Spacing of Interchanges and Grade Separations on Urban Freeways

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•IN planning urban freeways, the question always arises as to how local and arterial streets are to be redesigned where they intersect the proposed freeway. Should the intersecting street be terminated at the freeway? Should it be re-routed over a frontage road which is constructed parallel to the freeway? Or should it be provided with a grade separation for carrying traffic over or under the freeway?

Another equally important question concerns the location of points of interchange between the freeway and the local street system. Which arterial streets intersecting the freeway should be provided with a grade separation and ramp interchange facilities for access to and egress from the freeway?

The problem of spacing and location for interchanges and grade separations is very important to highway planners and geometric designers as they attempt to formulate optimum systems of arterial streets and freeways in metropolitan areas.

In the "Instruction Manual for the Preparation and Submission of Revised Estimate of Cost of Completing the Interstate System" (1), the following statement dealing with interchange location on the Interstate System appears:

> It is important that interchanges be located so as to properly discharge and receive traffic from other Interstate and Federal-aid system routes or major arterial highways or streets. It is equally important that they not be spaced so closely as either to unnecessarily increase the cost of the System or interfere with the free flow and safety of traffic on the Interstate System.

A general guide for selecting the location of and spacing between interchanges is suggested by Loutzenheiser (2), Owens (3) and Mitchell (4). The procedure involves reaching an acceptable compromise in the location and spacing of interchanges to obtain a balance between desirable efficiency and safety in traffic operations on the freeway, and desirable traffic service and operations on the city street system. The interchanges should be spaced so as not to create bottlenecks on the freeway or on the local streets leading to the freeways.

When interchanges are widely spaced, traffic operations on the freeway are likely to be good, since there are few points along the freeway where merging, diverging and weaving movements occur because of vehicles entering or leaving the freeway. However, the volume of traffic concentrated at each interchange may be quite high. The arterial streets leading to and from the interchanges may not be able to accommodate these large concentrations of traffic. A wide spacing of interchanges also results in fewer trips using the freeway than when interchanges are closer together. Less conveniently located access points on the freeway are provided when interchanges are widely spaced rather than closely spaced.

When interchanges are closely spaced (e.g., ½ mi apart), short-distance local traffic is encouraged to use the freeways with the results that more lanes are required on the freeway than would be required if the interchanges were widely spaced. These

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additional lanes, along with the relatively large number of interchanges and grade separation bridges due to the close spacing of interchanges, cause the construction cost of the freeway to be higher than if the interchanges were widely spaced.

With closely spaced interchanges, through freeway traffic is subjected to frequent points of turbulence and side friction, which tends to reduce the efficiency of the freeway for accommodating through traffic. Also, traffic flows entering and leaving at adjacent interchanges may produce conflicts due to lack of room for merging, diverging and weaving maneuvers.

When grade separations are widely spaced, the freeway can be a barrier to local traffic circulation. Closely spaced grade separations, on the other hand, provide better local traffic circulation, but increase the construction cost for the freeway facilities.

In the past, studies to determine whether to locate an interchange or grade separation at a point on a proposed freeway were based primarily on estimated traffic and physical conditions at that one point only. The benefits and costs for alternative designs for that specific location were analyzed. The economic analysis generally involved the computation of a separate benefit ratio for the interchange or grade separation being analyzed. When computing the user cost for calculating the benefit ratio, a frequent practice was to make a traffic assignment considering the interchange being analyzed as part of the freeway. The vehicular trips assigned to this interchange were than assumed to leave or enter the freeway at interchanges adjacent to the interchange being analyzed. Thus, one part of each trip that had been performed on the freeway was re-routed to local streets. The benefit for each trip derived from the interchange being analyzed was equal to the difference between the user cost incurred on the local streets for the part of the trip that was re-routed from the freeway and the user cost for the same part of the trip when it was performed on the freeway. A similar procedure was used when analyzing the effects of removing or adding grade separations for local streets on the freeway.

This economic analysis does not account for all of the re-routing of trips that would take place if the interchange being analyzed was removed from the freeway. It would be preferable to consider the entire freeway network and the local street network as one complete system when analyzing the economic effect of removing one or more interchanges and/or grade separations from the freeway.

OBJECTIVES

One objective of this study was to develop and test a model for analyzing the problem of determining the optimum spacing of interchanges and grade separations in an integrated system of urban freeways and arterial streets, and the interchanges between the two parts of the system. In determining the optimum spacing of interchanges and grade separations, consideration was given to system-wide effects of these spacings on (a) the use of each part of the street and freeway system, (b) the number of lanes required on the freeways and streets to accommodate traffic, (c) the cost of construction and right-of-way for the required facilities, and (d) the costs to the users of the system.

Another objective of the study was to determine the sensitivity of the optimum spacing of interchanges and grade separations to various values of the input parameters (time cost per hour, interest rate, amortization period, right-of-way cost per acre, level of service and volume levels) used in the economic analysis.

DESCRIPTION OF ANALYTICAL MODEL

Network Description

A system approach is used in this study of the spacing of grade separations and interchanges. The arterial street system with its collector streets, and the freeway system with its interchanges with the arterial streets, are considered as one complete network in the analysis.

It is assumed in the analytical model that a freeway-grid network with freeways spaced 4 mi on center is superimposed upon a grid system of arterial streets where the major arterials are spaced 1 mi apart, with secondary arterials at the $\frac{1}{4}$ and $\frac{1}{2}$-mi points.

The choice of the 4-mi spacing of freeways was influenced by the work of Creighton, Hoch, Schneider and Joseph (5, 6) of the Chicago Area Transportation Study (CATS); Peterson (7) of the California Division of Highways; and Horwood, Boyce, and Rieg (8) of the University of Washington. The choice of the grid pattern of arterials at $\frac{1}{4}$-mi spacings was made after examining the existing street patterns in Chicago and Detroit.

With a $\frac{1}{4}$-mi spacing of arterial streets and a 4-mi spacing of freeways, the only variables in the network of links representing the streets and freeways are the spacing between the points of interchange between the arterial streets and the freeways and the spacing of grade separations on the freeway where the arterial streets are carried over the freeway.

Criterion Function and Constraints

The purpose of the analytical model is to determine the best or optimum combination of these two variables. The criterion function used to determine this combination is that of minimizing the total annual transportation cost of satisfying the travel demand in the network after considering the several possible network configurations. The total annual transportation cost is defined as the annual cost of purchasing right-of-way and constructing the facilities on the arterial streets and the freeways necessary to accommodate the traffic assigned to the network plus the annual operating, accident and time costs of the users of the network.

This criterion function is subject to the constraint that all trip demands must be satisfied.

Several other factors might have been included in the criterion function: (a) land and community values or benefits as they are affected by the variation in spacing of interchanges and grade separations on the freeways, (b) maintenance costs on the network of streets and freeways, and (c) cost of comfort and convenience for the occupants of the vehicles using the network.

Levin (9), when discussing the measurement of nonuser benefits, states:

> Study of a particular facility may indicate a substantial increment in land value within the scope of its influence; but this eruption of values may be counterbalanced, in part at least, by a diminution of land value in another portion of an area. On the other hand, study of a particular facility may reveal a decrease in land values or sales volume in areas within the scope of its influence, but this might be more than offset by substantial increases in these items elsewhere.

He stressed that there is a need for quantification on a system-wide or regional basis rather than on an individual facility or freeway basis, if a true picture of changes in land values due to highway development is to be obtained.

Such system-wide studies have not been made. Not enough is presently known concerning the overall effects of highway improvements on the benefits in terms of market values (dollars). Thus, the net changes in land values as affected by highway improvements cannot be realistically included in a criterion function to be used to determine which network of many different possibilities might be the best for the whole community.

The foregoing discussion concerns freeway location. The problem being considered concerns not freeway location but spacing of interchanges and grade separations on freeways. Even less is currently known about the differential effect, if any, that various spacings of these two facilities might have on land values in a community. Thus any effect, plus or minus, that the variations between the various possible networks in spacing of freeway interchanges and grade separations might have on land values in the community is not included in the criterion function.

Maintenance costs on the network of streets and freeways are not included in the criterion function because of the difficulty in obtaining realistic costs, and because it is assumed that the differences in such costs between the various networks would be negligible and thus can be ignored.

The costs or benefits due to comfort and convenience accruing to the occupants of the vehicles using the highway improvements, although a very real benefit, are not included in the criterion function because of the lack of knowledge concerning the market value of such benefits. Rather than assume a dollar value for such benefits, they are omitted as an explicit cost but may be thought of as being implicitly included in the costs assumed for the value of time.

Optimizing Technique

The structure of the problem as to the regularity of the grid system of the arterial streets and freeways and the discrete nature of the two variables being studied make it possible to use a selective search technique in looking for the optimum combination of the two variables that will minimize the established criterion function.

Because of the spacing of major arterials at ½ mi and minor arterials at ¼ mi, the minimum spacing of grade separations that must be examined is ¼ mi with other spacings of ½, 1 and 2 mi. The upper limit of 2 mi is set by the maximum spacing that might be reasonable in an urban area. The minimum spacing of interchanges is set by geometric design standards. The normal minimum is ½ mi (10). Other spacings would be 1, 2 and 4 mi. The discrete spacings are set by the configuration of the arterial street system. The maximum spacing would allow one point of interchange between the arterial street system and the freeway system between the two freeway-freeway interchanges. With these discrete values for the two variables being studied, there are 13 feasible combinations of the variables. This makes it necessary to analyze 13 different network configurations, thus making a selective search technique possible.

Steps in Applying the Model

Described next is the methodology used to select from the 13 feasible combinations of the two variables being considered that combination which minimizes the criterion function.

A level of service is selected for each class of arterial streets (1 mi, ½ mi and ¼ mi) and for the freeway. These preselected levels of service are the average overall travel or operating speeds for the links in the network. The speeds are assumed to be independent of the volume of traffic traveling on the link because the link will be designed to accommodate the assigned volumes at the assumed level of service.

A common set of trip origins and destinations is used as the input to all of the network configurations analyzed. With this procedure the problem of trip distribution does not enter into the analysis. The assumption is made that the origin and the destination of each trip in the complete set of trips are independent of the arrangement of the links in the network of streets, freeways, grade separations, and interchanges. This is not completely true. Some short trips would be influenced by the spacing of grade separations. The origins or destinations of these trips would be reoriented to take into account the adverse travel distance made necessary by the location of the grade separations in the network. The number of trips so reoriented should be small when compared to the total number of trips in the set, and can be ignored. The variation in spacing of interchanges may also cause some reorientation of trip ends and may cause new trips to be generated. However, these changes should be small in number, and for purposes of this model one trip distribution pattern is used for all networks.

Next, the set of vehicular trips is input or assigned in turn to the 13 different network configurations by means of an electronic computer. The criterion function used in making the assignment is that of an uncapacitated, all or nothing, minimum time path assignment (11). The minimum time path from each origin node to each destination node (minimum time path tree) is determined by considering the travel times for each link in the network. All trips between the two nodes are assigned to this path or route in the network.

After the uncapacitated (desire) assignments of the set of trips are made to the networks, each arterial street and freeway network is designed to accommodate the assigned link traffic volumes at the assumed levels of service (average overall operating speed). It is assumed that, irrespective of the volumes of vehicles assigned to the various parts or links of the network, it is possible to design the facilities so that the assumed average overall operating speeds can be met.

A cost estimate for purchasing right-of-way and constructing the facilities and an economic analysis are made for each of the 13 networks. In the economic analysis the annual cost of the right-of-way and construction for the facilities is computed by using a capital recovery factor for a selected amortization period and interest rate. Annual road user operating, accident and time costs are calculated from daily vehicle miles and vehicle hours of travel on each part of each network being analyzed.

As part of the economic analysis, a sensitivity analysis is made involving the input parameters of time cost per hour, right-of-way cost per acre, interest rate, amortization period and operating speeds. The purpose of the sensitivity analysis is to see how the optimum or minimum cost combination of spacing of interchanges and grade separations changes as different values of the parameters are used. This type of analysis is necessary because of the controversy and lack of knowledge concerning the cost or value of time (12), and the lack of agreement among highway engineers, planners, and economists as to what amortization periods and interest rates should be used in economic analyses for highway improvements (13). Right-of-way costs are included as a variable in the sensitivity analysis because of the variance in these costs from location to location within a city. Operating speeds are varied in the economic analysis for the sole purpose of seeing how sensitive the two variables being studied are to variations in operating speeds.

The data from the economic analysis are then input to the criterion function and the combination of spacing of interchanges and grade separations which minimizes the annual total transportation cost is selected for each combination of the input parameters used in the sensitivity analysis (time cost per hour, right-of-way cost per acre, interest rate, amortization period, and operating speeds).

APPLICATION OF THE MODEL

Vehicular Trip Data

Travel patterns for the Chicago metropolitan area for 1956 were chosen for the input to the analytical model. The reasons for choosing Chicago were (a) the arterial system in Chicago is essentially a grid system with major arterials at the 1-mi and ½-mi points, which is the same as the arterial system specified in the analytical model; and (b) trip data for the area were available.

The vehicular trip data used as the common trip input data for all of the networks analyzed in the model were obtained from CATS. The 24-hr origin and destination data, from which the vehicular trip data were derived, were obtained from a 1956 home interview O-D survey (14). The area surveyed consisted of 1, 236. 5 sq mi with a resident population of 5. 2 million people. In 1956, on a typical weekday, there were 10, 500, 000 person trips and 6, 135, 000 vehicular trips. These vehicular trips included trips made by passenger automobiles and trucks of various sizes. To simplify data handling and computations, the truck trips were converted by CATS into what are called equivalent passenger vehicle trips. Since trucks take up more room than automobiles and are slower to accelerate, with the effect of increasing their occupancy of road space, it was decided to set heavy trucks (combination units) equal to three automobiles, medium trucks equal to two automobiles, and light trucks (panels and pickups) equal to one automobile. There were then 6, 765, 000 vehicle equivalent trips per average 24-hr weekday in the Chicago area in 1956. These trips were divided into approximately 42, 000 nondirectional interchange groups between 630 zones.

O-D data for 1956 were used for the trip input data for the analytical model rather than trips predicted for 1980 or some other year in the future because it was not thought necessary to interject into the model the problems and uncertainties involved in predicting trip distributions for some future year. Since the object of this study is to investigate the spacings of interchanges and grade separations and not to design a freeway for a specific area, it was concluded that any realistic set of trips would be sufficient for the model.

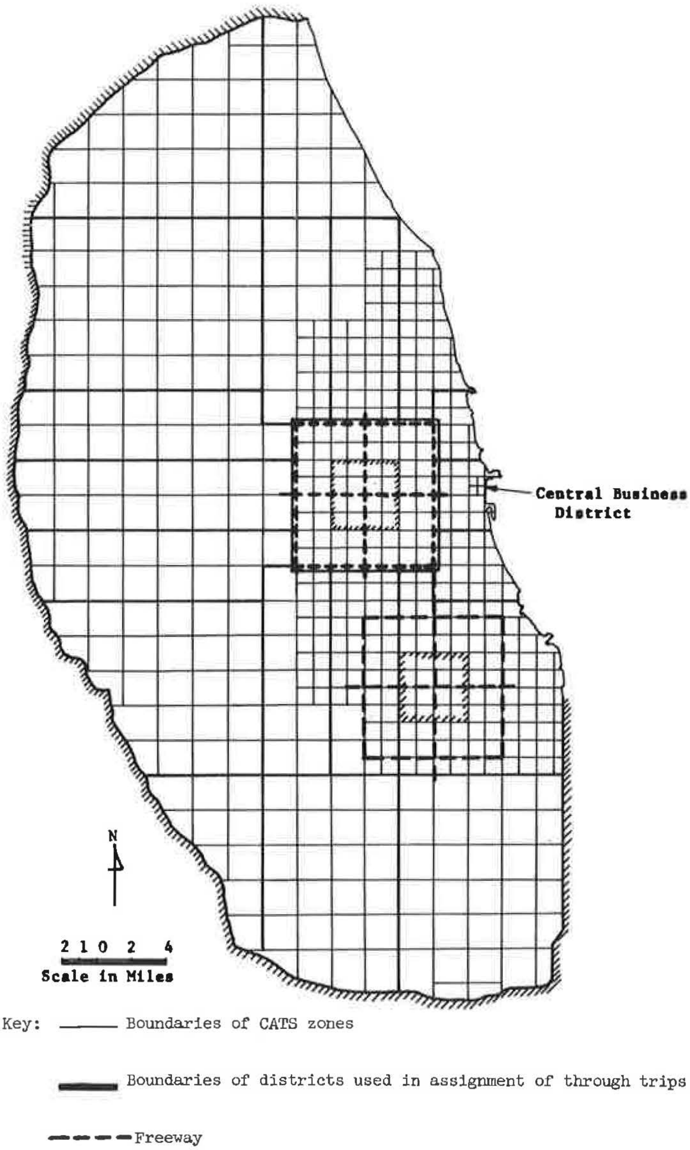
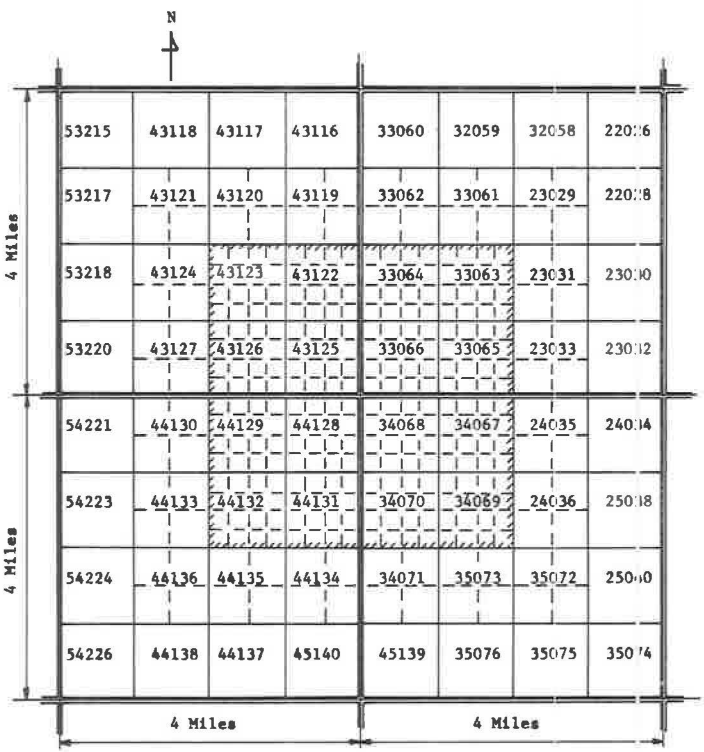


Figure 1. Analysis districts superimposed on CATS zone map.

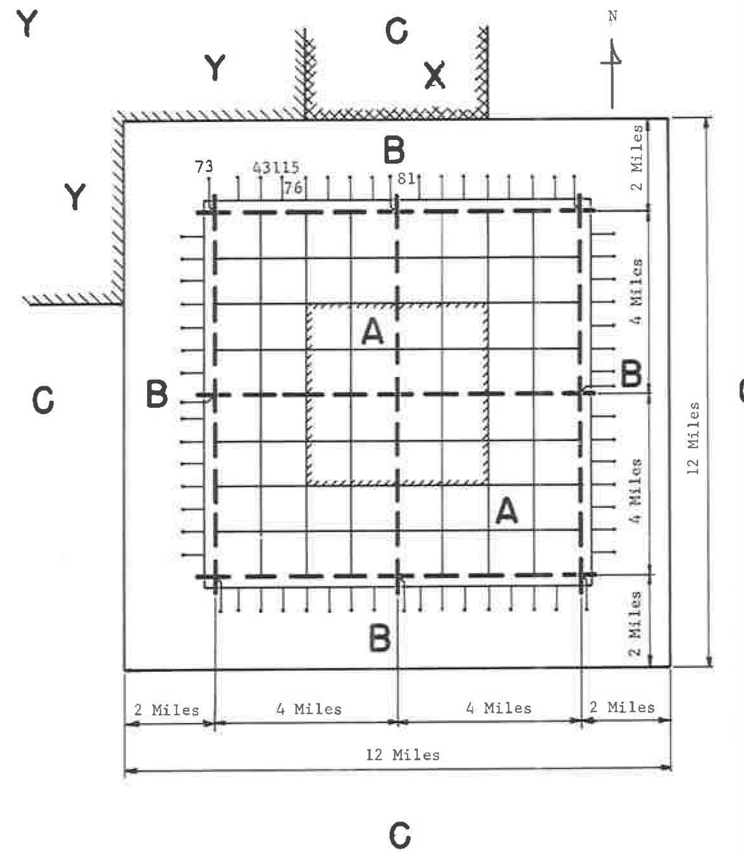
Analysis Area

Two areas were chosen to provide travel patterns for input into the model. One lies $6\frac{1}{2}$ mi directly west of the central business district (CBD) of Chicago and had an average population density of 21,000 persons per square mile in 1956. The other lies $11\frac{1}{2}$ mi south and $2\frac{1}{2}$ mi east of the CBD and had an average population density of 8,300 persons per square mile in 1956. Figure 1 shows the assumed grid system of freeways superimposed upon a portion of CATS analysis zone system. The areas included in the economic analysis part of the analytical model each consisted of 16 CATS 1-sq mi zones. These areas are outlined by the cross-hatched lines in Figure 1 and one area is shown in Figure 2. Two freeways intersect in a freeway-freeway interchange at the center of each area. Land-use information and trip-destination densities for each area for 1956 are included in Tables 1 and 2 (all Tables are located in the Appendix).



Key: Numbers shown are one-square mile CATS zone numbers
Freeways
— — — Line subdividing CATS zone
Boundary of area used in economic analysis

Figure 2. Subdivided CATS zones.



Key: Freeways

External loading node

A = 64 square mile area included within the peripheral freeways

B = Two mile wide tier of zones

C = All area in CATS study area excluding areas A and B

Figure 3. Group arrangement of CATS zones.

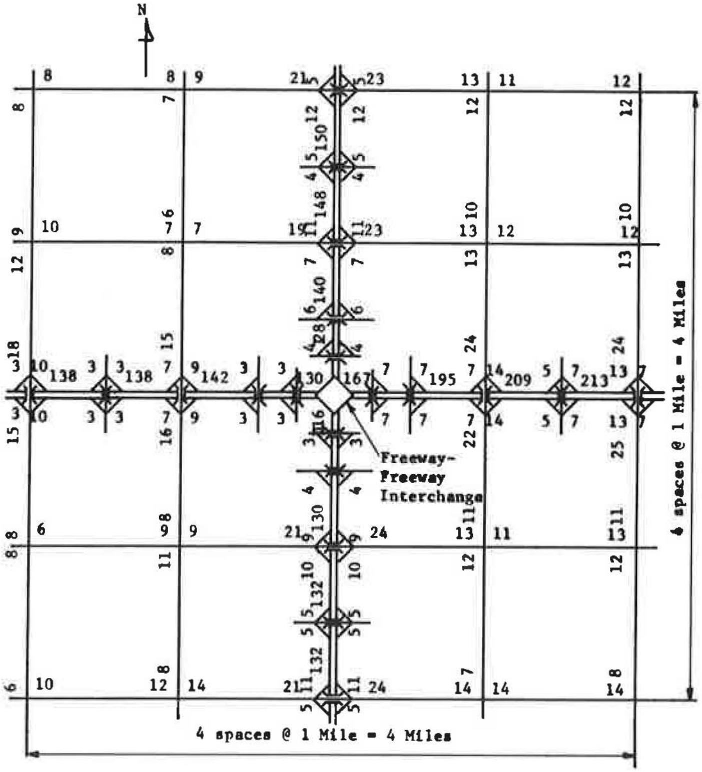


Figure 4. Average weekday volumes—interchange spacing ½ mi, grade separation spacing ½ mi, trip density = 23,000 destinations per sq mi. Numbers shown are 24-hr average two-way weekday equivalent passenger vehicular volumes in 1000's of vehicles except on interchange ramps where one-way volumes are shown.

Analysis Zones

Because the CATS zones in the area chosen for the analysis are 1 sq mi in area, it was necessary to divide these zones into smaller zones to permit analysis of the spacing of interchanges at ½ mi and grade separations at ¼ and ½ mi. Use of the large CATS zones would have had the effect of obscuring the possible use of the interchanges and grade separations spaced at distances closer then 1 mi. The arrangement of the subdivided CATS zones is shown in Figure 2. Each 1-sq mi CATS zone included in the area used in the economic analysis part of the model (enclosed by the cross-hatched line in Fig. 2) was divided into 16 equal subzones each with a zone centroid (loading node) located at the subzone center where trips for that subzone can be considered to have their origin or destination. Each 1-sq mi zone in the band of CATS zones immediately adjacent to the cross-hatched area was subdivided into 4 equal (¼ sq mi) subzones, each with a loading node at its center (Fig. 2). CATS zones in the next tier were not subdivided, but were left as 1-sq mi zones with a loading node at the center of each zone.

Loading nodes (called external loading nodes) were also provided at the freeway intersections along the periphery freeways and also at ½-mi intervals along the two-way arterial streets located just outside the peripheral freeways (Fig. 3). A total of 428 loading nodes (zone centroids and external loading nodes) was used.

A computer program was written to change the CATS 1956 O-D data into the proper form for input to the analytical model used in the study. The CATS data consisted of approximately 42, 000 card records on two magnetic tapes arranged in a nondirectional triangular trip table. Each card record included the CATS low-order zone number, the

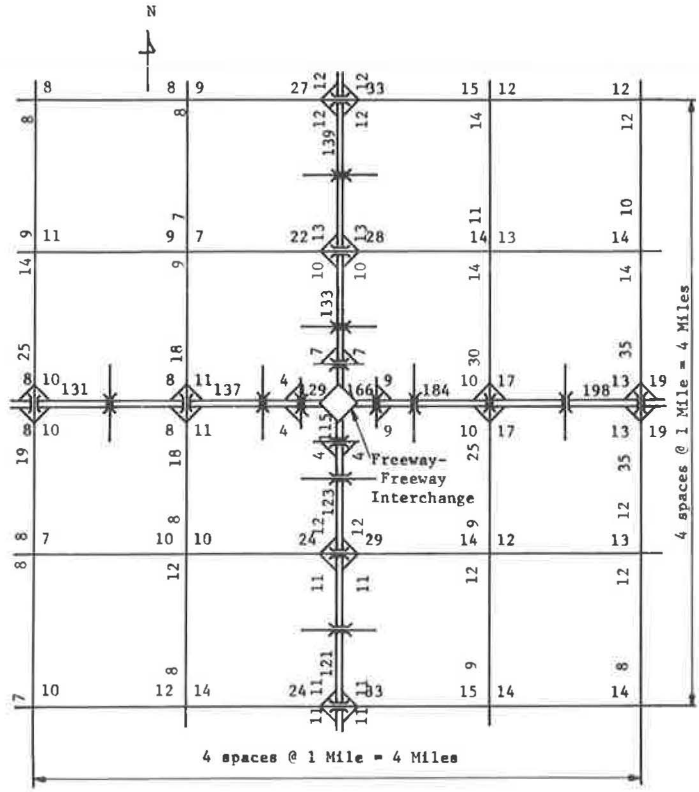


Figure 5. Average weekday volumes—interchange spacing 1 mi, grade separation spacing ½ mi, trip density = 23,000 destinations per sq mi. Numbers shown are 24-hr average two-way weekday equivalent passenger vehicular volumes in 1000's of vehicles except on interchange ramps where one-way volumes are shown.

high-order zone number, and the number of vehicle equivalent trips in both directions between those two zones. These zones were numbered from 1 to 692 by CATS.

All of the CATS zones in the entire CATS study area were then classified into three groups. Group A contained all CATS zones within the 64-sq mi area enclosed by the freeways (Fig. 3). Group B consisted of the CATS zones in the 2-mi wide band around area A. All of the other CATS zones were included in Group C.

Each CATS zone within Group A was assigned a new zone number. This system of numbers ranging from 1 to 128 was called the intermediate zone and external loading node number system. Each external loading node at the freeway-freeway intersections on the periphery of the area and at the ½-mi points along the arterial streets just outside the peripheral freeways was also assigned a number in the intermediate number system.

Every CATS zone other than those in Group A was then assigned an intermediate external loading node number, so that all trips having origins or destinations in areas B or C would be loading through loading nodes (65 to 128) on the periphery of the 64-sq mi area (area A). The loading node number assigned to the CATS zones in Groups B and C depended upon where trips having an origin or destination in these CATS zones would most likely enter or leave the system of external loading nodes which encircled the 64-sq mi area.

For example, all CATS zones in Group C included in the area 2 mi on either side of the extension of the center north-south freeway (shown as cross-hatched area X in Fig. 3) were assigned the intermediate system number 81, the external loading node number of the intersection of that freeway and the northernmost east-west freeway. All CATS

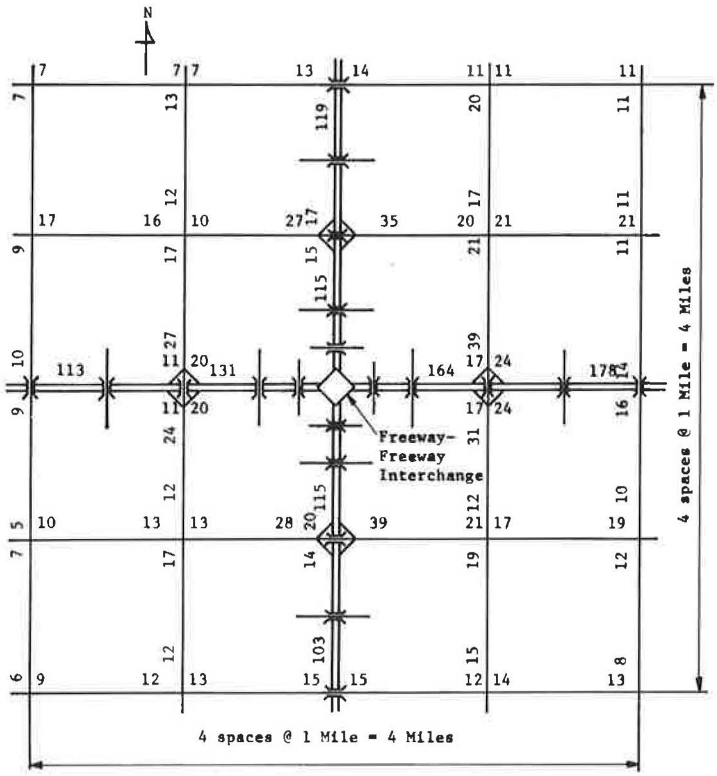


Figure 6. Average weekday volumes—interchange spacing 2 mi, grade separation spacing ½ mi, trip density = 23,000 destinations per sq mi. Numbers shown are 24-hr average two-way weekday equivalent passenger vehicular volumes in 1000's of vehicles except on interchange ramps where one-way volumes are shown.

zones in Group C which were located in an area northwest of area A (shown as cross-hatched area Y in Fig. 3) were assigned the intermediate system number 73, the number assigned to the external loading node at the northwestern intersection of the peripheral freeways. CATS zones in Group B were assigned the intermediate system number corresponding to the closest external loading node on the peripheral arterial street. For example, in Figure 3 CATS zone 43115 was assigned the intermediate system number 76.

A directional 128 × 128 trip table was then generated from the CATS nondirectional triangular trip table. Each CATS zone-to-zone interchange was read into the computer one at a time. Each CATS zone number was assigned an intermediate system number. If either or both of the CATS zones were in Group A or if both of the zones were in Group B, the trips between the zones were added into the 128 × 128 matrix trip table in the elements corresponding to their intermediate system numbers (I, J and J, I) to build a directional trip table. Otherwise, the zonal trip interchange was not processed. These unprocessed zonal interchanges correspond to trips having a length over 12 mi, and would be through trips on the freeway system if they did pass through the area being analyzed. These trips were considered later in the analysis.

When the 128 × 128 trip table was completed, all entries in the table were divided by two to compensate for each trip having been added into the 128 × 128 table twice so that a directional table could be made from the nondirectional CATS O-D trip table.

A final system of zone and external loading node numbers ranging from 1 to 428 was then set up. Each intermediate-system zone number corresponded to either 1, 4, or 16 final-system zone numbers (Fig. 2). The total number of trips either originating or destined for the intermediate-system zone was divided equally between the zones into

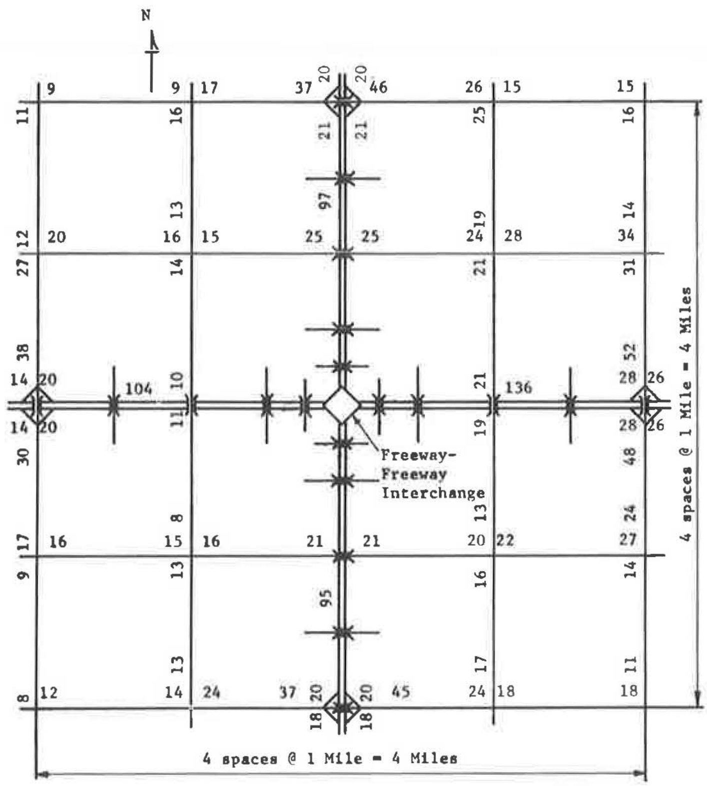


Figure 7. Average weekday volumes—interchange spacing 4 mi, grade separation spacing ½ mi, trip density = 23,000 destinations per sq mi. Numbers shown are 24-hr average two-way weekday equivalent passenger vehicular volumes in 1000's of vehicles except on interchange ramps where one-way volumes are shown.

which the intermediate system zones were divided, in the final system of zones. Each external loading node in the intermediate system had a one-to-one correspondence to the external loading nodes in the final system. The final output of the computer program was a 428 × 428 directional trip table where there were 364 zone-centroid loading nodes and 64 external loading nodes. This directional trip table was used as input to the trip assignment process.

Coding of Network

Each link in the grid system of freeways and arterial streets in the 64-sq mi area was coded for use in the trip assignment process. One-, ½- and ¼-mi streets were included in the grid system, except for the area within the 1-mi wide strip adjacent to the peripheral freeways where only the 1-mi and ½-mi streets were coded. The whole system consisted of approximately 4300 links and 2500 nodes, of which 428 were loading nodes.

Level of Service

A level of service as described by an average overall operating speed was selected for each functional type of facility in the network for input to the computer. Table 3 shows the levels of service recommended by the National Committee on Urban Transportation, the Minnesota Highway Department (Twin Cities Study), and the levels of service adopted for input to the computer in this analysis.

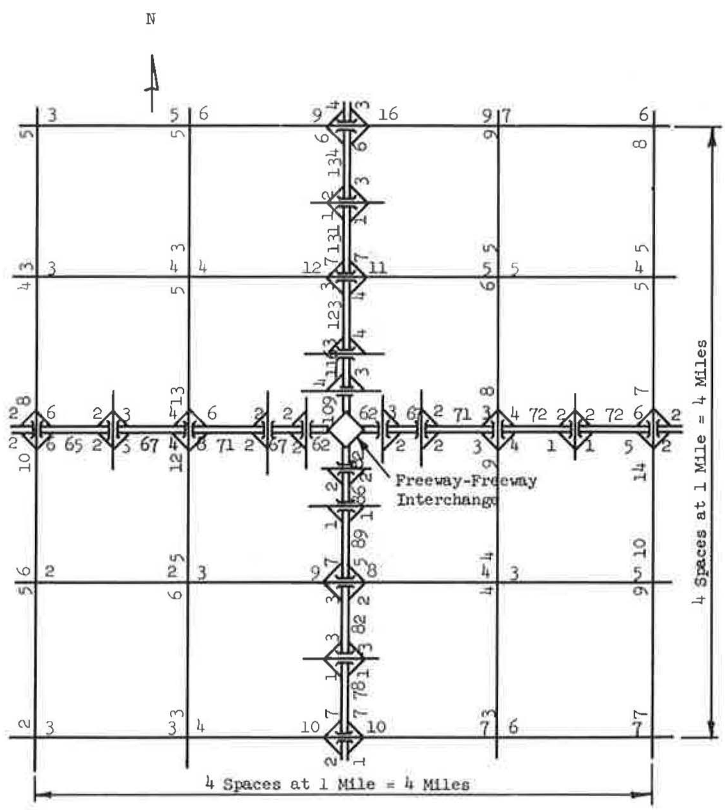


Figure 8. Average weekday volumes—interchange spacing ½ mi, grade separation spacing ½ mi, trip density = 11,000 destinations per sq mi. Numbers shown are 24-hr average two-way weekday equivalent passenger vehicular volumes in 1000's of vehicles except on interchange ramps where one-way volumes are shown.

Assignment of Trips

An all or nothing, minimum time path, directional assignment computer program was used to assign the trip table to the various networks.

The final output from the computer for each network was a printout which gave for a 24-hr average weekday the number of vehicles assigned to each directional link in the network, the turning movements made at each intersection, and the sum of the vehicle hours of travel and vehicle miles of travel on each functional classification of streets in the network.

Next, the entire CATS group of zones was divided into 20 districts (Fig. 1). The CATS triangular nondirectional trip table for trips between the 692 different CATS analsis zones was converted into a triangular nondirectional trip table for 20 districts using the computer. The trip interchanges assigned to the networks in the previous work were excluded from the district to district trip interchanges. All trips with neither an origin nor destination in the 144-sq mi area considered in the previous assignment procedure, but which did pass through the area, would be at least 12 mi in length. It was assumed that they would have traveled on one of the freeways in the area. These remaining trip interchanges were assigned by hand to the freeway part of the system.

Figures 4 through 11 show the 24-hr average weekday volume of traffic assigned to the 1-mi streets, the freeway-arterial interchange ramps, and the freeways for each network with a ½-mi spacing of grade separations.

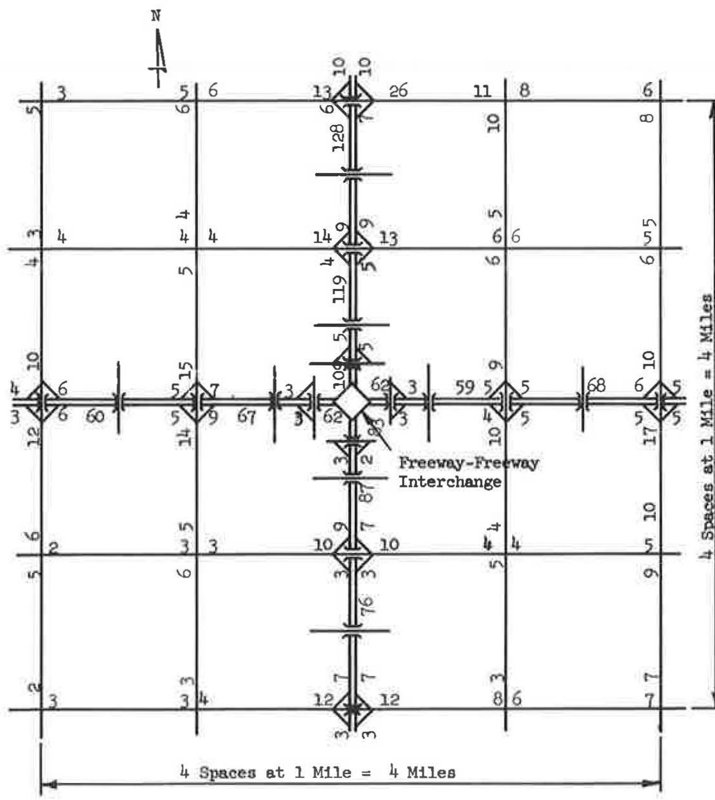


Figure 9. Average weekday volumes—interchange spacing 1 mi, grade separation spacing ½ mi, trip density = 11,000 destinations per sq mi. Numbers shown are 24-hr average two-way weekday equivalent passenger vehicular volumes in 1000's of vehicles except on interchange ramps where one-way volumes are shown.

At this point in the analysis, the networks with the freeway-arterial street interchanges spaced 4 mi apart were dropped from further consideration for the area with the population density of 21,000 persons per square mile. This decision was made because of the very high volumes (40,000 to 55,000 average daily two-way traffic volume) assigned to the arterial streets which serve as access streets to the interchanges. These access streets would have had to have been widened and made into an expressway facility to accommodate the high volumes assigned to them. Another reason for dropping the networks with interchanges spaced 4 mi apart from further analysis was the lack of adequate access to the freeways in these networks. Only 34 percent of the total vehicle miles of travel per day in the analysis area was assigned to these freeways (Table 5).

Design Hourly Volumes

Because 24-hr average weekday directional trips were assigned to the networks, it was necessary to select some percentage of the 24-hr directional volume which could be used for the design hourly volume. Thirteen percent of the directional average weekday flow was used for the design hourly volume for the predominant direction of travel and 9 percent for the other direction of flow for all arterials and for the freeway oriented toward the central business district (equivalent to 11 percent design hourly volume factor with a 60-40 split if nondirectional volumes had been used). Factors of 12 percent and 10 percent were used for the other freeway (equivalent to 11 percent design hourly volume factor with a 55-45 split if nondirectional volumes had been used).

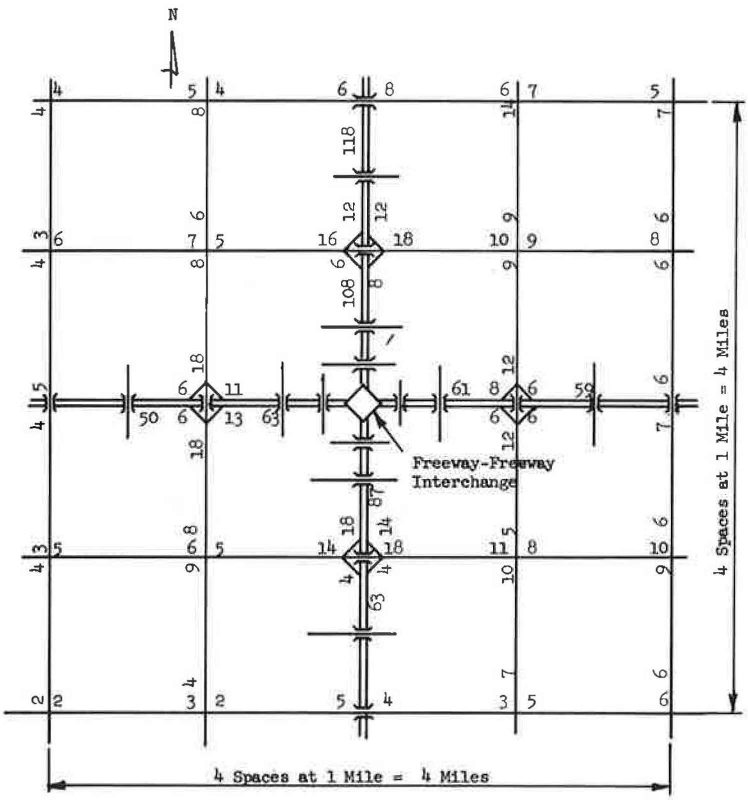


Figure 10. Average weekday volumes—interchange spacing 2 mi, grade separation spacing ½ mi, trip density = 11,000 destinations per sq mi. Numbers shown are 24-hr average two-way weekday equivalent passenger vehicular volumes in 1000's of vehicles except on interchange ramps where one-way volumes are shown.

Capacity of Arterial Street Intersections

Before checking the capacity of the arterial streets in the networks to see whether any widening of streets was necessary, assumptions had to be made concerning the rights-of-way widths and pavement widths of the existing arterial streets. After examining Chicago's Preferential Street Data Listing, it was decided to assume that all 1-mi arterial streets in the analysis area had rights-of-way widths of 80 ft and pavement widths of 60 ft with the exception of the east-west 1-mi arterials in the low trip density areas, which were assumed to have a right-of-way width of 66 ft and a 40-ft pavement width. One-half mile and ¼-mi arterials were assumed to be 66 ft wide with 40-ft pavement widths.

The arterial street intersections were checked to see whether the streets with their assumed widths had sufficient capacity to accommodate the design hourly volumes assigned to the intersections. The percent of green time of the total signal cycle time was calculated for each of the phases of the signal cycle required to handle the critical approaches to the intersections. Approaches with insufficient capacity to handle the assigned design hourly volumes were widened to provide the necessary capacity.

The methodology developed by Pinnell, Capelle and Drew (15, 16, 17, 18) was used for determining the signal phasing, and the capacity of the at-grade intersections involved in the design of the interchanges between the freeways and the arterial street system.

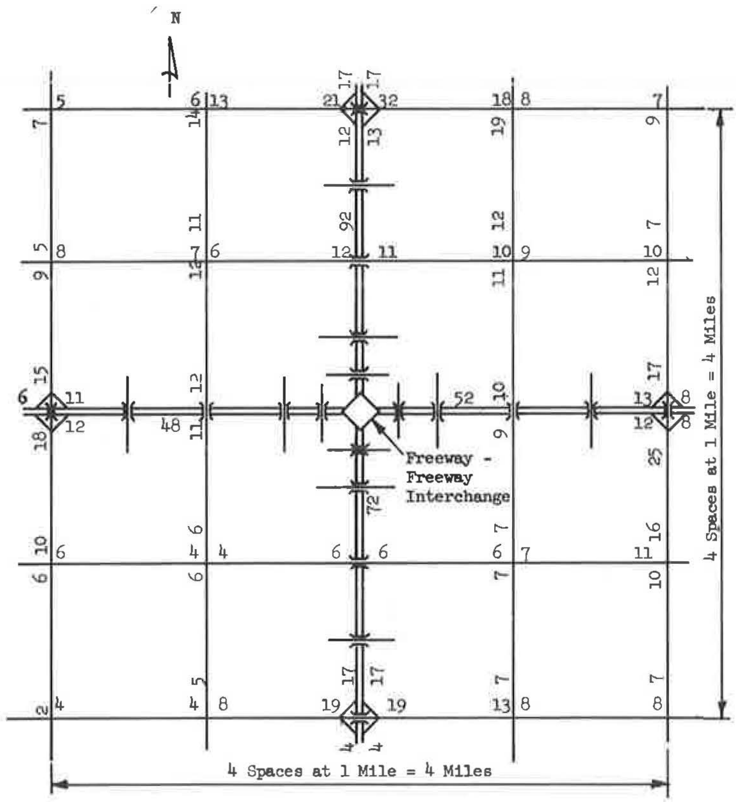


Figure 11. Average weekday volumes—interchange spacing 4 mi, grade separation spacing ½ mi, trip density = 11,000 destinations per sq mi. Numbers shown are 24-hr average two-way weekday equivalent passenger vehicular volumes in 1000's of vehicles except on interchange ramps where one-way volumes are shown.

Freeway Design

The freeways in the networks were designed according to the AASHO policy on design standards for the Interstate System (19) and policy on arterial highways in urban areas (20). Thus, the freeway was designed with full control of access and with no cross traffic at grade. The freeway was depressed below existing ground level throughout its length except at freeway-freeway interchanges. Between grade separation bridges the grade line was brought to within 4 to 6 ft of the existing ground line. Continuous frontage roads were provided throughout the length of the freeway on both sides to provide for flexibility in operation of the freeway and street network.

In addition to capacity-volume relationships, the arrangement and number of lanes on the freeways were based on the following considerations: lane balance, basic number of lanes, and flexibility in operation as stated by Leisch (21). Sketches of the final designs for the networks including the freeways and the arterials are shown in Figures 12 and 13.

If the design called for more than a 10-lane freeway, the total number of freeway lanes was divided up by means of medians with shoulders and barriers so that no freeway roadway would be more than 5 lanes in width. Transfer roadways were provided between the various roadways on the freeway to provide for flexibility of operation in the system.

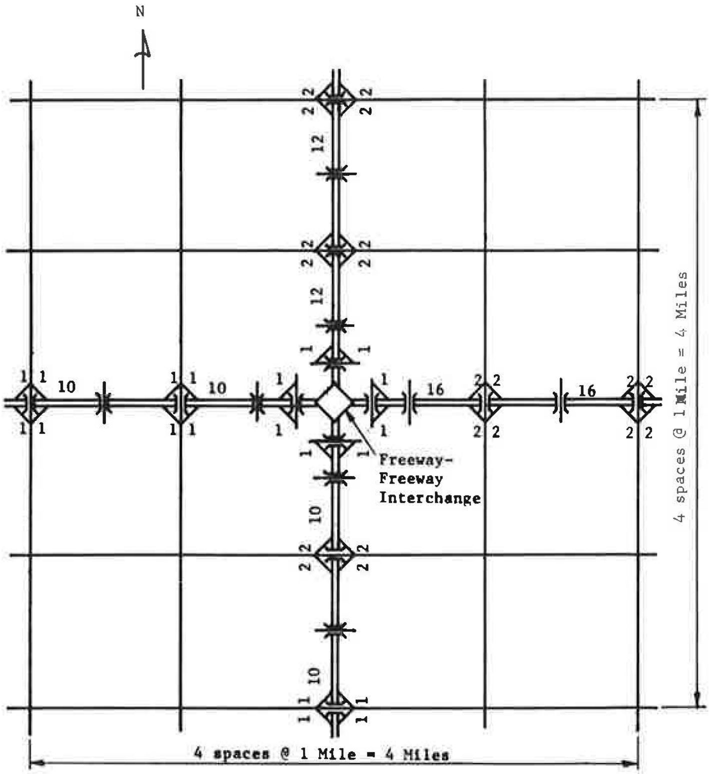


Figure 12. Geometric design for network with interchange spacing 1 mi, grade separation spacing ½ mi, trip density = 23,000 destinations per sq mi. Numbers shown on the freeways and interchanges are number of lanes, including auxiliary, local, express, and reversible lanes (see Table 13); all 1-mi arterial streets have six lanes; all ½-mi arterial streets have four lanes. Geometric design for networks with interchange spacing 1 mi and grade separation spacings of ¼ mi and 1 mi is same as is shown.

Construction Cost

The construction cost data used in the analysis were based on data obtained from the Bureau of Highways and Expressways, Department of Public Works, City of Detroit, and District 10 (Chicago Area) of the Illinois Division of Highways. A summary of the total construction cost for each network is given in Tables 15 and 16 of the Appendix.

Vehicle Operating and Accident Costs

Unit vehicle-operating and accident costs used in the study were taken from the work done by Joseph, Haikalis, Hoch and Jorgenson of the CATS staff (22, 23, 24, 25, 26).

Travel Time Costs

The value of travel time used in the analysis consisted of a range of values rather than a single value. A range of values was used because of the controversy among people involved in highway planning and economics concerning the value of time for passenger vehicles. Haney (12) in a survey of literature concerning the value of travel time for vehicles on highways found that since 1925 the values of time suggested for use in some 50 publications ranged from 30 cents to $4.80 per vehicle hour.

The values of time per hour per equivalent passenger vehicle chosen for use in the sensitivity analysis for studying the effect of different values of travel time on the optimum spacing of interchanges and grade separations were $0.00, $0.50, $1.00, $1.50, $2.00 and $3.00.

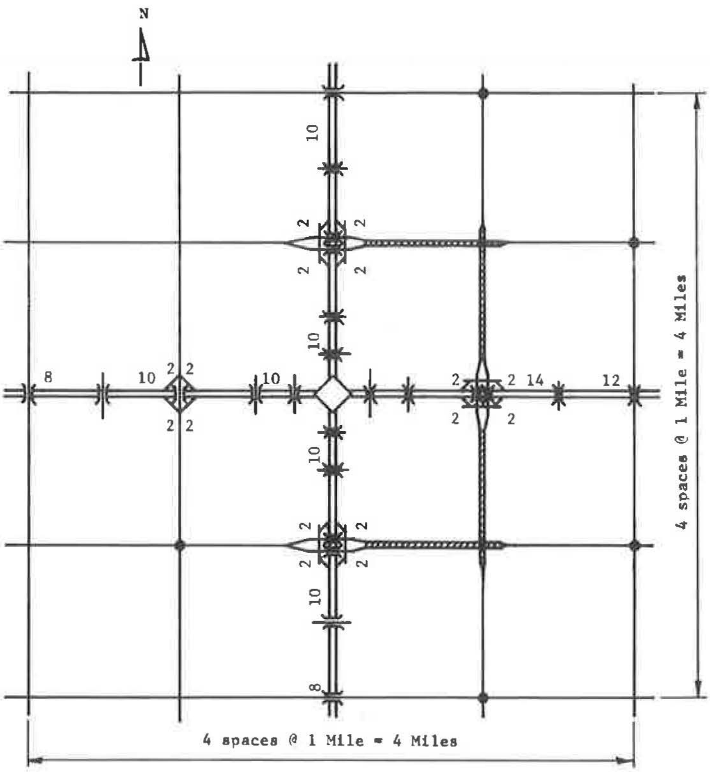


Figure 13. Geometric design for network with interchange spacing 2 mi, grade separation spacing ½ mi, trip density = 23,000 destinations per sq mi. Numbers shown on the freeways and interchanges are number of lanes, including auxiliary, local, express, and reversible lanes (see Table 13); all 1-mi arterial streets have six lanes unless noted; all ½-mi arterial streets have four lanes. Geometric design for networks with interchange spacing 1 mi and grade separation spacings of ¼ mi and 1 mi is same as is shown.

Economic Analysis

Since there is a variety of interest rates and amortization periods suggested for use in the literature in the field of economic analysis for highway improvements, a sensitivity analysis involving interest rates and amortization periods was made in the economic analysis. Interest rates of zero, 5, 7, 10 and 15 percent were used with amortization periods of 20 and 25 yr for the entire highway facility, and 40 yr for right-of-way costs with 20 and 25 yr for the remainder of the facilities.

The volumes of vehicular traffic used in calculating user costs (operating, accident, and time) for input to the criterion function were the 1956 origin-destination volumes for Chicago. These volumes were assumed to be the design year volumes. Thus, the analysis was one of finding the optimum combination of spacing of interchanges and grade separations to minimize the total transportation cost for the design year.

A sensitivity analysis was also made for the operating speeds (level of service) used in calculating the user costs in the economic analysis. It was assumed that 35 percent of the daily traffic would operate on the freeways and 1-mi arterials at speeds which are lower than those experienced by the remainder of the traffic during the day, since the volume-to-capacity ratios for the freeways and 1-mi arterial streets during these peak periods would be higher than in the off-peak periods. The operating speeds for the other streets in the network were assumed to remain the same throughout the day. Table 4 gives the operating speeds which were used to calculate the user costs in the economic analysis.

The right-of-way costs used in this study were derived from data obtained from the Bureau of Highways and Expressways of Detroit and District 10 of the Illinois Division of Highways. Right-of-way costs per acre of \$145, 000, \$180, 000, \$215, 000 and \$285, 000 were used in the economic analysis to see how sensitive the optimum combination of spacing of interchanges and grade separations is to different right-of-way costs per acre.

RESULTS AND DISCUSSION

Total Vehicle Miles and Vehicle Hours of Travel

The total vehicle miles and vehicle hours of travel for an average day resulting from assignments to the eight different network configurations are shown in Table 5 and Table 6 for the area with trip density of 23, 000 destinations per square mile. Tables 7 and 8 show the same information for the area with trip destination density of 11, 000 trips per square mile. All trip data are in terms of equivalent passenger vehicles.

The data in Tables 5 and 7 show the effect of the spacing of interchanges on the use of the freeways. As the spacing of points of interchange was increased, the accessibility to the freeway for many trips decreased. The result was that the percent of total miles of travel in the network which was performed on freeways decreased.

The data in Tables 5 and 7 also show that as the interchange spacing was changed from ½ mi to 1 mi, a small increase in total vehicle miles of travel occurred. For the two networks with a spacing of grade separations of ½ mi, a change in interchange spacing from ½ mi to 1 mi changed total vehicle miles of travel only 1 percent for the area with the higher trip destination density.

As the spacing of interchanges was changed from 1 mi to 2 mi there was a decrease of approximately 3 percent in the total average daily vehicle miles of travel. With the spacing of interchanges increased to 2 mi, more drivers found that both distance and travel time were shorter via arterial streets, as compared to freeways. When the interchange spacing increased from 2 to 4 mi the total average daily vehicle miles of travel increased.

Tables 9 and 10 show how the use of the different classes of streets in the arterial system changed as the spacing of interchanges was increased from ½ mi to 2 mi Spacing of grade separations was held constant at ½ mi. The decrease in use of the freeways with the increase in spacing of interchanges is evident. With a change of spacing of interchanges from ½ mi to 1 mi, there was only a slight change in the number of vehicle miles of travel on the ½-mi arterial streets. The largest changes were on the ¼-mi and 1-mi arterials. With a change in spacing of interchanges from 1 mi to 2 mi the reverse was true. There were only small changes in vehicle miles of travel performed on the ¼- and 1-mi arterials, but a relatively large change in the use of the ½-mi arterial streets.

Tables 6 and 8 show the effect that the spacing of grade separations has on total vehicle miles of travel. For a constant spacing of interchanges, the total vehicle miles of travel increased as the spacing of grade separations on the freeway increased. This increase in travel distance was very small when compared to the total vehicle miles of travel for the entire 16-sq-mi area.

Volumes on Arterial Streets and Freeways

The 24-hr average daily nondirectional volumes for the arterial streets and freeways are shown in Figures 4 through 11 for the networks with a ½-mi spacing of grade separations. Through trips are included in the volume shown.

As the accessibility of the freeway decreased because of increased spacing of the interchanges, the volume of traffic on the freeway decreased. For example, for the higher trip density area the easternmost section of the east-west freeway experienced a decrease in 24-hr nondirectional volume of 16 percent as the spacing of the interchanges on the freeway was changed from ½ mi to 2 mi. For a change in spacing of interchanges from ½ mi to 4 mi, a 36 percent decrease in freeway volume took place.

Accompanying the decrease in use of the freeways as the spacing of interchanges increased was an increase in the volumes on the 1-mi arterial streets. For example, for the higher trip density area in the northeastern quadrant of the network with interchanges spaced ½ mi apart, the volumes on the two north-south 1-mi arterials just south of the first 1-mi arterial north of the freeway were each 13, 000 vehicles per day, for a total of 26, 000 vehicles in the corridor. Both of these streets interchanged with the freeway. The same 1-mi arterials in the network with interchanges spaced 2 mi apart, with grade separations spaced ½ mi apart, had 24-hr volumes of 21, 000 and 11, 000 vehicles, respectively, for a total of 32, 000 vehicles in the corridor. The street with the 21, 000 vehicles interchanged with the freeway, while the street with the volume of 11, 000 vehicles per day did not. Thus, as the spacing of interchanges was changed from ½ mi to 2 mi, there was a 23 percent increase in arterial street volumes in this corridor.

Another pattern to observe is the change in volumes on the arterial streets which interchange with the freeway as the spacing of interchanges increased from network to network. As the number of interchanges with the freeway decreased, the volumes on the arterial streets that interchange with the freeway increased until the very high volume of 52, 000 vehicles per day was reached on the easternmost north-south 1-mi arterial at the freeway in the network with interchanges spaced 4 mi apart. Also, as the number of interchanges with the freeways decreased, the volumes on the ramps of the interchanges increased.

The pattern of volumes on the 1-mi arterial streets and on the interchange ramps shows that a large part of the traffic on the 1-mi arterials was oriented toward the freeways. The major arterial streets had the important function of serving as feeder streets for the freeways for the long trips in the networks. This also is shown by the fact that the combined right- and left-turn 24-hr volumes on the approaches of the intersections of the 1-mi arterial streets that were 1 mi from the freeways were from 15 to 50 percent of the total 24-hr approach volumes.

The average daily operating and accident costs for travel in the design year on each of the networks are given in Tables 11 and 12 for each of two levels of service.

Design

The final geometric designs selected for the networks (arterial streets, freeways, and interchanges) to accommodate the assigned volumes of traffic at the assumed levels of service for the area with trip density of 23, 000 destination per square mile are shown in Figures 12 and 13. A tabular summary of the design features of the networks is shown in Tables 13 and 14 for both areas.

Transfer roadways were provided between the reversible lanes and the adjacent through lanes at approximately 4 to 5-mi intervals.

In freeway sections where more than 5 through lanes for one direction of travel (not including the reversible lanes) were required, the roadway was divided into a set of express lanes and a set of local lanes by means of a median. Transfer roadways were provided between these two types of facilities every 2 mi. Interchange facilities between the freeway and the surface arterial street system were not provided on the express lanes, but on the right side of the local through lanes only. The ends of the ramps on the transfer roadways and the freeway-to-surface arterial street interchanges were arranged so that a driver cannot change from the express lanes to the local lanes and then immediately weave across the 3 or 4 local lanes to leave the freeway by means of an interchange ramp located on the right side of the local lanes.

The right-of-way requirements for the freeway facilities and for the arterial street widening are given in Tables 13 and 14 for each of the interchange spacings. The areas listed are not the total area required for the facilities, but are only that additional portion of the area which must be purchased. Existing streets and alleys required for the facilities (already publicly owned) are not included in the tables.

When interchanges were spaced 2 mi apart, 4 miles of existing 6-lane arterial street (1-mi arterial street) had to be widened into 8-lane divided arterial streets for the area with trip density of 23, 000 trip destinations per square mile. For the area with trip density of 11, 000 trip destinations per square mile it was necessary to widen the east-west

40-ft wide 1-mi arterials interchanging with the freeway to 6 lanes for 1 mi when the interchange spacing was 4 mi and the grade separation spacing was either ½ mi or 1 mi. No arterial street widening, other than isolated intersection widening to provide a left-turn lane, was required for the other interchange spacings.

Estimates of total construction cost, the construction cost per mile, and the construction cost per lane mile for each of the freeway-arterial street networks are given in Tables 15 and 16.

Economic Analysis: Minimization of Total Annual Transportation Cost

The data given in Tables 17 and 18 were obtained from the economic analysis using the feasible combinations of selected values of the input parameters in the sensitivity analysis for the design year volumes.

The various annual costs for all networks for one combination of the values of the input parameters are given in Tables 19 and 20. For each combination, the network with the lowest total annual cost is designated and the percentage difference between the highest total annual cost and the lowest total annual cost for the networks within the group is given. Also the network with the lowest total annual capital costs is designated. Another statistic given is the ratio of the total annual user cost to the total annual cost. This ratio is the average of the ratios for each network within the group.

A number of observations can be made from the data concerning the sensitivity of the optimum combination of spacing of interchanges and spacing of grade separations to different values for the input parameters used in the economic analysis.

In general, the optimum spacing of interchanges and grade separations was not sensitive to changes in the levels of service considered in the analysis, or to changes in right-of-way costs within the range of costs considered ($145, 000 per acre to $285, 000 per acre).

The optimum spacing of interchanges and grade separations was not found to be sensitive to change in amortization period for the periods examined in the analysis.

The optimum spacing of interchanges and grade separations was sensitive to the cost of time which was used in the economic analysis. For example, for the area with a trip density of 23, 000 destinations per square mile and for a time cost of $0. 00 per hour, the optimum spacing of interchanges was 2 mi and grade separations was 1 mi, or in some instances ½ mi, for almost all of the values of the other input parameters. A few exceptions were found when the highest right-of-way cost was used ($285, 000 per acre) in conjunction with the higher interest rates (10 percent and 15 percent). In these cases the optimum spacing of interchanges and grade separations was usually 1 mi.

As higher time costs were used, closer spacings of interchanges and grade separations were found to be optimum with these spacings generally being ½ mi for both interchanges and grade separations. The time cost at which this change in optimum spacing takes place varied with the interest rate used in the analysis.

The general effect of increasing the interest rate was to cause the change in optimum spacing to take place at a higher time cost. The following example for the area with trip density of 23, 000 destinations per square mile is based on design year volumes with an amortization period of 25 yr for construction and 40 yr for right-of-way; right-of-way cost of $145, 000 per acre; level of service of 25 mph on the 1-mi arterial streets and 45 mph on the freeways during the peak periods; and 30 mph and 55 mph respectively during the off-peak periods. With these held constant, the change in optimum spacing of interchanges from 2 mi to ½ mi and optimum spacing of grade separations from 1 mi to ½ mi took place at a time cost of $0. 50 per hour for an interest rate of zero percent; at $1. 00 per hour for interest rates of 5 percent and 7 percent; at $1. 50 per hour for 10 percent; and at $2. 00 per hour for 15 percent.

It was found, however, and this point should be emphasized, that the difference between the highest and the lowest total annual transportation costs for the design year for the 8 networks for each combination of the values of the input parameters for the area with the trip density of 23, 000 destinations per square mile was generally between 2 percent and 4 percent, except for the combinations where the time cost was $0. 00 or $0. 50 per hour where the difference sometimes ranged to approximately 9 percent.

For the area with trip density of 11, 000 destinations per square mile the difference between the highest and lowest total annual transportation costs for the 9 networks for each combination of the values of the input parameters was generally between 10 and 25 percent with the network with the interchanges spaced at 4 mi always being the highest cost network. If the networks with interchanges spaced 4 mi apart are excluded from consideration, the range of costs was generally from 2 to 4 percent as in the case for the area with the higher trip destination density.

Criteria For Determining Optimum Spacing of Interchanges and Grade Separations

The small differences (generally 2 to 4 percent) that were found in the economic analysis to exist between the total annual transportation cost for the networks studied make it rather difficult, if not impossible, to select the optimum or best spacing of interchanges and grade separations on the basis of only the economic factors considered in this research. Input data are not exact, and the traffic assignment process certainly cannot predict link volumes within 2 to 4 percent. Also, capital costs are based on estimates of quantities and unit costs which may vary from the values found to exist when construction takes place.

The selection of the best or optimum spacing of interchanges and grade separations must, therefore, be based on criteria other than economic analysis alone. Other criteria that might be used are: (a) the characteristics of traffic operations on the system, (b) the amount of land required for the transportation facilities which must be removed from the taxable base of the community, (c) the reorganization of land use patterns due to spacing of interchanges, and (d) convenience to the people of the community.

The process of selecting the best spacing of interchanges and grade separations based on criteria other than economics alone can be illustrated for the area used in the analysis with trip density of approximately 23, 000 destinations per square mile as follows.

In the economic analysis which minimized total annual transportation cost, a network with a ¼-mi spacing of grade separations was never found to be the lowest cost. Therefore, the ¼-mi spacing of grade separations would not be selected for the final design. The 1-mi spacing of grade separations, although found to be the optimum for the lower values of time (generally \$0. 00 and \$0. 50 per hour), would cause much inconvenience to the person traveling in the local community who must cross the freeway and would not be chosen. Therefore, the best spacing of grade separations would then be ½ mi.

The closest spacing of interchanges considered in the analysis (½ mi) presents a number of problems in freeway operations. The close spacing of the interchanges with the short weaving section between successive interchange ramps makes it difficult to place exit information signs on the freeway in such a way that drivers will have adequate time to react to the sign and then have sufficient time to make the necessary weaving maneuvers to leave the freeway in a safe, non-hazardous manner. Also, with the ½-mi spacing of interchanges many short trips will make use of the freeway thus making necessary a large number of lanes on the freeway. This large number of lanes coupled with the rather frequent points of turbulence caused by entering, exiting, and weaving vehicles may cause some confusion for the freeway user, especially the infrequent user. Thus, the ½-mi spacing of interchanges would usually not be recommended because of traffic operation considerations.

The network with the 2-mi spacing of interchanges required that 4 mi of arterial street be widened. A 4-mi strip of land along the arterial street had to be purchased in addition to the right-of-way required for the freeway. Because of the relatively wide spacing of interchanges, there was a large concentration of traffic at the interchanges. Split diamond interchanges with one-way roadways were required. Two-lane entrance and exit ramps which are difficult to operate were also required. Because of the above considerations, the 2-mi spacing of interchanges would usually not be selected.

For an area with trip destination densities of approximately 23, 000 per square mile, and with a grid system of arterial streets at ½-mi intervals, interchanges spaced 1 mi apart and grade separations spaced ½ mi apart would be the best or optimum design.

Similar reasoning can be applied to the selection of the optimum network for the area with trip density of 11, 000 destinations per square mile. The networks with 4-mi spacing of interchanges can be eliminated from consideration because they were always the highest cost network and also required widening of arterial streets. The ½-mi spacing of interchanges would not be recommended because of traffic conditions as discussed earlier. Thus the choice is between 1-mi and 2-mi spacing. Neither required widening of arterial streets. In the economic analysis the networks with 1-mi spacing of interchanges were always of higher cost than the networks with interchanges spaced 2 mi apart, although the difference was small.

The ¼-mi spacing of grade separations could not be justified for the area with the higher trip destination density, and thus was not considered for the area with the lower trip destination density. The networks with the 2-mi spacing of grade separations, although of slightly lower total annual transportation cost than the networks with either 1- or ½-mi spacing of grade separations, cannot be justified because of inconvenience to persons traveling in the local community who must cross the freeway.

For an area with trip destination densities of approximately 11,000 per square mile, and with a grid system of arterial streets at ½-mi intervals, interchanges spaced 2 mi apart and grade separations spaced either 1 mi or ½ mi apart would be the best or optimum design.

CONCLUSIONS

For a constant travel demand in an area with trip destination densities averaging either 11,000 or 23,000 trip destinations per square mile and with a grid system of arterial streets spaced ½ mi apart and freeways spaced 4 mi apart and with values of input parameters as cited, the following conclusions may be drawn:

1. The proportion of vehicle miles traveled via the freeway decreases with increases in the spacing of interchanges between the arterial street system and the freeways.
2. For a fixed spacing of interchanges, the total vehicle miles of travel in the network increases a very small amount as the spacing of grade separations increases.
3. For a fixed spacing of grade separations, the total vehicle miles of travel in the network first increase slightly and then decrease a small amount as the spacing of interchanges is increased.
4. For a fixed spacing of grade separations, the total vehicle hours of travel per average day increases with increases in the spacing of interchanges.
5. Using the criterion function of minimizing the total annual transportation costs, the optimum spacing of interchanges and grade separations is, in general, not sensitive to changes in amortization periods, levels of service, or right-of-way costs, but is sensitive to changes in time costs and interest rates.
6. The range in total annual transportation costs for systems with different spacing of interchanges and grade separations was very low (generally 2 to 4 percent). Thus, it is preferable to consider other factors along with the economic factors which were considered in the research (right-of-way costs, construction costs, time costs, and operating and accident costs) when selecting the optimum spacing of interchanges and grade separations. These other factors would include the characteristics of traffic operations on the system, the amount of land required for the transportation facilities which must be removed from the taxable base of the community, the comfort and convenience to the people of the community, and the reorganization of land-use patterns which might be expected to result from changes in the spacing of interchanges.

ACKNOWLEDGMENTS

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Appendix

TABLE 1

1956 LAND USE AND TRIP END DENSITIES FOR 16 CATS ZONES INCLUDED IN ANALYSIS

CATS Zone Number (One Square Mile Zones)	Land Use in 100,000 Square Feet - 1956										Vacant Land			1956 Vehicle Equivalent Trip Destinations (1000)	1956 Population Persons Per Square Mile (1000)
	Total Land Area	Residential	Manufacturing	Commercial	Public Buildings	Parking	Unusable	Streets and Alleys	Transportation	Public Open Space	Manu-facturing	Commercial	Residential		
33063	260	100.0	4.0	15.5	3.7	2.4	-	76.4	43.7	-	-	1.4	12.7	20	21.5
33064	299	88.5	28.5	15.7	6.4	6.2	-	75.2	66.9	-	5.7	1.8	4.4	26	16.5
33065	286	89.5	9.5	20.5	5.7	2.5	-	93.1	8.0	53.3	2.1	0.1	1.3	27	28.5
33066	275	108.0	14.8	28.7	6.8	2.7	-	90.8	11.8	0.6	3.9	1.9	5.1	31	28.0
34067	278	111.0	13.6	24.2	7.5	6.6	-	96.7	8.9	3.7	0.2	0.9	4.8	23	47.8
34068	272	47.1	42.4	24.1	2.1	9.9	-	79.2	41.5	-	15.4	2.2	8.1	21	11.2
34069	271	114.0	10.3	25.1	6.9	0.8	-	86.4	10.4	2.1	1.0	1.9	12.5	20	30.6
34070	287	74.2	55.7	15.2	2.7	5.0	-	73.8	47.0	0.4	0.4	6.0	6.9	28	13.6
43122	271	150.0	1.3	16.2	8.6	0.2	-	88.6	0.5	2.4	-	1.0	2.6	19	22.3
43123	277	161.0	1.1	9.1	12.0	0.2	-	82.8	6.0	2.6	-	0.3	2.0	17	12.0
43125	286	123.0	1.4	18.5	7.0	0.2	-	78.5	5.5	46.1	-	1.1	4.7	28	27.0
43126	281	166.0	-	12.8	5.6	0.2	-	89.3	1.0	1.6	-	1.2	2.7	18	16.7
44128	280	58.0	86.7	5.7	7.7	2.0	-	66.1	27.0	14.5	7.0	0.5	4.5	21	8.1
44129	280	147.0	0.2	8.6	5.8	-	-	100.2	2.7	2.2	-	2.4	11.2	15	17.9
44131	283	117.0	43.8	17.9	5.9	-	-	81.5	5.1	1.9	0.3	2.4	6.9	25	15.2
44132	283	156.0	0.3	14.3	4.1	0.1	-	98.9	2.9	0.3	-	1.8	4.3	25	19.6
												Average		22.8	21.0

Source: Table #100-1 CATS

TABLE 2

1956 LAND USE AND TRIP END DENSITIES FOR 16 CATS ZONES INCLUDED IN ANALYSIS

CATS Zone Number (One Square Mile Zones)	Land Use in 100,000 Square Feet - 1956										Vacant Land			1956 Vehicle Equivalent Trip Destinations (1000)	1956 Population Persons Per Square Mile (1000)
	Total Land Area	Residential	Manufacturing	Commercial	Public Buildings	Parking	Unusable	Streets and Alleys	Transportation	Public Open Space	Manu-facturing	Commercial	Residential		
56249	272	95.2	10.1	10.8	4.1	0.6	-	82.3	31.8	-	13.8	0.4	23.2	7	9.6
56250	277	116.6	0.4	11.8	8.8	0.4	-	82.9	2.1	28.7	-	6.3	18.9	14	13.1
56251	277	53.8	-	1.7	-	-	-	41.7	5.3	133.2	-	0.4	41.3	21	2.7
56252	280	67.6	-	3.5	8.3	-	-	40.1	4.9	99.0	-	9.5	46.7	13	5.3
56254	276	67.4	3.5	3.7	1.4	1.6	-	93.5	8.4	4.1	17.8	1.1	73.4	11	6.8
56255	278	152.2	0.3	9.6	8.3	0.8	-	77.5	9.0	5.1	-	3.7	11.6	11	10.0
56256	274	103.0	-	15.5	2.3	1.8	-	68.3	0.2	52.0	-	4.7	26.5	11	6.0
56257	280	125.3	0.7	8.0	10.3	0.0	-	81.9	4.6	-	-	3.6	45.5	9	7.4
56260	276	134.5	0.3	5.4	0.8	-	-	90.4	1.1	5.3	0.7	4.5	32.9	10	10.1
56261	290	147.6	11.2	8.6	5.5	-	-	81.7	14.9	2.9	-	1.0	16.4	9	8.4
56262	271	166.9	0.0	6.1	3.7	0.0	-	77.0	3.2	1.5	-	4.5	7.9	10	9.3
56263	276	108.5	0.1	2.7	8.6	2.4	-	72.8	5.0	27.1	-	1.4	47.0	9	8.1
66351	284	125.8	7.0	6.6	8.6	-	-	78.1	0.5	0.5	1.0	47.7	8.7	15	10.9
66352	270	99.0	0.4	7.5	6.1	-	-	96.3	7.7	2.5	0.0	6.8	44.1	5	9.2
66353	277	146.8	0.7	6.7	11.6	0.1	-	71.6	7.0	12.9	-	3.0	17.0	11	8.7
66354	281	118.3	0.1	5.0	5.3	-	-	50.7	5.5	68.7	-	1.8	25.7	3	7.7
												Average		10.6	8.3

Source: Table #100-1 CATS

TABLE 3

MINIMUM DESIRABLE LEVELS OF SERVICE FOR EXISTING URBAN FREEWAYS AND STREETS

Type of Street	NCUT (2) Overall Speed (MPH) Peak Hour	NCUT (2) Overall Speed (MPH) Off-Peak	Minnesota Highway (3) Department (Twin Cities Study) Overall Speed (MPH) Peak Hour	Minnesota Highway (3) Department (Twin Cities Study) Overall Speed (MPH) Off-Peak	Overall Speed Adopted For Traffic Assignment
Freeway	35	35-50	40-50	40-60	45
Major Arterial (undivided)	25	25-35	20-25	30-45	1 mile streets 25
Collector	20	20-25	20-25	20-25	1/2 mile streets 20
Local	10	10-20	15	10-20	1/4 mile streets 15

TABLE 4

OPERATING SPEEDS USED

IN THE ECONOMIC ANALYSIS

Street Classification	Design-Year Volumes: Average Daily Speed* (MPH)	Design-Year Volumes: Peak Period 35% of Trips (MPH)	Design-Year Volumes: Off Peak Period 65% of Trips (MPH)
Freeways	45	45	55
One Mile Arterials	25	25	30
1/2 Mile Arterials	20	20	20
1/4 Mile Arterials	15	15	15
Ratio of Freeway Speed to One Mile Arterial Speed	1.80	1.80	1.83

*Speeds used for assigning zone to zone interchange trips to the network. The other speeds were used only in the economic analysis.

TABLE 5

VEHICLE MILES OF TRAVEL PER DAY

Design Year

(through trips on freeways not included)

Interchange Spacing	Grade Separation Spacing	Arterials (Vehicle Miles)	Freeways (Vehicle Miles)	Total (Vehicle Miles)	Per Cent Travel on Freeways
1/2	1/4	693,000	910,500	1,603,500	57
1/2	1/2	694,700	910,700	1,605,400	57
1	1/4	763,200	855,700	1,618,900	53
1	1/2	768,000	854,100	1,622,100	53
1	1	772,100	864,100	1,636,200	53
2	1/4	817,800	747,300	1,565,100	48
2	1/2	823,800	748,100	1,571,900	48
2	1	831,800	750,500	1,582,300	47
4	1/4	1,090,800	552,800	1,643,600	34
4	1/2	1,095,200	552,700	1,647,900	34
4	1	1,108,700	552,800	1,661,500	33

NOTE: Trip density = 23,000 destinations/sq. mi.

TABLE 6

AVERAGE DAILY EQUIVALENT VEHICLE MILES OF TRAVEL AND EQUIVALENT VEHICLE HOURS OF TRAVEL FOR 16 SQUARE MILE AREA FOR DESIGN YEAR

(through trips not included)

		Average Daily Design Year Volumes			
			Average Daily Speed (MPH)	Peak Period Speed 35% of Trips (MPH)	Off-Peak Period Speed 65% of Trips (MPH)
Freeways			45	45	55
One Mile Arterials			25	25	30
Network					
Interchange Spacing	Grade Separation Spacing	Average Daily Vehicle Miles of Travel	Vehicle Hours of Travel for Average Day		
1/2	1/4	1,603,500	50630	46150	
1/2	1/2	1,605,400	50690	46210	
1	1/4	1,618,900	52610	48050	
1	1/2	1,622,100	52780	48210	
1	1	1,636,200	53200	48530	
2	1/4	1,565,100	52890	48590	
2	1/2	1,571,900	53160	48840	
2	1	1,582,300	53620	49220	

NOTE: Trip density = 23,000 destinations/sq. mi.

TABLE 7

VEHICLE MILES OF TRAVEL PER DAY

Design Year

(through trips on freeways not included)

Inter-change Spacing	Grade Separation Spacing	Arterials (Vehicle Miles)	Freeways (Vehicle Miles)	Total (Vehicle Miles)	Per Cent Travel on Freeways
1/2	1/2	334,302	505,609	839,911	60.2
1	1/2	368,003	482,801	850,804	56.7
1	1	370,595	491,654	862,249	57.0
2	1/2	399,849	430,410	830,259	51.8
2	1	403,771	431,513	835,284	51.7
2	2	387,645	452,278	839,923	53.8
4	1/2	536,999	336,217	873,216	38.5
4	1	546,153	337,481	883,634	38.2
4	2	550,619	379,270	929,889	40.8

NOTE: Trip density = 11,000 destinations/sq. mi.

TABLE 8

AVERAGE DAILY EQUIVALENT VEHICLE MILES OF TRAVEL AND

EQUIVALENT VEHICLE HOURS OF TRAVEL FOR 16 SQUARE MILE AREA

FOR DESIGN YEAR

(through trips not included)

		Average Daily Design Year Volumes			
			Average Daily Speed (MPH)	Peak Period Speed 35% of Trips (MPH)	Off-Peak Period Speed 65% of Trips (MPH)
Freeways			45	45	55
One Mile Arterials			25	25	30
Network					
Inter-change Spacing	Grade Separation Spacing	Average Daily Vehicle Miles of Travel	Vehicle Hours of Travel for Average Day		
1/2	1/2	839,911	26,243	23,497	
1	1/2	850,804	27,275	24,640	
1	1	862,249	27,623	24,752	
2	1/2	830,259	27,665	24,991	
2	1	835,284	27,916	25,204	
2	2	839,923	27,759	25,059	
4	1/2	873,216	31,431	28,491	
4	1	883,634	32,380	28,909	
4	2	929,889	33,646	30,706	

NOTE: Trip density = 11,000 destinations/sq. mi.

TABLE 9

AVERAGE DAILY EQUIVALENT VEHICLE MILES OF TRAVEL
FOR 16 SQUARE MILE AREA FOR DESIGN YEAR
BY STREET CLASSIFICATION FOR NETWORKS
WITH GRADE SEPARATIONS SPACED 1/2 MILE APART
(through trips not included)

Network		Vehicle Miles of Travel				
Interchange Spacing (miles)	Grade Separation Spacing (miles)	1/4 Mile Arterial Streets	1/2 Mile Arterial Streets	1 Mile Arterial Streets	Freeway	Total
1/2	1/2	35,600	171,600	487,500	910,700	1,605,400
1	1/2	49,400	176,400	542,200	854,100	1,622,100
2	1/2	49,500	226,100	548,100	748,200	1,571,900

NOTE: Trip density = 23,000 destinations/sq. mi.

TABLE 10

AVERAGE DAILY EQUIVALENT VEHICLE MILES OF TRAVEL
FOR 16 SQUARE MILE AREA FOR DESIGN YEAR
BY STREET CLASSIFICATION FOR NETWORKS
WITH GRADE SEPARATIONS SPACED 1/2 MILE APART
(through trips not included)

Network		Vehicle Miles of Travel				
Interchange Spacing (Miles)	Grade Separation Spacing (Miles)	1/4 Mile Arterial Streets	1/2 Mile Arterial Streets	1 Mile Arterial Streets	Freeway	Total
1/2	1/2	16,830	79,775	237,697	505,609	839,911
1	1/2	22,874	81,822	263,307	482,801	850,804
2	1/2	22,788	110,932	266,129	430,410	830,259
4	1/2	22,019	144,253	370,727	336,217	873,216

NOTE: Trip density = 11,000 destinations/sq. mi.

TABLE 11

AVERAGE DAILY OPERATING AND ACCIDENT COSTS
FOR THE DESIGN YEAR
(through trips not included)

		Average Daily Speed (MPH)	Peak Period Speed 35% of Trips (MPH)	Off-Peak Period Speed 65% of Trips (MPH)
Freeways		45	45	55
One Mile Arterials		25	25	30
Network				
Inter-change Spacing (miles)	Grade Separation Spacing (miles)	Average Daily Operating and Accident Cost (dollars)	Average Daily Operating and Accident Costs (dollars)	
1/2	1/4	54,400	55,100	
1/2	1/2	54,500	55,200	
1	1/4	55,700	56,100	
1	1/2	55,900	56,300	
1	1	56,300	56,700	
2	1/4	55,100	55,100	
2	1/2	55,300	55,400	
2	1	55,700	55,800	

NOTE: Trip density = 23,000 destinations/sq. mi.

TABLE 12

AVERAGE DAILY OPERATING AND ACCIDENT COSTS

FOR THE DESIGN YEAR

(Through Trips Not Included)

		Average Daily Speed (MPH)	Peak Period Speed 35% of Trips (MPH)	Off-Peak Period Speed 65% of Trips (MPH)
Freeways		45	45	55
One Mile Arterials		25	25	30
Network				
Interchange Spacing (miles)	Grade Separation Spacing (miles)	Average Daily Operating and Accident Costs (dollars)	Average Daily Operating and Accident Costs (dollars)	
1/2	1/2	28135	28695	
1	1/2	28870	29284	
1	1	29246	29659	
2	1/2	28785	29051	
2	1	29006	29250	
2	2	29030	29375	
4	1/2	31425	31093	
4	1	31862	31482	
4	2	33759	33619	

NOTE: Trip density = 11,000 destinations/sq. mi.

TABLE 13

SUMMARY OF DESIGN FEATURES OF NETWORKS

Spacing of Inter-Changes	Spacing of Grade Separa-tions	Number of Lanes on Freeway (between Interchanges)	
		North-South Freeway	
		North Section	South Section
1/2 1/2	1/4 1/2	1 aux. lane NBD[1] 4 loc. lanes NBD 2 exp. lanes NBD 2 exp. lanes SBD 4 loc. lanes SBD 1 aux. lane SBD[1] total 12 lanes + 2 aux. lanes	1 aux. lane NBD[1] 5 lanes NBD 5 lanes SBD 1 aux. lane SBD[1] total 10 lanes + 2 aux. lanes
1 1 1	1/4 1/2 1	1 aux. lane NBD[1] 5 lanes NBD 5 lanes SBD 1 aux. lane SBD[1] total 10 lanes + 2 aux. lanes	1 aux. lane NBD[1] 4 lanes NBD 4 lanes SBD 1 aux. lane SBD[1] total 8 lanes + 2 aux. lanes
2 2 2	1/4 1/2 1	1 aux. lane NBD[1] 4 lanes NBD 4 lanes SBD 1 aux. lane SBD[1] total 8 lanes + 2 aux. lanes	1 aux. lane NBD[2] 4 lanes NBD 4 lanes SBD 1 aux. lane SBD[2] total 8 lanes + 2 aux. lanes

NOTE: Trip density = 23,000 destinations/sq. mi.

Key:

aux. - auxiliary
loc. - local
exp. - express
rev. - reversible

NBD - Northbound Direction
SBD - Southbound Direction
EBD - Eastbound Direction
WBD - Westbound Direction

[1] Auxiliary lane, 12 feet wide and of color and texture that contrasts with that of the through lanes, extends from the nose of the on ramp to to the nose of the next exit ramp.

[2] Auxiliary lane, 12 feet wide and of color and texture that contrasts with that of through lane, extends from nose of the ramp for 1/2 mile where it is then tapered gradually into the through lanes.

TABLE 13 (cont.)

Spacing of Inter-changes	Spacing of Grade Separa-tions	Number of Lanes on Freeway (between Interchanges) East-West Freeway East Section	West Section	Interchange Type
1/2 1/2	1/4 1/2	1 aux. lane WBD[1] 5 loc. lanes WBD 2 exp. lanes WBD 2 rev. lanes 2 exp. lanes EBD 5 loc. lanes EBD 1 aux. lane total 16 lanes + 2 aux. lanes	1 aux. lane WBD[1] 4 lanes WBD 2 rev. lanes 4 lanes EBD 1 aux. lane EBD[1] total 10 lanes + 2 aux. lanes	Diamond Interchange
1 1 1	1/4 1/2 1	1 aux. lane WBD[1] 4 loc. lanes WBD 2 exp. lanes WBD 2 rev. lanes 2 exp. lanes EBD 4 loc. lanes EBD 1 aux. lane EBD[1] total 14 lanes + 2 aux. lanes	4 lanes WBD 2 rev. lanes 4 lanes EBD total 10 lanes	Diamond Interchange
2 2 2	1/4 1/2 1	1 aux. lane WBD[1] 1 aux. lane WBD[2] 4 lanes WBD 2 rev. lanes 4 lanes EBD 1 aux. lane EBD[2] 1 aux. lane EBD[1] total 10 lanes + 4 aux. lanes	1 aux. lane WBD[2] 3 lanes WBD 2 rev. lanes 3 lanes EBD 1 aux. lane EBD[2] total 8 lanes + 2 aux. lanes	All Split Diamond Interchanges with One Way Roads Except for One Ordinary Diamond Interchange (West Section)

Spacing of Inter-changes	Spacing of Grade Separa-tions	Number of Lanes on Arterial Freeway Interchange Ramps	ROW Required for 8 Miles of Freeway	Arterial Street Widening
1/2 1/2	1/4 1/2	One lane for all ramps except for two on ramps and two off ramps on the East section where the ramps are two lanes	N 475' S 405' E 555' (1½ blocks) W 425' 1 block + 15' area = 290 acres	none
1 1 1	1/4 1/2 1	Five interchanges have one lane ramps, five interchanges have two lane ramps	N 390' S 370' E 555' (1½ blocks) W 410' (1 block) area = 272 acres	none
2 2 2	1/4 1/2 1	Two lanes for all ramps	N 360' S 360' E 410' (1 block) W 410' (1 block) area = 244 acres	Four miles of eight lane divided arterial street + five intersection widenings = 68 acres required, but 43 acres are sold after widening has been done
			area for freeways and arterial street widening = 269 acres	

TABLE 14

SUMMARY OF DESIGN FEATURES OF NETWORKS

Spacing of Interchanges	Spacing of Grade Separations	Number of lanes on Freeway (between Interchanges) — North-South Freeway: North Section	North-South Freeway: South Section
1/2	1/2	1 aux. lane NBD[1] 4 loc. lanes NBD 2 rev. lanes 4 loc. lanes SBD 1 aux. lane SBD[1] total 10 lanes plus 2 aux. lanes	1 aux. lane NBD[1] 4 loc. lanes NBD 4 loc. lanes SBD 1 aux. lane SBD[1] total 8 lanes plus 2 aux. lanes
1 1	1/2 1	1 aux. lane NBD[2] 4 loc. lanes NBD 2 rev. lanes 4 loc. lanes SBD 1 aux. lane SBD[2] total 10 lanes plus 2 aux. lanes	5 loc. lanes NBD 5 loc. lanes SBD total 10 lanes
2 2 2	1/2 1 2	4 loc. lanes NBD 2 rev. lanes 4 loc. lanes SBD total 10 lanes	5 loc. lanes NBD 5 loc. lanes SBD total 10 lanes
4 4 4	1/2 1 2	1 aux. lane NBD[1] 4 loc. lanes NBD 4 loc. lanes SBD 1 aux. lane SBD[1] total 8 lanes plus 2 aux. lanes	1 aux. lane NBD[1] 4 loc. lanes NBD 4 loc. lanes SBD 1 aux. lane SBD[1] total 8 lanes plus 2 aux. lanes

Note: Trip density = 11,000 destination per square mile.

Key

aux. - auxiliary
loc. - local
rev. - reversible

NBD - Northbound Direction
SBD - Southbound Direction
EBD - Eastbound Direction
WBD - Westbound Direction

[1]Auxiliary lane, 12 feet wide and of color and texture that contrasts with that of the through lanes, extends from the nose of the on ramp to the nose of the next off ramp

[2]Auxiliary lane, 12 feet wide and of color and texture that contrast with that of through lane extends from nose of the ramp for 1/2 mile where it is tapered gradually into the through lanes.

TABLE 14 (cont.)

Spacing of Interchanges	Spacing of Grade Separations	Number of Lanes on Freeway (Between Interchanges) East-West Freeway: East Section	Number of Lanes on Freeway (Between Interchanges) East-West Freeway: West Section	Interchange Type
1/2	1/2	1 aux. lane WBD[1] 3 loc. lanes WBD 3 loc. lanes EBD 1 aux. lane EBD[1] total 6 lanes plus 2 aux. lanes	1 aux. lane WBD[1] 3 loc. lanes WBD 3 loc. lanes EBD 1 aux. lane EBD[1] total 6 lanes plus 2 aux. lanes	Diamond
1 1	1/2 1	4 loc. lanes WBD 4 loc. lanes EBD total 8 lanes	4 loc. lanes WBD 4 loc. lanes EBD total 8 lanes	Diamond
2 2 2	1/2 1 2	1 aux. lane WBD[1] 3 loc. lanes WBD 3 loc. lanes EBD 1 aux. lane EBD[1] total 6 lanes plus 2 aux. lanes	1 aux. lane WBD[1] 3 loc. lanes WBD 3 loc. lanes EBD 1 aux. lane EBD[1] total 6 lanes plus 2 aux. lanes	Diamond
4 4 4	1/2 1 2	1 aux. lane WBD[1] 3 loc. lanes WBD 3 loc. lanes EBD 1 aux. lane EBD[1] total 6 lanes plus 2 aux. lanes	1 aux. lane WBD[1] 3 loc. lanes WBD 3 loc. lanes EBD 1 aux. lane EBD[1] total 6 lanes plus 2 aux. lanes	One Split Diamond with One-Way Roads; Rest Diamonds

Spacing of Inter-changes	Spacing of Grade Separa-tions	Number of Lanes on Arterial-Freeway Interchange	Right-of-Way Required for 8 Miles of Freeway	Arterial Street Widening
1/2	1/2	One lane for all ramps.	N 410' (1 block) S 370' E 410' W 370' = 240.4 ac	None
1 1	1/2 1	Three interchanges have two two-lane ramps and two one-lane ramps; all other ramps one lane	Same as 1/2 - 1/2 240.4 acres	Widen two intersections to provide left turn lanes.
2 2 2	1/2 1 2	One interchange has all two-lane ramps; one has two two-lane and two one-lane ramps; all other ramps one lane.	Same as 1/2 - 1/2 240.4 acres	Widen five intersections to provide left turn lanes; widen five diamond approaches.
4 4	1/2 1	Two interchanges have two two-lane and two one-lane ramps; all other ramps two-lane.	Same as 1/2 - 1/2 240.4 acres	Widen one mile of arterial to six-lane divided; also ten intersections; three approaches. - 15.2 acres.
4	2	One intersection has two two-lane ramps and two one-lane ramps; all other ramps two lanes.	Same as 1/2 - 1/2 240.4 acres	Widen one and one-half miles of arterial to six-lane divided; eleven intersections; two approaches. - 26.2 acres

TABLE 15

CONSTRUCTION COST FOR

FREEWAY-ARTERIAL STREET NETWORKS

Network		Construction Cost			Freeways Only		
Inter-change Spacing	Grade Separation Spacing	Freeway ($1,000)	Arterial Widening ($1,000)	Total ($1,000)	Construction Cost Per Mile ($1,000,000)	Average Number of Through Lanes/Mile	Cost Per Lane Mile ($1,000,000)
1/2	1/4	70,784	-	70,784	8.8	12	0.74
1/2	1/2	62,230	-	62,230	7.8	12	0.65
1	1/4	66,066	-	66,066	8.3	10-1/2	0.79
1	1/2	57,689	-	57,689	7.2	10-1/2	0.69
1	1	53,740	-	53,740	6.7	10-1/2	0.64
2	1/4	56,514	2,748	59,262	7.1	8-1/2	0.83
2	1/2	49,831	2,748	52,579	6.2	8-1/2	0.73
2	1	46,217	2,817	49,034	5.8	8-1/2	0.68

NOTE: Trip density = 23,000 destinations/sq. mi.

TABLE 16

CONSTRUCTION COST FOR

FREEWAY-ARTERIAL STREET NETWORKS

Network		Construction Cost			Freeways Only		
Inter-change Spacing	Grade Separation Spacing	Freeway ($1000)	Arterial Widening ($1000)	Total ($1000)	Construction Cost Per Mile ($1,000,000)	Average Number of Through Lanes/Mile	Cost Per Lane Mile ($1,000,000)
1/2	1/2	47717	---	47717	6.0	8.2	0.73
1	1/2	46590	27	46617	5.8	8.2	0.71
1	1	43696	27	43723	5.5	8.2	0.67
2	1/2	43441	139	43580	5.4	7.2	0.75
2	1	40618	139	40757	5.1	7.2	0.71
2	2	38069	139	38208	4.8	7.2	0.67
4	1/2	44222	702	44924	5.6	7.0	0.80
4	1	40796	702	41498	5.2	7.0	0.74
4	2	39649	960	40609	5.1	7.0	0.73

Note: Trip density = 11,000 destinations per square mile.

TABLE 17

SPACINGS OF INTERCHANGES AND GRADE SEPARATIONS
(For Design Year Volumes)

Freeway Spacing of 4 Miles; 23,000 Trip Destinations per Square Mile; 7 per cent Interest Rate; Amortization Period-Construction 25 years, Right-of-Way 25 years; Level of Service-Freeways 45 mph, One Mile Arterials 25 mph.

Time Cost $/hr.	Network with Lowest Total Annual Transportation Cost: Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)	Network with Highest Total Annual Transportation Cost: Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)	Network with Lowest Total Annual Capital Cost: Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)
Right of Way $145,000/acre									
0.00	2	1	26866	1/2	1/4	28244	2	1	26866
0.50	2	1	35968	1	1/4	37048	2	1	35968
1.00	1/2	1/2	44681	1	1/4	45978	2	1	45070
1.50	1/2	1/2	53286	1	1/4	54908	2	1	54172
3.00	1/2	1/2	79102	1	1/4	81699	2	1	81478
Right of Way $215,000/acre									
0.00	2	1	28656	1/2	1/4	29996	1	1	28806
0.50	2	1	37758	1	1/4	38709	1	1	37837
1.00	1/2	1/2	46404	1	1/4	47639	1	1	46868
1.50	1/2	1/2	55010	1	1/4	56569	1	1	55899
3.00	1/2	1/2	80825	2	1/4	83411	1	1	82992

NOTE: Trip density = 23,000 destinations/sq. mi.

Freeway Spacing of 4 miles; 23,000 Trip Destinations per Square Mile 7 per cent Interest Rate; Amortization Period-Construction 25 years, Right of Way 40 years; Level of Service-Freeways 45 mph, One Mile Arterials 25 mph.

Time Cost $/hr.	Network with Lowest Total Annual Transportation Cost: Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)	Network with Highest Total Annual Transportation Cost: Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)	Network with Lowest Total Annual Capital Cost: Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)
Right of Way $145,000/acre									
0.00	2	1	26396	1/2	1/4	27778	2	1	26396
0.50	2	1	35498	1	1/4	36604	2	1	35498
1.00	1/2	1/2	44223	1	1/4	45534	2	1	44600
1.50	1/2	1/2	52828	1	1/4	54465	2	1	53702
3.00	1/2	1/2	78644	1	1/4	81255	2	1	81008
Right of Way $215,000/acre									
0.00	2	1	27960	1/2	1/4	29310	2	1	27960
0.50	2	1	37062	1	1/4	38056	2	1	37062
1.00	1/2	1/2	45730	1	1/4	46986	2	1	46164
1.50	1/2	1/2	54335	1	1/4	55916	2	1	55266
3.00	1/2	1/2	80150	1	1/4	82707	2	1	82572

TABLE 17 (cont.)

Freeway Spacing of 4 Miles; 23,000 Trip Destinations per Square Mile; 7 per cent Interest Rate; Amortization Period-Construction and Right of Way 25 years; Level of Service-Freeways 45 and 55 mph, One Mile Arterials 25 and 30 mph.

	Network with Lowest Total Annual Transportation Cost			Network with Highest Total Annual Transportation Cost			Network with Lowest Total Annual Capital Cost		
Time Cost $/hr.	Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)	Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)	Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)
				Right of Way $145,000/acre					
0.00	2	1	26876	1/2	1/4	28487	2	1	26876
0.50	2	1	35231	1	1/4	36407	2	1	35231
1.00	1/2	1/2	43400	1	1/4	44563	2	1	43587
1.50	1/2	1/2	51244	1	1/4	52719	2	1	51942
3.00	1/2	1/2	74776	2	1/4	77194	2	1	77009
				Right of Way $215,000/acre					
0.00	2	1	28666	1/2	1/4	30239	1	1	28923
0.50	2	1	37021	1	1/4	38068	1	1	37162
1.00	1/2	1/2	45123	1	1/4	46224	1	1	45400
1.50	1/2	1/2	52967	1	1/4	54380	1	1	53639
3.00	1/2	1/2	76499	2	1/4	79065	1	1	78354

Freeway Spacing of 4 miles; 23,000 Trip Destinations per Square Mile; 7 per cent Interest Rate; Amortization Period-Construction 25 years, Right of Way 40 years; Level of Service-Freeways 45 and 55 mph, One Mile Arterials 25 and 30 mph.

	Network with Lowest Total Annual Transportation Cost			Network with Highest Total Annual Transportation Cost			Network with Lowest Total Annual Capital Cost		
Time Cost $/hr.	Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)	Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)	Inter-change Spacing	Grade Separa-tion Spacing	Total Annual Cost ($1000)
				Right of Way $145,000/acre					
0.00	2	1	26406	1/2	1/4	28022	2	1	26406
0.50	2	1	34761	1	1/4	35963	2	1	34761
1.00	1/2	1/2	42942	1	1/4	44119	2	1	43117
1.50	1/2	1/2	50786	1	1/4	52275	2	1	51472
3.00	1/2	1/2	74318	1	1/4	76743	2	1	76538
				Right of Way $215,000/acre					
0.00	2	1	27970	1/2	1/4	29553	2	1	27970
0.50	2	1	36326	1	1/4	37415	2	1	36326
1.00	1/2	1/2	44448	1	1/4	45571	2	1	44681
1.50	1/2	1/2	52292	1	1/4	53727	2	1	53037
3.00	1/2	1/2	75824	2	1/4	78339	2	1	78103

TABLE 18

SPACINGS OF INTERCHANGES AND GRADE SEPARATIONS
(For Design Year Volumes)

Freeway Spacing of 4 miles; 11,000 Trip Destinations per Square Mile; 7 per cent Interest Rate; Amortization Period - Construction 25 Years, Right-of-Way 25 Years; Level of Service-Freeways 45 MPH, One-Mile Arterials 25 MPH.

Time Cost $/hr.	Network with Lowest Total Annual Transportation Cost			Network with Highest Total Annual Transportation Cost			Network with Lowest Total Annual Capital Cost		
	Inter-change Spacing	Grade Separation Spacing	Total Annual Cost ($1000)	Inter-change Spacing	Grade Separation Spacing	Total Annual Cost ($1000)	Inter-change Spacing	Grade Separation Spacing	Total Annual Cost ($1000)
Right of Way $145,000/acre									
0.00	2	2	16149	4	2	18233	2	2	16149
0.50	2	2	20796	4	2	23870	2	2	20796
1.00	1/2	1/2	25415	4	2	29506	2	2	25443
1.50	1/2	1/2	29804	4	2	35143	2	2	30089
3.00	1/2	1/2	42971	4	2	52054	2	2	44029
Right of Way $215,000/acre									
0.00	2	2	17593	4	2	19806	2	2	17593
0.50	2	2	22240	4	2	25443	2	2	22240
1.00	1/2	1/2	26859	4	2	31080	2	2	26887
1.50	1/2	1/2	31248	4	2	36717	2	2	31533
3.00	1/2	1/2	44415	4	2	53628	2	2	45473

NOTE: Trip density = 11,000 destinations/ sq. mi.

Interest Rate 7%; Amortization Period-Construction 25 Years, Right of Way 40 Years; Level of Service-Freeways 45 MPH, One Mile Arterials 25 MPH

Time Cost $/hr.	Network with Lowest Total Annual Transportation Cost			Network with Highest Total Annual Transportation Cost			Network with Lowest Total Annual Capital Cost		
	Inter-change Spacing	Grade Separation Spacing	Total Annual Cost ($1000)	Inter-change Spacing	Grade Separation Spacing	Total Annual Cost ($1000)	Inter-change Spacing	Grade Separation Spacing	Total Annual Cost ($1000)
Right of Way $145,000/acre									
0.00	2	2	15770	4	2	17819	2	2	15770
0.50	2	2	20416	4	2	23456	2	2	20416
1.00	1/2	1/2	25039	4	2	29093	2	2	25063
1.50	1/2	1/2	29428	4	2	34730	2	2	29710
3.00	1/2	1/2	42594	4	2	51640	2	2	43650
Right of Way $215,000/acre									
0.00	2	2	17032	4	2	19195	2	2	17032
0.50	2	2	21679	4	2	24832	2	2	21679
1.00	1/2	1/2	26301	4	2	30468	2	2	26325
1.50	1/2	1/2	30690	4	2	36105	2	2	30972
3.00	1/2	1/2	43857	4	2	53016	2	2	44912

TABLE 18 (cont.)

Interest Rate 7%; Amortization Period - Construction and Right of Way 25 Years;
Level of Service - Freeways 45 and 55 MPH, One Mile Arterials 25 and 30 MPH.

Time Cost $/hr.	Network with Lowest Total Annual Transportation Cost			Network with Highest Total Annual Transportation Cost			Network with Lowest Total Annual Capital Cost		
	Interchange Spacing	Grade Separation Spacing	Total Annual Cost ($1000)	Interchange Spacing	Grade Separation Spacing	Total Annual Cost ($1000)	Interchange Spacing	Grade Separation Spacing	Total Annual Cost ($1000)
Right of Way $145,000/acre									
0.00	2	2	16266	4	2	18185	2	2	16266
0.50	2	2	20520	4	2	23398	2	2	20520
1.00	2	2	24774	4	2	28610	2	2	24774
1.50	1/2	1/2	28794	4	2	33822	2	2	29028
3.00	1/2	1/2	40759	4	2	49459	2	2	41789
Right of Way $215,000/acre									
0.00	2	2	17710	4	2	19759	2	2	17710
0.50	2	2	21964	4	2	24971	2	2	21964
1.00	2	2	26218	4	2	30184	2	2	26218
1.50	1/2	1/2	30238	4	2	35396	2	2	30472
3.00	1/2	1/2	42203	4	2	51033	2	2	43233

Interest Rate 7%; Amortization Period - Construction 25 Years, Right of Way 40 Years;
Level of Service - Freeways 45 and 55 MPH, One-Mile Arterials 25 and 30 MPH.

Time Cost $/hr.	Network with Lowest Total Annual Transportation Cost			Network with Highest Total Annual Transportation Cost			Network with Lowest Total Annual Capital Cost		
	Interchange Spacing	Grade Separation Spacing	Total Annual Cost ($1000)	Interchange Spacing	Grade Separation Spacing	Total Annual Cost ($1000)	Interchange Spacing	Grade Separation Spacing	Total Annual Cost ($1000)
Right of Way $145,000/acre									
0.00	2	2	15887	4	2	17771	2	2	15887
0.50	2	2	20141	4	2	22984	2	2	20141
1.00	2	2	24394	4	2	28196	2	2	24394
1.50	1/2	1/2	28417	4	2	33409	2	2	28648
3.00	1/2	1/2	40383	4	2	49046	2	2	41409
Right of Way $215,000/acre									
0.00	2	2	17149	4	2	19147	2	2	17149
0.50	2	2	21403	4	2	24359	2	2	21403
1.00	2	2	25657	4	2	29572	2	2	25657
1.50	1/2	1/2	29679	4	2	34784	2	2	29910
3.00	1/2	1/2	41645	4	2	50421	2	2	42672

TABLE 19

ANNUAL COST FOR DESIGN YEAR
(All Costs in Thousands of Dollars)

INTEREST RATE 7% TIME COST $1.50/hour ROW COST $215,000/acre

AMORTIZATION PERIOD:
Const. 25 years
R.O.W. 40 years

LEVEL OF SERVICE
Freeways 45 mph
One-Mile Arterials 25 mph

	Interchange Spacing	Grade Separation Spacing	Annual Construction Cost	Annual R.O.W. Cost	Total Annual Capital Cost	Annual Operating and Accident Cost	Annual Time Cost	Total Annual User Cost	Total Annual Cost	Benefit Ratio/
	1/2	1/4	6074	4764	10838	18472	25784	44256	55094	1.10
*	1/2	1/2	5340	4687	10027	18493	25815	44308	54335	1.94
	1	1/4	5669	4534	10203	18922	26791	45713	55916	0.44
	1	1/2	4950	4428	9378	18972	26878	45850	55228	1.11
	1	1	4611	4431	9042	19125	27093	46218	55261	2.49
	2	1/4	5085	5043	10128	18691	26933	45624	55752	0.55
	2	1/2	4512	4825	9337	18780	27071	45851	55188	1.26
**	2	1	4208	4831	9038	18922	27306	46228	55266	0.00

Total Annual User Cost/Total Annual Cost = 0.8, (Average value for all networks)

$$\text{Range of Total Annual Cost} = \left\{\frac{\text{highest total annual cost} - \text{lowest total annual cost}}{\text{lowest total annual cost}}\right\}100) = 2.91\%$$

*Network with lowest total annual cost.
**Network with lowest total annual capital cost.
/ Base network is network with lowest total annual capital cost.

Note: Trip density = 23,000 destination per square mile.

TABLE 20

ANNUAL COST FOR DESIGN YEAR
(All Costs in Thousands of Dollars)

INTEREST RATE 7% TIME COST $1.50/hour ROW COST $215,000/acre

AMORTIZATION PERIOD:
Const. 25 years
R.O.W. 40 years

LEVEL OF SERVICE
Freeways 45 mph
One-Mile Arterials 25 mph

Interchange Spacing	Grade Separation Spacing	Annual Construction Cost	Annual R.O.W. Cost	Total Annual Capital Cost	Annual Operating and Accident Cost	Annual Time Cost	Total Annual User Cost	Total Annual Cost	Benefit Ratio/
1/2	1/2	4095	3877	7972	9552	13167	22719	30690	1.36
1	1/2	4000	3879	7879	9801	13687	23488	31367	0.44
1	1	3752	3879	7631	9929	13852	23781	31412	0.03
2	1/2	3740	3898	7637	9773	13890	23663	31300	0.29
2	1	3497	3898	7395	9848	14016	23864	31259	-0.31
2	2	3279	3898	7176	9856	13940	23796	30972	0.00
4	1/2	3736	4090	7826	10669	15777	26446	34272	-4.08
4	1	3561	4090	7651	10817	16025	26842	34494	-6.41
4	2	3485	4249	7733	11461	16911	28372	36105	-8.21

Total Annual User Cost/Total Annual Cost = 0.8, (Average value for all networks)

Range of Total Annual Cost = 17.7%

*Network with lowest total annual cost.
**Network with lowest total annual capital cost.
/Base network is network with lowest total annual capital cost.

Note: Trip density = 11,000 destinations per square mile.