INTRAURBAN ACCESSIBILITY

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Transportation costs have been traditionally treated as the major spatial input in manufacturing and commercial location decisions. A recent review of contemporary location research by Stevens and Bracket [14, p. 9] indicated that the role of transportation costs as location determinants has changed with current emphasis being placed on the complex issues of accessibility, dependability, and transport flexibility. The objective of the following study is to provide a comprehensive measure and evaluation of one aspect of the above, intraurban network accessibility. It may be noted that accessibility is associated with the geographic notion of situation, thus it is related to the elements of spatial relationships, interaction, and connectivity. The term accessibility as used in this study will imply relative nearness either in the sense of a direct linkage or a minimum expenditure of travel cost or time. The intent is to construct a multivariate measure of accessibility that combines both static and dynamic criteria.

The regional scope of this paper is limited to a comparative analysis of Indianapolis, Indiana and Columbus, Ohio for 1954 to 1965. The preceding cities were chosen because they share similar site and situation characteristics, are surprisingly comparable in socioeconomic structure, and they exhibit contrasting highway development patterns. The choice of the two time periods is based on the following considerations: the two cities from 1954 to 1965 had undergone major network changes resulting in the addition of internal interstate highway linkages, and they experienced maximum contrast in the spatial pattern of their highway construction programs. In 1964 Columbus was characterized by an essentially internal circulation net with Indianapolis reflecting a strong circumferential orientation of limited access highways.

The derivation of the accessibility index consists of three analytical phases. The first phase uses finite graph theory to define the geometric structure of the test networks. The second phase utilizes flow analysis to provide dynamic criteria of network accessibility. The third phase employs principal components analysis to group the variables generated in phases one and two, and to identify spatial regularities in the accessibility pattern.

The Graph Analysis

The transportation networks for the cities of Columbus and Indianapolis were treated as planar graphs. The edges of the graphs were defined by the major thoroughfares in the cities with the intersection of these thoroughfares providing the vertices. Figure 1 illustrates the pre and postinterstate net-

1 It is obvious in dealing with the intraurban road network that all roadways could not be included in the study. As in most types of analysis a sampling procedure was followed based on the Indianapolis Transportation and Land Development Plan [1, p. 68]. The preceding plan classified road linkages into the following hierarchical structure: freeways, expressways, primary arterials, secondary arterials, collectors, and local streets. Here the edges of the graph are defined by utilizing the first four types of road links, and the intersection of such routes as the vertices of the graph. Since this study deals primarily with industrial and commercial locations, the major thoroughfares are assumed to reflect the relevant linkages of the transport network.

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Fig. 1. Indianapolis and Columbus pre and postinterstate networks.
works for Columbus and Indianapolis. It may be observed that the Indianapolis network is slightly larger than the Columbus system.

An analysis of the incidence structure for the networks provides an initial set of accessibility measures. The binary connectivity matrix for both networks shows a predominance of zeros (absence of a link) with ones (existence of a link) being concentrated primarily in the vicinity of the diagonal. The latter suggests that a high degree of local connection exists. Powering the connection matrix to its diameter and extracting the Shimbel distance matrix gives a relative-ly powerful measure of nodal accessibility. The elements of the Shimbel distance matrix indicate that linkages to other nodes in the system are indirect and do not occur until the higher powers of the connection matrices are reached. Nodes characterized by the above may be considered structurally inaccessible. Nodes centrally located on the network would generally demonstrate smaller row sums and would be considered accessible to the network system.

Figure 2 illustrates the results of the preceding method by grouping the ranked row sums of the Shimbel matrix into quintiles with the first quintile indicating nodes having the lowest 20 percent, and with subsequent quintiles representing nodes having larger row sums. In 1954 both Indianapolis and Columbus showed patterns which declined outward from the center. The 1964 linkages were not greatly different. Indianapolis still revealed a gradient pattern of declining accessibility and the Columbus network showed a slight sectoral pattern of higher accessibility to the southeast. Correlations computed from the Shimbel node accessibility levels confirm the preceding cartographic observations. Correlations between the 1954 and 1964 Shimbel row sums were .85 and .86 for the respective networks of Columbus and Indianapolis.

Two additional graph measures that may easily be extracted from the incidence structure are the degree of the node and the associated number. The degree of the node reflects the number of network links that are incident to a particular node. Nodes that are characterized by a large number of linkages to other nodes may be assumed to be more accessible than those having only a few linkages. Both cities show a generally uniform pattern as indicated by the degree of the node with only a few of the central nodes having significantly larger numbers of connections. The associated number is a more powerful measure of accessibility, indicating the number of links in the shortest path from a particular node to its most remote node. The lower the associated number of a node the higher the accessibility level of that node to the system. Both the degree of node and the associated number variables tend to favor the central portions of the network relative to the periphery.

In a second analysis, the linkages were weighted by travel time based on posted speed limits. By powering the weighted connectivity matrix and summing across the rows a measure of accessibility was generated (Figure 3). Considerable similarities appear to exist with the previous analysis (Figure 2). Both criteria, weighted or nonweighted, indicated the significance of the central nodes in their dominance of the higher quintile positions. The weighted pattern, for both networks, illustrated lesser uniformity in the peripheral sections of the network than was characterized by the nonweighted pattern. The Indianapolis network in the pre and postinterstate periods showed a high accessibility corridor from the city's northwest quadrant to its southeast sections; this weakened in

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2 A basic introduction to graph theory may be obtained from Busacker and Saaty [3] or from Berge [2]. For general discussion of applications of graph theory in geography see Haggart and Chorley [9], Garrison [5], Garrison and Marble [6], and Kansky [10].

3 This is referred to as the "neighborhood effect" by Garrison and Marble and was observed in their analysis of the Argentine air transport network [6, p. 32].
Fig. 2. Binary accessibility patterns.
Fig. 3. Weighted accessibility patterns.
the postinterstate period. The northeastern sections of Indianapolis during both periods remained generally inaccessible even though the outer belt of the freeway system made inroads into the north-central sections. A correlation analysis for the two time periods suggests that significant changes have occurred in the Indianapolis road network. A correlation coefficient of .41 for the weighted accessibility criteria between 1954 and 1964 confirms that the changes have been primarily related to travel time. The binary accessibility criteria for the same period showed a correlation coefficient of .86 suggesting only limited changes in the nonweighted incidence structure.

Columbus reveals a similar sectoral pattern in accessibility, especially if the dominance of the center is ignored. The addition of the freeway system does not significantly change the peripheral accessibility pattern. The southeast has the highest accessibility levels with only limited improvements in accessibility having occurred in the north-central sections of the city. Verification of the preceding may be noted by examining the correlation coefficients for the weighted criteria between the two study periods. Columbus has a correlation coefficient of .96 suggesting almost no change. The addition of the interstate linkages to the Columbus system has merely duplicated existing linkages, while the Indianapolis system was significantly altered on the basis of the travel-time weighted linkages.

In summary, the graph theory analysis has defined accessibility primarily on the basis of weighted and nonweighted, static, geometric criteria. Potential for movement is one of the chief considerations in a location decision, but has not been adequately considered by the previous measures of accessibility. The following section examines the topological structure of the network within the framework of its propensity to generate movements at a minimum expenditure of time.

**Minimum Path Analysis**

Figure 4 illustrates the operational framework employed to define the flow structure of the networks. It may be noted in the diagram that the dummy source and dummy sink nodes are used to interject a flow into the feeder nodes and to recover it from the collector nodes of the road network. The digraph is symmetrical with feeder, collector, and intermediate nodes supporting the potential flow movements in two directions. The only linkages which fail to have the symmetrical structure are the links leading from the dummy source to the feeders, the links leading from the collectors to the dummy sink, and the linkage between the dummy sink and dummy source. The above one-way linkages are operationally necessary in order to interject flows into the network system. It should be emphasized that they play no role in circulation within the actual network.

The objective of the flow analysis is to define a minimum time path through the transport network. In order to attain a more realistic evaluation of the nature of the minimum time path and its associated nodes, a sampling of several time paths was utilized. This was accomplished by a 360° rotation of the source and sink nodes, while injecting flows at 45° intervals with subsequent changes in the respective feeder and collector nodes, thus providing eight time paths which traversed the network from all major compass directions. It was necessary for reasons which will become apparent in a later section to have a complete rotation, although minimum paths defined from 0° to 135° and from 180° to 315° were reciprocals of one another.

The method used to define the minimum time paths of the network was the Ford-Fulkerson, Out of Kilter algorithm [4]. The above approach assumes a network to be finite, oriented, connected, and characterized by the following integer values: \( l_{xy} \) which defines the lower bound of an arc \( xy \); \( c_{xy} \) which defines
the upper boundary of an arc \( xy \); and \( a_{xy} \) which indicates the cost of flows along the arc \( xy \). The objective of the Ford-Fulkerson method is to construct a flow that satisfies the following:

\[
f(x, N) - f(N, x) = 0 \quad \forall x \in N \quad (1)
\]

\[
I(x, y) \leq f(x, y) \leq c(x, y) \quad \forall (x, y) \in \mathcal{E} \quad (2)
\]

while minimizing the linear cost function:

\[
\sum a(xy) f(xy) \quad (3)
\]

where: \( N \) consists of a collection of vertices,

\( \mathcal{E} \) consists of ordered pairs of edges,

\( f \) consists of a quantity of flow on arc \( xy \).

The Ford-Fulkerson approach aims at placing all the arcs in the transport network in a state of kilter.\(^4\) A nonnegative number referred to as the kilter number may be computed for each state of an arc. When an arc is in kilter, its kilter number equals zero, while an Out of Kilter arc will have a kilter number that is positive. The algorithm attempts to meet the feasibility and optimal state by employing the Ford-Fulkerson labeling process in order to reduce the kilter number of an arc to zero. Figure 5 illustrates the paths defined by the algorithm. It may be noted that the above time paths deviate from reality in that they assume continuous noninterrupted flows at the maximum legal speed limit. Their values come from their situation and orientation in relation to other nodes rather than in defining an optimum routing solution for actual travel in the network.

The identification of the minimum paths for the preinterstate and postinterstate periods in the Columbus road net-

\(^4\) The primary purpose of this study is to define the minimum path rather than to allocate maximum flows. Examples of applications aimed at incorporating limits on the upper and lower bounds may be seen in the works of Gauthier [7], and the King, Casetti, Odland, and Semple study [11]. The Out of Kilter program was used primarily to generate variables that express accessibility relationships.
Fig. 5. Minimum time paths-rotation.
work indicated only limited changes (Figure 5). In the preinterstate era, movement was primarily generated internally on the major north-south and east-west routes. This pattern was not drastically changed in the postinterstate period which is characterized by internal movements on linkages associated with the interstate.

The impact of the interstate linkages on the Indianapolis network appeared to have had a greater effect than was visible for Columbus. Preinterstate paths for Indianapolis were primarily generated internally, with the postinterstate paths following an entirely circumferential routing pattern. The above findings are also consistent with the previous graph theory analysis which indicated that significant changes in the network had occurred due to the addition of the limited access highway system. In summary, one may note that there is little question that circulation has been improved for both networks, however, relative changes for nodes in the system appear to vary significantly for Indianapolis and only to a minor degree for Columbus.

The minimum time path through the network may be utilized to generate variables that express a node's accessibility to the minimum paths in a quantitative manner. Figure 6 shows the shortest distance to the minimum path as an example of a variable that indicates a node's accessibility generated from the preceding minimum path approach. It is computed on the basis of the shortest travel time by network links to the minimum time path. Nodes located on the minimum time path had values of zero with those at increasing distance away from the path demonstrating larger values. Each node's value was recorded for rotations 0°, 45°, 90°, and 135°. The computed values were then summed with the totals revealing how accessible a particular node was to the minimum time paths. Nodes which were distant from the paths revealed high total values while nodes on or near the minimum paths had sums considerably lower. The preceding values were ranked and then grouped into quintiles, with the lowest 20 percent characterizing the most accessible nodes and subsequent quintiles indicating lesser degrees of accessibility. An examination of the resulting maps indicates the significant impact that the peripheral Indianapolis interstate nodes experienced as a result of the completion of the southern portion of the outerbelt (Figure 6). In the preinterstate period the optimum circulation nodes were located along an internal north-south corridor. The postinterstate period defined the minimum path nodes primarily in the southern portion of the network. The above changes are confirmed when a correlation analysis is run for the two time periods and a coefficient of correlation of \(-0.64\) is extracted for Indianapolis. Columbus during the same period experienced limited circulation changes, with the preinterstate period characterized by a gradient of declining accessibility focused on the center of the network and the postinterstate period typified by a more sectoral pattern of accessibility. A correlation coefficient of \(0.52\) computed for the two time periods in Columbus suggests a relatively limited alteration in the accessibility pattern.

The second flow variable generated is the node price that the Out of Kilter program assigns to individual nodes in the labeling process. The node price is used to evaluate the level of optimality achieved by the program. The calculation of node prices is similar to the computational procedure employed to generate the shortest distance to the minimum path variable with the exception that node prices increase at a minimal level away from the point of origin of the minimum path. The interpretation of this variable is similar to the evaluation

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5 For a detailed explanation of node price vectors and their role in defining a state of optimality refer to Ford and Fulkerson's treatment of the general, minimal cost flow problem [4, pp. 113–27].
Fig. 6. Node shortest distance to minimum paths.
of the shortest distance to the minimum path variable with the nodes located close to the origin and along the path being assigned lower values than nodes more distant from the path. Unlike the shortest distance to the minimum path variable, node prices located on the path will have values greater than zero. Due to the focus of the node prices on the origin of the minimum path and the gradient of increasing prices away from the point of origin of the path, it is necessary to have a 360° rotation. The above prevents over weighting the significance of the northern and eastern sections of the network where the origins of the paths are located in a 180° rotation. Node prices were computed for rotations of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° and then summed, giving each node a total price.

The preceding totals next were mapped and price lines drawn to show the general spatial pattern of prices (Figure 7). The Indianapolis preinterstate node prices showed a gradient of increasing prices from the eastern portion of the network to the western sections. The postinterstate period was characterized by circumferential accessibility patterns that favored the eastern, southern, and western peripheral nodes. Node prices for Columbus indicated a more sectoral pattern for both time periods with the preinterstate era characterized by high accessibility in the central and eastern nodes and the postinterstate period having high accessibility nodes along the path of the interstate.\(^6\)

In summary, the flow analysis has identified the relative accessibility of individual nodes to various directional flows through the network. The shortest distance to the minimum path variable and the node prices of the Out of Kilter program both indicate that significant changes have occurred in the flow structures of the two cities. The analysis suggests that the changes in the flow pattern have had their greatest impact on the internal accessibility of individual nodes in Indianapolis. The above findings are consistent with the earlier graph theory conclusions.

**Regionalization of the Networks**

The preceding flow and graph theory analyses have suggested that spatial regularities exist in the pattern of accessibility for both cities. This section will identify the location of high accessibility regions by employing principal components analysis. It is believed that this approach will not only extract regularities in the spatial pattern, but also identify the internal relationships between graph and flow analyses variables used to measure accessibility.

The variables utilized in the principal components analysis included the following:

1) degree of node,
2) associated number of the node,
3) shimbel binary index of accessibility,
4) weighted accessibility index,
5) rotated shortest distance to the minimum path,
6) mean shortest distance of the node,
7) rotated and summed Out of Kilter node prices.

The results of the principal components analysis are presented in Table 1. Two significant components having eigenvalues greater than 1.00 were extracted, except for the Columbus preinterstate system which had one significant component.\(^7\) Total common group variance ranged from 64 percent to 80 percent levels of explanation. The first factor extracted, for both Columbus and

\(^6\) Correlations between the shortest distance to the minimum path variable and the node prices are .76 and .82 for the pre and postinterstate periods in Columbus and -.85 and +.57 for the pre and postinterstate patterns of Indianapolis. The above results verify the cartographic similarities of the two patterns on Figure 6 and Figure 7.

\(^7\) The eigenvalue for the Columbus preinterstate period’s second factor was 0.94 which placed it below the accepted significance level.
Fig. 7. Out of Kilter program node prices.
Indianapolis, loaded high on variables that favor central accessibility. The distribution of high positive factor scores characterized the dominant central nodes. The pre and postinterstate periods for Factor I are structurally similar, the factor scores illustrating a strong focus toward the center of the network. The second factor suggests a relationship to the flow variables. The scores from Factor II indicate a circumferential orientation in Indianapolis and a sectoral pattern for Columbus. The preceding shows that Factor II is closely related to the interstates with its greater sensitivity to peripheral accessibility. Factor I, on the other hand, appears to measure the accessibility within the network’s core.

The above analysis suggests a dualistic pattern in the variable space between the flow measures of accessibility and the graph analysis criteria. Based on the preceding it is assumed that an overall measure of accessibility should combine qualities of both factors. An index of accessibility was derived by multiplying the percentage of common group variance associated with Factors I and II by the respective factor scores, and summing the product. The above index provides a secondary weighting of the individual nodes to both the central and peripheral accessibility factors.

Evaluation of the magnitude and orientation of the internal accessibility pattern employed the preceding index to construct a surface of accessibility for the two time periods for each city. This was accomplished by overlaying each city with a grid calibrated into square-mile units. Each cell of the grid was given an accessibility value based on the transport accessibility index. When a cell contained a node of the transport network that cell received an accessibility value equivalent to the node’s accessibility. Cells which did not contain a node were given an accessibility assignment based on interpolation of an accessibility gradient generated from IBMs contour mapping program. The interpolation included maximum distances of less than six miles and in most cases distances less than three miles. A diagrammatic representation of the ac-

### Table 1: Principal Components Analysis Flow and Graph Variables

#### Indianapolis Factor I Loadings

<table>
<thead>
<tr>
<th></th>
<th>Preinterstate</th>
<th>Postinterstate</th>
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<tbody>
<tr>
<td>Percent of variance</td>
<td>56 percent</td>
<td>53 percent</td>
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<tr>
<td>Degree of node</td>
<td>+.40</td>
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<td>Associated number</td>
<td>+.92</td>
<td>+.92</td>
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<td>Weighted graph</td>
<td>+.58</td>
<td>+.53</td>
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<tr>
<td>Shortest path to the minimum path</td>
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<td>-.18</td>
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<tr>
<td>Binary accessibility</td>
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<td>+.89</td>
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<tr>
<td>Mean shortest distance</td>
<td>+.90</td>
<td>+.72</td>
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<tr>
<td>Node prices</td>
<td>-.09</td>
<td>+.02</td>
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#### Indianapolis Factor II Loadings

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<tr>
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</thead>
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<tr>
<td>Percent of variance</td>
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<td>16 percent</td>
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<tr>
<td>Degree of node</td>
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<td>+.70</td>
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<td>Associated number</td>
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<td>Weighted graph</td>
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<td>Shortest path to the minimum path</td>
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<tr>
<td>Binary accessibility</td>
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<td>+.39</td>
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<tr>
<td>Mean shortest distance</td>
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<td>+.50</td>
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<tr>
<td>Node prices</td>
<td>+.92</td>
<td>-.84</td>
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#### Columbus Factor I Loadings

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<tr>
<th></th>
<th>Preinterstate</th>
<th>Postinterstate</th>
</tr>
</thead>
<tbody>
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<td>Percent of variance</td>
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<td>58 percent</td>
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<td>Degree of node</td>
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<tr>
<td>Associated number</td>
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<td>Weighted graph</td>
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<td>+.78</td>
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<td>Shortest path to the minimum path</td>
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<td>+.06</td>
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<tr>
<td>Binary accessibility</td>
<td>+.93</td>
<td>+.91</td>
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<tr>
<td>Mean shortest distance</td>
<td>+.93</td>
<td>+.88</td>
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<tr>
<td>Node prices</td>
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<td>+.24</td>
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#### Columbus Factor II Loadings

<table>
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<tr>
<th></th>
<th>Preinterstate</th>
<th>Postinterstate</th>
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</thead>
<tbody>
<tr>
<td>Percent of variance</td>
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<td>19 percent</td>
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<tr>
<td>Degree of node</td>
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<tr>
<td>Binary accessibility</td>
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<td>Mean shortest distance</td>
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<tr>
<td>Node prices</td>
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*The assignment of accessibility values employed a computer numerical surface and contour map plotting program supplied by IBM—IBM Application Program, 1130 Numerical Surface Techniques and Contour Map Plotting, (1130-CX-11X).*
accessibility surfaces for Indianapolis and Columbus in the pre and postinterstate periods are presented in Figures 8 and 9. In order to provide a uniform viewing angle, the surfaces in Figures 8 and 9 were rotated 45° eastward from the south and 60° above the horizontal. The difference between the Columbus and Indianapolis surfaces are most apparent. Columbus is characterized by a greater degree of centrality and corridor development compared to the Indianapolis surface which exhibits a generally more uniform accessibility pattern. A comparison of the pre and postinterstate periods for each city shows considerable variations in the networks. The centrality of the Columbus preinterstate system is greater than the centrality of the postinterstate which is characterized by the development of a high accessibility corridor in the southern portions. The star-shaped high accessibility zones characterizing the preinterstate period of Indianapolis are replaced in the postinterstate period by considerable peripheral development in the northwestern and southern sections of the city.

Evaluation of the overall impact of the interstate system on the orientation of the accessibility surface is provided in Figure 10 and Figure 11. Utilizing the rotation options of the mapping program the viewing angles were shifted to 0° (south to north) and 90° (east to west), with the viewing angle above the

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**Fig. 8.** Indianapolis transport accessibility surfaces.

**Fig. 9.** Columbus transport accessibility surfaces.
Fig. 10. Profiles of the Indianapolis transport surface.
Fig. 11. Profiles of the Columbus transport surface.
surface set at 0°. Based on the above angles the resulting diagrams are profiles of the accessibility surfaces.

A comparison of the post and preinterstate Columbus surfaces reveals that the prefreeway pattern reflects a much simpler spatial orientation. The postinterstate phase indicates that the base level of the network has experienced an overall uplifting of the accessibility level. It may also be observed in the Columbus postinterstate period that the south central, as well as specific portions of the periphery have experienced improved accessibility levels. The Indianapolis system is characterized by similar changes with the postinterstate surface noticeably higher than the preinterstate surface. It may also be observed that the variations in accessibility from the lowest to the highest points have been reduced in the postinterstate phase. One may conclude from the above that the Indianapolis system is moving toward greater homogeneity in accessibility while the Columbus system remains rather sectoral. A correlation analysis of the accessibility index for the study periods substantiates the earlier graph and flow analysis patterns. The Columbus pre and postinterstate periods reveal a strongly focused sectoral pattern with only limited changes in relative total accessibility. The preceding is confirmed by a correlation coefficient of .77 for the index during the two time periods. Indianapolis appears to have experienced a greater change in the accessibility pattern with a movement away from a sectoral orientation. The above is verified by the lower correlation coefficient (.35) between the two time periods.

**Summary**

In summary, this paper has evaluated the changes, both macro and micro, resulting from the addition of a partially completed interstate network. It has confirmed the hypothesis that the Columbus system experienced only limited changes in accessibility relative to significant peripheral changes characterizing the Indianapolis system. It has also defined by a quantitative measure the nature and orientation of the transport accessibility surface. It is suggested that the delineation of the accessibility surface provides a more realistic input of the transportation variable in applied and theoretical location problems. The relationship of shifts in industrial and commercial locations may be evaluated with respect to changes in the accessibility surface. The implications of the above to the policymaker and planner would be of use in assessing the potential impact that a new highway system would exert on industrial and commercial development. Delineation of the accessibility surface also provides a multi-dimensional normative view of accessibility to which perceived images of accessibility may be compared. The nature and degree of departure from the above normative pattern would be of value in structuring behavioral models founded on nonoptimal criteria.

**Literature Cited**


