relative utilities of lives and dollars. If I decide that A is better than B, then this decision means that two lives/year are worth more than $10,000. If A and B seem equally good, then this means that $10,000 is worth exactly the same as two lives/year."

This argument, as it stands, is wrong. To be right, it requires that the two utility scales, dollars (D) and lives (L), be comparable, for it is only then that we can make the step from $(D_A + L_A) = (D_B + L_B)$, to $(D_A - D_B) = (L_A - L_B)$, and can conclude that saving 2 lives/year is worth $10,000. In order to add and subtract utilities, functions like $(D_A - D_B)$ and $(D_A + L_A)$ must be defined and meaningful. Since D_A, L_A are not necessarily susceptible to the operations of addition and subtraction, this is not necessarily so.*

There is a second objection to the comparability assumption. Suppose location A is likely to cause hold-ups at rush hour, while location B, which causes less hold-ups, is more expensive for the maintenance department to maintain. Even if we assume that each road user has a clear idea of how much toll he is prepared to pay for location B, to avoid hold-ups, we still cannot be sure that it is fair to equate his dollars with the dollars of his neighbor, or with the dollars of the maintenance department, because we still don't know how much a dollar is worth to him. In order to regard even the dollar values of A and B, from the point of view of maintenance and

*Of course, such arithmetic operations require that the several utilities be cardinal functions. This cardinality assumption can itself be questioned, if for no other reason than the practical difficulty of assigning cardinal utilities instead of ordinal.

hold-up, as comparable (so that functions like $(M_A - H_A)$* become well defined), we still have to make the assumption that the dollar is an acceptable unit for interpersonal comparison. This is known to be false in many cases. The problem of interpersonal comparisons of utility remains an almost insoluble problem in utility theory.**

There is a third, and even stronger objection to the comparability assumption. We all admit that any attempt to equate dollars and lives is invidious. What makes it invidious is not the need to reach decisions through compromise among the conflicting desires represented by different utilities, but the assumption that there is a single fixed mechanical equation relating the utilities of lives and dollars which, once discovered by some experimental introspections, would perpetually permit us to go from dollars to lives and back again in any and all situations. In fact, as we well know, their relative value changes with the situation: sometimes we are prepared to sacrifice a great deal for a life; at other times, if we are starving, and our pockets are completely empty, perhaps dollars seem worth more than stranger's lives. Utility theory as developed to data has not been able to propose a systematic way of incorporating the specific and unique details of an individual situation explicitly into the manipulation of utilities. For this reason, any assumption

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*Where M_A is the maintenance utility of A and H_A is the hold-up utility.

**Luce, R. Duncan, and Howard Raiffa, GAMES AND DECISIONS. New York: John Wiley and Sons, Inc. (1957), pp. 33-34.

of comparability, especially the strong assumption that the dollar is a reasonable common scale, is seriously wrong.

We shall demonstrate a way of combining utility scales which avoids these assumptions. By concentrating on the configurational, or pattern, properties of the highway as a path, we base the amalgamation of utilities on the specific details of individual choice situations.

V. THE DETERMINATION OF CONFLICTS AND THE TREE

In chapter two, we said that, by identifying requirements and conflicts among requirements in a design problem, we can obtain a program for design. This program is a hierarchical, or tree-like, arrangement of the requirements.

In chapter three, we described the set of requirements which are important in highway location, and we also described the diagrams as constructed to represent each requirement.

In chapter four, we discussed the difficulties of combining diagrams. In this chapter (V), we describe briefly how to determine the conflicts between requirements, and how to get a tree from them. Finally, in chapter six, we shall explain how the tree must be used as a basis for combination. We suggest that throughout the discussion of combination and recombination of diagrams in these last two chapters, the reader refer repeatedly to figures 4 and 5.

It is well-known that complex problems can be solved better if they are attacked piece-meal. First of all, therefore, we divide the set of requirements into a number of smaller sets, as in Figure 4. The general reasons for this are described in the references cited in Chapter I. In the case of the location problem, there are two specific reasons for doing this directly related to the objections raised in the last chapter:

1. Even if we had a precise statement of the pattern properties a highway needs, it would still not always be possible to use it to pick a highway path from point-defined utility diagrams. For example, given a single composite utility map consisting of uniform east-west striations, it would be impossible to select a non-arbitrary north-south path -- the transverse striations have no north-sourth pattern in them which can be the basis for the kind of orderly path a highway must have. Or, given a composite diagram which is uniformly greay all over, there is no way of picking out a non-arbitrary best path, because the grey is homogeneous.

   What we need is a design process in which we can prevent such unworkable composite diagrams from occurring. We do this by dividing up the set of requirements in a particular way, as illustrated by the tree of Figure 4. The use of the tree then allows the pattern properties of the location to develop gradually.

2. As far as the resolution of utility conflicts is concerned, we shall be forced to use judgment in order to avoid the traps of the comparability assumption. Since judgment cannot be applied to many utility scales at once, the use of judgment calls for a design process in which only a few requirements are considered at a time. This again leads naturally to a tree-like program.*

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*We suspect that even a formal procedure, if there were one, would best be served by a tree-like structure.

Of course, just breaking up the set of requirements into small groups and arranging them randomly in a tree will not be satisfactory; the kind of tree which we can expect to be useful as a design process must have certain properties. For instance, at some point in the process we might be called upon to combine two diagrams, one consisting of horizontal striations, and the other consisting of vertical striations. Since the composite is a uniform grid, it would be hard to extract any kind of simple path from it. We know that many diagrams will conflict in this fashion (though probably not so severely), so that this kind of trouble will occur quite often as the designer works his way up the tree. However, note this important fact: as the design process proceeds, the diagrams become less and less flexible. That is, when the designer is working at the lower levels of the tree, it is easier to combine two conflicting diagrams than when he is near the top of the tree. This is illustrated in Figure 5, where we see that the diagrams higher in the tree are more specific and less diffuse than those lower. It is thus natural to try to get a tree in which conflicts are encountered as early as possible.

Determining the conflicts

To get this kind of a tree, we use the theory cited in Chapter II, which requires that we identify, not only the requirements in a particular problem, but also the conflicts between pairs of requirements.* The kind of diagrams we use in the route location problem give "conflict" an obvious meaning: two requirements are in conflict, if one diagram is the negative of the other. That is, a "total" conflict would exist if one diagram has black everywhere that the other has white, and vice versa. (For instance, 6 and 24 or 8 and 26.) Or, in the case of diagrams which are symbolic rather than literal - (for instance, 25 and 11) - the diagrams would be in total conflict if everywhere that one implied a north-south location, the other implied an east-west one (recall the striation example above).

These kinds of very extreme conflicts rarely occur.** Usually, the decision that two requirements conflict requires judgment. What we do is take each possible pair of requirements, and compare the two corresponding diagrams. Thinking carefully about what each diagram says about where the best location is from its own point of view, we decide whether their respective implications are in conflict, or whether it is relatively easy to find a location satisfying both requirements at once.

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*The work reported here was done at a stage when conflicts seemed to be the only important interactions between requirements. However, the theory, as now developed, is based on the use of all interactions--both conflicts and concurrences. Cf. Alexander, NOTES, and Alexander and Manheim, THE DESIGN OF HIGHWAY INTERCHANGES.

**In fact, as we shall see in chapter 6, this whole procedure is based on the fact that requirements are almost never wholly contradictory, so that their diagrams contain at least a few points of agreement.

In practice, we also use information not explicitly carried by the diagram, but implicit in its verbal definition. Thus, at first sight the diagrams for "user costs" (7) and "weather effects" (17), seem to conflict. When we think about it, though, we realize that "user costs" calls for gently sloping terrain, and that "weather effects" calls for the south-west side of hills; these two are independent. Even though they may conflict by chance in various places, there is no intrinsic reason for conflict between them.

The conflicts between requirements in the route location problem are enumerated in the next section.

The conflicts

REQUIREMENT	-IS LINKED TO REQUIREMENTS
1	3,4,6,8,9,10,11,12,13,14,17,18,19,20,25,26
2	6,10,11,12,13,14,15,16,17,19,21,22
3	1,5,6,10,12,14,15,16,17,18,25,26
4	1,5,6,9,12,14,21,25,26
5	3,4,8,9,10,13,17,18,20,21,23,24
6	1,2,3,4,7,8,9,11,17,20,22,23,24
7	6,8,10,12,14,16,18,25,26
8	1,5,6,7,12,13,15,16,18,21,25,26
9	1,4,5,6,12,13,14,15,16,17,18,21,22,23,24,25,26
10	1,2,3,5,7,12,13,16,19,21,22,23,25,26
11	1,2,6,16,21,22,23,25
12	1,2,3,4,7,8,9,10,20,22,23,24
13	1,2,5,8,9,10,14,18,20,24
14	1,2,3,4,7,9,13,19,21,22
15	2,3,8,9,20,23,24
16	2,3,7,8,9,10,11,20,22,24
17	1,2,3,5,6,9,22,24
18	1,3,5,7,8,9,13,19,21
19	1,2,10,14,18,20,23,24
20	1,5,6,12,13,15,16,19,25,26
21	2,4,5,8,9,10,11,14,18,24
22	2,6,9,10,11,12,14,16,17,24
23	5,6,9,10,11,12,15,19,26
24	5,6,9,12,13,15,16,17,19,21,22,25,26
25	1,3,4,7,8,9,10,11,20,24
26	1,3,4,7,8,9,10,20,23,24

Obtaining the tree

The list of requirements and the list of conflicts together describe the structure of the route location problem. This structure can be represented by a linear graph (a topological one-complex), which consists of a set of vertices (or points) and a set of links, each link connecting a specific pair of vertices. Each vertex stands for a requirement. There is a link between two vertices wherever the two corresponding requirements conflict.

The tree is the result of a hierarchical decomposition of the set of vertices. A criterion derived from information-theoretic considerations is used to partition the set of vertices into two subsets connected by as few links as possible. Each of these subsets is itself partitioned into two further subsets. This process is repeated, until the original set of vertices has been decomposed completely into its constituent elements.*

The tree shown in figure 4 is a hierarchical arrangement of these successive partitions: the original full set of vertices is at the top, the two subsets of the first partition form the second level, the level below this contains the two pairs of subsets into which these first two were themselves

*For details of the criterion, and of the process of decomposition, see Alexander, NOTES, Appendix 2. The decomposition is actually performed by a computer program. Cf. Alexander and Manheim, HIDECS 2: A COMPUTER PROGRAM.

partitioned, etc.*

Because the criterion leads to partitions whose subsets are always as independent as possible, the tree works well as a design program. Each set of requirements at any level of the tree contains requirements which conflict more with one another than with the requirements in other sets at the same level. The tree therefore makes the search for suitable configurations and the resolution of utility conflicts easier, by making the design process piecemeal and sequential, and by providing an order which is especially well suited to the resolution of conflicts.

*Note that this tree applies only to the problem of locating Route I-91 in the Springfield-Northampton area. For a road in some other area, the diagrams would be different. Some pair-wise comparisons of diagrams would yield the same "conflict" or "no conflict" decision as for the I-91 problem; others would not. The set of conflicts would therefore be slightly different, resulting in a differenttree.

VI. AMALGAMATION OF REQUIREMENTS: THE DESIGN PROCEDURE

Use of the tree

Now, how do we actually use this tree? The order of combination presented by the tree is not enough to guarantee solution. Even when we combine the 26 diagrams in the order which the tree prescribes, we shall still always get the same result if we do no more than add them; we shall still not overcome the objections to straightforward combinations, raised in chapter four.

Let us be specific about what we must achieve at each level of the tree, when we combine diagrams.

1. The combination must stress the pattern properties required by a highway, so that configurations which do have these properties begin to emerge in the new diagram.
2. The diagrams must not be combined according to any rule which depends on assumptions about their relative weights (i.e. they must not even be assumed to have equal weight).

We can only achieve these two objectives if, at each new level of the tree, we stop and review our progress. Essentially, each set of requirements in the tree constitutes a subproblem, and it is the opportunity for regarding it as such which makes the use of the tree important. We are given a set of diagrams - say, those for requirements 1, 3, 10, 25, as in figure 5.1. We combine these four diagrams by superimposing them photographically.* This produces the diagram shown in the second level of figure 5.1 (marked by a thin surround; also shown as an ellipse in figure 4). Now we redraw this composite diagram, bringing out its principal pattern characteristics as strongly as we can, and get a new composite diagram, shown on the top level of figure 5.1. (In practice we do this redrawing by making a transparency of the original composite photograph, projecting it onto the drawing board, and going over the projected image in such a way as to bring out and strengthen its pattern.)

In this process, what we are really doing is trying to work out what each of the separate sets of requirements has to say about the problem; in other words, what implications it has for the overall pattern of the location. The new diagram is a map of the combined implications of 1,3,10,25, just as the old diagrams were maps of the implications of single requirements.

Let us see now precisely why this process does (1) introduce the required pattern properties, and (2) avoid the comparability assumption.

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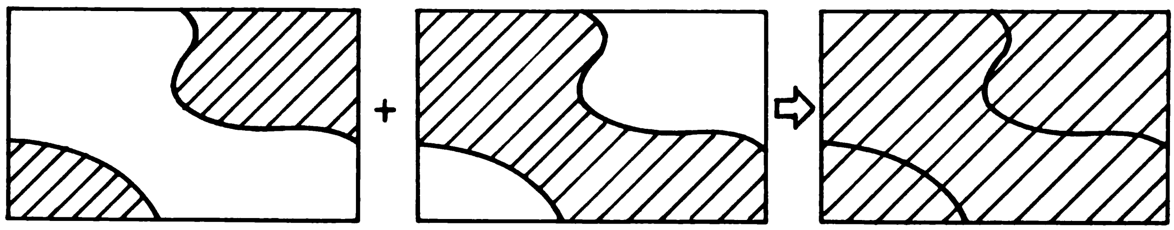
*This superposition was done as follows: we made a photographic negative of each diagram, in such a way that all the negatives were in register. We then printed the composite by giving each negative a partial exposure on the same positive. By adjusting the relative exposure times, we could vary the weights of different diagrams very simply.

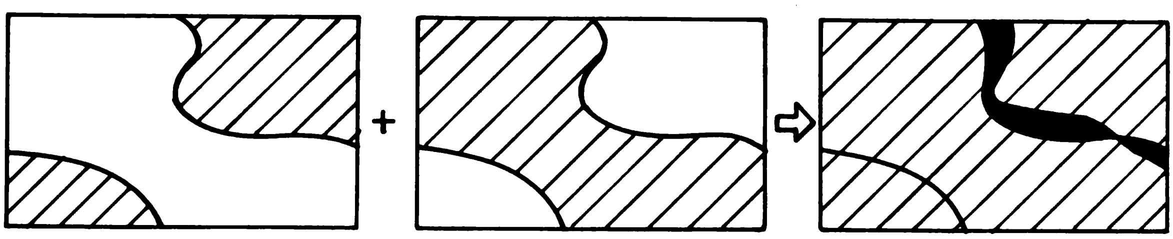
(1) The pattern properties

The requirements in any subset are in conflict with one another. However, they are never in conflict at every point of the terrain. There are always some parts of the two diagrams which reinforce one another.

IN THEORY



WHAT ACTUALLY HAPPENS IN PRACTICE



When we superimpose these diagrams mechanically, the areas where this reinforcement occurs come out blackest, of course. However, in this first composite, these dark areas will be discontinuous, zigzaging, running in several directions at once, of unclear overall shape, etc. In other words, the mechanically composite photograph is a relatively unstructured pattern of greys.

However, the eye, being what it is, we can always detect an underlying pattern in such a diagram, and we can bring this underlying structure out. This process is known as "levelling and sharpening". It is usually defined as the process of establishing the basic pattern properties of a stimulus more firmly than they exist in the original stimulus.* The effect of redrawing the original composite, then, is to bring out just the kinds of property a highway has to have as a "path".

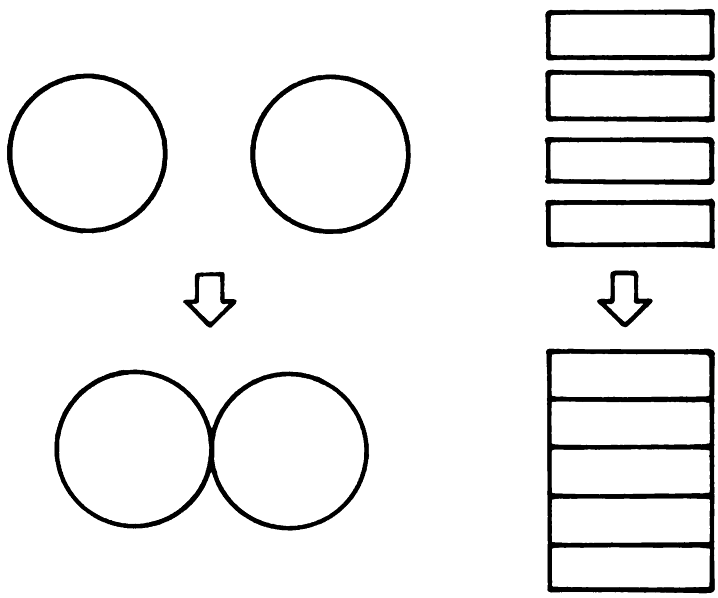
(2) The non-comparable utilities

The individual diagrams which we have to combine all contain areas of varying density. If we propose to add these diagrams to one another, it seems inevitable that we must somehow contrive to weight the various diagrams we combine. Naturally, if we give one diagram 100 times the weight of another in a photographic composite, the first will entirely overshadow the second. Yet, on the other hand, there is no acceptable reason for giving them equal weight; any such action contains the very assumption about utility scales being comparable, which we are trying to avoid.

We get round this as follows. It has long been known that certain configurations have "better" organization than others (in some sense not quite understood). They have variously been described as more stable configurations, as forms with better gestalt, etc.** These terms summarise precisely the kinds of quality which we are trying to introduce during the process of combination. When two organised

*Arnheim, Rudolf, ART AND VISUAL PERCEPTION. Berkeley: University of California Press (1954); Wulf, Friedrich, "Tendencies in figural variation," in D. Ellis, A SOURCEBOOK OF GESTALT PSYCHOLOGY. London: K. Paul, Trench, Trubner and Company (1938). pp. 136-148.

**Kohler, Wolfgang, GESTALT PSYCHOLOGY. New York: H. Liverwright (1929) entities are superimposed, it usually happens that the composite organization yields an entirely new organised entity. As shown below, when two circles are put together in a certain way, a figure eight emerges as a new visual organisation with properties very different from the properties of the individual circles; a number of rectangles put side by side form a "ladder".*



If we look at the examples in Figure 5, we see the same thing happening. As we combine diagrams, entirely new organisations emerge, and the critical fact about these new organisations is this: in almost every case the new organisation is very stable, and independent of the weights given to the component organizations. In fact, experiment showed us that the photographic composite exhibited the same basic

*Gottschaldt, Kurt, "Gestalt factors and repetition," in Ellis, op. cit., pp. 109-135.

organisation even when the weights of the component diagrams varied by as much as a factor of ten. This means that the utility scales need not be assumed comparable. The weight given to different diagrams is irrelevant, and does not affect the outcome, provided we look only for the basic pattern and organisation of the composite.*

Summary of the process

We now summarise the process which we have described:

1. Make a list of requirements which the location of an Interstate Highway between Springfield and Northampton must meet.

2. For each requirement, construct a diagram which indicates the relative desirability of each terrain point, for a highway passing through it, from the point of view of that requirement. (These are the utility diagrams.)

3. For every pair of requirements, determine whether or not a conflict exists between those requirements, by comparing the diagrams.

4. Use the computer program (HIDECS 2) to analyse the linear graph described by (1) the set of requirements and (2) the set of conflicts between requirements. The result of the analysis is a hierarchical decomposition of the set of requirements, called a tree.

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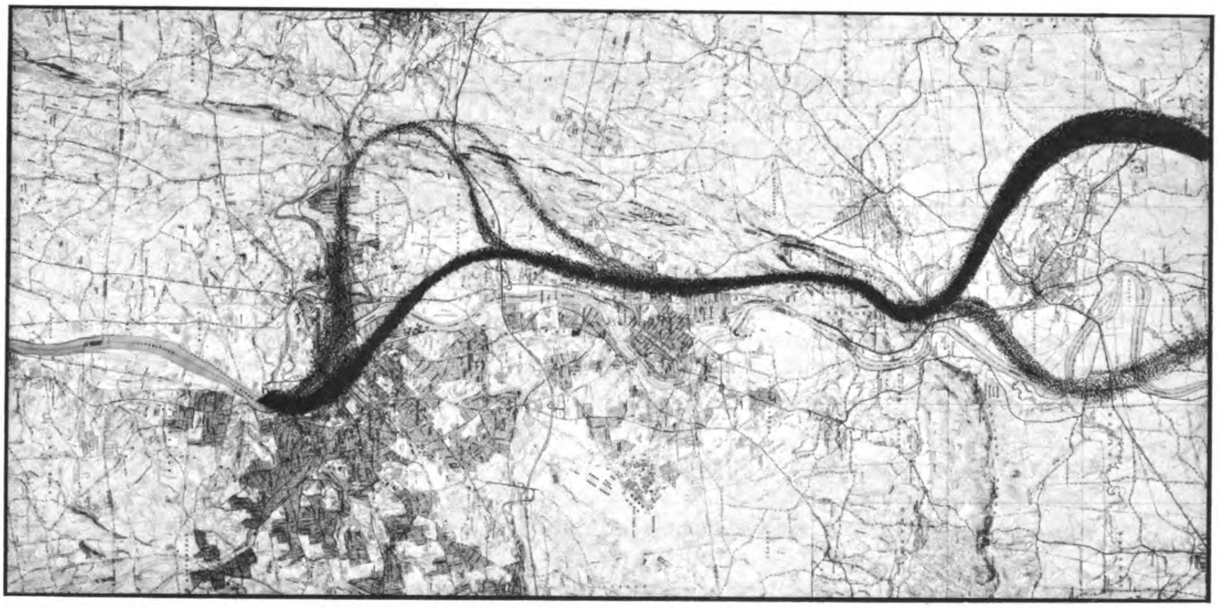
*Wherever there was any doubt about the emergent organisation we chose to weight the component diagrams in such a way that the new organisation suggested by the composite diagram came out most strongly.

5. This tree serves as a program for combining the requirement diagrams. For each set of diagrams at the lowest level of the tree, make a single composite diagram by photographic superposition. For this superposition, choose the relative weights of each diagram to bring out the strongest possible new organisation.

6. Make a transparency of the photographic composite. Using an enlarger to project it on a drawing board, redraw the image in such a way as to bring out its essential organisational features. Each time that the result of a photographic superposition of several diagrams is analysed and then redrawn, emphasize those parts of the composite diagram which have the kind of pattern that a highway route should have: continuity, consistent direction, etc. At each stage, the introduction of additional requirements influences the way in which the pattern is located over the terrain, but the <u>kind</u> of pattern remains that of a highway.

7. Each of these modified, composite diagrams has precisely the same character as the original diagrams, except that it represents a set of requirements rather than a single one, and therefore appears at a higher level in the tree. Each of these new diagrams now becomes the basic element of a second combination process, just like the first. The cycle of photographic superposition, projection, and modification is repeated (steps 6 and 7), to get to the third level of the

tree. This cycle is repeated again and again until the final diagram, representing the set of requirements at the top of the tree (i.e. all 26 requirements), is completed. The path shown on this diagram is the solution to the location problem.



Conclusions

In this last chapter, we have presented a way of combining the twenty-six utility diagrams defined over terrain points, to get one best path.

We agree with Roberts that the complexity of problems like this calls for the use of some kind of computer. The question is, what kind. Our objections to the procedure proposed by Roberts centered on two issues: (1) failure to take into account the configurational properties of a highway route, and (2) the assumption that different utilities are comparable. While it may be possible in principle to deal with these matters analytically and program them for digital computers, in practice, present digital computer techniques and utility theory are too little advanced to be of much use.

However, we do have a suitable special-purpose computer available to us. The human eye (and the associated parts of the nervous system) is well equipped to detect, isolate, and manipulate these kinds of pattern properties. Also, being linked to the brain which is flexible enough not to need rigid relations between utilities, the eye is able to take the significant details and implications of each individual pattern into account.

Of course people have used their eyes and heads before. But the idea that the human eye is a special-purpose computer for solving problems of this type, shows us the process outlined as a framework in which this computer can be used intelligently and efficiently.

For the moment, this framework is so roughly worked out, that it cannot be used as a basis for detailed location design; the fine structure of the path still has to be established by traditional means. We do recommend, though, that this framework can and should be used in the preliminary stages of location design, to establish the gross organisation. We also suspect that the framework will hold good, even when the eye is replaced by more precise techniques.

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