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Contents

Use of Gravity Model for Describing Urban Travel

An Analysis and Critique[1]

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This research provides evaluations of the gravity model as an analytical tool for simulating present and forecasting future urban trip distribution patterns. The evaluations were made by comparing gravity model trip interchanges with those found in home interview origin and destination surveys conducted in Washington, D. C., in 1948 and 1955. The 1955 survey data were used for calibrating the basic gravity model and for testing this model for its ability to simulate current travel patterns. The 1948 survey provided comprehensive data to analyze the forecasts made by the calibrated model.

The gravity model will give satisfactory results if properly calibrated and tested. The level of accuracy obtained by forecasting trip distribution patterns in 1948 was comparable to the level of model accuracy for the base year.

•THE GRAVITY MODEL trip distribution formula has been used in transportation planning studies in many urban areas during the past few years. The theory of this formula and the general procedures used to simulate the present travel patterns have been documented to some extent in the literature (1, 2, 3). The use of this model to forecast future travel patterns in several urban areas has also been reported (1, 2). To date, however, there are little published data available to illustrate factually the ability of the gravity model to either simulate existing travel patterns or to forecast future patterns.

About three years ago the Urban Planning Division of the U. S. Bureau of Public Roads in cooperation with the Washington Metropolitan Area Transportation Study (WMATS) began a research project to refine and document detailed procedures for calibrating and testing a gravity model trip distribution formula for use in simulating present travel patterns and forecasting future travel patterns in an urban area. This project also included the development of a series of IBM 704/7090 electronic computer programs for implementing the analytical procedures devised. To accomplish such a project, adequate data on travel patterns for two time periods were required. At that time the Washington, D. C., metropolitan area was the only large area in the country having complete and adequate home interview surveys for two separate time periods.

During the summer of 1948, a comprehensive origin-destination survey was conducted in 5 percent of the dwelling units in the Washington metropolitan area (4). In 1955 a repeat origin-destination survey was conducted in the same area (5). Within the District of Columbia, occupants of 3 percent of the dwelling units were interviewed. Elsewhere in the area, occupants of 10 percent of the dwelling units were interviewed. Consequently, the Washington area provided an ideal situation for testing and evaluating the ability of the gravity model to simulate travel patterns for one period of time and also to forecast such patterns for a different period of time.

[1] The full report, of which this is a condensation, can be obtained from the U. S. Bureau of Public Roads, Washington, D. C.

Paper sponsored by Committee on Origin and Destination.

This paper describes research in methods for calibrating a gravity model for a large urban area and for testing this model for its ability to simulate present trip distribution patterns. It also discusses investigations into the ability of this model to predict trip distribution patterns for another point in time. Both the calibrating and forecast testing phases of the research, supplemented by necessary background information relating to each phase, as well as the detailed procedures utilized and results obtained (when compared with comprehensive home interview data) are reported in this paper.

GRAVITY MODEL THEORY

The gravity model theory states that the trip interchange between zones depends on the relative attraction of each of the zones and on some function of the spatial separation between zones. This function of spatial separation adjusts the relative attractiveness of each zone for the ability, desire, and necessity of the trip maker to overcome spatial separation. Mathematically, this theory is stated:

$$T_{(i-j)} = \frac{P_i A_j F_{(t_{i-j})} K_{(i-j)}}{\sum_{x=1}^{n} A_x F_{(t_{i-x})} K_{(i-x)}} \qquad (1)$$

where

$T_{(i-j)}$ = trips produced in zone i and attracted to zone j;

P_i = trips produced in zone i;

A_j = trips attracted to zone j;

$F_{(t_{i-j})}$ = empirically derived travel time factor (one for each 1-min increment of travel time, t_{i-j}) which expresses average areawide effect of spatial separation on trip interchange between zones; and

$K_{(i-j)}$ = specific zone-to-zone adjustment factor to allow for incorporation of effect on travel patterns of social-economic linkages not otherwise considered in gravity model formula.

This formulation shows that five separate parameters are required before trip interchanges can be calculated. Two of these are concerned with the use of the land in the study area and with the social and economic characteristics of the people who make trips. These are the number of trips produced (P_i) and the number of the trips attracted (A_j) by each traffic zone in the study area. The use of these factors permits the effects of various land-use patterns to be brought to bear on trip distribution patterns.

A third parameter is concerned with the extent and level of service provided by transportation facilities in the area. This is the measure of spatial separation (t_{i-j}) between zones and is usually composed of the minimum path driving time between zones plus a measure of terminal time in each zone, included to account for zonal differences in congestion and available parking facilities. The incorporation of this parameter allows the effects of various transportation improvements to be brought to bear on trip distribution patterns.

A fourth parameter, the travel time factor $F_{(t_{i-j})}$, is used to express the average areawide effect of spatial separation on trip interchange between zones. The use of a set of travel time factors, rather than the traditional inverse exponential function of travel time, greatly simplifies the computational requirements of the model. It also allows the effect of spatial separation to increase as the separation increases, which has been shown to occur, particularly for some trip purposes.

The fifth parameter required by the gravity model is a set of zone-to-zone adjustment factors, $K_{(i-j)}$ incorporated into the model to account for social and economic factors which are not otherwise considered by the model but have a significant effect on travel patterns. To date, these factors have not been completely identified or quantified, but there is some indication that they are related to such factors as income and occupation or to some unique relationship between the use of land and trip making which may exist in a particular part of the urban area. The inclusion of such a factor in this research project was designed to permit the determination of the level of adjustment required and to allow additional research into the determination of the social-economic conditions that create the need for $K_{(i-j)}$ factors.

Since this research project was primarily concerned with the trip distribution aspects of the gravity model, trip production and attraction values for each zone were obtained directly from the home interview origin-destination survey for both 1948 and 1955. Travel times between zones were calculated from data collected in the field on the type and extent of the transportation facilities available in the area in 1948 and 1955. The travel time factors $F(t_{i-j})$ and the zone-to-zone adjustment factors $K_{(i-j)}$ were determined by an iterative procedure for 1955 and these same factors were used to estimate travel patterns for 1948.

STUDY AREA

That part of the Washington, D. C., metropolitan area used in this research is shown in Figure 1. As previously mentioned, there were comprehensive origin-destination studies made in Washington in 1948 and 1955. All phases of these surveys (i.e., internal, external, truck and taxi) used procedures and sample sizes recommended by

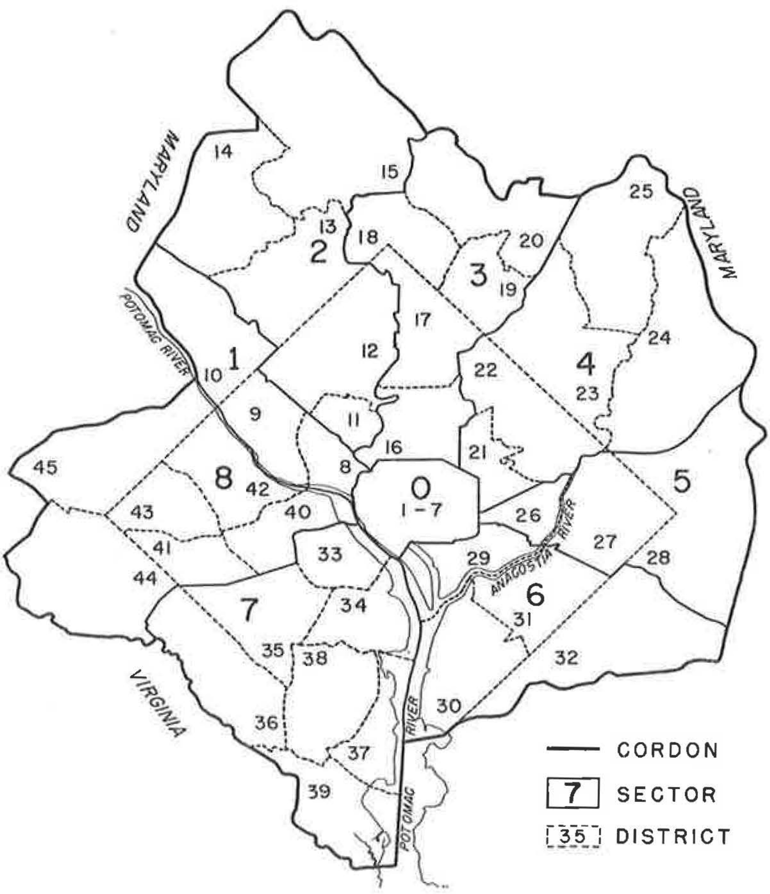

Figure 1. Study area, Washington, D. C., 1948 and 1955.

the U. S. Bureau of Public Roads (6). In 1948 data were collected only on travel patterns (4). Information on 1948 transportation facilities, however, was subsequently derived from secondary sources. In addition to 1955 travel data, information was also available on the type, extent and capacity of the transportation facilities in the area, as well as the use of land in terms of the type and intensity of use. For this reason, the 1955 data were used to calibrate and test the base year gravity model. Using the base year model, trip distribution patterns were then forecast for 1948. Although not reported here, the research on the 1955 data also included a comprehensive trip generation study. The fact that this trip generation study would be accomplished in the Urban Planning Division research program also influenced the decision to select 1955 for the base year model. Although this unconventional approach is the reverse of the usual way of making a forecast, it more effectively served the purpose of this research.

The cordon lines were located in approximately the same position both in 1948 and 1955. In some areas the 1955 cordon line was extended outward, but in most cases this additional area covered was incorporated to cover new development. The zone boundaries were not the same for the two periods; since subzone boundaries were available for both surveys, any discrepancies were adjusted during the data processing phases of the research. A total of 400 internal zones and 19 external zones was used in 1948 and 1955. For summary and general analysis purposes, these 419 zones were combined into 47 districts or analysis areas. District and sector boundaries are shown in Figure 1.

Probably the most significant change in the study area in the 7-year period was the decentralization of many activities of the urban population. Residential, employment, and shopping activities were all relatively less oriented to the central business district (CBD) in 1955 than in 1948 (7).

The total population increased 38 percent to approximately 1.5 million during the 7-year interval, and the number of person trips for all purposes increased slightly over 50 percent. The number of autos owned almost doubled, increasing 96 percent. This increase was reflected in the almost 90 percent increase in auto driver trips. Mass transit trips showed a slight decrease in absolute numbers. Several significant improvements and additions in the transportation system were made during the period between the two surveys.

INITIAL DATA ANALYSIS

This section of the report deals with those processes required before actual model calibration can begin. It discusses the sequence of operations and the procedures involved in selecting the basic data from both 1948 and 1955 and making initial analysis of these data.

Initial Decisions on Model Development

In the use of any trip distribution model, a great many choices on the manner in which the model will be used are available to the analyst. These choices concern the universe of trips to be used (i.e., peak hour vs total daily trips, person trips vs auto driver and mass transit trips, total trips in the study area vs trips made only by the residents of the study area, and purpose stratification) and the measure of spatial separation to be used (i.e., driving distance, time or cost vs travel distance; time or cost which includes a measure of terminal time in each zone to account for the congestion involved in parking; and peak hour vs nonpeak hour conditions).

This research project worked with the total daily person trips made by all residents of the area inside the cordon line. Total daily trips were used because, in a city as large as Washington, it is desirable to have the total daily patterns rather than a single peak period. Peak traffic demands on different facilities in a large city occur at different times. The major peak hour movements are still associated with the CBD, but off-peak movements and weekend travel are more closely associated with outlying or crosstown shopping centers, amusement parks, etc. Such conditions could not be determined with a single peak hour model. Consequently, the transportation system developed on the basis of traffic estimates for one of the daily peak periods would be insufficient to satisfy those movements not associated with the CBD. Person trips were used because it was necessary to evaluate different levels of both highway and public transit service to arrive at a properly balanced transportation system.

This research used only those trips made by the residents of the study area because the trip length characteristics and, in fact, the basic reasons for making trips for those persons residing within the study area were different from those persons residing outside but traveling to and from the study area. Finally, this research stratified the total travel demands of the area into the following six trip purpose categories:

1. Home-based work—those trips between a person's place of residence and his place of employment for the purpose of work;
2. Home-based shop—those trips between a person's place of residence and a commercial establishment for the purpose of shopping;
3. Home-based social-recreation—those trips between a person's place of residence and places of cultural, social, and recreational establishments for social and recreational purposes;
4. Home-based school—those trips, by students, between the place of residence and school for the purpose of attending classes;
5. Home-based miscellaneous—all other trips between a person's place of residence and some form of land use for any other trip purpose, including personal business, medical, dental, and eat-meal trips; and
6. Nonhome-based—all trips having neither origin nor destination at home, regardless of the basic trip purpose.

At first it was felt that these six categories of trips sufficiently characterized the different types of travel patterns in the area. However, this stratification was later thought to be insufficient for the size and character of the study area involved.

The measure of spatial separation between zones (t_{i-j}) used in this study was the off-peak minimum path driving time between zones plus the terminal time in the production and the attraction zones connected with the trip. Time was used because it was felt to be the most realistic measure of spatial separation. Terminal times were added to driving times at both ends of the trip to allow for differences in parking and walking times in these zones, as caused by differences in congestion and available parking facilities. The terminal times used in this study were estimated from personal knowledge of these conditions within the study area. Off-peak hour conditions were used because this information was readily available and because about two-thirds of the daily travel in Washington occurs during the off-peak period.

Analysis of Basic Data on Travel Patterns

All information from the 1948 and 1955 travel inventories had previously been verified, coded, and punched into detail trip cards. Trip cards from the home interview survey (No. 2 cards) in both 1948 and 1955 were edited to insure that all pertinent information had been correctly punched. This was done using procedures developed by the Chicago Area Transportation Study (8).

The edited records which were originally coded during the home interview survey as change mode of travel or serve passenger trips were linked. Because of the standard home interview definition of a trip, a single trip may be represented by two or more trip records (i.e., a trip involving change of mode). If each of these trip segments were analyzed separately, the relationships between the actual starting point, the ultimate destination, and the purpose of the trip, as well as the relationship to type and intensity of land use, would be lost. By linking trips these problems can be substantially alleviated. This was accomplished using procedures similar to those developed by the Pittsburgh Area Transportation Study (9). By applying this process to the 1948 data, approximately 5 percent of the total trips and an estimated 3 percent of the person minutes of travel were lost. In 1955 the results were similar. In both cases, these reductions appeared to be geographically unbiased and, therefore, this linking process was judged to be acceptable. Similar findings have also been made in Pittsburgh (9) and Chicago (10).

The edited and linked records were then separated into the six trip purpose categories previously outlined. Then a table of zone-to-zone movements was prepared for each of the six trip purpose categories. The total number of trips produced by and attracted to each zone in the study area was also determined. These zonal trip production and attraction values for each trip purpose were two of the parameters required by the gravity model formula for both 1948 and 1955. The zone-to-zone movements were used to test the ability of the gravity model to simulate the 1955 travel patterns and forecast the 1948 patterns.

Determining Spatial Separation Between Zones

The next step in the process was to determine travel times between zones for both 1948 and 1955. In the development of a model for forecasting person movements, the determination of interzonal separation involves considerable compromise because of the great range between the levels of service (speed of travel) offered by the various modes of travel.

Since off-peak driving times for all segments of the major 1955 transportation system were available, these data were prepared and analyzed first. From records of time runs made in the field and information on the location and length of all segments of the major transportation system of the area, an IBM 7090 Build Network Description Program was used to prepare a description of the system for computer analysis. From this description, the minimum path driving time between each pair of zones was obtained. To these minimum driving time paths were added terminal times for an overall measurement of spatial separation between zones. Although briefly described here, this process of determining minimum driving time paths between zones is quite involved (11, 12).

To determine the minimum path driving times between zones for 1948, full use was made of the previous analyses on the 1955 system. The limited data available on driving times for the 1948 transportation system consisted of an isochronal chart of off-peak driving time from a downtown zone centroid to several points on the external cordon. Such information is not detailed enough to permit the direct calculation of minimum driving time paths between all zones. Consequently, it was assumed that any localized changes in minimum time paths between 1955 and 1948 would be caused only by basic changes in the transportation system between these two years. This would then be checked by comparing the estimated 1948 minimum path driving times against the isochronal charts available for 1948.

The first step in calculating the 1948 minimum path driving times was to delete all those segments not existing in 1948 from the basic network description previously prepared to describe the 1955 major transportation system. The principal facilities deleted include the outlying portions of the Shirley Highway, the Spout Run Parkway, the Baltimore-Washington Parkway, and the South Capital Street, East Capital Street, and New York Avenue Bridges. Next, the minimum driving time paths for several representative zones were calculated. The selected zones included several downtown zones and two zones lying near the external cordon in each of the four quadrants of the study area. From these sample calculations, an isochronal chart was prepared which represented the calculated 1948 driving times in the Washington area. This isochronal chart was compared to that available from field tests. Differences between these charts were negligible for most of the area. However, where discrepancies were observed, they were prorated to each segment of the transportation system in that part of the area. A new description of the 1948 network was then prepared and minimum driving time paths between all zones were calculated.

Since intrazonal times cannot be obtained through the standard procedures just outlined for interzonal times, they had to be determined separately. The 1955 driving time to adjacent zones was examined for several selected zones of varying sizes in downtown and outlying areas. Intrazonal times were then estimated and applied to all zones of similar size in the vicinity of the selected zones. Intrazonal times ranged in value from 2 to 4 min. The same intrazonal times used in 1955 were also used in 1948.

An estimate of 1955 terminal time was also made for each zone in the study area. This estimate, based on the type and intensity of land development within each zone, was quite subjective, but it was incorporated in this study for two reasons: (a) it was felt that people consider the total travel time (driving time plus terminal time) rather than only the driving time associated with a contemplated trip; and (b) perhaps one of previous research in this field had indicated that the exponent of distance for a given purpose varies with trip length because terminal time was excluded from the measurement of zonal separation. The estimated terminal times varied from 6 min within the central portion of the region to 3 min in the outlying suburban residential areas. The same 1955 terminal times were also used in 1948.

Obtaining Trip Length Frequency Distribution

The next step in the gravity model calibration process was to obtain a trip length frequency distribution by 1-min driving time increments for each trip purpose. This distribution was used in the trial and adjustment procedure for developing the effect of travel time on trip interchange $F(t_{i-j})$. All information required to produce these distributions has been obtained as previously described. Data on travel patterns supply information on zonal trip interchanges for 1955 and 1948 by trip purpose. Likewise, data on local transportation facilities are available for 1948 and 1955 in the form of minimum driving time paths between zones. The trip length frequency distributions were obtained by combining the number of trips between two zones with minimum driving travel times between the two zones and repeating this process for all possible zone pairs.

The trip length frequency curves from the 1955 and 1948 survey data for work trips are shown in Figures 2 and 3, respectively. Table 1 summarizes pertinent information on these curves for all trip purposes. It is important to note that this information is presented on trip distribution patterns with respect to the minimum path driving times, rather than minimum path travel times, because terminal times (travel times minus driving time) were not coded directly into the description of the transportation network and, consequently, could not be considered in the computer determination of zone-to-zone separation. In calculating trips by the gravity model formula, however, terminal times in both zones associated with every trip are added directly to the calculated driving times between the appropriate zones, so that total travel time is the measure of spatial separation used. Even so, to permit the comparison of actual and

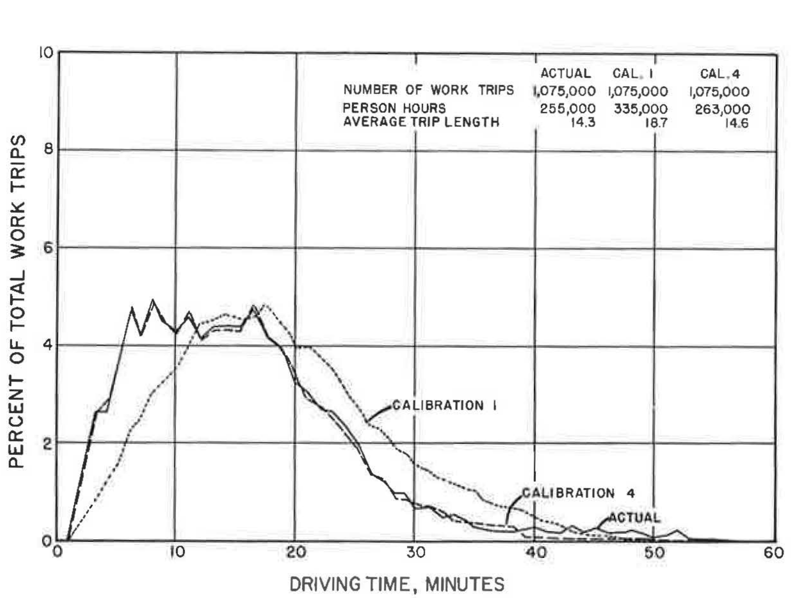

Figure 2. Trip length distribution for work trips, 1955.

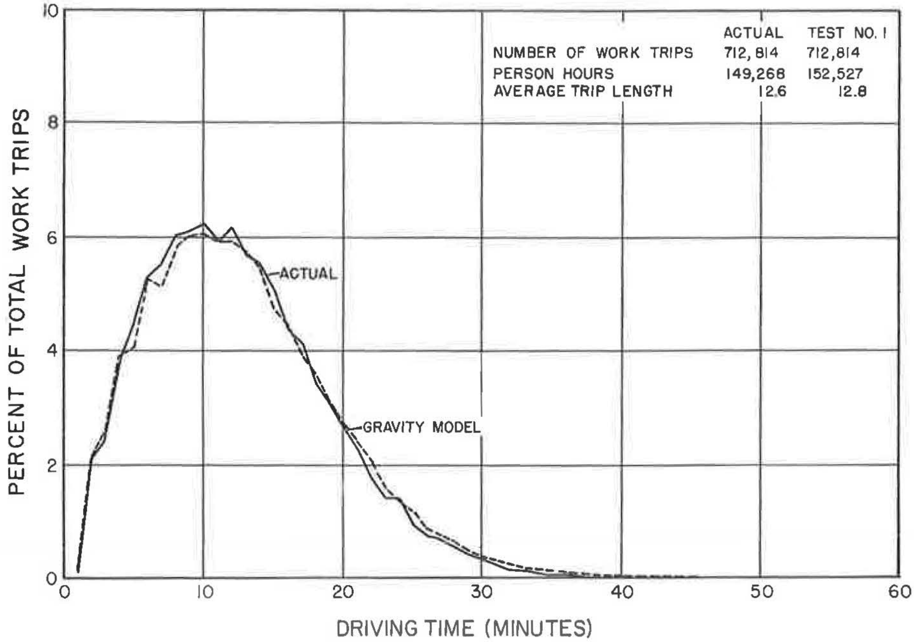

Figure 3. Trip length distribution for work trips, 1948.

TABLE 1

DISTRIBUTION OF TOTAL PERSON TRAVEL BY PURPOSE OF TRIP[a]

Trip Purpose	Person Trips				Person Hours of Travel				Avg. Trip (min)[b]	
	1948		1955		1948		1955			
	No.[c]	Percent	No.[c]	Percent	No.[c]	Percent	No.[c]	Percent	1948	1955
Home-based:										
Work	713	43.2	1,075	43.4	149	50.2	255	53.7	12.6	14.3
Shopping	156	9.5	335	13.5	21	7.2	40	8.5	8.1	7.2
Social-rec.	305	18.5	326	13.1	54	18.1	63	13.2	10.6	11.6
School	73	4.4	217	8.7	11	3.7	29	6.1	8.9	8.0
Miscellaneous	181	11.0	247	9.9	31	10.4	44	9.3	10.1	10.8
Nonhome-based	222	13.4	282	11.4	31	10.4	44	9.2	8.3	9.3
Total	1,650	100.0	2,482	100.0	297	100.0	475	100.0	10.8	11.5

[a]Based on linked trip figures derived from 1948 and 1955 home interview survey, Washington, D. C.
[b]Based on minimum path zone-to-zone driving time.
[c]In thousands.

estimated trip length frequency curves, a direct output of the gravity model calculations is a frequency distribution of estimated trips vs driving time. A better procedure would have been to code terminal time directly into the network, thereby allowing the calculations and the trip length frequency output to be compatible in all cases.

CALIBRATION OF 1955 GRAVITY MODEL

General Method

After the information on 1955 zonal trip production and attraction and zonal separation was prepared, as just described, the six purpose gravity model was calibrated to reflect the overall travel characteristics of the Washington metropolitan area for 1955. Part of this phase of the research has been reported by Hansen (3), but several additional analyses have been performed and to insure continuity, several of Hansen's findings will be restated in this report.

The calibration phase of the research involved four steps for each trip purpose:

1. Determining a set of travel time factors $F(t_{i-j})$ to express the average areawide effect of spatial separation on trip interchange between zones;
2. Adjusting zonal trip attraction values to assure that the trips attracted to each zone by the gravity model closely agree with the zonal controls shown by the home interview survey;
3. Accounting for topographical or geographical barriers which tend to bias model results; and
4. Accounting for social and economic factors which affect travel patterns but are not otherwise considered by the model.

These were not distinct steps, but rather overlap so that adjustments in one step influence the others. This process was an iterative procedure aimed at bringing the model in until it accurately simulated the existing travel pattern, the theory being that if it did this mathematically, it could also reasonably estimate future travel patterns.

To accomplish these four steps, ten calibrations were required, although only eight of these contributed to the study. Operationally, a study should require no more than four or five such calibrations. A summary of the adjustments made to the model during each of the calibrations appears in Table 2. The first four of these calibration runs were necessary to accomplish Step 1. The last three steps in the calibration process were accomplished in Calibrations 7 to 10. Calibrations 5 and 6 did not contribute to this research.

Determining Travel Time Factors

Previous research in this field has indicated that a single exponential function of time is not adequate to express the effect of spatial separation on zonal trip interchange (3, 4). Likewise, a specific mathematical equation or function adequately expressing the effect of spatial separation on zonal trip interchange $F(t_{i-j})$ has yet to be determined. Consequently, a process of trial and adjustment was necessary to determine the best set of average areawide travel time factors $F(t_{i-j})$.

An initial set of travel time factors was assumed for each trip purpose. These, together with the other necessary parameters (i.e., zonal productions and attractions and zonal separation), were used to obtain a gravity model estimate of trip interchanges. By comparing the resulting estimated interchanges with the actual interchanges from the home interview survey, the initial sets of travel time factors were revised. This process was repeated until the data from the two sets of interchanges were in close agreement. Since this trial and adjustment procedure is aimed at quantifying the effect of spatial separation on trip interchange, the data used to reflect trip interchanges are the trip length frequency curves, which show the percentage of trips for each trip purpose occurring at each 1-min increment of driving time.

Specifically then, trip interchanges were initially calculated for each trip purpose by the gravity model formula using zonal trip production and attraction figures as taken from the 1955 home interview survey, zonal separation figures taken from the inventory of transportation facilities, and a constant value of 1.0 for each $F(t_{i-j})$ and for each $K_{(i-j)}$. This was done using an IBM 7090 Gravity Model Program designed for this purpose (11). These estimated trip interchanges were combined with minimum path zone-to-zone driving times to determine the number and the percentage of estimated trips occurring during each 1-min increment of driving time, the person hours of travel, and the average trip length for each trip purpose. A plot of these data for work trips is shown in Figure 2.

TABLE 2

SUMMARY INFORMATION FOR EACH GRAVITY MODEL CALIBRATION RUN, 1955

Calibration No.	Trip Purposes	Special Remarks
1 2 3 4	Home-based: Work Shopping Social-rec. School Miscellaneous Nonhome-based	Each was used in developing travel time factors for each trip purpose. At end of Calibration 4, adequate factors had been developed.
5 6	Same as 1, 2, 3, and 4	These runs were special tests of gravity model using production and attraction estimates. They were not part of main research effort and are not important to this report.
7	Home-based work	Work trip travel time factors developed in Calibration 4 were used. Work trip attractions were balanced for closer agreement with O-D results.
8	Same as 1, 2, 3, and 4	A 2.5-min time barrier was added to all links crossing Potomac River. Trip attractions were balanced for all trip purposes except work trips balanced in Calibration 7.
9	Same as 1, 2, 3, and 4	A 6.0-min time barrier was added (after 2.5-min barrier was removed) to all links crossing Potomac River. Shopping trip attractions were balanced again.
10	Same as 1, 2, 3, and 4	After 6.0-min barrier was deleted, 5.0-min barrier was added to all links crossing Potomac River. Shopping and nonhome-based trip attractions were balanced. Zonal adjustment factors $K_{(i-j)}$ were applied to all work trips to CBD.

A visual comparison of the differences between the curves obtained by plotting the trip length frequency distribution for the home interview survey data and the gravity model results was made for each trip purpose. The percentage difference between the actual and the estimated person hours of travel and average trip length was computed for each trip purpose. If these differences were within 3 percent of each other and the visual inspection check was satisfactory, it was assumed that an acceptable set of average areawide travel time factors had been obtained. If not, the travel time factors for each time increment were revised for each trip purpose.

Figure 2 shows that the results of Calibration 1 were unsatisfactory for work trips. All travel time factors were assumed to be 1.0 in this initial run (it was assumed that travel time had no effect on trip interchange) and therefore, results for the other trip purposes were similar. This was done to determine how fast the trial and adjustment procedure would close on the desired trip length frequency. Operationally, a more satisfactory starting point for determining travel time factors would be to use factors obtained from other urban areas of similar size and character.

Since the first calibration was entirely unsatisfactory, the initial travel time factors were adjusted. The previous estimate of the factor was multiplied by the ratio of the percentage of home interview survey trips to that of gravity model trips occurring during the minute increment of travel time being considered. These new travel time factors for each 1-min increment of travel time were then plotted for each trip purpose on log-log graph paper vs the appropriate 1-min time increment (11). Lines of best fit (determined by judgment) were drawn through the plotted points and new sets of travel time factors $F(t_{i-j})$ for

TABLE 3

CALIBRATED VS HOME INTERVIEW (O-D) DATA FOR AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, 1955

Trip Purpose	Avg. Trip Length (min)[a]					Person Hours (thousands)[a]				
	Calib. 1	Calib. 2	Calib. 3	Calib. 4	O-D	Calib. 1	Calib. 2	Calib. 3	Calib. 4	O-D
Home-based:										
Work	18.7	16.1	15.2	14.6	14.3	335	288	273	263	255
Shopping	23.0	8.0	7.5	7.2	7.2	128	45	42	40	40
Social-rec.	22.5	12.5	12.5	11.6	11.6	122	68	68	63	63
School	23.2	8.6	8.6	7.8	8.0	84	31	31	28	29
Miscellaneous	20.0	12.6	11.9	11.1	10.7	82	52	49	46	44
Nonhome-based	17.8	11.7	10.6	9.2	9.3	84	55	50	43	44

[a]Based on minimum path zone-to-zone driving time.

each 1-min time increment were selected from these lines of best fit. Trip interchanges were then recalculated by the gravity model program for each trip purpose, using the same zonal trip production and attraction values and zonal separation values as used in the initial calibration and the new estimates of travel time factors selected from the lines of best fit. A value of 1.0 for each $K_{(i-j)}$ was used.

This process of trial and adjustment to determine travel time factors was repeated until the criteria discussed previously were satisfied. Four calibration runs were required to satisfy these criteria, but operationally this step should take no more than two calibrations using a reasonable first estimate of travel time factors. Table 3 shows how the average trip length and person hours of travel changed from calibration to calibration for each trip purpose, indicating to some extent the sensitivity of the trial and adjustment procedure. It also shows a comparison of these variables resulting from Calibration 4 with the same variables of the home interview survey. Figure 2 shows the same results in graphical form for work trips. Figure 4 shows the final travel time factor curves for each trip purpose. These factors, shown as a function of total travel time, were used throughout the remainder of the study.

The tendency of these travel time factors to curve down at the lower travel time increments is probably caused partially by the low estimates of intrazonal time. A comparison of intradistrict movements estimated by the gravity model formula in Calibration 4 with those from the home interview survey indicated that the estimated movements were approximately 10 percent low for all trip purposes. Another reason

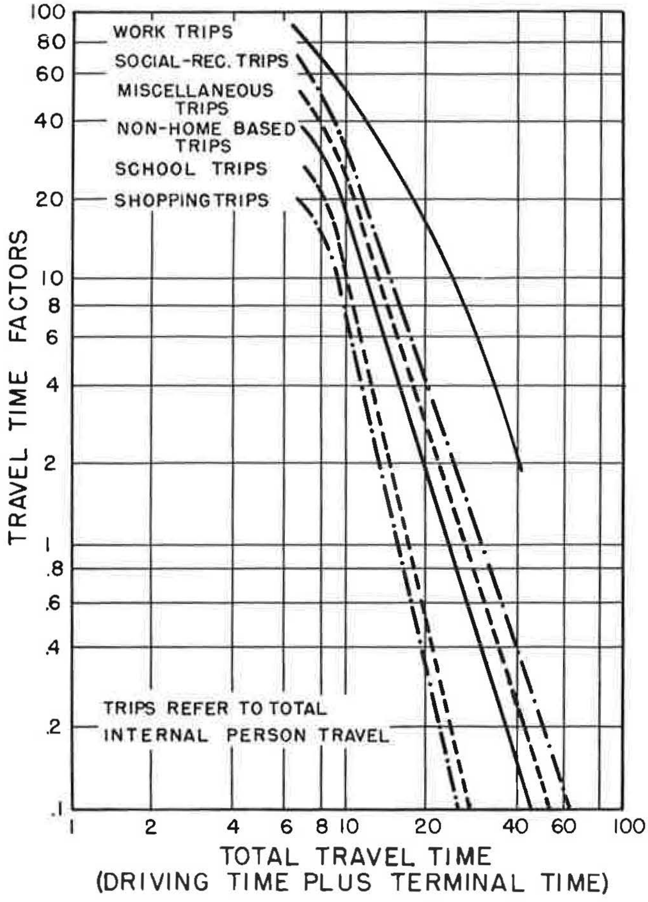

Figure 4. Final travel time factors, 1955.

is that the estimate of the terminal time in each zone may have been too low. Terminal times were estimated by judgment alone.

Adjusting Zonal Trip Attractions

A review of the gravity model formula shows that there is no certainty that the total number of trips attracted to each zone for each trip purpose by the gravity model will necessarily equal the zonal attraction values used in the distribution formula. This is a difficulty inherent in all existing trip distribution techniques, including growth factor methods and interarea travel formulas. Therefore, the next step in the calibration process was the adjustment of the measure of attraction to bring the number of trips attracted to a given zone by the gravity model formula into balance with the trip attraction of that zone as shown by the home interview survey.

The need for this adjustment became evident in this research when the work trip attractions for each zone as estimated by the gravity model formula in Calibration 4 were compared directly with the work trip attractions from the home interview survey. For most zones the differences were surprisingly small. However, there was a discernible pattern to these differences. The central area of the city had received too many work trips, whereas the zones in the outlying portions of the area had received too few. It was felt that this variation could have been substantially improved if work trips had been further stratified into government and nongovernment work trips. That is, a separate model should have been used to distribute work trips to the relatively concentrated government work centers and another model to distribute work trips to the nongovernment centers which are more evenly distributed throughout the area. Since differences in work trip attractions were noted, all other trip purposes were also analyzed.

Shopping trips showed a pattern which was the reverse of that observed for work trips. The central area of the region received too few trips and the suburban areas too many. The extent of the underestimate to the central area was quite large (40 percent). It is felt that this variation would have been considerably improved if shopping trips were further stratified into convenience and shopping goods trips; that is, a separate model should have been used to distribute the larger, less frequent travel related to the purchase of specialized major items found only in the central area and major competing suburban shopping centers.

Social-recreation and miscellaneous trips exhibited a pattern similar to shopping trips, but to a lesser extent. School trips varied considerably, primarily as a result of the small volumes involved.

The results obtained in this phase of the calibration process would vary considerably from city to city. In smaller cities, where decentralization of employment and shopping facilities is normally not as pronounced as it is in the larger metropolitan areas, the extent of the adjustments required could be expected to be considerably less than required in this study. For example, in other research, particularly that associated with Sioux Falls, S. D. (13), the adjustments required were negligible.

To examine the effects on travel patterns of the differences between trip attractions estimated by the gravity model and those shown by the home interview survey, selected work trip interchanges estimated by the gravity model formula in Calibration 4 were compared directly with the work trip interchanges from the home interview survey. Work trips were selected because of their large volumes and importance to total travel patterns. A cursory examination of the results of this comparison (Table 4) indicated that the gravity model had overestimated work trips crossing the Potomac River. This same table indicates that no such problem existed for work trips crossing the Anacostia River, probably because there are relatively few jobs on the Maryland side of this river, making it necessary for those persons living on the Maryland side to cross the river in order to work.

To bring the work trip attractions determined from the gravity model estimates into closer balance with those shown by the home interview survey, an adjusted work trip attraction factor was computed for each zone. This was done by multiplying the ratio of the home interview survey work trip attractions to the work trips attracted by

TABLE 4

HOME-BASED WORK TRIPS CROSSING POTOMAC AND ANACOSTIA RIVERS, 1955

Calibration	Potomac River						Anacostia River					
	Thousands of Trips Originating in						Thousands of Trips Originating					
	Virginia			Maryland and D. C.			South of River			North of River		
	Survey	Model	Diff. (%)[a]	Survey	Model	Diff. (%)[a]	Survey	Model	Diff. (%)[a]	Survey	Model	Diff. (%)[a]
4	97	141	+45	72	87	+20	134	137	+2	25	25	+2
7	97	127	+30	72	100	+38	134	137	+2	25	26	+4

[a]Computed before rounding.

the application of the gravity model by the work trip attraction as shown by the home interview survey as follows:

$$\frac{A_{(O-D)}}{\sum_{x=1}^{n} T_{(x-i)}} \times A_{(O-D)} = A_{(Revised)} \qquad (2)$$

The amount of adjustment required for work trips was relatively small and in most zones, the adjustment amounted to less than ±15 percent from the original value determined from the O-D survey.

Following this zonal adjustment, work trip interchanges were recalculated (Calibration 7) by the gravity model formula using the same zonal trip production factors as used in previous calibrations in combination with the new zonal trip attraction factors just calculated and the final estimate of travel time factors as obtained in Calibration 4. A value of 1.0 for each $K_{(i-j)}$ was used. An examination of the results (Table 4) showed that this step put work trip attractions in balance. At this point, it was decided to balance zonal trip attraction values for all trip purposes. However, before this was done for the other five trip purposes, the research staff felt it was necessary to investigate further the problem of overestimation by the gravity model of work trips crossing the Potomac River.

Topographical Barriers

Both the home interview work trips and those estimated in Calibration 7 were examined to determine the effect on the overestimation of balancing work trip attractions by zone. Table 4 indicates that this overestimate was only slightly improved. It was concluded that something other than the unbalanced trip attractions was affecting the accuracy of the gravity model estimates. Since the overestimate appeared to be common to the residents on both sides of the river, it was concluded that the factor creating this overestimate was directly associated with the river and the transportation network in the vicinity of the river. Evidently, the high peak hour congestion associated with 1955 Potomac River crossings reduced the travel demands to the extent shown because off-peak travel times used in this study did not reflect a true measure of the service offered in this area. This was by no means an isolated case. Similar results have been observed in the application of the gravity model in Hartford (1), Boston (14), and New Orleans (15). Other studies have experienced similar phenomena with the use of other traffic models.[2] Consequently, to correct this situation, a 2.5-min time penalty was added to all transportation facilities crossing the Potomac River. (This

[2]Unpublished reports by the Upstate New York Transportation Study, Wilbur Smith and Associates, and the Fox River Valley Transportation Study (CATS) indicate the need to incorporate time barriers into transportation networks.

TABLE 5

ADJUSTED DISTRIBUTION OF TOTAL PERSON TRAVEL, 1955[a]

Trip Purpose	Person Trips (thousands)	Person Hours of Travel (thousands)		Avg. Trip Length (min)	
		2.5-Min Barrier	6.0-Min Barrier	2.5-Min Barrier	6.0-Min Barrier
Home-based:					
Work	1,075	263	272	14.6	15.2
Shopping	335	40	41	7.2	7.3
Social-rec.	326	65	66	12.0	12.1
School	217	29	30	8.0	8.2
Miscellaneous	247	44	45	10.8	10.9
Nonhome-based	282	45	47	9.6	10.2
Total	2,482	486	501	11.7	9.7

[a]Based on minimum path zone-to-zone driving time, with 2.5- and 6.0-min barriers added to all driving times on links crossing Potomac River.

TABLE 6

TRIPS CROSSING POTOMAC RIVER, 1955

Trip Purpose	Person Trips Orig. in Md. and D. C.					Person Trips Orig. in Va.				
	Survey	Calib. 8	Diff. (%)[a]	Calib. 9	Diff. (%)[a]	Survey	Calib. 8	Diff. (%)[a]	Calib. 9	Diff. (%)[a]
Home-based:										
Work	72	83	+15	64	-12	97	120	+24	104	+ 6
Shopping	2	3	+75	2	-16	6	7	+ 8	4	-30
Social-rec.	12	13	+ 4	10	-19	19	21	+13	17	-11
School and Misc.	9	9	-	7	-22	12	15	+29	11	- 8
Nonhome-based	13	14	+ 3	N. A.	N. A.	12	13	+10	N. A.	N. A.
Total	108	122	+12	N. A.	N. A.	146	176	+21	N. A.	N. A.

[a]Between calibration and survey results, computed before rounding.

penalty was applied to all trip purposes even though, up to this point, the need for such a penalty had been established for work trips only.)

Because the addition of this time increment would increase the person hours of travel and the average trip length of the home interview trips when compared with the figures obtained without the barrier, it was necessary to recalculate these variables for the home interview data. Ideally the operation necessary to obtain the home interview trip length distribution would have been repeated with the river barriers included in the transportation system. However, the cost of this operation was prohibitive, so a new estimate of the person hours of travel and average trip length for each trip purpose was made by multiplying the number of home interview trips crossing the river by 2.5 min and adding this product to the results of the previously calculated person minutes of travel. The results are shown in Table 5. This procedure was based on the assumption that the shape of the trip length frequency curves for each trip purpose would remain the same with the time barrier added because trips of all driving time lengths would be equally affected. This assumption was later shown to be slightly in error, as will be discussed in the section of this report dealing with the 1948 forecasts.

With this adjustment made, trip interchanges were then recalculated for each trip purpose (Calibration 8), using the 2.5-min time penalty on the Potomac River links, zonal trip production values from the home interview survey, and trip attraction values adjusted for all trip purposes in the same manner as previously described. Travel time factors for each trip purpose were those developed during Calibration 4 (Fig. 4).

A value of 1.0 was used for $K_{(i-j)}$ in all cases. The newly estimated trips crossing the Potomac River were examined closely. Table 6 (Calibration 8) illustrates that work trip river crossings were improved, but not enough. It can be seen that the assumption that some time penalty should be applied to all trip purposes was correct since estimates are high for all trip purposes crossing the Potomac River. This table also indicates to some extent that the high peak hour congestion associated with the present river crossings was the major underlying factor associated with the overestimates, since work trips were overestimated to a greater extent than the other trip purposes. The calculated interchanges (Calibration 8) were also compared with the home interview interchanges (adjusted for 2.5-min barrier on the Potomac River) to determine the differences in person hours of travel and average trip length, by trip purpose (Table 7). The data in this table indicate that these estimated measures of overall travel demand still agree closely with those from the home interview survey.

TABLE 7

AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, 1955[a]

Trip Purpose	Avg. Trip Length (min)		Person Hours of Travel (thousands)	
	Survey	Calib. 8	Survey	Calib. 8
Home-based:				
Work	14.6	15.4	263	277
Shopping	7.2	7.5	40	42
Social-rec.	12.0	12.3	65	67
School	8.0	8.0	29	29
Miscellaneous	10.8	11.5	44	48
Nonhome-based	9.6	9.6	45	45

[a]Based on minimum path zone-to-zone driving times, with 2.5-min barrier added to all driving times on links crossing Potomac River.

TABLE 8

AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, 1955[a]

Trip Purpose	Avg. Trip Length (min)		Person Hours of Travel (thousands)	
	Survey	Calib. 9	Survey	Calib. 9
Home-based:				
Work	15.2	15.4	272	277
Shopping	7.3	7.7	41	43
Social-rec.	12.1	12.1	66	66
School	8.2	8.0	30	29
Miscellaneous	10.9	11.4	45	47
Nonhome-based	10.2	9.6	47	44

[a]Based on minimum path zone-to-zone driving times, with 6.0-min barrier added to all driving times on links crossing Potomac River.

Since these results indicated that the 2.5-min time penalty was insufficient, an additional 3.5-min barrier was added to the bridges crossing the Potomac River. The person hours of travel and average trip length were recalculated for the home interview data for all trip purposes to reflect the effect of the 6.0-min river barrier. The results are shown in Table 5. Trip interchanges were then recalculated (Calibration 9) using the 6.0-min time penalty on the Potomac River, trip production values for each trip purpose from the home interview survey, adjusted trip attraction values, and the travel time factors as used in Calibration 4. A value of 1.0 was used for $K_{(i-j)}$ in all cases. The recalculated interchanges crossing the Potomac River were examined again (Table 6, Calibration 9).

These results indicated that an overcorrection had been made and it was decided to reduce the barrier to 5.0 min. However, before making a new gravity model estimate, an additional and more detailed analysis was made to determine how well the model was simulating the 1955 interzonal travel patterns as surveyed in the home interview study. The effect of the 6.0-min barrier was also applied to the home interview total person hours of travel and average trip length and the results compared with the gravity model output. The results (Table 8) indicate close agreement.

Developing Zone-to-Zone Adjustment Factors

To determine the accuracy of estimated trip distribution patterns, work and nonwork trips to the CBD were analyzed in detail. The study area was divided into nine sectors as shown in Figure 1, and the differences between the actual and estimated trips from each district to the zero sector were examined. Figure 5, showing the results for work trips, indicates that a significant geographical bias is present. The results for nonwork trips (Fig. 6) indicate that nonwork trips are approximately in balance when examined on a sector basis. Work trips from Sectors 1, 2, 3, and 8 to the zero sector

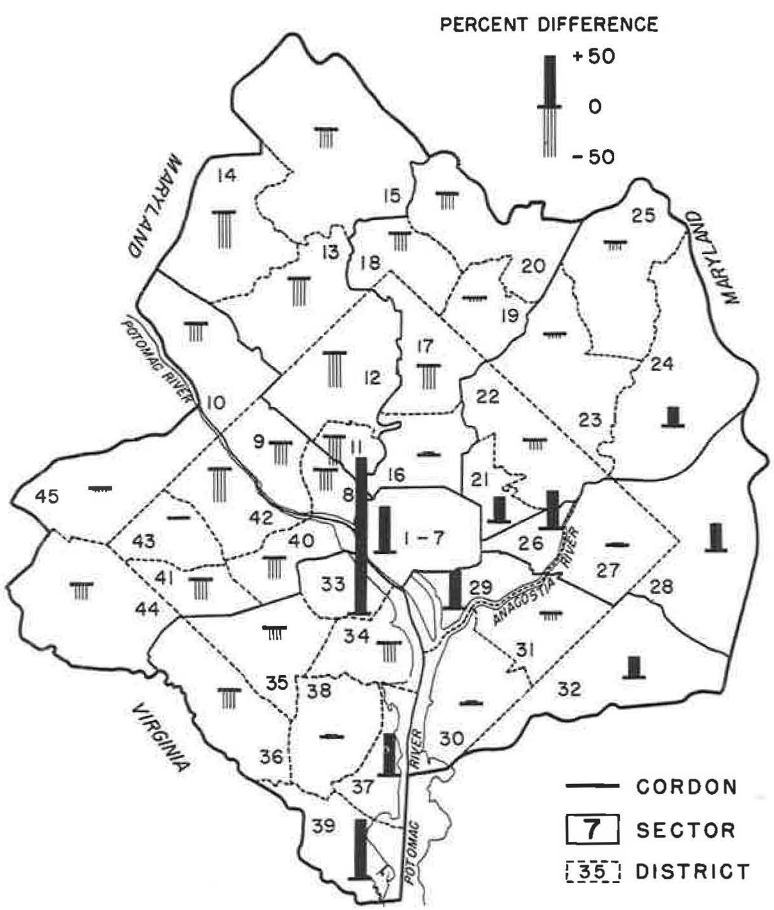

Figure 5. Differences between actual and estimated work trips to zero sector, Calibration 9.

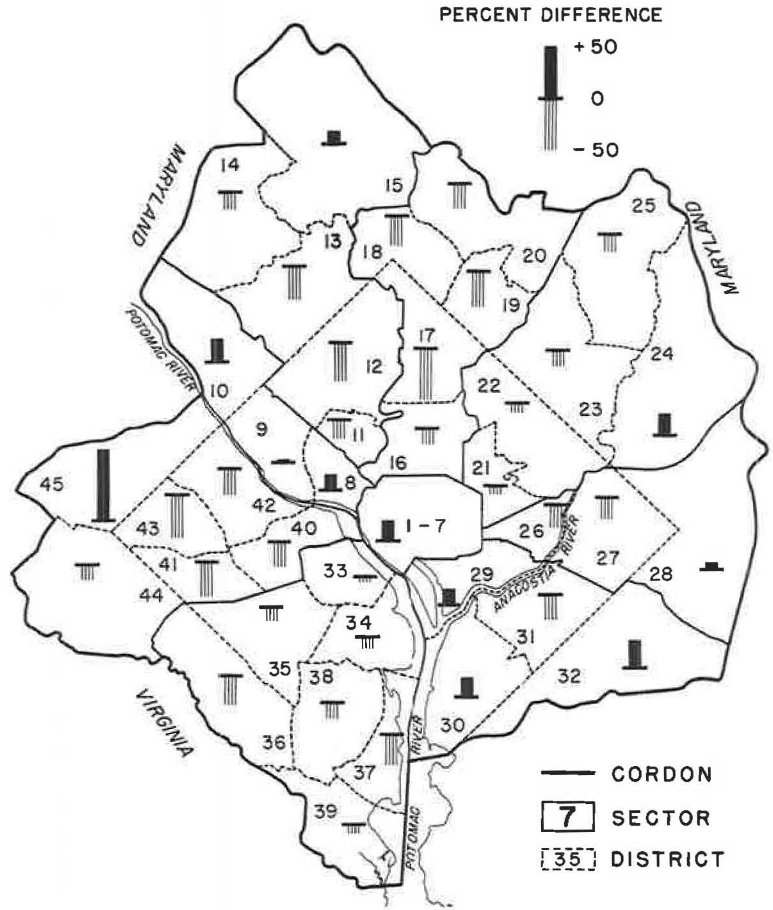

Figure 6. Differences between actual and estimated nonwork trips to zero sector, Calibration 9.

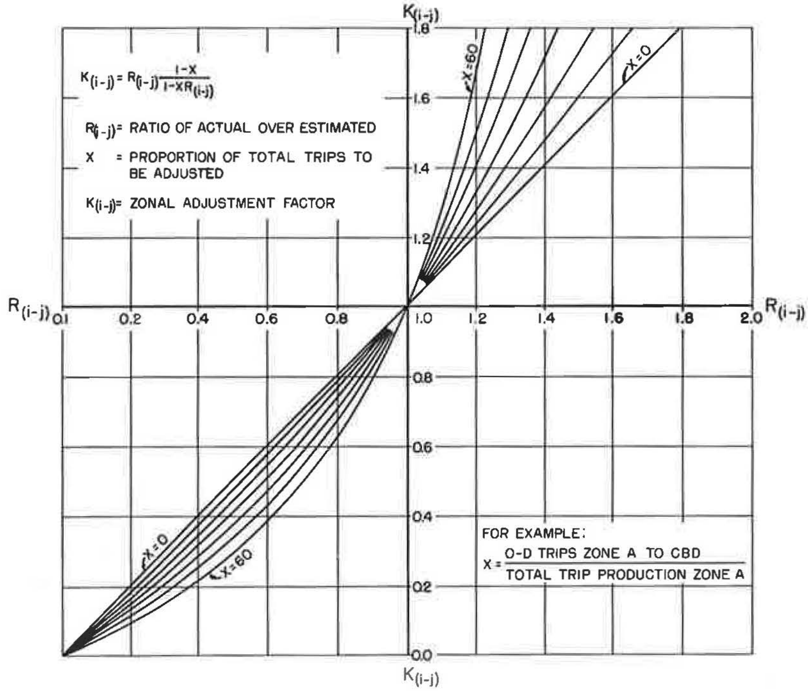

Figure 7. Adjustment factor curves for work trips to CBD, 1955.

were underestimated by the gravity model by about 15 percent. Work trips from Sectors 4, 5, 6, and 7 to the zero sector were overestimated by about the same amount. It was necessary to apply zonal adjustment factors to all work trips to the zero sector to reduce the effect of the geographical bias to the model. Nonwork trips were not adjusted. Consequently, $K_{(i-j)}$ factors were developed empirically by trial and error to account for the differences between the estimated and the actual interchanges, and the proportion of the total zonal production which would be affected by the adjustment (i.e., CBD-oriented trips). The curves which were finally developed to determine the appropriate adjustment factors for work trips are shown in Figure 7.

Trip interchanges were recalculated (Calibration 10) for all trip purposes, using the reduced barrier of 5.0 min on all facilities crossing the Potomac River, trip production figures from the home interview study, the adjusted trip attraction values used in Calibration 8 and the travel time factors used in Calibration 4. Values of $K_{(i-j)}$ for each zonal interchange for work trips to the zero sector (i.e., zones from 1 to 69) were taken directly from the curve in Figure 7. No $K_{(i-j)}$ factors were used for non-CBD-oriented work trips or for trips for purposes other than work.

River crossings as predicted by the gravity model were examined to determine the effect of using a 5.0-min time barrier. Table 9 indicates that by using this barrier, the river crossings were improved substantially. Since both a 5.0- and 6.0-min barrier had been used, it was concluded that no more adjustments of this type were warranted. Some thought, however, was given to applying

TABLE 9

TRIPS CROSSING THE POTOMAC RIVER, CALIBRATION 10, 1955

Trip Purpose	Trips (thousands)		Diff. (%)
	Survey	Model	
Home-based work	169	180	+6
All other trips	86	82	-5
Total	255	262	+3

TABLE 10

AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, CALIBRATION 10, 1955[a]

Trip Purpose	Avg. Trip Length (min)		Person Hours of Travel (thousands)	
	Survey	Calib. 10	Survey	Calib. 10
Home-based:				
Work	15.2	15.6	270	280
Shopping	7.3	7.9	41	44
Social-rec.	12.1	12.1	66	66
School	8.2	8.0	30	29
Miscellaneous	10.9	11.4	45	47
Nonhome-based	9.8	9.2	46	43

[a]Based on minimum path zone-to-zone driving times, with 5.0-min barrier added to all driving times on links crossing Potomac River.

a barrier of 4.0 min to nonwork trips to bring the estimated nonwork trips crossing the river into closer agreement with those from the home interview survey. The results of applying different time barriers indicated that the effect of this physical barrier was more pronounced for work trips than for nonwork trips. This was to be expected because nonwork trips occurred to a much greater extent in the off-peak periods when the time runs were made for the system coding. Severe congestion occurring on the Potomac River during the peak hours would naturally affect work trips to a greater extent. Nevertheless, the application of the 4.0-min barrier was not made, mainly because the volumes involved in the discrepancies for nonwork trips crossing the Potomac River were in about the same order of magnitude as those involved for work trips. In addition,

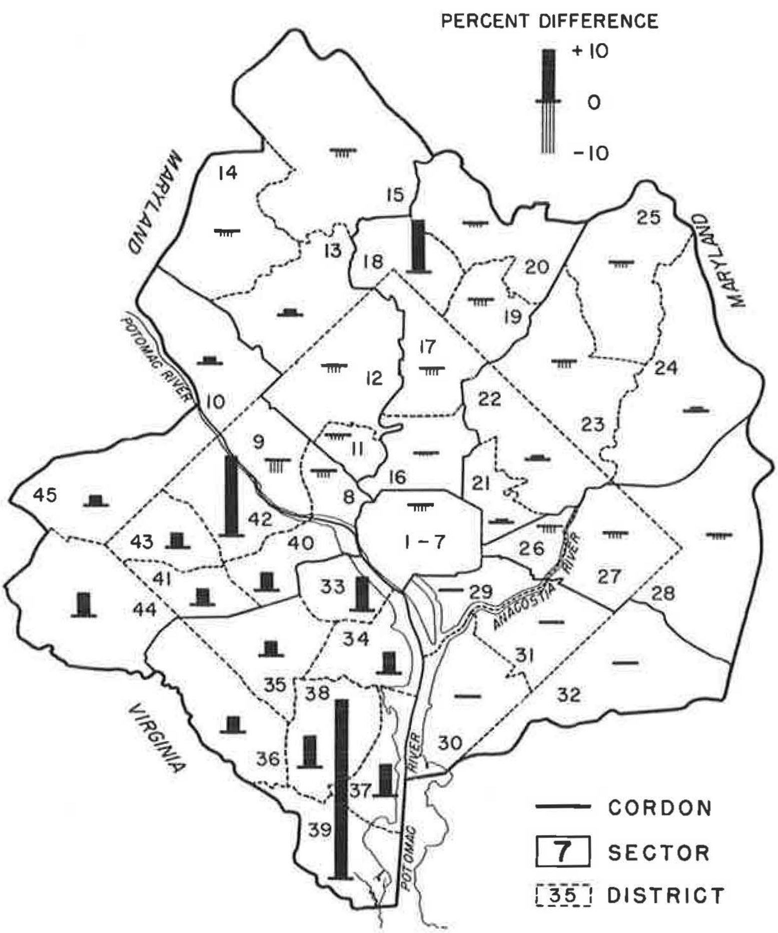

Figure 8. Differences between actual and estimated work trips to zero sector, Calibration 10.

most nonwork trips occur at various hours throughout the day rather than in the peak period, so the effect of these discrepancies from a design point of view was rather small. Later work indicated that even though a different barrier for nonwork trips was not warranted as a practical matter, from the standpoint of research such a barrier should have been used.

The estimated total person hours of travel and average trip lengths for each trip purpose were also compared with the appropriate data from the home interview survey (adjusted to reflect the 5.0-min time barrier on the Potomac River crossing). These results (Table 10) are in close agreement, indicating that the gravity model is distributing approximately the correct number of trips to each increment of travel time for each trip purpose. The estimated work trips from all districts to the zero sector were also compared with those shown by the home interview survey (Figure 8). This figure shows no significant geographical bias in trip patterns to the CBD and a relatively close agreement between the actual and the estimated figures.

Final Results

Three tests of the ability of the gravity model to simulate the 1955 trip distribution patterns for the Washington, D. C., area were previously described. The comparisons of trip length frequency for the gravity model and origin-destination work trip data were shown in Figure 2. Table 10 summarizes information on trip length for all trip purposes. Trips estimated from each district to the zero sector are compared with origin-destination data for nonwork and work trips in Figures 6 and 8. Finally the trips crossing the Potomac River were examined in Table 9. Four other tests were also made to provide a more comprehensive picture of how well the travel patterns were simulated.

The final estimated interchanges (Calibration 10) were assigned to a spider network[3] for work and nonwork trip purposes. A similar assignment was made with the results of the home interview survey. The results of these two assignments were compared by crossing a comprehensive series of screenlines for each of the two trip categories (Figs. 9 and 10). In both cases over 50 screenlines were compared.

The estimated work trips, as might be suspected, show a much better correspondence to the home interview figures than do the estimated nonwork trips. Only four of these screenline comparisons show a greater than 10 percent difference for work trips, whereas for nonwork trips 17 comparisons exhibited at least that much error. A review of the nonwork trip estimates indicated that much of the discrepancy in this category of trips was a result of the shopping trip estimates, indicating again that additional stratification of this type of trip would have substantially improved these results.

Another significant test of the ability of the calibrated gravity model to simulate the 1955 travel patterns in the Washington area was a statistical test of the differences between the gravity model estimates and the information shown by the home interview survey assigned in an identical manner to the spider network. Table 11 illustrates the analysis of these loadings by volume group. The reliability of the estimates increases as the volumes increase, and for volumes greater than 10,000 trips, two-thirds of the time the model results were within 15 percent of the observed values.

In addition to the statistical checks made on assigned volumes to the spider network for work and nonwork trips, the estimated district-to-district interchanges were compared with the actual interchanges for each of the six trip purposes. A simple statistical analysis of the differences between the actual and estimated interchanges was made and the root-mean-square error (RMSE) was calculated by volume group for each of the trip purposes. (See Figs. 20 and 21.)

Finally, to determine the accuracy of crosstown estimates made by the gravity model, all sector-to-sector movements from the gravity model estimates were extracted and compared with similar information from the origin-destination survey. Tables 12 and 13 illustrate the results of these comparisons for work and nonwork trips.

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[3]A spider network is a simplified and artificial transportation system consisting of straight-line links which connect zone centroids of adjacent zones.

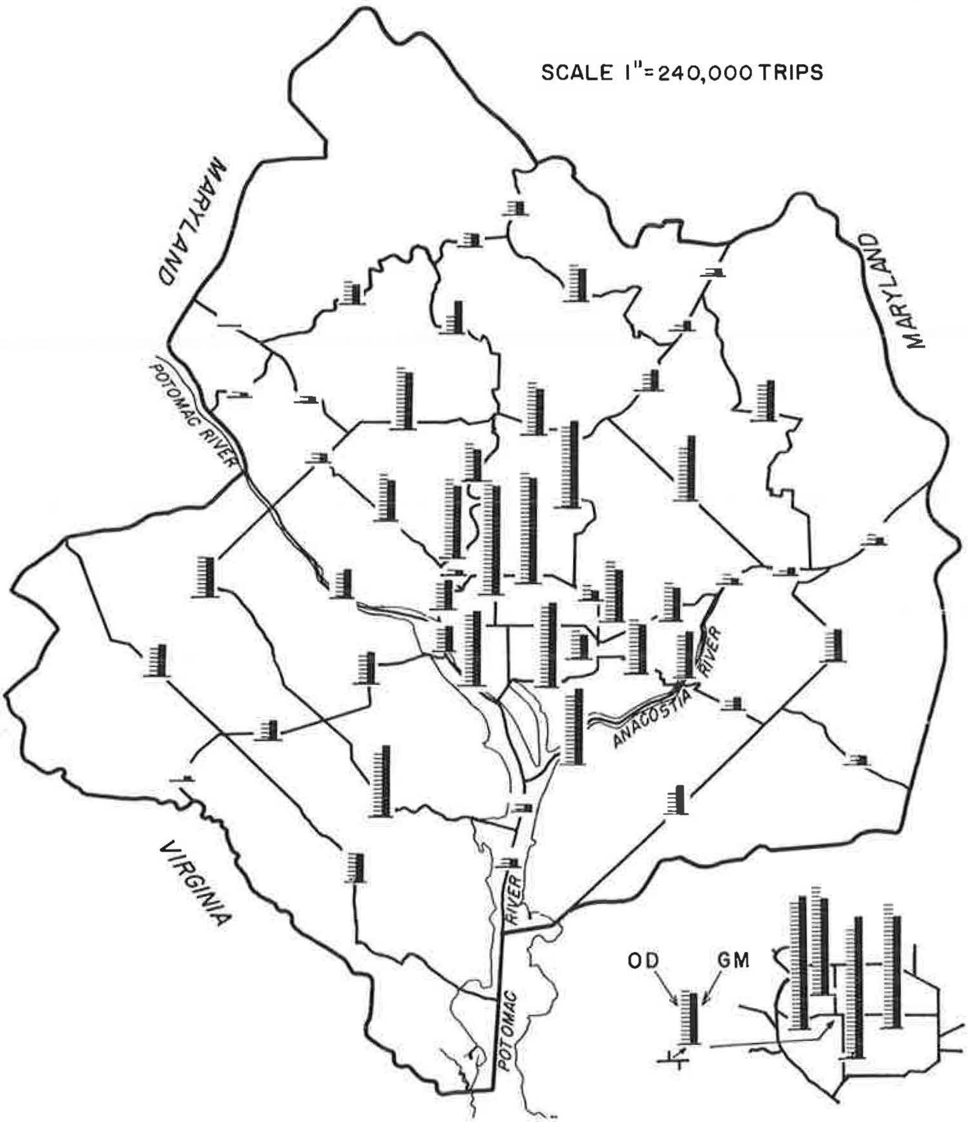

Figure 9. Comparison of screenline crossings, work trips, 1955.

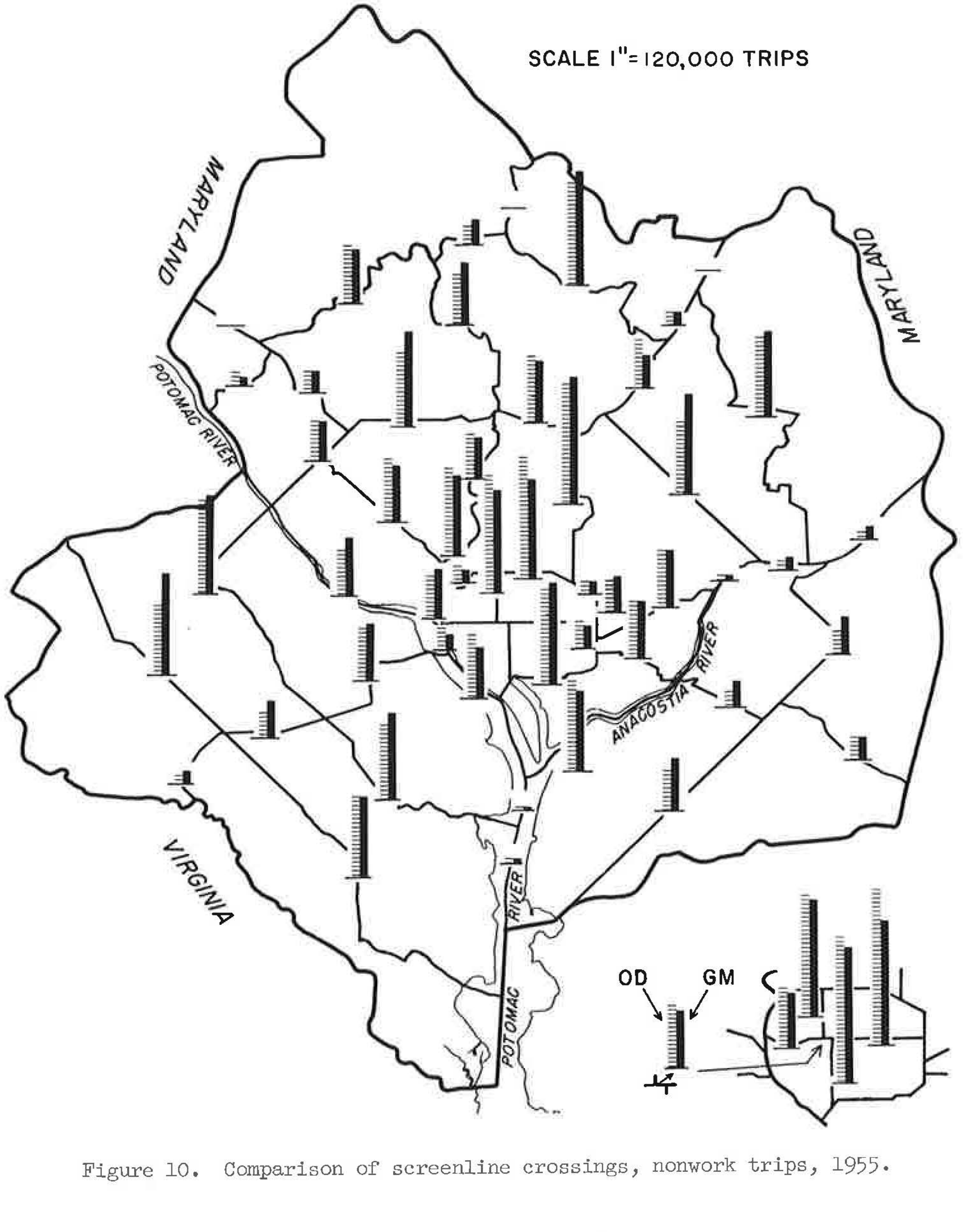

Figure 10. Comparison of screenline crossings, nonwork trips, 1955.

TABLE 11

ANALYSIS OF DIFFERENCES, GRAVITY MODEL VS HOME INTERVIEW SURVEY, 1955[a]

Volume Group	Work Trips				Nonwork Trips			
	No. of Interchanges	Mean Value	RMSE	RMSE/Mean x 100	No. of Interchanges	Mean Value	RMSE	RMSE/Mean x 100
0- 499	34	265	145	55	22	279	220	79
500- 999	40	763	271	36	30	707	438	62
1,000- 1,999	101	1,496	408	27	76	1,553	506	33
2,000- 2,999	94	2,512	701	28	72	2,519	849	34
3,000- 3,999	65	3,522	734	21	84	3,479	968	28
4,000- 4,999	63	4,522	839	19	80	4,469	1,202	27
5,000- 5,999	47	5,414	816	15	77	5,489	1,324	24
6,000- 7,999	61	6,995	1,145	16	109	7,021	1,531	22
8,000- 9,999	55	9,028	1,055	12	78	8,939	1,815	20
10,000-14,999	116	12,343	1,541	12	148	12,296	1,873	15
15,000-19,999	80	17,445	1,880	11	62	17,447	2,776	16
20,000-24,999	39	22,186	2,072	9	33	22,267	2,222	10
25,000-49,999	96	34,886	2,711	8	42	33,261	3,645	11
50,000-74,999	14	60,798	5,126	8	4	53,235	646	1
75,000 +	10	85,531	4,505	5	-	-	-	-

[a]Loaded on spider network.

TABLE 12

SECTOR-TO-SECTOR MOVEMENTS OF HOME-BASED WORK TRIPS, GRAVITY MODEL VS HOME INTERVIEW SURVEY, 1955[a]

From Sector	To Sector								
	0	1	2	3	4	5	6	7	8
0	36,640 36,254	4,066 3,738	7,872 4,920	8,320 9,260	5,378 6,545	1,365 2,259	5,267 7,408	8,956 8,275	2,500 1,921
1	26,007 25,795	3,632 2,961	3,964 4,000	2,137 2,409	1,416 1,051	583 339	777 1,450	2,767 2,786	412 884
2	59,531 59,285	4,075 4,666	23,565 21,031	12,088 12,948	3,763 4,514	1,025 989	2,583 3,032	6,100 5,112	711 1,545
3	113,398 113,631	6,920 6,510	16,519 18,878	43,632 39,323	12,507 18,192	4,355 3,765	10,610 9,295	14,416 11,374	2,941 2,942
4	62,588 63,640	3,608 3,079	7,165 7,305	14,690 17,582	31,806 27,009	5,772 6,293	11,241 11,168	6,755 7,781	1,452 1,754
5	39,602 39,368	3,588 1,887	4,828 3,065	8,515 6,816	10,698 11,910	8,601 9,639	12,235 15,699	6,966 7,108	1,339 1,394
6	55,096 54,988	2,350 2,428	4,273 3,156	5,947 5,580	7,529 7,613	5,377 6,053	31,243 30,022	8,934 10,501	1,049 1,974
7	35,896 38,068	1,463 2,361	2,243 2,772	1,548 3,323	999 2,347	753 1,097	4,349 5,542	52,705 45,077	6,437 7,730
8	38,615 40,471	2,206 2,713	2,523 3,067	2,139 2,912	1,277 1,775	472 757	3,391 3,684	24,929 25,129	19,857 13,636

[a]Legend: Survey / Model

TABLE 13

SECTOR-TO-SECTOR MOVEMENTS OF NONWORK TRIPS, GRAVITY MODEL VS HOME INTERVIEW SURVEY, 1955[a]

From Sector	To Sector 0	1	2	3	4	5	6	7	8
0	75,550 90,700	5,738 5,788	8,014 5,974	19,789 17,192	8,012 7,505	6,473 3,222	7,575 6,991	6,101 3,203	4,897 3,227
1	16,404 19,252	22,324 18,932	20,976 19,450	4,365 6,202	1,261 1,361	250 500	1,359 1,319	1,035 1,474	2,254 2,452
2	25,533 20,224	9,317 10,453	128,310 123,719	26,278 34,658	4,048 4,789	487 901	1,713 1,617	2,140 1,667	1,635 2,215
3	56,229 45,742	4,153 4,506	18,327 25,726	136,758 235,895	16,130 24,543	3,872 2,709	4,044 3,155	3,152 2,018	1,863 2,034
4	26,440 28,278	1,611 1,463	3,023 4,966	23,540 30,006	96,076 84,216	6,772 9,273	4,847 5,288	1,225 1,305	1,207 1,066
5	17,554 16,314	603 627	415 1,075	7,022 4,410	1,369 13,566	33,507 31,283	11,403 14,098	791 979	332 658
6	27,854 31,097	1,617 1,511	1,879 1,682	7,172 4,602	8,306 7,214	10,147 12,771	68,136 66,823	2,361 2,527	1,616 1,683
7	18,422 16,538	1,580 1,881	2,467 1,991	3,059 3,015	1,322 1,434	608 886	2,536 2,770	98,547 92,639	20,628 28,686
8	12,342 11,558	3,316 2,692	2,311 2,642	2,308 2,756	752 1,067	448 588	1,931 1,659	16,390 20,343	120,560 116,449

[a] Legend: Survey / Model

To analyze further the causes of geographic bias in the model and to arrive at a method of estimating future $K_{(i-j)}$ factors, the factors used to adjust the 1955 work trip model for CBD-oriented trips were correlated with several items of social-economic data relative to the zones concerned. Of these various correlations, one appeared to be significant. Figure 11 shows a plot of the relationship between the income group of persons living in each district of the study area and the $K_{(i-j)}$ factor which was required to adjust CBD-oriented work trips produced in that district. Unfortunately, a finer breakdown of income data by each district was not available. The correlation coefficient of this relationship was +0.88 and the standard error of estimate was 0.2255.

FORECASTING 1948 TRAVEL PATTERNS

Thus far this report has described the step-by-step procedure used to calibrate and test the gravity model for its ability to simulate the 1955 trip distribution patterns for the Washington metropolitan area. Three principal adjustments were made, each of which require projection to the future during the course of an operational transportation planning study. First, a set of travel time factors $F_{(t_{i-j})}$ was developed for each trip purpose to reflect the average areawide effect of spatial separation on zonal trip interchange. Second, a 5.0-min adjustment was made to the transportation facilities crossing the Potomac River to account for the relatively high peak hour congestion associated with these facilities. Finally, individual zone-to-zone adjustment factors were developed

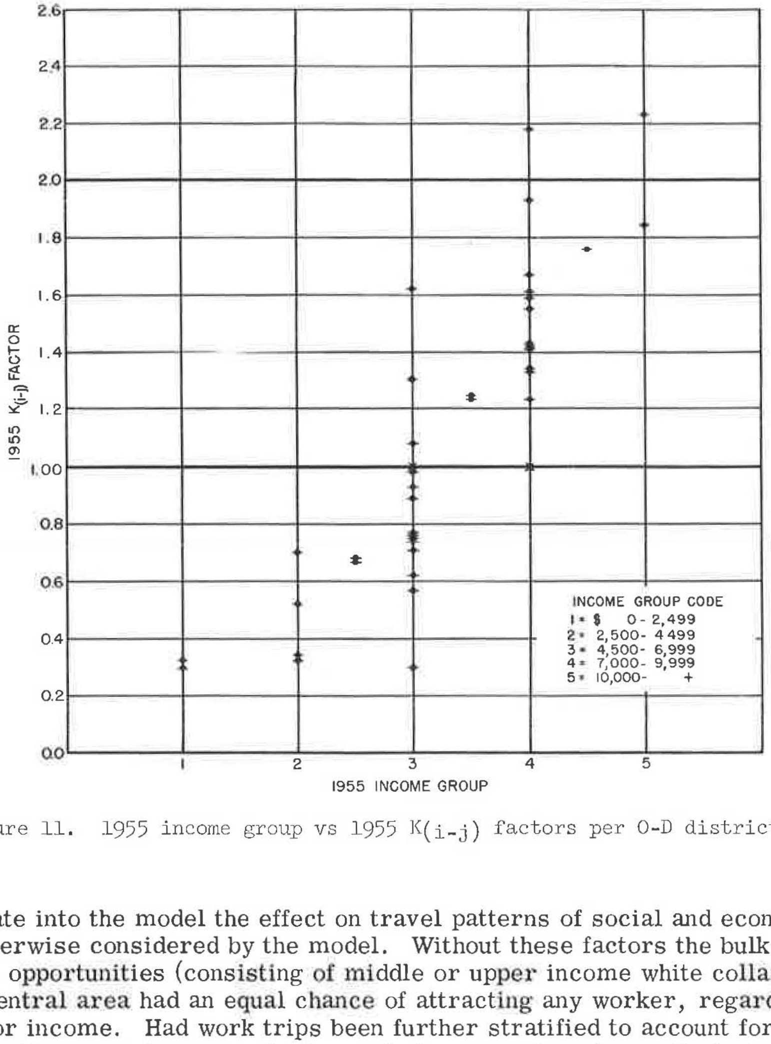

Figure 11. 1955 income group vs 1955 $K_{(i-j)}$ factors per O-D district.

to incorporate into the model the effect on travel patterns of social and economic linkages not otherwise considered by the model. Without these factors the bulk of the employment opportunities (consisting of middle or upper income white collar jobs) within the central area had an equal chance of attracting any worker, regardless of occupation or income. Had work trips been further stratified to account for this condition, the need for zone-to-zone adjustment factors may have been eliminated.

The purpose of this section of the report is to discuss investigations into the stability of these various adjustments over time. Travel time factors $F_{(t_{i-j})}$, developed for the 1955 model, are shown in Figure 4 for each of the six trip purpose categories. It has generally been accepted in past uses of the gravity model that these travel time factors $F_{(t_{i-j})}$ would hold constant over the forecast period. To evaluate this assumption, the 1955 travel time factors were used as input to the 1948 test runs. If these travel time factors were actually constant over time, then the resulting trip interchanges predicted by the gravity model as reflected by the trip length frequency curves should closely match the trip length frequency curves from the 1948 home interview survey data.

Adjustments made to the transportation facilities crossing the Potomac River to account for the relatively high peak hour congestion associated with these facilities were developed in a trial and adjustment procedure in Calibrations 8 through 10. The final adjustment of a 5.0-min time barrier was necessary before the gravity model estimated the correct number of trips crossing this barrier for all trip purposes. Work trips were in better balance than nonwork trips and, consequently, some consideration was given to making an additional calibration using a less restrictive barrier for the nonwork trips. Based on an analysis of the various barriers applied in the trial and adjustment procedure, a 4.0-min barrier for nonwork trips probably would have been more appropriate.

In the past, operational transportation studies had to make certain assumptions as to the need for and the quantity of travel barriers existing during the forecast period. The fact that such barriers were required for the present period implies that the future construction necessary to provide an entirely free flowing condition over these barriers may be extremely costly. Because of this, the assumption generally made in the past was that the level of congestion would remain about the same over these facilities in the future and, therefore, barriers existing at the base year would also exist at about the same level for the forecast period. Another primary purpose of this research was to investigate the validity of this assumption.

The individual zone-to-zone adjustment factors $K_{(i-j)}$ were empirically derived for 1955 in Calibration 10 to adjust work trips to the zero sector. This was done when evaluation of the model results showed that this adjustment was necessary to account for differences in social and economic conditions of residents of specific geographic portions of the study area. These factors, when related to various social and economic characteristics, were found to have the most significant relationship to income.

Operationally, a transportation study would be required to forecast the independent variable, in this case income, and derive future zone-to-zone adjustment factors $K_{(i-j)}$ for the forecast period.

The balancing of attractions for the 1955 period to adjust zonal attraction values (A_j) to insure that the number of trips attracted to each zone by the gravity model closely agreed to those zonal controls determined from the home interview survey was made automatically during the 1948 test runs.

The processing of data on 1948 travel patterns and facilities to obtain information on zonal productions, attraction and zonal separation has been previously discussed. A summary of this 1948 information for the total study area is shown in Table 1. The 1948 trip length frequency curves for each trip purpose were also discussed; the curve for work trips is shown in Figure 3.

Several gravity model test runs were made. A summary of these runs is shown in Table 14. The tests were carried out in such a way that each of the results of the three steps necessary to calibrate the gravity model could be evaluated separately.

Testing Travel Time Factors

The first step in the 1948 phase of this research was to test the stability over time of the travel time factors expressing the effect of spatial separation on the distribution of trips. Therefore, the first test used the following parameters and was specifically directed to evaluating the ability of the 1955 travel time factors to duplicate the trip length frequency characteristics of the 1948 home interview data by purpose:

1. Zonal trip production and attraction values for each trip purpose were taken directly from the 1948 home interview survey data.

2. The travel time factors $F_{(t_{i-j})}$ associated with each 1-min travel time were taken directly from the 1955 Calibration 4.

3. $K_{(i-j)}$ factors were set equal to 1.0 for all trip purposes.

4. Spatial separation between zones was taken directly from the 1948 transportation network.

5. Trips attracted to each zone were balanced to equal approximately the trip attraction (A_j) taken from the 1948 home interview survey.

Table 15 shows in summary form the average trip length for the estimated interchanges. It also shows the percentage difference between the estimated data and the 1948 home interview survey data. Trip length frequencies of work trips for the 1948 home interview data are compared in Figure 3 with the results obtained from Test Run 1 of the gravity model.

An examination of Table 15, Figure 3, and similar plots for other trip purposes indicates that the use of the 1955 travel time factors $F_{(t_{i-j})}$ to forecast 1948 patterns

TABLE 14

SUMMARY INFORMATION FOR EACH GRAVITY MODEL TEST RUN, 1948

Test Run No.	Trip Purposes	Special Remarks
1	Home-based: Work Shopping Social-rec. School Miscellaneous Nonhome-based	This run was specifically used to test 1955 travel time factors $F_{(t_{i-j})}$ for stability over forecast period.
2	Same as Test Run 1	A 5.0-min barrier was added to all links crossing Potomac River.
3	Same as Test Run 1	A 3.0-min barrier was added (after 5.0-min barrier was deleted) to all links crossing Potomac River.
4	Same as Test Run 1	A 2.0-min barrier was added (after 3.0-min barrier was deleted) to all links crossing Potomac River.
5	Home-based work	Zonal adjustment factors $K_{(i-j)}$ were applied to all work trips to CBD.
6	Home-based work	Same as Run 5 with exception that 4.0-min barrier replaced 2.0-min barrier on Potomac River.

TABLE 15

AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, TEST RUN 1, 1948

Trip Purpose	Person Hours of Travel (thousands)		Avg. Trip Length (min)		
	Survey	Run 1	Survey	Run 1	Diff. (%)
Home-based:					
Work	149	153	12.6	12.8	+1.6
Shopping	21	22	8.4	8.1	-3.6
Social-rec.	54	54	10.6	10.7	+0.9
School	11	10	8.9	8.2	-7.9
Miscellaneous	31	33	10.1	10.8	+6.9
Nonhome-based	31	32	8.1	8.6	+2.4
Total	297	304	10.8	11.0	+1.8
All nonwork	148	151	9.5	9.6	+1.1

provides an adequate duplication of trip length frequency found in the 1948 home interview survey. Only two of the six trip purposes considered gave a difference between the estimated and actual person minutes of travel and average trip length of greater than 4 percent. When the trip purposes were recombined into work and nonwork, the average trip lengths for the gravity model and the 1948 home interview differ by less than 2 percent. Considering the limits set on the calibration accuracy, the resulting trip length frequency forecasted to 1948 was very good.

Topographical Barriers

The next item to be checked by the 1948 tests was the stability over time of the 5.0-min time barrier which was necessary for all facilities crossing the Potomac River in 1955 to account for peak hour congestion problems not reflected by the basic travel times used. The gravity model adequately reproduced trips crossing this river as shown by the 1955 home interview survey only after this barrier was applied. Several test runs were required before this barrier was quantified for 1948 conditions because the 5.0-min barrier found necessary for 1955 conditions did not apply to the 1948 conditions. The test runs also provided additional data to allow research into the underlying factors causing this phenomenon. The first test run described previously permitted an evaluation of the number of trips crossing this river with no time barriers.

TABLE

TRIPS CROSSING POTOMAC AN

Trip Purpose	Potomac River: Trips Orig. in Va. (thousands)									Potomac River: Trips Orig. in Md. and D. C. (thousands)							
	Survey	Run 1	Diff. (%)[a]	Run 2	Diff. (%)[a]	Run 3	Diff. (%)[a]	Run 4	Diff. (%)[a]	Survey	Run 1	Diff. (%)[a]	Run 2	Diff. (%)[a]	Run 3	Diff. (%)[a]	Run 4
Home-based:																	
Work	70	83	+19	62	-12	67	- 4	70	+ 1	44	58	+ 30	31	-31	38	- 15	41
Shopping	8	12	+50	4	-52	6	-26	7	- 8	-[b]	3	+791	1	+58	1	+150	1
Social-rec.	22	28	+24	16	-29	19	-15	21	+ 6	9	14	+ 65	2	-78	2	- 78	2
School	5	5	+12	3	-47	4	-26	4	-15	-[b]	1	+595	-[b]	+78	-[b]	+123	-[b]
Miscellaneous	12	17	+47	10	-12	12	+ 5	13	+15	5	9	+108	2	-47	3	- 23	4
Nonhome-based	9	14	+43	9	- 9	11	+15	12	+28	10	14	+ 42	5	-47	8	- 17	10
All nonwork	56	76	+35	41	-27	51	- 8	58	+ 3	24	41	+ 71	11	-56	15	- 38	18

[a]Between test run and survey results, computed before rounding.
[b]Less than 1,000.

Table 16 compares results of this gravity model run with the 1948 home interview trips crossing the Anacostia and Potomac Rivers for each trip purpose category. It also gives the results of these comparisons when the movements were combined into work and nonwork trip categories. These summaries clearly indicate that similar conditions existed in 1948 with respect to the need for a time barrier on the Potomac River crossings, since the 1948 gravity model overestimated the number of trip crossings for all trip purpose categories. As found in the 1955 gravity model tests, the model accurately reflected the movements crossing the Anacostia River.

The second test run used the same input as Test Run 1 with the exception of the 1948 network which was revised to reflect a 5.0-min time barrier on the Potomac River. Table 17 gives the total person hours of travel and average trip length by purpose for this test run and the 1948 home interview movements. The travel time factors used in this run were adequate. The results of this run were then processed to extract the information necessary to evaluate the use of the 5.0-min barrier by examining the estimated trips crossing the Potomac River (Table 16). The 5.0-min time barrier added to these facilities was found to overcorrect for congestion conditions on the Potomac River crossings in 1948 in that the gravity model sent too few trips across the Potomac River for each of the six trip purpose categories. Consequently, an assumption that the time barrier remains the same for the forecast period in Washington appears invalid. At this point in the research, additional consideration was given to the underlying factors affecting congestion, since in the vicinity of the Potomac River crossings, it appeared to be the principal reason for the barrier. One measure of congestion on a facility is the volume-capacity ratio. It was reasoned that this ratio was different on those facilities crossing the Potomac River in 1948 than it was in 1955. To test this reasoning, the same trial and adjustment procedure as was used to determine the 1955 barrier was also used to determine the proper 1948 time barrier. The differences between the 1955 and the 1948 time barriers were then analyzed with respect to the volume-capacity ratios existing on the facilities crossing the Potomac River in these years.

The 1948 network then was further revised by changing the time barrier on the Potomac River from 5.0 to 3.0 min. The gravity model was rerun with all other input the same as Runs 1 and 2 but with this revised network. The results of Run 3 were evaluated, to check if the model was sending the correct number of trips across the two rivers in the area. Results (Table 16) indicated that the gravity model was still considerably underestimating trips across the Potomac River. Again the Anacostia River crossings were in balance. Table 18 gives a comparison of average trip length and total person hours of travel by purpose for Run 3 of the gravity model and the 1948 home interview survey.

Test Run 4 was made using a 2.0-min time barrier on the Potomac River. All other input data remained the same as previous runs. The data (Table 16) indicate that with

16

D ANACOSTIA RIVERS, 1948

	Anacostia River																	
	Trips Orig. South of River (thousands)									Trips Orig. North of River (thousands)								
Diff. (%)[a]	Survey	Run 1	Diff. (%)[a]	Run 2	Diff. (%)[a]	Run 3	Diff. (%)[a]	Run 4	Diff. (%)[a]	Survey	Run 1	Diff. (%)[a]	Run 2	Diff. (%)[a]	Run 3	Diff. (%)[a]	Run 4	Diff. (%)[a]
- 6	83	84	+2	82	- 1	82	- 1	82	-1	16	18	+ 9	15	- 6	15	- 5	16	- 5
+222	10	10	+1	11	+ 3	11	+ 2	11	+2	1	1	+150	1	+132	1	+141	1	+143
- 78	25	24	-6	23	- 6	24	- 5	24	-5	10	9	- 12	8	- 25	8	- 24	8	- 23
+165	7	7	+2	7	+ 2	7	+ 2	7	+2	-[b]	-[b]	+304	1	+438	1	+458	1	+472
- 5	15	15	-1	15	- 1	15	- 1	15	-1	2	2	- 3	2	- 17	2	- 17	2	- 16
+ 2	5	5	+4	6	+11	6	+12	6	+12	7	7	-	6	- 6	6	- 5	6	- 6
- 25	62	61	-2	62	- 1	62	- 1	62	- 1	20	20	- 1	18	- 11	18	- 10	18	- 9

TABLE 17

AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, TEST RUN 2, 1948

Trip Purpose	Person Hours of Travel (thousands)		Avg. Trip Length (min)		
	Survey	Run 2	Survey	Run 2	Diff. (%)
Home-based:					
Work	160	151	13.5	12.7	-5.9
Shopping	22	22	8.4	8.5	+1.2
Social-rec.	57	51	11.2	10.1	-9.8
School	11	11	9.4	8.7	-7.4
Miscellaneous	32	31	10.6	10.4	-1.9
Nonhome-based	33	34	9.0	9.1	+1.1
Total	315	300	11.5	10.9	-2.7
All nonwork	155	149	10.0	9.6	-3.9

TABLE 18

AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, TEST RUN 3, 1948

Trip Purpose	Person Hours of Travel (thousands)		Avg. Trip Length (min)		
	Survey	Run 3	Survey	Run 3	Diff. (%)
Home-based:					
Work	156	150	13.2	12.6	-4.5
Shopping	22	22	8.3	8.6	+3.6
Social-rec.	56	52	11.0	10.1	-8.2
School	11	11	9.3	8.8	-5.4
Miscellaneous	32	31	10.4	10.4	-
Nonhome-based	33	34	8.8	9.2	+4.5
Total	310	300	11.2	10.9	-2.7
All nonwork	153	150	9.8	9.6	-2.0

this 2.0-min time barrier placed on the Potomac River, the gravity model satisfactorily duplicated the actual river crossings as shown in the home interview survey. Trip purposes with large percentage differences also have a small percentage of the total trips. When the trip purposes are combined into work and nonwork trips, the estimated and actual crossings differ by only 1.6 percent and 5.5 percent, respectively. Table 19 gives a comparison of estimated vs actual trip length and person hours of travel for this run. Apparently the congestion level, or the volume-capacity ratio, on those facilities crossing the Potomac River in 1948 was such that only a 2.0-min time barrier was necessary to indicate the effect of this congestion to the gravity model. In 1955, these conditions required a 5.0-min time barrier.

TABLE 19

AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, TEST RUN 4, 1948

Trip Purpose	Person Hours of Travel (thousands)		Avg. Trip Length (min)		
	Survey	Run 4	Survey	Run 4	Diff. (%)
Home-based:					
Work	155	149	13.0	12.5	-3.8
Shopping	22	22	8.3	8.6	+3.6
Social-rec.	56	52	10.9	10.1	-7.3
School	11	11	9.2	8.8	-4.3
Miscellaneous	31	31	10.4	10.4	-
Nonhome-based	32	34	8.7	9.2	+5.7
Total	306	299	11.1	10.9	-1.8
All nonwork	150	150	9.7	9.6	-1.0

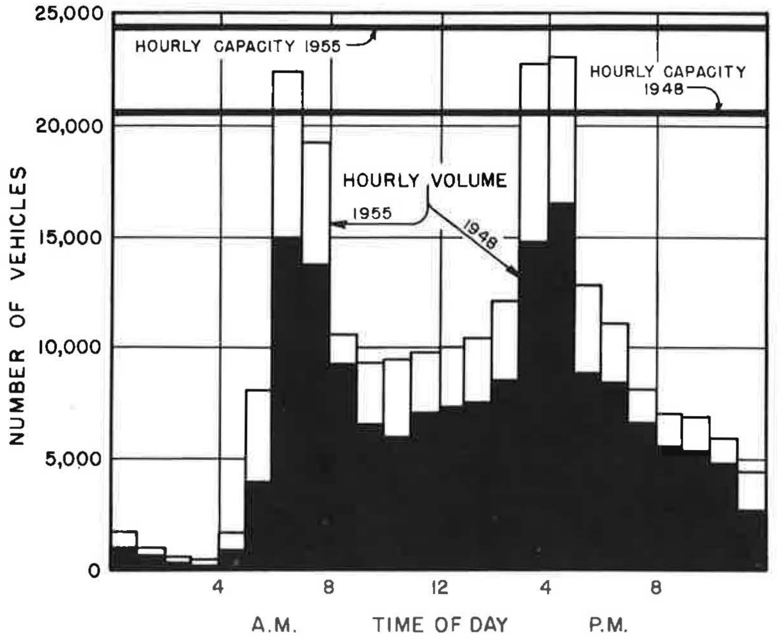

Figure 12. Potomac hourly traffic and capacity for 1948 and 1955.

An investigation of traffic using the Potomac River crossings and the capacity provided by these facilities in both 1948 and 1955 provides substantial evidence that the quantity of these barriers does actually depend on the relative congestion on the bridges. As shown in Figure 12, the level of congestion was much higher in 1955 than for 1948 for both peak and off-peak trips crossing the Potomac River. However, off-peak trips crossing the river increased by a much larger percentage than did peak trips between 1948 and 1955. This also indicates that the level of congestion would have also increased at a greater rate for nonwork trips than for work trips.

TABLE 20

THEORETICAL DETERMINATION OF POTOMAC RIVER BARRIERS IN 1948

Trip Purpose	1955		1948	
	Volume/Capacity	1.0-Min Barrier[a]	Volume/Capacity	Theoretical Barrier (min)[b]
Home-based work[c]	0.858	0.171	0.687	4.08
Nonwork[d]	0.218	0.0545	0.127	2.1

[a]Obtained by dividing total volume/capacity by time barrier required in 1955.
[b]Obtained by dividing Column 3 into Column 4.
[c]Four peak hours.
[d]Remaining 20 hours.

Many researchers have previously related a volume-capacity ratio to speed changes in working with the capacity restraint characteristics of the traffic assignment problem. Many curves have been derived empirically by different study groups. The problem of the Potomac River bridges acting as a barrier to free traffic movement is very closely related to the capacity restraint research carried out previously. Unfortunately, the testing of the gravity model presented very limited data for developing a solid base to describe relationships between relative congestion and the barrier effect to free traffic movement in the Washington area. In essence only two points existed where all the necessary information was available to analyze the relationship involved. Volumes and capacity were available by hour on the Potomac River bridges for both 1948 and 1955, and the time barriers required to balance the estimated and actual trip crossings were determined for both 1948 and 1955.

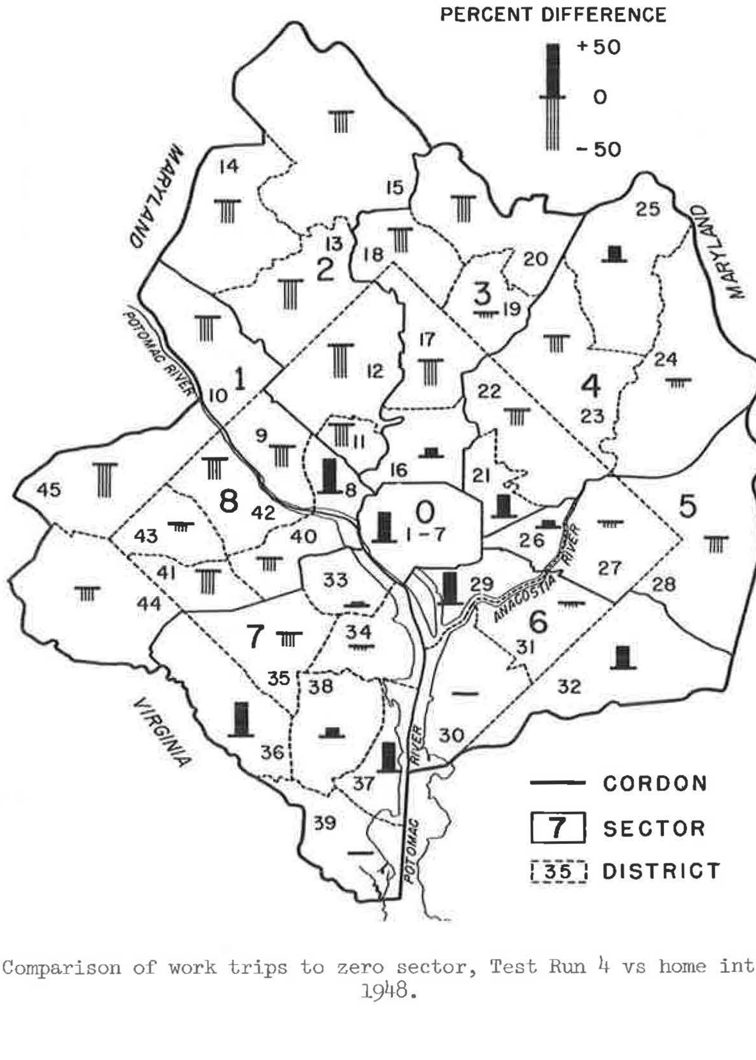

Figure 13. Comparison of work trips to zero sector, Test Run 4 vs home interview survey, 1948.

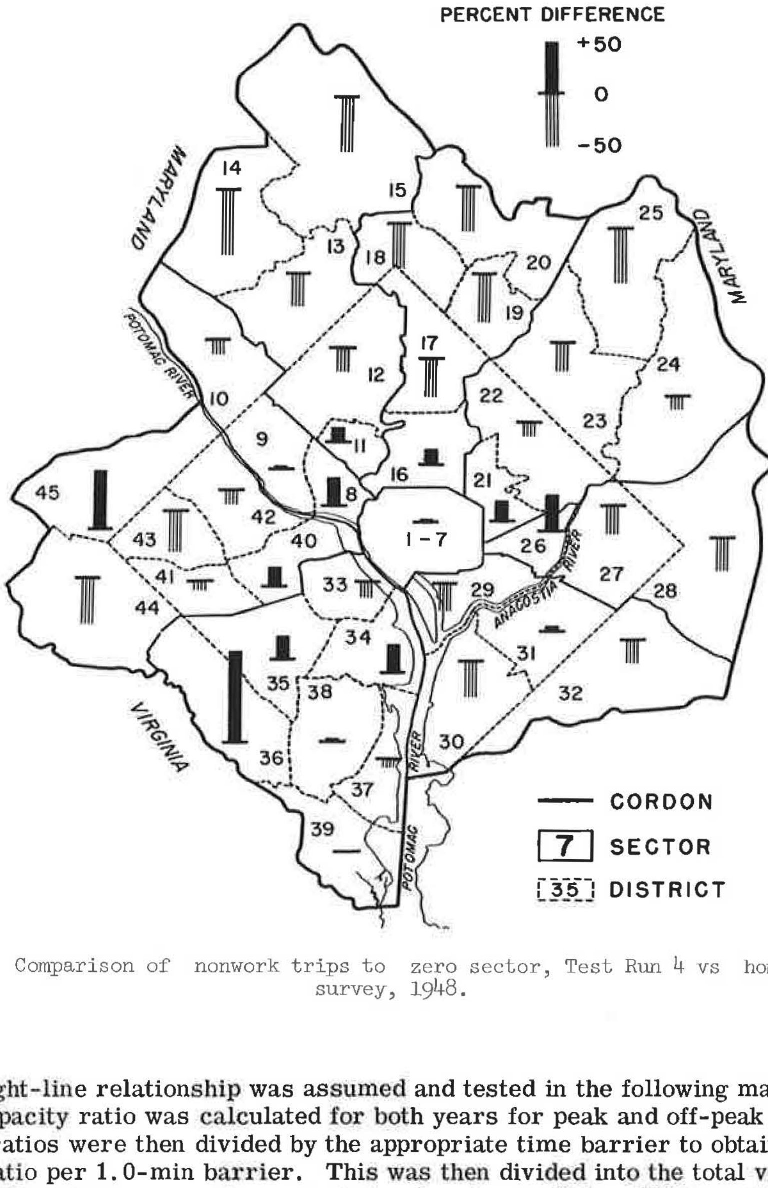

Figure 14. Comparison of nonwork trips to zero sector, Test Run 4 vs home interview survey, 1948.

A straight-line relationship was assumed and tested in the following manner. The volume-capacity ratio was calculated for both years for peak and off-peak time periods. The 1955 ratios were then divided by the appropriate time barrier to obtain the volume-capacity ratio per 1.0-min barrier. This was then divided into the total volume-capacity ratio in 1948 to determine a theoretical time barrier in 1948. This process is formulated as follows:

$$\frac{\text{1955 volume for appropriate time period}}{\text{1955 capacity for appropriate time period}} = \text{Total volume-capacity ratio (1955)} \quad (3)$$

$$\frac{\text{1955 total volume-capacity ratio}}{\text{1955 time barrier required (min)}} = \text{Ratio per 1.0-min time barrier (1955)} \quad (4)$$

$$\frac{\text{1948 total volume-capacity ratio}}{\text{Ratio per 1.0-min time barrier}} = \text{1948 time barrier (theoretical)} \quad (5)$$

This theoretical time barrier was compared with the actual barrier found to be necessary for the 1948 test runs for work and nonwork trips. For nonwork trips this comparison was very good; for work trips it was not good at all (Table 20). In analyzing the reasons why the work trip theoretical barrier checked so poorly, attention was focused on the effects that the 1955 zonal adjustment factors had on the Potomac

River crossings. An analysis was made of the differences between the gravity model trips crossing the Potomac River in Calibrations 9 and 10 during the 1955 simulation study, keeping in mind that there was a 1.0-min difference in the time barriers applied in these two calibrations, as well as zonal adjustment factors $K_{(i-j)}$. This analysis indicated that the 2.0-min time barrier applied to the 1948 Potomac River bridges in the test just described would probably need modifying for work trips when the zonal adjustment factors were applied and that the final time barrier for work trips would probably be close to the theoretical barrier shown for this trip purpose in Table 20.

Zone-to-Zone Adjustment Factors

Both the home interview survey data and the Run 4 gravity model trip distribution patterns were compressed to district-to-district movements and the estimated vs actual movements to the zero sector were compared for work and nonwork trips (Figs. 13, 14). Figure 13 shows this comparison for work trips and illustrates a pattern of geographical bias in the 1948 gravity model results similar to that found in the 1955 results, before specific zone-to-zone adjustment factors $K_{(i-j)}$ were applied. The similarity can be seen by comparing this figure with Figure 5. Figure 14 shows that, as found in 1955, the nonwork trip patterns estimated by the gravity model had no such geographical bias. To be sure, every estimated district movement to the CBD was not balanced with the actual distribution, but there was no pattern readily discernible with regard to any specific section of the metropolitan area. Each sector, when trips were accumulated along the sector corridor, displayed an adequate balance in the trips estimated to the zero sector.

Examination of Figure 13 indicated the need for adjustment of the work trip movements to the CBD. Income data were available for each of the 1948 districts in generally the same categories as 1955. Ideally, an equation would have been developed reflecting the relationship in 1955 and the independent variable of income group for each district for 1948 could be used to determine $K_{(i-j)}$ adjustment factors for 1948. This was not done for three reasons: (a) 1948 income data were available according to slightly different groupings than in 1955 and the district boundaries in 1948 (before data processing) were slightly different than those in 1955; (b) very few of the districts actually changed income groups between the two study periods; and (c) as stated in the earlier discussion of the relationship between income group and $K_{(i-j)}$ factors in 1955, if income had been available in finer breakdowns, a much improved relationship would probably have resulted. Figure 15 shows the relationship of 1948 income group to 1955 $K_{(i-j)}$ factor. It is very similar to Figure 11 showing this relationship for 1955. The correlation coefficient of the data shown in Figure 15 was +0.88 and the standard error of estimation was 0.2369.

Therefore, the same $K_{(i-j)}$ factors as were found necessary in 1955 were used in the next test run (Run 5) which considered only work trips. Productions (P_i) and attractions (A_j) were taken directly from the 1948 survey data. Travel time factors $F(t_{i-j})$ were the same as those used for work trips in 1955 and in the previous four test runs. $K_{(i-j)}$ factors were the same as those developed and used in 1955 for each of the zones considered. A system was used which reflected 2.0-min time barriers on each of the Potomac River crossings. Tables 21 and 22 give a comparison of the estimated vs actual Potomac River crossings and person hours of travel and average trip length. Figure 16 shows a comparison of home interview data and work trips to the zero sector resulting from the application of the $K_{(i-j)}$ factors (Run 5). The distribution of work trips to the CBD was very much improved by the application of the 1955 $K_{(i-j)}$ factors. As was expected, however, the check of river crossings shows that the application of the $K_{(i-j)}$ factors has caused the gravity model Potomac River crossings to be overestimated by approximately 16 percent.

Because the gravity model trips crossing the Potomac River were overestimated in Test Run 5, it was decided to increase the barrier to 4.0 min and keep other input the same for Run 6.

The results of Run 6 were examined in some detail. Table 22 compares work trips estimated in this test run with those shown by the home interview survey. The results

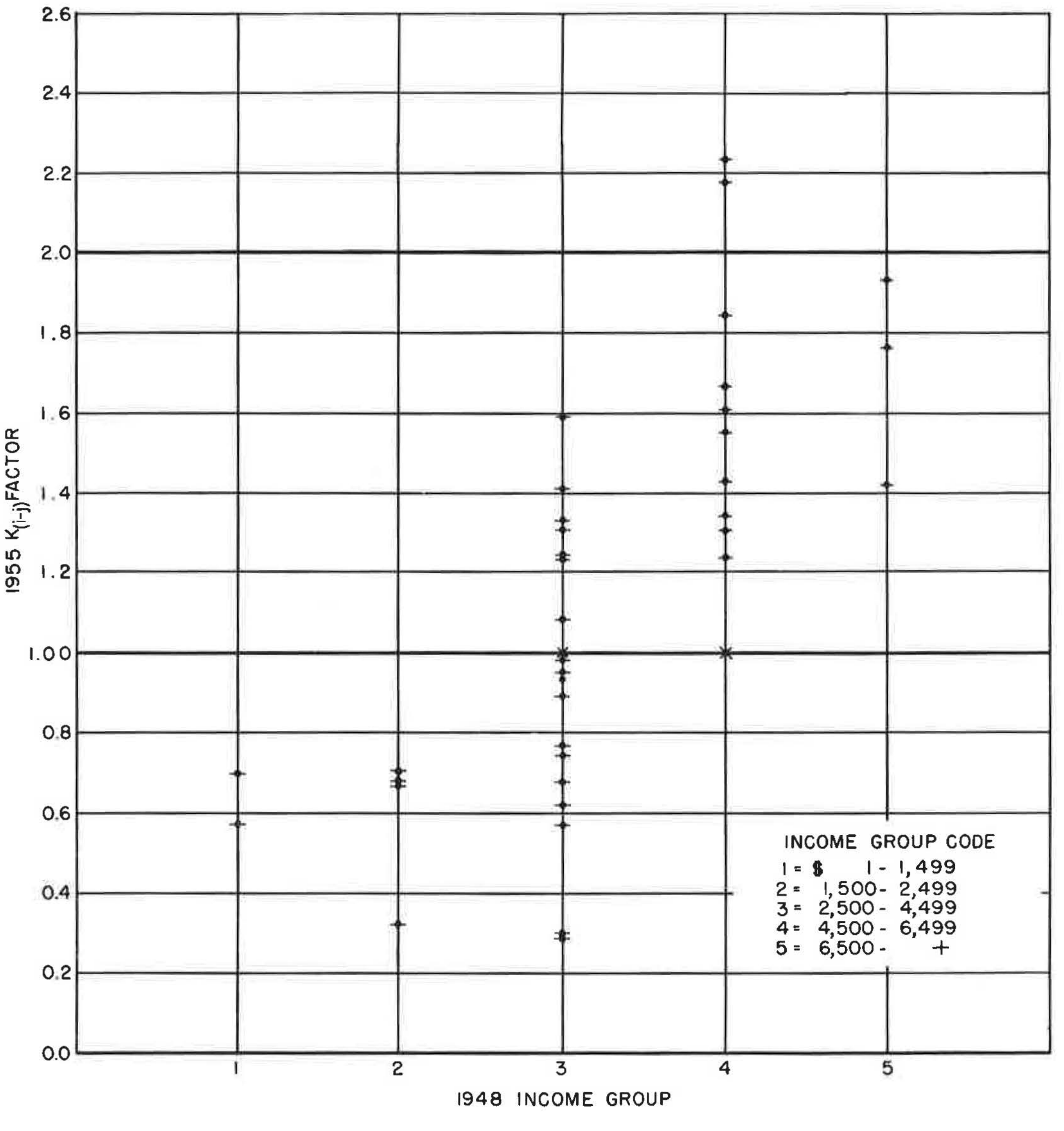

Figure 15. 1948 income group vs 1955 $K_{(i-j)}$ factors for O-D district.

TABLE 21

AVERAGE TRIP LENGTH AND PERSON HOURS OF TRAVEL, 1948

Test Run[a]	Person Hours of Travel (thousands)		Avg. Trip Length (min)		
	Survey	Model	Survey	Model	Diff. (%)
5	155	159	13.0	13.4	+3.1
6	158	158	13.33	13.31	-0.15

[a]Purpose, home-based work.

TABLE 22

TRIPS CROSSING THE POTOMAC AND ANACOSTIA RIVERS, 1948

Test Run[a]	Potomac River: Trips Orig. in (thousands): Virginia			Maryland and D. C.			Anacostia River: Trips Orig. (thousands): South of River			North of River		
	Survey	Model	Diff. (%)[b]	Survey	Model	Diff. (%)[b]	Survey	Model	Diff. (%)[b]	Survey	Model	Diff. (%)[b]
5	70	79	+14	44	53	+19	83	85	+2	16	18	+11
6	70	74	+ 6	44	46	+ 5	83	85	+2	16	18	+11

[a]Purpose, home-based work. [b]Computed before rounding.

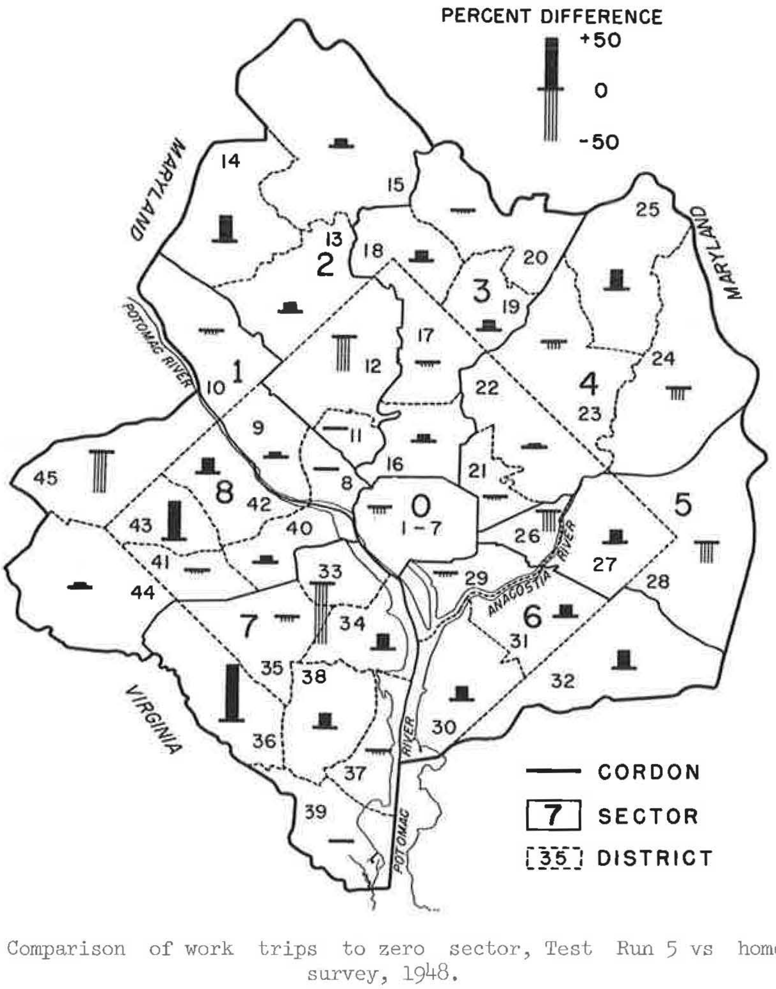

Figure 16. Comparison of work trips to zero sector, Test Run 5 vs home interview survey, 1948.

indicate that these trips were now in approximate balance. Table 21 compares average trip length for work trips in Run 6 and the home interview survey results with a 4.0-min time barrier applied to the Potomac River crossings. Figure 17 compares work trips from each district to the zero sector as estimated in Run 6 with those trips found to occur in the survey data.

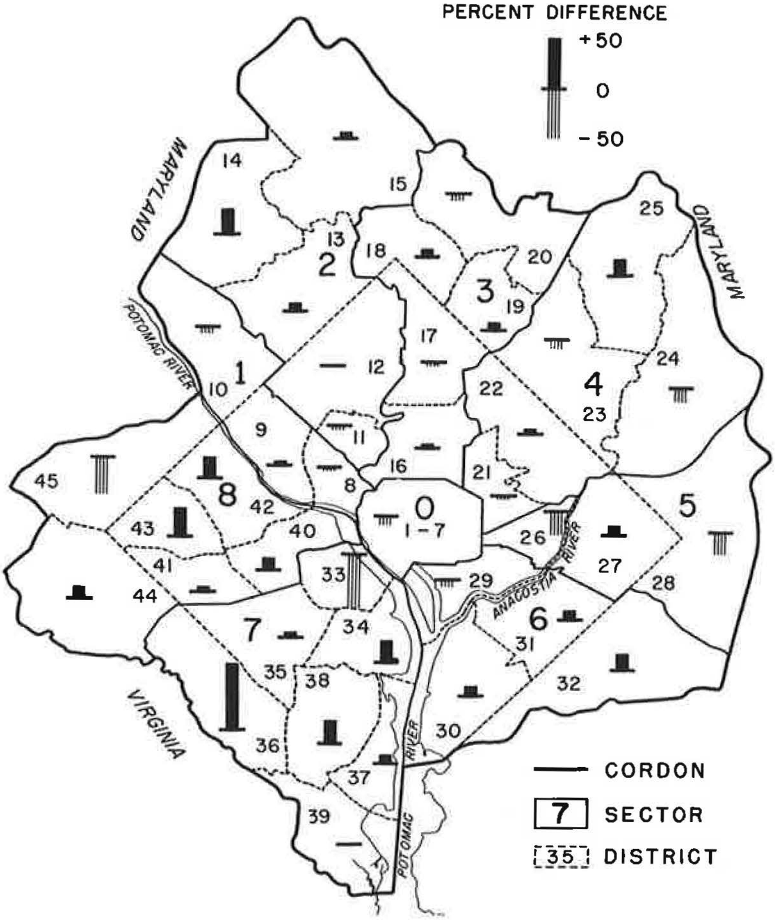

Figure 17. Comparison of work trips to zero sector, Test Run 6 vs home interview survey, 1948.

Final Results

The forecasted trip distribution patterns of the final 1948 test run were evaluated using the same tests as previously discussed in testing the final 1955 calibration. Three tests of the ability of the gravity model to forecast the 1948 trip distribution patterns for the Washington, D. C., area were previously described. The stability of the 1955 travel time factors $F(t_{i-j})$ over time was demonstrated by the comparison of trip length frequency for gravity model and the home interview survey work trip data shown in Figure 3. Table 15 summarizes comparisons between the model and survey trip length data for all trip purposes. Trips estimated from each district to the zero sector are compared with origin-destination data for nonwork and work trips in Figures 14 and 17. Finally, trips crossing the Potomac River for nonwork and work trips are examined in Tables 16 and 22. Four additional tests (again similar to tests made on the 1955 model results) were made to further evaluate the ability of the gravity model as a trip distribution forecasting procedure.

The final estimated interchanges (Test Run 4 for nonwork trips and Test Run 6 for work trips) were assigned to the same spider network as used in 1955. Similar assignments were made for work and nonwork trips from the home interview survey. The results of these assignments were compared by crossing the same screenlines as

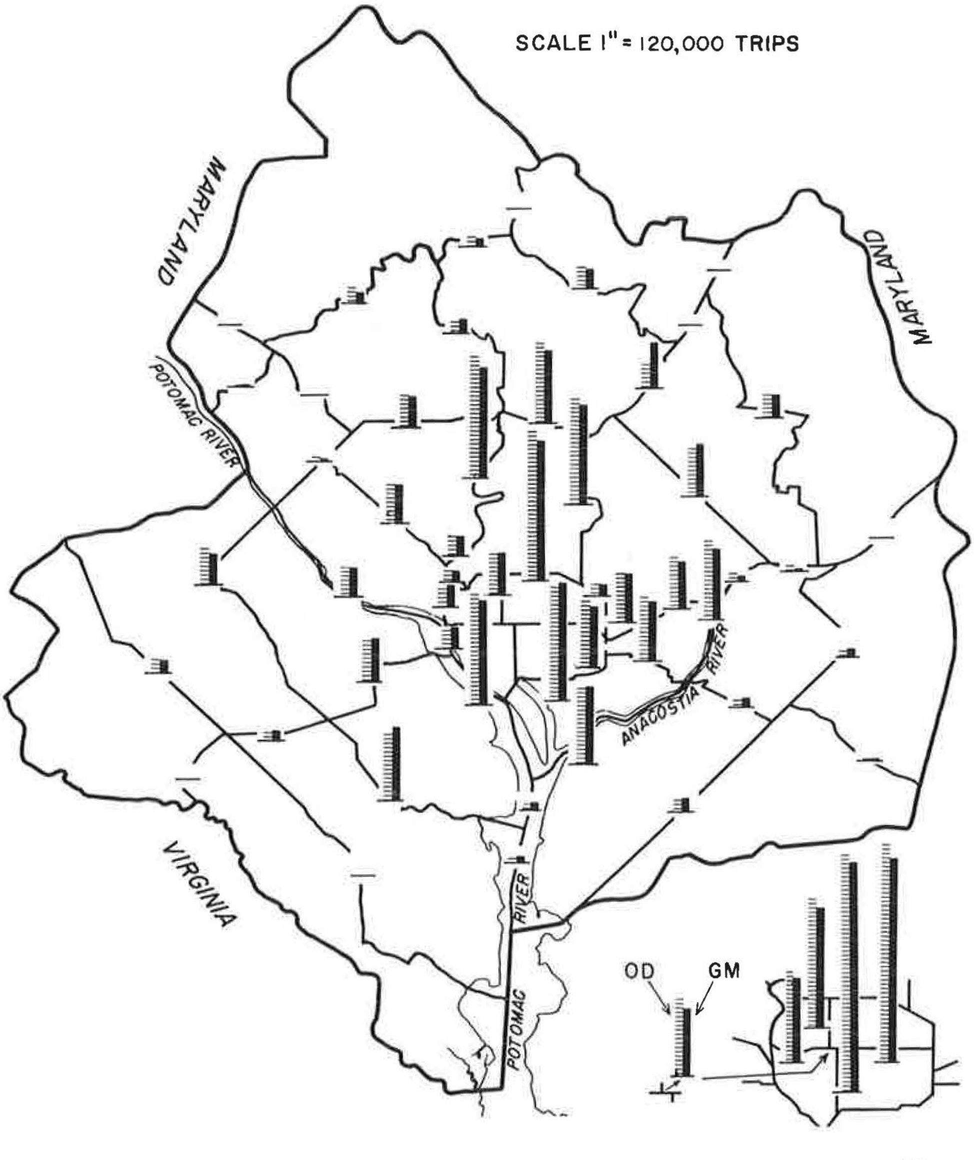

Figure 18. Comparison of screenline crossings for nonwork trips, 1948.

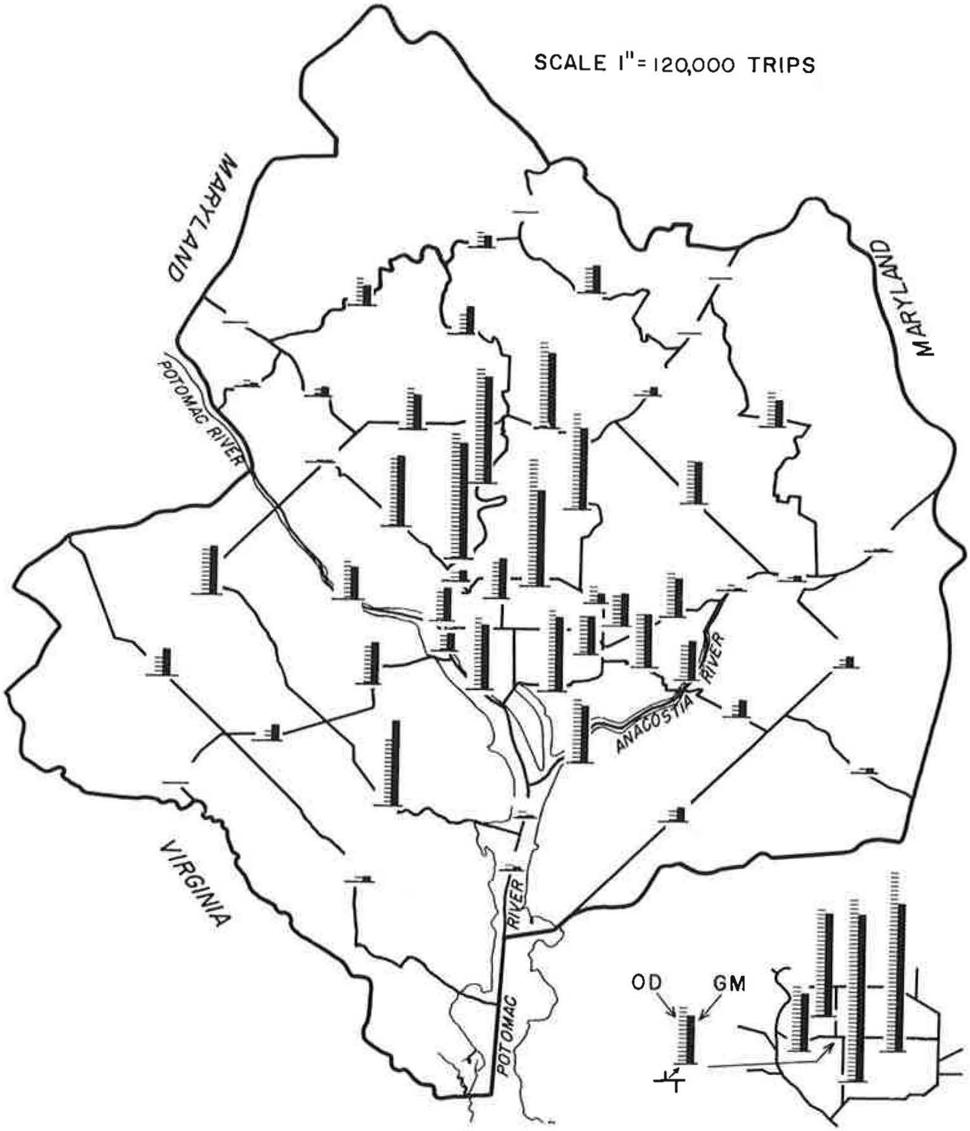

Figure 19. Comparison of screenline crossings, for nonwork trips, 1948.

TABLE 23

ANALYSIS OF DIFFERENCES, GRAVITY MODEL VS HOME INTERVIEW SURVEY, 1948[a]

Volume Group	Work Trips				Nonwork Trips			
	No. of Interchanges	Mean Value	RMSE	RMSE/Mean x 100	No. of Interchanges	Mean Value	RMSE	RMSE/Mean x 100
0- 499	120	195	139	71	84	186	227	122
500- 999	81	726	333	46	59	743	420	57
1,000- 1,999	105	1,446	398	28	97	1,540	700	45
2,000- 2,999	92	2,463	503	20	93	2,674	1,049	39
3,000- 3,999	42	3,482	639	18	66	3,406	1,201	35
4,000- 4,999	43	4,477	739	17	61	4,449	1,533	34
5,000- 5,999	35	5,491	871	16	45	5,423	1,265	23
6,000- 7,999	40	7,014	824	12	64	6,901	1,199	17
8,000- 9,999	43	8,968	1,168	13	59	8,915	1,557	17
10,000-14,999	74	12,212	1,320	11	75	12,184	1,844	15
15,000-19,999	46	17,177	1,508	9	52	17,201	2,404	14
20,000-24,999	33	22,401	1,650	7	27	22,319	3,154	14
25,000-49,999	56	33,588	2,683	8	36	34,359	4,230	12
50,000-74,999	14	56,291	3,845	7	6	59,538	7,706	13
75,000 +	1	75,272	1,712	2	-	-	-	-

[a]Loaded on spider network.

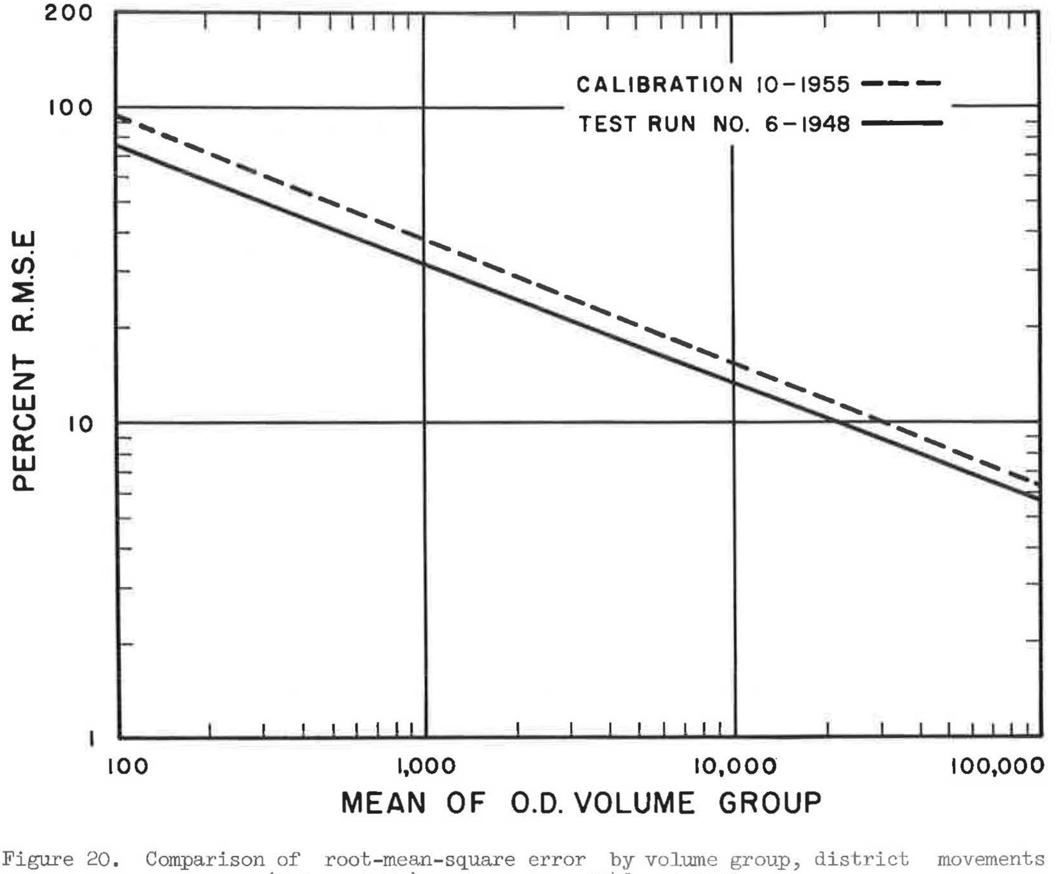

Figure 20. Comparison of root-mean-square error by volume group, district movements (O-D vs G.M.) work trips, 1948 and 1955.

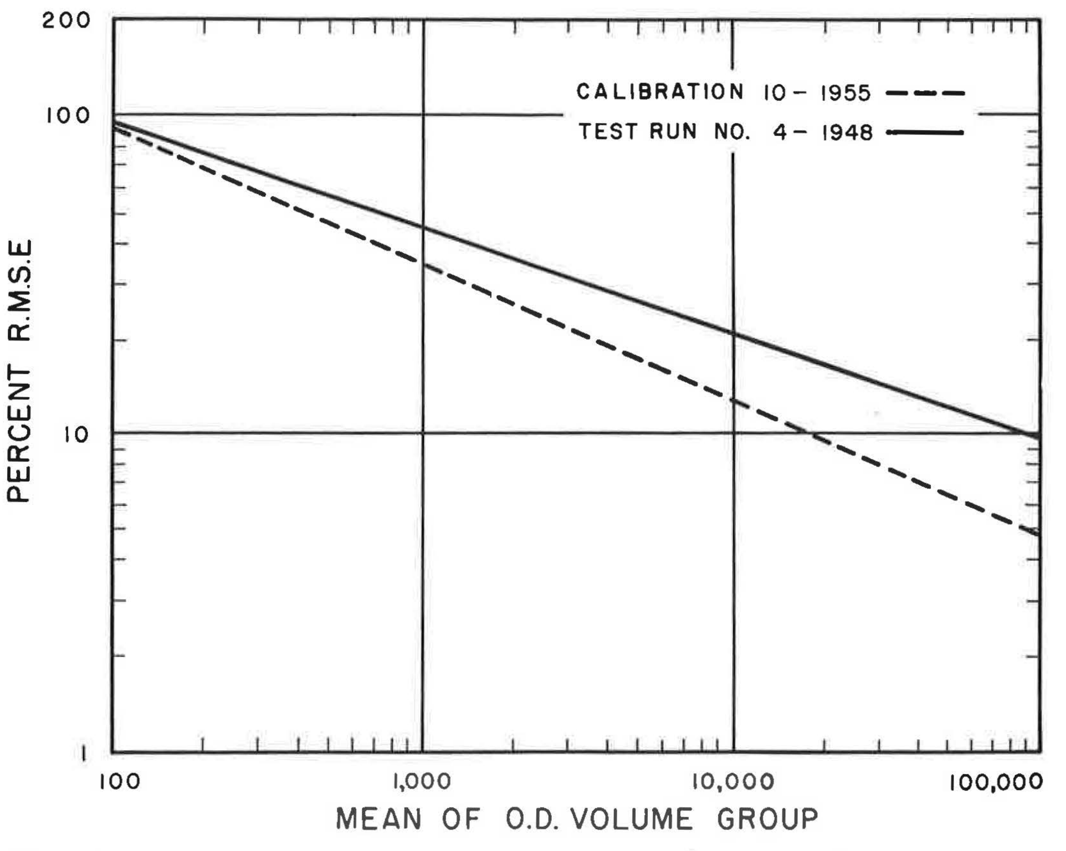

Figure 21. Comparison of root-mean-square error by volume group, district movements (O-D vs G.M.) social-rec. trips, 1948 and 1955.

used in 1955 for each of the two trip purposes. These comparisons are illustrated in Figures 18 and 19.

Again as was shown in the 1955 tests, the estimated work trips demonstrated better correspondence to the home interview figures than the estimated nonwork trips. Only six of these screenlines show a difference greater than 10 percent for work trips, whereas for nonwork trips 19 comparisons exhibited at least that much error. Generally, the comparisons made with estimated 1948 trip distributions to those from the 1948 home interview survey are of the same level of accuracy as the tests made with the final 1955 model results.

Another significant test of the ability of the gravity model to forecast the 1948 travel patterns was a statistical test of the differences between the gravity model estimates and 1948 home interview survey data assigned to the spider network. Table 23 shows the analysis by volume group of these assignments. The percent of differences in the estimated volumes decreases as the volume increases, and for volumes greater than 10,000 trips the errors are less than 15 percent. The results of this analysis of the accuracy of the estimated 1948 travel patterns may be directly compared to similar results of the 1955 gravity model by comparing Tables 11 and 23.

In addition to the statistical checks made on assigned volumes to the spider network for work and nonwork trips, the estimated district-to-district interchanges were compared with the actual interchanges for each of the six trip purposes. A simple statistical analysis of the differences between the actual and estimated interchanges was made and the root-mean-square error was calculated by volume group for each of six trip purposes. Plots of this information can be found in Figures 20 and 21. Also shown is

TABLE 24

SECTOR-TO-SECTOR MOVEMENTS OF HOME-BASED WORK TRIPS, GRAVITY MODEL VS HOME INTERVIEW SURVEY, 1948[a]

From Sector	To Sector 0	1	2	3	4	5	6	7	8
0	46,609	2,373	5,702	9,319	4,586	1,547	6,005	7,577	1,335
	44,170	2,978	4,236	9,469	5,340	1,496	7,292	8,499	1,573
1	19,726	2,021	1,757	1,826	452	248	976	2,247	329
	19,920	1,692	2,210	1,670	584	147	920	1,881	558
2	34,604	1,773	8,112	4,420	1,538	276	1,237	3,054	199
	35,781	1,886	6,852	4,830	1,378	257	1,284	2,280	665
3	100,937	4,137	9,599	29,534	6,632	1,844	8,289	11,931	1,460
	102,522	4,127	11,111	27,966	9,923	1,707	6,672	8,503	1,832
4	52,082	1,936	3,219	8,134	16,360	2,457	8,633	5,430	643
	51,485	1,704	3,726	10,920	13,894	2,749	8,072	5,355	989
5	36,445	1,524	2,002	5,803	7,030	4,299	8,901	3,698	556
	34,007	1,118	1,849	5,034	6,699	4,297	11,172	5,209	873
6	38,567	1,474	2,286	4,758	5,046	2,093	20,791	5,049	875
	40,634	1,327	1,762	3,859	4,114	2,552	18,492	7,076	1,123
7	30,227	930	997	1,347	871	478	2,596	28,864	2,693
	29,552	1,356	1,606	2,377	1,299	507	3,612	15,143	3,551
8	25,259	1,328	1,017	1,698	688	512	1,746	9,774	7,487
	26,374	1,242	1,357	1,521	743	274	1,907	10,864	5,227

[a] Legend: Survey / Model

similar information for the final calibration run in 1955. Again the level of accuracy is similar for both 1955 and 1948 results.

Finally, to determine the accuracy of crosstown estimates made by the gravity model over the 7-year period, all sector-to-sector movements from both the gravity model estimates and the home interview survey were extracted and compared. The results of these analyses are shown for work and nonwork trips in Tables 24 and 25. The accuracy of these forecasted trip patterns can be compared directly with similar analyses made on the final 1955 calibrated model by comparing these two tables with Tables 12 and 13.

In all test results made on the forecasted travel patterns in 1948, the level of accuracy obtained by using the gravity model to forecast these patterns to 1948 compared quite favorably with the level of accuracy of the final 1955 calibration.

SUMMARY—ANALYSIS AND CRITIQUE

This research provides evaluations of the gravity model as an analytical tool for simulating present and forecasting future urban trip distribution patterns. The evaluations were made by comparing gravity model trip interchanges with those found in home interview origin and destination surveys conducted in Washington, D. C., in 1948 and 1955. The 1955 survey data were used for calibrating the basic gravity model and for testing this model for its ability to simulate current travel patterns. The 1948 survey provided comprehensive data to analyze the forecasts made by the calibrated model.

TABLE 25

SECTOR-TO-SECTOR MOVEMENTS OF NONWORK TRIPS, GRAVITY MODEL VS HOME INTERVIEW SURVEY, 1948[a]

From Sector	To Sector 0	1	2	3	4	5	6	7	8
0	87,112	5,182	7,952	23,253	7,477	4,432	7,381	5,656	3,142
	89,539	6,648	6,414	20,646	7,248	3,496	8,640	5,542	3,413
1	17,034	13,832	13,030	3,621	1,437	306	1,010	1,855	1,379
	19,891	9,298	14,236	5,314	505	183	677	1,212	2,188
2	23,188	7,430	62,805	15,447	2,427	323	1,354	1,482	1,321
	20,057	11,612	56,304	23,012	1,516	322	705	975	1,294
3	60,264	4,536	14,592	93,237	9,416	3,314	4,784	2,226	1,497
	56,017	4,299	21,122	92,775	13,703	1,557	1,843	1,385	1,166
4	28,580	1,547	1,788	12,937	39,632	5,373	3,618	1,193	732
	28,093	694	2,009	19,314	34,657	5,715	3,725	693	497
5	19,581	615	919	7,765	6,521	14,784	8,437	537	520
	19,510	352	502	3,741	8,055	14,384	12,088	687	360
6	27,554	1,553	1,172	6,329	3,400	5,776	33,779	2,134	476
	29,052	717	725	2,810	4,246	8,887	32,416	1,870	852
7	23,485	1,946	1,861	3,001	999	667	2,841	69,500	10,972
	25,338	2,025	1,333	2,542	804	604	2,921	63,572	16,136
8	12,761	3,074	1,351	2,299	796	204	555	8,653	40,480
	12,805	3,598	1,799	1,793	447	296	1,231	13,828	34,376

[a] Legend: Survey / Model

Several conclusions reached concern the proper gravity model calibration procedures to simulate present travel patterns in an urban area. First, to conduct this calibration procedure, in areas of a population size and complex development such as Washington, adequate and stable data showing the pattern of interchange of trips between the zones in the study area must be available. In this research project, such information was required to develop adjustment factors to correct for geographical bias.

Secondly, the calibration process should consist of an orderly group of procedures as follows:

1. Develop average areawide travel time factors $F_{(t_{i-j})}$ for each trip purpose using a trial and adjustment process. These factors are adjusted until the actual and estimated average trip length figures are within 2 or 3 percent of each other and the two trip length frequency distributions are in close agreement.

2. Check the trips attracted to each zone by the gravity model against those shown by the survey data. If the discrepancies between the actual and estimated values are significant, and a discernible pattern can be illustrated, further trip stratification should be attempted to alleviate these problems. If further stratification is used, new travel time factors must be developed for all trip purposes affected. If further stratification is not used, attraction factors are balanced to insure agreement between the actual and estimated trips attracted to each zone, and travel time factors may require small revisions to meet the criteria previously outlined.

3. Actual and estimated trip interchanges between zones or districts must then be compared to determine whether any geographical bias exists in the model results. Such bias often results from factors neither considered by the gravity model formula nor reflected in the basic data used to calibrate the model. For example, if the measure of spatial separation between any two parts of the region does not adequately portray the level of service of the transportation facilities in the area, bias in this geographical area will result. Furthermore, if unique relationships exist in the trip making between any two parts of the region and this is not indicated to the model, geographical bias will result. Characteristics such as income or occupation may be variables that influence travel, particularly for work and shopping, from certain residential zones to other zones having unique opportunities. Such conditions can only be indicated to the model by further trip stratification or by adjustment factors. If bias exists in the model for either of these two conditions, and it often does in large urban areas, adequate data must be available to demonstrate the need for adjustment, the reasons behind this need, and the quantitative value of the adjustment required. If any adjustments are made in the model, the previous two steps must be repeated and their criteria satisfied.

These procedures were followed quite closely in the calibration of the 1955 gravity models. The final results indicated that the gravity model can adequately simulate present travel patterns. In addition, valuable insight was gained concerning those factors affecting travel patterns in Washington, and possibly in other large and complex urban areas as well. For example, one of the valuable findings of this study was a measurement of the influence that factors other than those of trip generation and travel time have on travel patterns and the need to analyze, understand, and incorporate the effect of these factors when estimating urban travel demands. This research indicated that two additional degrees of trip stratification probably would have improved model accuracy. Work trips should have been further stratified to permit the development of separate models for government and for nongovernment work travel; likewise, shopping trips should have been further stratified to permit the development of separate models for convenience goods and for shopping goods trips. Such operations could have reduced the need for zone-to-zone adjustment factors. When conducting gravity model studies in large urban areas, the degree of trip stratification must be such that the unique patterns for all major types of trips are considered. Since Washington is an extremely large government center and contains many large regional-type shopping centers, these unique conditions must be reflected in the gravity model. If the model is to be used in other cities with unique travel characteristics or major concentrations of a particular industry, similar consideration should be given to analyzing these trip patterns separately. When considering a finer degree of trip stratification, however, one must also analyze the ability of procedures to forecast trip generation on a finer basis.

In addition, this research into the ability of the gravity model to simulate current travel patterns illustrated the need to indicate carefully to the model the spatial separation between zones, as it truly exists. If peak hour congestion is particularly critical in one part of the area, it should be indicated to the model, preferably before the calibration procedure begins. Finally, this research has provided some knowledge of the variables behind zone-to-zone adjustment factors. In the case of Washington, D. C., close correlation between these factors and zonal income existed both in 1948 and 1955.

Detailed tests were also made of the forecasting ability of the gravity model formula. From these tests, several conclusions were apparent. The travel time factors developed for 1955 conditions adequately reproduced the 1948 trip length frequency characteristics. Therefore, the assumption that these factors are stable over time is warranted. One must be careful to note, however, that the forecast period was relatively short, even though there were significant changes made in the transportation system during the 7-year period.

The relationship between zonal adjustment factors $K_{(i-j)}$ and income as developed for the 1955 condition remained relatively constant over the forecast period. The results are somewhat clouded, however, in that there were no large changes in the relative income of the residents of the various zones in the area.

Physical barriers requiring time penalties in the model are directly related to congestion levels. A useful method to forecast these barriers into the future can be developed by relating the volume-capacity ratios between the two time periods on that part of the transportation system requiring the barrier. This approach requires a preliminary independent estimate for the forecast year of the level of congestion tolerable on the facilities over the topographical barrier.

In conclusion, the use of the gravity model to describe present and future trip distribution patterns will give satisfactory results if properly calibrated and tested. The level of accuracy obtained by forecasting trip distribution patterns in 1948 was comparable to the level of model accuracy for the base year.

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Evaluation of a New Modal Split Procedure

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A U. S. Bureau of Public Roads evaluation of a new modal split technique of interest to urban transportation planners responsible for estimating future public transit requirements is presented. The new modal split technique was developed by the Traffic Research Corporation for the use of the National Capital Transportation Agency in estimating 1980 transit requirements for the Washington, D. C., area. Because sound estimates of transit patronage are required for the development of comprehensive urban transportation plans, Public Roads conducted a two-phase test of this procedure. In the first phase, the effectiveness of the new modal split procedure to reproduce a known situation was tested. In the second phase, the sensitivity of the procedure (i.e., its ability to reflect changes in input variables) was assessed. The evaluation tended to confirm the usefulness of this new modal split procedure but also revealed limitations that should be considered before further application. Comments of three transportation planning officals on the evaluation and the findings therefrom have also been included with this article.

•THE DEVELOPMENT of comprehensive urban transportation plans requires sound estimates of transit patronage. The Traffic Research Corporation (TRC) under contract to the National Capital Transportation Agency (NCTA) developed a new modal split procedure for estimating the relative usage of the private and public modes of transportation. This procedure, utilized by the NCTA in developing a 1980 transportation plan for the Washington, D.C., area, has been evaluated by the U. S. Bureau of Public Roads to gain insight into its accuracy and to provide potential users with a quantitative analysis of a research application.

The evaluation project conducted by the Bureau consisted of two distinct phases:

1. A test of the modal split technique as a means of reproducing a known situation, specifically the transit usage reported in the 1955 Washington, D. C., origin and destination survey; and

2. A test of the sensitivity of this new modal split procedure to changes in the input parameters.

BACKGROUND

The relationship of the usage of private automobiles and of public transportation is growing in importance, particularly in large cities. Although useful planning techniques were available for developing comprehensive urban transportation plans, the ultimate in such techniques has not been attained. One of the techniques developed relates the proportion of use of public transportation to car ownership and population density; another relates the proportion of use of public transportation to some function of the travel time required for transit and automobile travel.

Paper sponsored by Committee on Origin and Destination.

Many factors influence the choice of a mode of transportation, according to different studies reported. One study conducted in 1957 in Cook County, Ill., revealed that 32.4 percent of travelers consider time the most important factor in choosing a mode of travel. Other prime factors reported were comfort, 17.4 percent; cost, 5.3 percent; and walking distance, 8.0 percent. A car was reported to be a requisite for transportation by 12.5 percent of those surveyed, and 12.8 percent reported they had no choice other than public transportation. Miscellaneous factors were reported by 11.6 percent (1).

MODAL SPLIT TECHNIQUE

Two basic approaches to the modal split technique are possible. In one, the split between private and public transportation trips for each zone is estimated and the transit and automobile trips are distributed separately between zones. In the other approach, used by the new modal split procedure, the split is considered after the distribution of total person movements between zones has been made.

The new modal split technique is basically a diversion curve procedure in which relative transit usage is related to five selected variables:

1. Ratio of door-to-door travel time by public transit to door-to-door travel time by private automobile;
2. Ratio of excess travel time by public transit to excess travel time by private automobile (used as a measure of relative travel service and referred to as service ratio);
3. Ratio of out-of-pocket travel cost by public transit to out-of-pocket travel cost by private automobile;
4. Economic status of person making trip; and
5. Trip purpose.

The items considered in the development of the five variables are shown in the following equations:

$$\text{Travel time ratio} = \frac{a + b + c + d + e}{f + g + h} \tag{1}$$

where

- a = time on transit vehicle;
- b = transferring time between transit vehicles;
- c = time spent in waiting for transit vehicle;
- d = walking time to transit vehicle;
- e = walking time from transit vehicle;
- f = automobile driving time;
- g = parking delay time at destination;
- h = walking time from parking place to final destination;
- i = gasoline cost $\left(\frac{\text{gallons}}{\text{mile}} \times \text{distance} \times \frac{\text{cost}}{\text{gallon}}\right)$;
- j = oil change and lubrication cost (cost of oil change per mile times distance);
- k = parking cost at destination; and
- L = number of persons per vehicle.

$$\text{Service ratio} = \frac{b + c + d + e}{g + h} \tag{2}$$

$$\text{Cost ratio} = \frac{\text{transit fare}}{\left(\dfrac{i + j + \frac{k}{2}}{L}\right)} \tag{3}$$

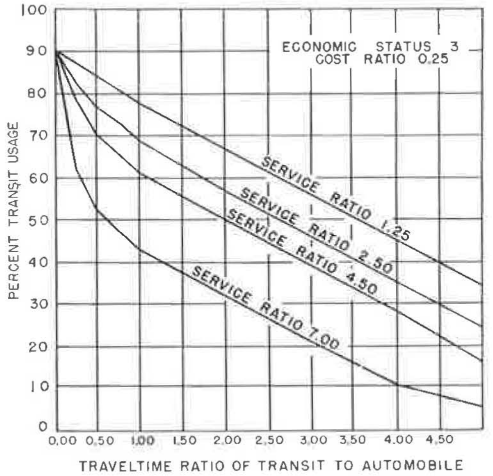

Figure 1.—Example of modal split relationship.

Economic status = median income per worker (4)

Trip purpose = either home-based work trips or all nonwork trips except those made to school (5)

To develop the modal split relationships for each trip purpose, determinations were made of the percentage of travelers using public transit and private automobiles from each origin to each destination. This usage was then related to the four basic determinant factors—travel time ratio, travel cost ratio, service ratio, and economic status. The trip information, from which these relationships were developed, was obtained from travel surveys made in the Washington area and from supporting evidence gathered in other cities (2). All observations from each study were stratified by trip purpose. Next, divisions were

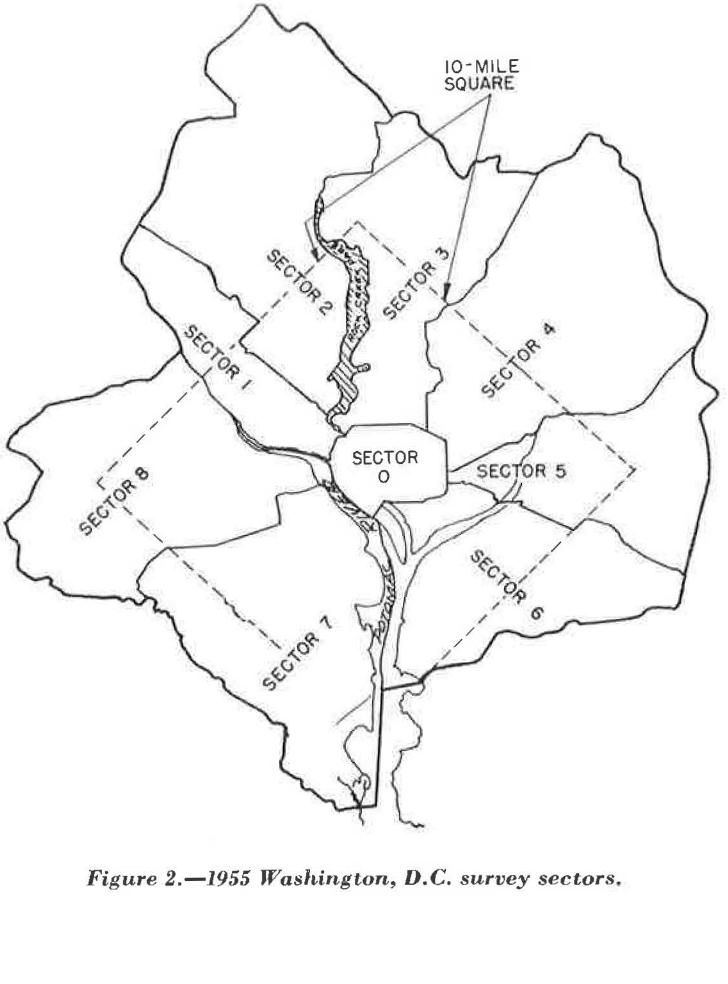

Figure 2.—1955 Washington, D.C. survey sectors.

made of the cost ratio into four ranges, the excess time ratio into four ranges, and the income level into five ranges. By multiplying the number of ranges (4 × 4 × 5), 80 individual combinations of these three determinant factor ranges were obtained, thereby providing 80 time-ratio diversion curves for each trip purpose. For each of the 80 combinations, the observations concerning modal split were plotted against the travel time ratio. Figure 1 shows four of these curves.

Information for curve development was obtained from the 1955 Washington, D. C., origin and destination survey and from the 1961 Federal employee survey. For the work-trip relationships, those trips arriving at zero sector destinations (Fig. 2) between 6:54 a.m. and 9:06 a.m. were analyzed. For nonwork, nonschool trips the data studied were for the period 9:12 a.m. to 3:45 p.m. Selected trips to nonzero sector destinations were also used to supplement the zero sector-oriented data. Data for 1955 and 1961 were combined, after adjustments had been made to put the two sets of information on an equal basis, and average grouped points were calculated to obtain one set of relationships. As sufficient information on which to base the relationships was not available from Washington, D. C., travel survey data from Toronto, Canada, and Philadelphia, Pa., were used to supplement it (2). Basically, these data were necessary to extrapolate the curves developed from Washington data for the 1980 estimate because little information was available for Washington that showed travel time ratios of less than one and cost ratios of less than 0.5. A computer program was developed to apply the modal split procedure. Briefly, this program has been written for a 7090 computer in the FORTRAN language. A complete description of the modal split relationship development has been given previously (2, 6).

SUMMARY OF FINDINGS

The U. S. Bureau of Public Roads test of the new modal split technique developed by TRC for use of the NCTA to estimate 1980 transit usage in Washington, D. C., shows that it may be a useful tool for forecasting transportation system usage. Although the tests confirmed its usefulness, they also revealed limitations that should be considered before further application of this particular modal split technique. A more accurate and useful tool may be developed on further investigation and analysis of this method.

The results of the BPR test against 1955 O-D data indicate that the technique can reasonably reproduce the conditions from which the modal split relationships were developed. The estimate of transit work trips to the zero sector from the entire area obtained by use of the procedure was within one root-mean-square error of the 1955 O-D survey estimate, which was as good as could be expected. Total nonzero sector-destined transit work trips were less accurately estimated by the modal split procedure, probably because the curves were developed almost entirely from zero sector-oriented trips. Additional research may well indicate that separate sets of curves are required for trips oriented to the central business district (CBD) and those that are non-CBD oriented.

The restraint added to the transfer matrix in the test, which eliminated certain non-CBD to non-CBD trips, may be unnecessary if a separate set of non-CBD curves is developed or if a new set of relationships that indicate zero transit ridership at a travel time ratio of 5.00, instead of 10.00, is used. The corridor analysis indicated a geographical bias in the modal split estimates for work trips.

The estimate of nonwork transit trips to zero sector destinations from the entire area was also within acceptable limits of accuracy, although it was not as accurate as for work trips. Perhaps this difference in accuracy was caused by the nonwork curves being developed from off-peak time period data and applied to the peak period. Further research is needed to evaluate the application to another time of a set of relationships developed for one time period.

On a corridor basis, estimates for all trips having origins outside the zero sector and destinations in the zero sector were slightly less accurate than the O-D estimate. The analysis of district-to-district trips for both work and nonwork showed the variation between the estimate of transit trips and O-D trips to be less than the expected variation in the O-D trips.

All the variables considered in the test of the modal split technique appear to relate to modal choice. However, this alone does not necessarily indicate a generally applicable procedure. Estimates of necessary input variables must be sufficiently accurate so as not to impair seriously the accuracy of the estimated transit usage. The sensitivity tests showed that substantial weight is given to certain of the input variables that are difficult to estimate. The observed change in the modal split when automobile excess time was varied indicates the high weight placed on this parameter. Adding 2 min to automobile parking delay and walking times in the CBD had a greater effect on the modal split of trips destined to the CBD than did doubling fares, doubling parking costs, factoring transit or highway times by 0.75, or factoring transit times by 1.5. These excess time values are among the most difficult to estimate. The 2-min increase in excess time (test C) is not considered unrealistic in that the mean 1955 CBD excess automobile time used in the development of the curves was 3.6 min and the mean excess automobile time estimated for 1980 was 6.7 min.

The sensitivity analysis indicated that parameters reflecting 1980 automobile terminal conditions (parking delay, walking time, and parking costs) had a far greater weight in the modal split determination than any of the parameters reflecting the proposed transit system. The range of meaningful cost ratio values was too narrow to permit evaluation of alternate fare structures.

Additional work indicated as being desirable includes: (a) extension of the cost ratio ranges and level of service ratio ranges to reflect wider variations in system conditions; (b) better estimating procedures to improve the accuracy of those model inputs showing the greatest sensitivity to modal split; and (c) testing of time differences rather than, or in conjunction with, time ratios, which may produce greater sensitivity of the procedure to highway and transit system changes.

TEST OF MODAL SPLIT TECHNIQUE AGAINST 1955 O-D SURVEY

The modal split technique was used by NCTA for estimating 1980 transit usage on a proposed system. The Bureau developed parameters reflecting highway system and transit system 1955 operating characteristics and applied the modal split procedure to 1955 conditions. The estimated transit usage was then compared to the transit usage reported in the 1955 Washington, D. C., O-D survey. The 160 modal split diversion curves (80 for each purpose) used in the BPR test were the same curves used by NCTA in developing the 1980 transit usage estimates.

Two principles were established for the test procedure:

1. The data from the 1955 Washington, D. C., origin and destination survey were to be adhered to as closely as possible in preparing the input parameters.
2. The same procedures used by NCTA in preparing input parameters for the application of the modal split procedure to estimate the 1980 transit usage were to be used.

The modal split technique was tested to determine its ability to predict: (a) areawide modal split; (b) areawide to CBD destination (zero sector) modal split; (c) areawide to non-CBD destination modal split; (d) modal split from each of eight survey sectors (corridors) to the CBD; (e) modal split between each of the survey sectors; and (f) modal split between each district in the survey area.

Preparation of Input Data

Generally, data were developed on a zone basis for each of the 400 survey zones considered. Adjustments were made in the zonal data so that the summary of this zonal data by district would closely match the district data used for curve development. This was in accordance with a goal of the test, i.e., to evaluate the modal split technique rather than the manner in which the input parameters were prepared.

System Parameters

O-D Interchanges.—TRC in its development of the modal split relationships reproduced the 1955 O-D trip data in a linked form (3). The only deviations from the normal linking process made by TRC are described in the next paragraph.

Linked trips that originated at home but had intermediate change mode or serve passenger purposes and finally were destined for home were omitted from the linked trip file. The procedure usually followed is to produce two trips, for example, one from home to personal business and another from personal business to home. All unlinkable, serve passenger, or change travel mode trips were omitted in this test. Normally, each trip is evaluated and a decision is reached as to the purpose to be considered. For example, a change mode trip having a destination at any airport—not a linkable trip as the person presumably leaves the area—is usually classified as a business trip.

Only trips made during the peak traffic period of 6:54 a.m. to 9:06 a.m. were considered for this test. However, the modal split nonwork curves were developed from off-peak traffic data for the period between 9:12 a.m. and 3:54 p.m. Work trip curves were developed from data on peak traffic period trips—6:54 to 9:06 a.m. Since the modal split model had been used to estimate 1980 transit usage in the a.m. peak traffic period, both work and nonwork curves—were applied to the peak traffic period for this test.

Two sets of origin and destination survey trip interchanges were developed for the test: trips to and from work, and all nonwork trips except those to and from school. For each set two trip files were required: (a) total person trips—automobile driver, transit passenger, and truck, taxi, and automobile passenger—for input to the modal split program; and (b) trips by transit for comparison with the output of the modal split program.

Highway Times and Distances.—A necessary input to the modal split procedure is the travel time between zones via the highway network. These times were obtained from the 1955 O-D survey for use in the development of the modal split relationships. For testing the 1980 application of the modal split procedure, times were obtained from "trees" or minimum time paths (4). Again, the procedure used by NCTA for their 1980 estimate of transit usage was followed as the guide for this test. A highway network was coded to obtain these minimum time paths.

A 1955 highway network was available for use in this testing. However, the times coded on each section of highway derived from 1955 speed runs were more representative of average daily travel times than the peak traffic times required. The average daily travel times obtained from trees built with this system had to be adjusted to match those peak traffic times used for developing the modal split relationship (district-to-district reportings from O-D survey). The adjusted highway times used in combination with highway distances to obtain a gasoline cost per mile were determined from minimum time routes obtained in this process.

Transit Time.—Available traffic assignment programs that build minimum time paths between zones were utilized for the determination of zone-to-zone time via the transit system. The general rules for coding a highway network were followed for this purpose (5).

The route schedules for the 7- to 9-a.m. time period for each of the four transit companies operating in the Washington, D. C., area in 1955 were used for the preparation of a transit network. Link lengths were determined by measurement from scaled maps showing actual route locations and times. All connections from zone centroids to the transit stops were coded as having zero distance and time because these excess travel times were coded as zone parameters.

The transit times reported in the 1955 O-D showed such great variation that it was impossible to develop general rules for adjusting the tree times obtained from the transit network prepared from schedules. As there was no apparent bias in the use of tree times, O-D times sometimes being less than and sometimes greater than tree times, the schedule times were utilized in this test.

Transit-Fare Matrix.—The modal split procedure requires input information that will provide the zone-to-zone cost via transit. It was obvious that if all 400 zones were considered, a matrix having 160,000 entries would be required. Because many zone-to-zone movements have similar costs, larger areas, termed superzones, can usually be used for this representation. For this test, the 68 districts of the 1955 O-D survey were used.

Transit Transfer Matrix.—The excess travel time for a transit trip includes the time spent transferring between vehicles. Again, as for the fare matrix, a determination of these times for each zone-to-zone movement would have been a very time-consuming task. Many district-to-district transfer times were already available from the work accomplished in the development of the modal split relationships. The coded transit system provided the necessary detail for the computation of the remaining transfer times. Transfer times were determined by tracing the most logical route(s) between pairs of districts and accumulating one-half the headway for each transit route to which a transfer was made. This procedure deviates from that used when the NCTA estimates were made of 1980 transit usage. For 1980, corridors of influence were drawn about the major radial transit lines, and the times to transfer between these corridors were determined and later expanded to zone-to-zone movements by the modal split program.

The results obtained from the work done by TRC in developing the modal split relationships were used as a general control on the procedure. That is, many of the transfer times available were recalculated for checking purposes and to provide a consistent means for developing the remaining transfer times.

During NCTA's calibration of the procedure to estimate 1980 transit usage, it appeared that illogical zonal trip interchanges by transit between areas outside the 10-mile square (Fig. 2) had been estimated by the modal split procedure. To eliminate these illogical interchanges, excessively large transfer times had been entered into the transfer matrix for these movements. These excessive times tended to produce a travel-time ratio greater than 10, thereby producing a zero percent transit usage. To conform with this NCTA procedure, certain interchanges between areas outside the 10-mile square were also eliminated in the BPR test of the procedure against the 1955 O-D survey.

Zonal Parameters

Economic Status.—TRC, in the development of the modal split relationships, calculated the median 1955 income per worker. As travelers' incomes were not reported in the 1955 O-D survey, average district incomes were calculated from 1950 and 1960 census reports and converted to median income per worker. This calculation was made by multiplying the census income per dwelling unit by the ratio of dwelling units per worker from the expanded household data obtained in the 1955 home interview survey (6). The results obtained for district incomes are tabulated in Volume 2 of the TRC reports. These reported incomes were used directly for the Bureau of Public Roads test after they were coded into the five economic status groups.

Parking Cost.—Average parking costs are required for inclusion in the cost ratio in the modal split procedure. As every trip is considered to have a return portion, only one-half of the parking cost was assessed at the destination end when the cost ratio was calculated. The parking costs for 1980 were developed basically for work trips. To obtain an estimate of parking costs for nonwork trips, costs calculated for work trips were divided by two. Parking costs were assessed only for zero sector destinations and were developed for each zone. The 1955 average automobile parking costs were obtained for each of the nine zero sector districts by determining the weighted average cost of commercial and government parking facilities in each district.

Car Occupancy.—Car occupancy rates are required by the modal split procedure. In calculating automobile costs for each zone-to-zone movement, the sum of the automobile operating costs and one-half of the total daily parking rate was divided by the number of persons per vehicle to obtain an average automobile travel cost per person. Although the modal split program allows the use of car occupancy at the origin and/or destination, destination car occupancy rates were used in the Bureau test because they were the rates used in the NCTA estimate for 1980. Car occupancy rates also were used to convert the person trip output from the modal split technique to automobile driver trips. As car occupancy rates for 1980 were developed on a district basis, district rates also were used for the test. These rates were developed by TRC by a special run of the 1955 O-D data through available summary programs.

Walking Time.—Walking times from parking places to destinations were developed on a district basis for the 1980 estimate and for the development of the modal split technique. One-minute walking time was used for every district outside the zero sector.

For zero sector districts, the district walking times from parking places to destinations, which had been used by TRC for curve development, were used. All walking time was calculated from blocks reported as walked in the travel surveys.

Parking Delay Time.—For curve development, and in the tests with the 1955 O-D data, parking delay times were based on delays of 1 min at government parking lots and garages and of 2 min at public and private lots and garages; weighted averages were used for each zero sector district (6). A 1-min time was used for each district outside the zero sector.

Transit Waiting Times.—For both the curve development with 1955 data and the 1980 application of the procedure, transit waiting times were determined from a map showing all transit routes, vehicle headways, and transfer points. In general, one-half the average headway of the transit facility serving a zone was used where only one facility served the area. The modal split program allows only one figure as the average transit waiting time for the passengers of each zone. For this reason, the zonal transit waiting times were calculated by utilizing the peak hour transit network, which had been coded for this test. These zonal estimates were averaged by district for comparison with the district waiting times used by TRC for curve development; when different, adjustments were made to the zonal estimates.

Transit Walking Time.—Average walking times to and from transit stops in each zone were determined in a systematic manner based on empirical formulas in the initial development of the modal split technique (6). For the 1980 estimates of transit usage, the walking times were obtained from an analysis of the relationship between the location of each zone centroid and the transit routes available in the zone. This latter relationship was used for developing walking times by zone. Again, the average transit walking time obtained for a district for use in this test was compared with the district times used in the development of the modal split technique. Adjustments were made when necessary. These transit walking times were applied at both the origin and destination of a trip.

Single Parameters

The modal split procedure requires that certain constants be specified. The constants used for the test are cost per gallon of gasoline, $0.295; cost of oil change and lubrication, $2.85; and miles between oil change and lubrication, 1,000. These are the same constants used for curve development. The coefficients used in the equations for the calculation of car operating costs (6) are the same as those used for development of the modal split technique. The modal split relationships used by the Bureau were the same relationships used for NCTA's 1980 estimates. Other than as heretofore explained, all parameters used in the Bureau test were the same as those used for the 1980 transit usage estimates (6).

Results

The data described in the foregoing paragraphs were used as input to the modal split computer program to obtain an estimate of zone-to-zone transit usage. This estimate was obtained by applying the modal split technique to the total person trip file. These estimates of zone-to-zone transit usage could then be compared with the transit usage observed from the 1955 O-D survey.

Modal Split to Entire Area.—As indicated in Table 1, the number of transit work trips for the entire area obtained by application of the modal split procedure to the 1955 O-D survey data was 5.9 percent less than the actual number reported in the survey. The modal splits differed by 1.9 percent; transit work trips reported in the 1955 O-D survey were 33.7 percent of total usage and those estimated by application of the procedure were 31.8 percent. A greater difference between the actual 1955 data and the test data was obtained for nonwork trips, but this difference was an overestimate of 25.4 percent by application of the modal split technique. Total trips via transit were underestimated by 4.6 percent, a 1.5 percent difference.

Estimates of citywide transit trips based on relationships developed from actual data would be expected to correspond closely to the base data. In this test the procedure

Table 1.—Results of modal split procedure applied to entire study area

Trip	1955 O–D data	BPR test estimates	Percentage point difference	Percent trip difference
Work:				
All modes	389,301.0	389,301.0		
Transit passenger	131,066.2	123,305.2		−5.9
Percent transit usage	33.7	31.8	−1.9	
Nonwork:				
All modes	30,294.0	30,294.0		
Transit passenger	5,614.4	7,040.8		+25.4
Percent transit usage	18.5	23.0	+4.5	
TOTAL:				
All modes	419,595.0	419,595.0		
Transit passengers	136,680.6	130,346.0		−4.6
Percent transit usage	32.6	31.1	−1.5	

reproduced the base data reasonably well for work trips. However, the modal split technique produced a nonwork trip figure showing a larger difference from the actual data than should be acceptable on a citywide basis. This was true although the volume of nonwork trips was relatively small in comparison to the number of work trips. The difference in test results and actual data for nonwork trips might have been caused by the following conditions: (a) the nonwork trip curves were developed from data for off-peak traffic hours but applied to the peak hour traffic; and (b) input parameters were highly oriented to work trips. The only input variable changed for the nonwork trips was the parking cost, and this was estimated to be equal to one-half of the parking costs for work trips. Other variables such as car occupancy, walking times, and parking delay time generally were developed for peak hour work trips but were applied unchanged to nonwork trips.

Modal Split to Zero Sector.—The test with the modal split to the zero sector reproduced the 1955 O-D transit usage remarkably well for work trips. The nonwork trip test estimate differs from the O-D transit usage by +9.37 percent. From the data in Tables 1 and 2, the following conclusions might be drawn:

1. As the modal split relationships for the test were developed almost entirely from zero sector-oriented trips, it would be expected that such trips would have been reproduced more accurately than nonzero sector destination trips. Only about 100 nonzero sector interchanges were considered when the modal split relationships were developed.

2. The modal split technique was more accurate for estimating work trips than nonwork trips because the work trip input data were developed from and applied to peak hour traffic conditions, whereas the nonwork trip data were applied to the peak hour traffic but had been developed from nonpeak hour traffic conditions.

Table 2.—Modal split to zero sector (excludes intrazero sector trips)

Trip	1955 O–D data	BPR test estimates	Percentage point difference	Percent trip difference
Work:				
All modes	171,329.9	171,329.9		
Transit passenger	76,723.9	75,678.0		−1.36
Percent transit usage	44.8	44.2	−0.6	
Nonwork:				
All modes	5,141.0	5,141.0		
Transit passenger	2,203.5	2,410.0		+9.37
Percent transit usage	42.9	46.9	+4.0	
TOTAL:				
All modes	176,470.9	176,470.9		
Transit passengers	78,927.4	78,088.0		−1.06
Percent transit usage	44.7	44.2	−0.5	

Table 3.—Modal split to nonzero sector destination

Trip	1955 O-D data	BPR test estimates	Percentage point difference	Percent trip difference
Work:				
All modes	203,942.8	203,942.8		
Transit passenger	45,529.4	38,459.2		−15.53
Percent transit usage	22.3	18.9	−3.4	
Nonwork:				
All modes	22,776.6	22,776.6		
Transit passenger	2,607.1	3,423.9		+31.33
Percent transit usage	11.4	15.0	+3.6	
TOTAL:				
All modes	226,719.4	226,719.4		
Transit passengers	48,136.5	41,883.1		−12.99
Percent transit usage	21.2	18.5	−2.7	

Table 4.—Modal split from each corridor to CBD

Sector (origin)	All modes	1955 O-D data		BPR test estimates		Percentage point difference	Percent trip difference
		Transit trips	Percent transit usage	Transit trips	Percent transit usage		
A—WORK TRIPS							
			Percent		*Percent*	*Percent*	*Percent*
0	14,028.3	8,807.9	62.8	9,168.0	65.4	+2.6	+4.1
1	9,529.9	5,114.1	53.7	4,407.3	46.2	−7.5	−13.8
2	25,231.3	9,209.5	36.5	8,428.8	33.4	−3.1	−8.5
3	45,720.9	23,748.7	51.9	25,337.6	55.4	+3.5	+6.7
4	24,291.8	9,948.0	41.0	10,948.0	45.1	+4.1	+10.1
5	12,348.1	6,199.9	50.2	6,484.1	52.5	+2.3	+4.6
6	21,119.2	10,272.4	48.6	10,569.9	50.0	+1.4	+2.9
7	15,750.7	6,315.9	40.1	4,922.6	31.3	−8.8	−22.1
8	17,338.0	5,915.4	34.1	4,579.7	26.4	−7.7	−22.6
B—NONWORK TRIPS							
0	2,376.4	803.8	33.8	1,206.9	50.8	+17.0	+50.2
1	240.7	67.2	27.9	91.1	37.8	+9.9	+35.6
2	601.2	108.8	18.1	142.6	23.7	+5.6	+31.1
3	1,663.8	821.1	49.4	969.8	58.3	+8.9	+18.1
4	626.8	326.2	52.0	354.8	56.6	+4.6	+8.9
5	569.5	369.5	64.9	306.6	53.8	−11.1	−17.0
6	712.4	339.8	47.6	355.6	49.9	+2.3	+4.7
7	368.8	105.5	28.6	140.8	38.2	+9.6	+33.0
8	357.8	65.4	18.3	48.7	13.6	−4.7	−26.0
C—WORK AND NONWORK TRIPS							
0	16,404.7	9,611.7	58.6	10,374.9	63.2	+4.6	+7.9
1	9,770.6	5,181.3	53.0	4,498.4	46.0	−7.0	−13.2
2	25,832.5	9,318.3	36.1	8,571.4	33.2	−2.9	−8.0
3	47,384.7	24,569.8	51.9	26,307.4	55.5	+3.6	+7.1
4	24,918.6	10,274.2	41.2	11,302.8	45.4	+4.2	+10.0
5	12,917.6	6,569.4	50.9	6,790.7	52.6	+1.8	+3.4
6	21,831.6	10,612.2	48.6	10,925.5	50.0	+1.4	+3.0
7	16,119.5	6,421.4	39.8	5,063.4	31.4	−8.4	−21.1
8	17,695.8	5,980.8	33.8	4,628.4	26.2	−7.6	−22.6

3. Application of nonwork relationships to the peak traffic hours implied that relationships established for any period of the day could be used satisfactorily with the modal split technique. The results obtained in the test against the 1955 O-D data did not substantiate this implication. Therefore, further stratification of data for the input curves by destination—downtown separate from nondowntown—and time of day may be warranted.

Table 5.—Modal split between each of survey area sectors—work trips

Sector: Origin	Sector: Destination	All modes	1955 O-D data: Transit trips	1955 O-D data: Percent transit usage	BPR test estimates: Transit trips	BPR test estimates: Percent transit usage	Percentage point difference	Percent trip difference
				Percent		*Percent*	*Percent*	*Percent*
0	0	14,028.3	8,807.9	62.8	9,168.0	65.4	+ 2.6	+ 4.1
0	1	1,304.7	803.4	61.6	483.1	37.0	−24.6	−39.8
0	2	2,704.8	1,611.8	59.6	965.1	35.7	−23.9	−40.1
0	3	3,408.6	1,956.1	57.4	1,491.0	43.7	−13.7	−23.8
0	4	2,151.4	1,163.8	54.1	818.8	38.1	−16.0	−29.6
0	5	1,158.9	501.2	43.2	434.5	37.5	− 5.7	−13.4
0	6	2,136.0	1,089.2	51.0	644.4	30.2	−20.8	−40.8
0	7	3,738.3	2,026.4	54.2	1,435.2	38.4	−15.8	−29.2
0	8	1,043.0	441.1	42.3	430.1	41.2	− 1.1	− 2.5
1	0	9,529.9	5,114.1	53.7	4,407.3	46.2	− 7.5	−13.8
1	1	1,455.6	149.9	10.3	284.2	19.5	+ 9.2	+89.4
1	2	1,492.4	156.0	10.5	126.8	8.5	− 2.0	−18.6
1	3	881.7	209.7	23.8	215.5	24.4	+ 0.6	+ 2.9
1	4	692.8	125.2	18.1	180.5	26.1	+ 8.0	+43.9
1	5	281.2	71.2	25.3	82.9	29.5	+ 4.2	+16.8
1	6	379.1	36.9	9.7	70.8	18.7	+ 9.0	+92.1
1	7	1,275.4	190.8	15.0	194.7	15.3	+ 0.3	+ 2.1
1	8	181.8	0.0	0.0	3.3	1.8	+ 1.8	--------
2	0	25,231.3	9,209.5	36.5	8,428.8	33.4	− 3.1	− 8.5
2	1	1,512.5	221.1	14.6	86.4	5.7	− 8.9	−61.0
2	2	8,518.3	340.8	40.0	56.7	0.7	−39.3	−83.3
2	3	4,185.9	119.0	2.8	137.4	3.3	+ 0.5	+15.1
2	4	1,650.0	10.3	0.6	112.9	6.8	+ 6.2	+1000.0
2	5	445.2	74.0	16.6	35.5	8.0	− 8.6	−51.4
2	6	1,117.9	148.4	13.3	124.1	11.1	− 2.2	−16.2
2	7	2,795.7	378.9	13.6	442.5	15.8	+ 2.2	+16.9
2	8	193.8	0.0	0.0	6.5	3.4	+ 3.4	--------
3	0	45,720.9	23,748.7	51.9	25,337.6	55.4	+ 3.5	+ 6.7
3	1	2,420.4	875.2	36.2	676.8	28.0	− 8.2	−22.6
3	2	58,961.1	1,670.8	2.8	1,125.5	1.9	− 0.9	−32.6
3	3	13,076.2	3,223.1	24.6	2,883.4	22.1	− 2.5	−10.5
3	4	4,628.5	786.3	17.0	803.0	17.3	+ 0.3	+ 2.2
3	5	1,513.1	338.9	22.4	515.7	34.1	+11.7	+52.2
3	6	4,224.9	1,063.0	25.2	1,373.7	32.5	+ 7.3	+29.2
3	7	6,726.1	2,180.9	32.4	2,926.3	43.5	+11.1	+34.2
3	8	951.8	241.3	25.4	263.8	27.7	+ 2.3	+ 9.1
4	0	24,291.8	9,948.0	41.0	10,948.0	45.1	+ 4.1	+10.1
4	1	1,118.1	217.2	19.4	251.0	22.4	+ 3.0	+15.6
4	2	2,412.1	524.4	21.7	524.8	21.8	+ 0.1	+ 0.0
4	3	4,715.7	847.7	18.0	930.4	19.7	+ 1.7	+ 9.8
4	4	10,517.3	1,391.4	13.2	725.2	6.9	− 6.3	−47.9
4	5	2,017.9	274.2	13.6	372.1	18.4	+ 4.8	+35.7
4	6	4,204.0	799.0	19.0	659.3	15.7	− 3.3	−17.5
4	7	3,324.5	582.6	17.5	957.4	28.8	+11.3	+64.3
4	8	392.2	68.8	17.5	107.9	27.5	+10.0	+56.7
5	0	12,348.1	6,199.9	50.2	6,484.1	52.5	+ 2.3	+ 4.6
5	1	789.2	417.0	52.8	273.5	34.7	−18.1	−34.5
5	2	1,255.6	624.0	49.7	391.9	31.2	−18.5	−37.2
5	3	2,468.3	950.6	38.5	1,001.5	40.6	+ 2.1	+ 5.4
5	4	3,378.9	881.0	26.1	742.4	22.0	− 4.1	−15.8
5	5	1,981.7	233.4	11.8	335.6	16.9	+ 5.1	+43.7
5	6	3,960.1	1,153.9	29.1	783.7	19.8	− 9.3	−32.1
5	7	2,528.8	606.6	24.0	931.2	36.8	+12.8	+53.6
5	8	342.5	114.0	33.3	71.7	20.9	−12.4	−36.8
6	0	21,119.2	10,272.4	48.6	10,569.9	50.0	+ 1.4	+ 2.9
6	1	908.2	286.1	31.5	332.0	36.6	+ 5.1	+16.1
6	2	1,689.9	689.2	40.8	616.4	36.5	− 4.3	−10.6
6	3	2,073.1	1,018.7	49.1	904.1	43.6	− 5.5	−11.3
6	4	2,530.9	693.0	27.4	595.2	23.5	− 3.9	−14.1
6	5	1,804.5	469.1	26.0	413.1	22.9	− 3.1	−11.9
6	6	10,869.1	1,545.7	14.2	2,131.9	19.6	+ 5.4	+37.9
6	7	3,623.6	582.9	16.1	1,054.3	29.1	+13.0	+80.8
6	8	353.5	112.0	31.7	65.2	18.4	−13.3	−42.0
7	0	15,750.7	6,315.9	40.1	4,922.6	31.3	− 8.8	−22.1
7	1	553.0	68.4	12.4	53.7	9.7	− 2.7	− 2.7
7	2	876.5	164.5	18.8	71.0	8.1	−10.7	−57.1
7	3	707.6	99.6	14.1	134.2	19.0	+ 4.9	+35.1
7	4	436.5	51.4	11.8	47.7	10.9	− 0.9	− 7.8
7	5	448.0	22.2	5.0	15.8	3.5	− 1.5	−27.0
7	6	1,884.1	107.0	5.7	127.2	6.8	+ 1.1	+18.7
7	7	20,788.9	4,955.0	23.8	2,242.2	10.8	−13.0	−54.8
7	8	2,405.4	158.4	6.6	81.4	3.4	− 3.2	−48.6
8	0	17,338.0	5,915.4	34.1	4,579.7	26.4	− 7.7	−22.6
8	1	911.0	102.4	11.2	19.0	2.1	− 9.1	−81.0
8	2	1,029.1	55.0	5.3	58.5	5.7	+ 0.4	+ 5.4
8	3	738.3	22.2	3.0	62.2	8.4	+ 5.4	+180.2
8	4	447.3	22.7	5.1	41.8	9.3	+ 4.2	+83.7
8	5	175.7	0.0	0.0	4.0	2.3	+ 2.3	--------
8	6	1,447.5	34.0	2.3	55.9	3.9	+ 1.6	+64.7
8	7	11,169.4	1,833.4	16.4	584.1	5.2	−11.2	−68.1
8	8	6,435.4	541.2	8.4	255.1	4.0	− 4.4	−52.8

Table 6.—Modal split between each of survey area sectors nonwork trips

Sector		All modes	1955 O-D data		BPR test estimates		Percentage point difference	Percent trip difference
Origin	Destination		Transit trips	Percent transit usage	Transit trips	Percent transit usage		
				Percent		*Percent*	*Percent*	*Percent*
0	0	2,376.4	803.8	33.8	1,206.9	50.8	+17.0	+50.2
0	1	112.4	0.0	0.0	39.3	35.0	+35.0	--------
0	2	224.6	39.8	17.7	110.2	49.1	+31.4	+176.9
0	3	650.5	372.0	57.2	343.3	52.8	−4.4	−7.7
0	4	251.1	40.3	16.0	146.2	58.2	+42.2	+262.0
0	5	204.2	74.9	36.7	87.9	43.0	+6.3	+17.4
0	6	339.4	75.4	22.2	156.5	46.1	+23.9	+107.6
0	7	199.7	63.8	31.9	152.3	76.3	+44.4	+138.7
0	8	141.6	0.0	0.0	65.1	46.0	+46.0	--------
1	0	240.7	67.2	27.9	91.1	37.8	+9.9	+35.6
1	1	407.7	0.0	0.0	1.2	0.3	+0.3	--------
1	2	258.7	0.0	0.0	8.0	3.1	+3.1	--------
1	3	10.8	0.0	0.0	0.0	0.0	0.0	--------
1	4	47.4	0.0	0.0	0.5	1.0	+1.0	--------
1	5	--------	--------	--------	--------	--------	--------	--------
1	6	--------	--------	--------	--------	--------	--------	--------
1	7	--------	--------	--------	--------	--------	--------	--------
1	8	59.3	0.0	0.0	0.2	0.0	0.0	--------
2	0	601.2	108.8	18.1	142.6	23.7	+5.6	+31.1
2	1	334.7	12.0	3.6	6.4	1.9	−1.7	−46.7
2	2	2,522.3	57.3	2.3	0.0	0.0	−2.3	--------
2	3	524.1	0.0	0.0	0.6	0.0	0.0	--------
2	4	131.5	0.0	0.0	0.0	0.0	0.0	--------
2	5	11.1	0.0	0.0	0.0	0.0	0.0	--------
2	6	10.0	0.0	0.0	0.0	0.0	0.0	--------
2	7	50.8	0.0	0.0	1.2	2.4	+2.4	--------
2	8	44.8	0.0	0.0	0.0	0.0	0.0	--------
3	0	1,663.8	821.1	49.4	969.8	58.3	+8.9	+18.1
3	1	75.2	35.6	47.3	42.6	56.6	+9.3	+19.7
3	2	297.7	0.0	0.0	38.2	12.8	+12.8	--------
3	3	3,113.5	356.0	11.4	399.4	12.8	+1.4	+12.2
3	4	402.6	68.6	17.0	99.8	24.8	+7.8	+45.6
3	5	131.1	76.1	58.0	94.5	72.1	+14.1	+24.2
3	6	204.4	155.6	76.1	66.2	32.4	−43.7	−57.5
3	7	139.3	0.0	0.0	48.5	34.8	+34.8	--------
3	8	11.3	0.0	0.0	0.0	0.0	0.0	0.0
4	0	626.8	326.2	52.0	354.8	56.6	+4.6	+8.9
4	1	9.9	0.0	0.0	0.0	0.0	0.0	--------
4	2	162.3	0.0	0.0	0.0	0.0	0.0	--------
4	3	808.4	92.7	11.5	223.1	27.6	+16.1	+140.8
4	4	1,668.5	57.3	3.4	67.9	4.1	+0.7	+19.2
4	5	133.5	0.0	0.0	17.1	12.8	+12.8	--------
4	6	168.5	0.0	0.0	50.7	30.1	+30.1	--------
4	7	31.8	0.0	0.0	7.4	23.2	+23.2	--------
4	8	39.0	39.0	100.0	28.8	73.8	−26.2	−25.6
5	0	569.5	369.5	64.9	306.6	53.8	−11.1	−17.0
5	1	11.6	0.0	0.0	0.1	0.0	0.0	--------
5	2	--------	--------	--------	--------	--------	--------	--------
5	3	221.3	77.8	35.2	67.5	30.5	−4.7	−12.8
5	4	319.8	33.6	10.5	148.0	46.3	+35.8	+339.3
5	5	458.4	71.8	15.7	2.9	0.6	−15.1	−96.1
5	6	315.5	11.6	3.7	20.7	6.6	+2.9	+77.6
5	7	50.7	0.0	0.0	25.6	50.5	+50.5	--------
5	8	33.6	0.0	0.0	26.4	78.5	+78.5	--------
6	0	712.4	339.8	47.6	355.6	49.9	+2.3	+4.7
6	1	39.8	39.8	100.0	3.6	9.0	−91.0	−90.5
6	2	57.4	11.4	19.9	11.1	19.3	−0.6	0.0
6	3	300.4	158.0	52.6	184.4	61.4	+8.8	+16.5
6	4	367.3	11.7	3.2	110.2	30.0	+26.8	+837.6
6	5	487.4	86.2	17.7	142.0	29.1	+11.4	+65.0
6	6	1,111.6	171.1	15.4	147.9	13.3	−2.1	−13.5
6	7	134.2	0.0	0.0	34.5	25.7	+25.7	--------
6	8	22.0	11.0	50.0	15.7	71.4	+21.4	+45.5
7	0	368.8	105.5	28.6	140.8	38.2	+9.6	+33.0
7	1	21.1	0.0	0.0	6.8	32.2	+32.2	--------
7	2	34.4	10.9	31.7	1.4	4.1	−27.6	−87.2
7	3	86.3	21.9	25.4	11.2	13.0	−12.4	−48.9
7	4	74.6	12.3	16.5	0.0	0.0	−16.5	−100.0
7	5	10.7	0.0	0.0	0.0	0.0	0.0	0.0
7	6	43.1	21.2	49.2	17.5	40.6	−8.6	−17.5
7	7	2,015.5	85.2	4.2	115.9	5.8	+1.6	+36.4
7	8	229.0	0.0	0.0	12.1	5.3	+5.3	--------
8	0	357.8	65.4	18.3	48.7	13.6	−4.7	−26.0
8	1	57.3	0.0	0.0	0.0	0.0	0.0	0.0
8	2	108.3	31.5	29.1	0.0	0.0	−29.1	−100.0
8	3	45.9	23.6	51.4	0.5	1.1	−50.3	−100.0
8	4	11.6	0.0	0.0	0.0	0.0	0.0	0.0
8	5	11.3	0.0	0.0	0.0	0.0	0.0	0.0
8	6	33.2	0.0	0.0	0.0	0.0	0.0	0.0
8	7	433.3	0.0	0.0	1.8	0.4	+0.4	--------
8	8	1,696.3	100.1	5.9	12.9	0.8	−5.1	−86.9

Modal Split to Nonzero Sector Destinations.—Results of the analysis of test results obtained with the modal split technique for nonzero sector destinations, as indicated in Table 3, strengthen the conclusions reached from data shown in Tables 1 and 2. That is, estimates for zero sector trips were more reliable than estimates for nonzero sector trips.

Modal Split from Each Corridor to CBD.—Table 4 indicates that the amount of transit travel along individual corridors or sectors to the downtown area shows a greater dispersion than does the areawide test estimate. The sectors considered are shown in Figure 2. An analysis of the test results indicated a geographical bias in the estimates of modal split for work trips. Sectors 1, 2, 7, and 8 are all west of a line set by Rock Creek Park and the Potomac River. For these sectors the estimates of transit trips were about 16 percent less than shown by the O-D data. For all sectors east of this line, a 6 percent overestimate of transit trips was obtained with the modal split technique.

The nonwork trip dispersion was far greater than dispersion for work trips in this test, but the test result for the nonwork trips does not indicate the same geographical bias as the work trip estimate. The total estimate (work and nonwork) shows the same geographical bias as the estimate for the work trips because the number of nonwork trips was relatively small. Knowledge of the weakness of the modal split in providing reliable estimates for transit travel along corridors to the CBD is particularly important because these corridor movements are used for system planning when transit usage must be estimated for some future period.

Modal Split Between Survey Area Sectors.—The data on the modal split between survey area sectors given in Tables 5 and 6 were used in the development of the previously discussed tables. The test results for dispersion in trip estimation between sectors did not follow any clearly observable pattern. The tables are presented for reference purposes.

Analysis of District-to-District Transit Trips.—Tables 7 and 8 present the zone-to-zone transit trip files for both the test estimated and O-D trips as summarized into district-to-district movements for the 68 districts within the 1955 O-D survey area. These movements were classified into volume groups, in accordance with the O-D survey movements, and compared. The statistical procedure used was the root-mean-square (RMS) error analysis (7):

$$\text{RMS error} = \sqrt{\frac{\sum_{i=1}^{n} (\text{O-D} - \text{model})^2}{n}} \qquad (6)$$

Table 7.—Root-mean-square-error analysis of district-to-district transit work trips

Volume group	Frequency	Total[1]		Mean		RMS error	Percent RMS error
		O-D trips	BPR test estimates	O-D trips	BPR test estimates		
5.0-9.9	13	125.2	99.4	9.6	7.6	13.7	142.4
10.0-14.9	203	2,237.6	1,229.6	11.0	6.1	12.9	117.2
15.0-19.9	3	55.7	103.7	8.6	34.6	24.4	131.3
20.0-24.9	72	1,589.3	1,127.3	22.1	15.7	22.9	103.9
25.0-29.9	10	277.2	382.8	27.7	38.3	43.3	156.3
30.0-39.9	274	9,711.9	8,353.0	35.4	30.5	31.5	88.8
40.0-49.9	112	4,746.6	3,389.2	42.4	30.3	29.6	69.9
50.0-59.9	33	1,822.4	1,186.3	55.2	36.0	34.0	61.6
60.0-74.9	98	6,624.1	6,345.5	67.6	64.8	54.2	80.2
75.0-99.9	90	7,366.9	5,454.5	81.8	60.6	47.5	58.0
100.0-124.9	79	8,961.4	7,914.1	113.4	100.2	62.8	55.4
125.0-149.9	31	4,319.7	3,130.6	139.4	101.0	64.2	46.1
150.0-499.9	187	48,308.0	44,268.4	258.3	236.7	102.0	39.5
500.0 and more	43	34,910.4	31,973.1	811.9	743.6	239.2	29.5
TOTAL	1,248	131,056.4	114,957.5	--------	--------	--------	--------

[1] Difference in totals caused by certain movements having zero O-D trips and some model trips.

Table 8.—Root-mean-square-error analysis of district-to-district transit nonwork trips

Volume group	Frequency	Total[1]		Mean		RMS error	Percent RMS error
		O-D trips	BPR test estimates	O-D trips	BPR test estimates		
5.0-9.9	4	38.2	34.1	9.6	8.5	11.7	122.3
10.0-14.9	60	660.7	280.7	11.0	4.7	11.0	99.4
15.0-19.9	1	18.2	0	18.2	0	18.2	100.0
20.0-24.9	11	239.7	123.7	21.8	11.2	13.1	59.9
25.0-29.9	3	89.1	58.1	29.7	19.4	18.4	62.1
30.0-39.9	58	2,127.3	1,328.7	36.7	22.9	22.1	60.3
40.0-49.9	18	741.6	609.6	41.2	33.9	23.5	57.0
50.0-59.9	1	56.6	65.4	56.6	65.4	8.8	15.5
60.0-74.9	4	277.1	158.9	69.3	39.7	31.8	46.0
75.0-99.9	7	565.2	347.1	80.7	49.6	36.2	44.8
100.0-124.9	4	452.8	566.9	113.2	141.7	38.7	34.2
125.0-149.9	0	--------	--------	--------	--------	--------	--------
150.0-499.9	2	347.9	294.9	174.0	147.4	37.8	21.7
500.0 and above	0	--------	--------	--------	--------	--------	--------
TOTAL	173	5,614.4	3,868.1	--------	--------	--------	--------

1 Difference in totals caused by certain movements having zero O-D trips and some model trips.

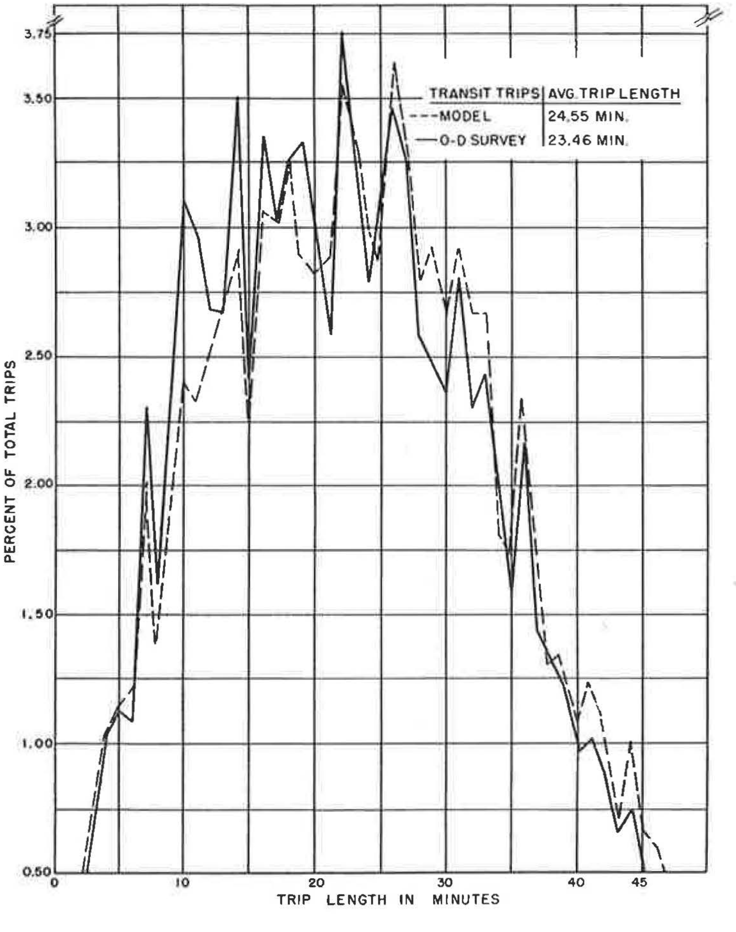

Figure 3.—Trip length frequency distribution comparison.

Table 9.—Cumulative trip length frequency data

Time increment	Accumulated percent of transit trips		Percentage point difference
	1955 O-D data	BPR test estimates	
Minute	*Percent*	*Percent*	*Percent*
0-9	10.85	10.57	−0.28
0-19	41.25	37.90	−3.35
0-29	71.27	69.00	−2.27
0-39	90.93	90.01	−0.92
0-49	97.27	97.60	+0.33
0-59	99.34	99.50	+0.16
0-69	99.89	99.90	+0.01

where

O-D = movement between pair of districts from O-D survey for a specified volume group;

model = movement between the same pair of districts from modal split procedure; and

n = number of O-D pairs in volume group.

The percent RMS error, equal to the RMS error divided by the mean O-D volume for the volume group, was used as the measure of comparison to relate the accuracy of the test results obtained from the model to the O-D survey data and also to state the accuracy of the O-D survey volumes. The Washington, D. C., 1955 survey was made with an average dwelling unit sample of 6.2 percent. From the results of previous research (7), the percent RMS errors to be expected from such a sample were known. For both work and nonwork trips, the percent RMS error between the estimate of transit trips produced by the modal split technique and the 1955 O-D survey estimate of these trips is less than the error expected in the expanded 6.2 percent sample of survey volumes.

If the comparison had shown a greater error between O-D and modal split procedure transit trips than was shown between the O-D trips and actual trips, it could be stated that the estimate of actual transit trips made with the model was worse than the estimate made by the O-D survey. However, the results obtained only indicate that the variation between the O-D and model estimates was less than the variation in the survey. On this basis, the modal split procedure would appear to give reasonable results.

Trip Length Frequency.—Figure 3 presents a comparison of trip length frequency distributions from the O-D survey and modal split estimates for work trips. The modal split procedure produced an average trip length estimate just slightly longer than that produced by the O-D survey, 24.6 and 23.5 min, respectively. The trip length distributions were in reasonably close agreement. A cumulative frequency by 10-min increments is shown in Table 9.

SENSITIVITY TESTS

Sensitivity tests were also developed by the Bureau to assess the reliability of the procedure when input variables were changed. The effectiveness of the modal split procedure realistically to project changes that might occur in the input variables over a period of time were not assessed as part of the previous evaluation. As the 1955 O-D survey data were a primary source for development of the procedure, a test performed on the same data would basically indicate whether the procedure would recreate the information from which it had been developed. The sensitivity tests were made because the change in the modal split that would be predicted if, for example, the headways on the transit system were halved had not been measured against the 1955 O-D.

The tests with the 1955 O-D data and the sensitivity tests were made concurrently, necessitating use of the 1980 NCTA estimates as a basis for the sensitivity tests. Data developed by the NCTA for 1980 were used for all sensitivity tests, except for the changes made in items selected for testing purposes. Only work trips were evaluated. This evaluation was made by using person trip estimates from 1980 land-use plan B (corridor plan). Inputs changed were transit fare, median income, automobile parking delay and walking time, transit waiting and transfer times, parking costs, transit vehicle times, highway vehicle times, parking costs in combination with automobile excess times, and highway times in combination with parking costs and automobile trip walking times. In these sensitivity analyses, feedback between the automobile and transit systems and the estimates of the usage of the systems was not considered.

Procedure

The modal split computer program is designed to permit changes in input data with a minimum of effort. Certain parameters may be varied by changing a single constant on an input punch card; others require substitution of one input tape. As summarized, 13 runs of the model were made. Initially only one parameter was changed per run. In two of the last runs, several parameters were changed so that joint effects could be analyzed. Although the changes were not necessarily intended to reflect realistic changes in system operation, they were made so that justifiable conclusions could be drawn as to the effect of the change in a particular parameter on the estimated modal split.

Base—NCTA Run 23.—NCTA run 23 was used throughout the sensitivity analysis as a base for comparison purposes. It was the final run for the 1980 NCTA plan B (corridor plan) morning peak traffic hour (7:30 to 8:30) work trips. The output data were NCTA's final estimate for this land-use plan and its recommended transportation system.

Sensitivity Test A.—A $0.15 fare increase was applied to each zonal interchange. This change was accomplished by changing the transit fare matrix and rerunning the model; NCTA run 23 data were used for all other inputs.

Sensitivity Test B.—The 1980 zonal incomes were factored by 1.5. This change effectively raised the median economic status areawide to 50 percent above the 1960 level. Because the 1980 income distribution is related to the 1980 land-use plan, the change (1960-1980) was not necessarily 50 percent for each zone.

Sensitivity Test C.—One minute was added to both the parking delay time at the destination and the time spent walking from the parking space to the ultimate destination. These two items constitute the denominator (excess time via automobile) in the level of service ratio.

Sensitivity Test D.—The time spent waiting for transit in the origin zone and the time spent transferring between transit vehicles was factored by 1.5. This was equivalent to a drastic cutback in transit service. This change had a large effect on the level of service ratio and a lesser effect on the travel time ratio.

Sensitivity Test E.—Parking costs, which were applied only to zero sector zones, were doubled.

Sensitivity Test F.—The transit vehicle travel time between all zones was factored by 0.75. This, in effect, speeded up all transit vehicles.

Sensitivity Test G.—The automobile time on the highway system was factored by 0.75, in effect increasing the speed of automobile travel between all zones.

Sensitivity Test H.—Transit fares were doubled. This run, which parallels sensitivity test A, was designed to evaluate the range of application of the cost ratio curves.

Sensitivity Test I.—The excess automobile times for 1980 were replaced by the 1955 estimates of these times used for development of the modal split curves.

Sensitivity Test J.—The transit vehicle travel time was factored by 1.5.

Sensitivity Test K.—The 1980 estimates of parking costs, parking delay time, and walking time to the ultimate destination from the parking place were replaced by 1955 O-D survey data used for the development of the relationships. This test was designed to determine the effect on transit usage caused by changes in automobile terminal conditions (1955-1980).

Sensitivity Test L.—Highway travel times were factored by 0.75, parking cost by 0.66, and walking time from the automobile parking place by 0.66. This test was designed to evaluate the effect of changes favorable to highway travel.

Sensitivity Test M.—Median incomes (1980) were factored by 1.2. This run paralleled sensitivity test B and was designed to evaluate the procedure's sensitivity to a modest increase in median incomes.

Results

Table 10 details the results of the 13 sensitivity runs. Results from each run are not discussed individually, but the runs have been related to the four main modal split variables. Trip purpose was not considered because only work trips were evaluated.

Table 10.—Modal split sensitivity analysis

	Base [1]	A [2]	B [3]	C [4]	D [5]	E [6]	F [7]	G [8]	H [9]	I [10]	J [11]	K [12]	L [13]	M [14]
Total person trips	465,825	465,825	465,825	465,825	465,825	465,825	465,825	465,825	465,825	465,825	465,825	465,825	465,825	465,825
Number via transit	108,169	102,731	103,265	143,586	91,864	115,972	117,287	93,848	99,752	90,308	93,249	76,133	80,571	10,552
Percent diversion	0.2322	0.2205	0.2217	0.3082	0.1972	0.2490	0.2517	0.2015	0.2141	0.1939	0.2002	0.1634	0.1730	0.2265
Percent change		−5.0	−4.5	+32.7	−15.1	+7.2	+8.4	−13.2	−7.8	−16.5	−13.8	−29.6	−25.5	−2.4
Person trips to CBD	148,390	148,390	148,390	148,390	148,390	148,390	148,390	148,390	148,390	148,390	148,390	148,390	148,390	148,390
Number via transit	85,952	82,185	84,463	94,841	76,205	92,609	88,931	81,302	80,078	68,091	80,447	53,915	68,025	84,633
Percent diversion	0.5794	0.5538	0.5692	0.6391	0.5135	0.6241	0.5993	0.5479	0.5396	0.4589	0.5421	0.3633	0.4584	0.5703
Percent change		−4.4	−1.7	+10.3	−11.3	+7.7	+3.5	−5.4	−6.8	−20.8	−6.4	−37.3	−20.9	−1.5
Non-CBD oriented person trips	317,435	317,435	317,435	317,435	317,435	317,435	317,435	317,435	317,435	317,435	317,435	317,435	317,435	317,435
Number via transit	22,217	20,546	18,802	48,744	15,659		28,356	12,546	19,674	22,217	12,802	22,217	12,546	20,889
Percent diversion	0.0700	0.0647	0.0592	0.1536	0.0493	0.0700	0.0893	0.0395	0.0620	0.0700	0.0403	0.0700	0.0395	0.0658
Percent change		−7.5	−15.4	+119.4	−29.5		+27.6	−43.5	−11.4		−42.4		−43.5	−6.0
TOTAL REVENUE	$37,337	$51,030	$35,984	$48,987	$31,647	$39,623	$40,781	$32,009	$68,545	$31,076	$31,634	$26,315	$27,401	$36,564

[1] Base, NCTA run 23, a.m. peak traffic hours, work trips only.
[2] $0.15 added to base fares.
[3] 1.5×median incomes.
[4] 2 minutes added to auto parking and walking times.
[5] 1.5×waiting and transfer times.
[6] 2.0×parking costs.
[7] Transit times factored by 0.75.
[8] Highway times factored by 0.75.
[9] Base fares doubled.
[10] 1955 auto parking and walking times used.
[11] Transit times factored by 1.5.
[12] 1955 parking costs and auto waiting and walking times used.
[13] 0.75×highway times, 0.66×parking costs, 0.66×auto walking time.
[14] 1.2×median incomes.

Economic Status.—The economic status variable indexes the set of 16 out of 80 diversion curves for each purpose that will determine the modal split. The five levels of economic status were determined by the following groupings of median income of workers:

Group 1	$0-2,499
Group 2	$2,500-3,999
Group 3	$4,000-5,499
Group 4	$5,500-6,999
Group 5	$7,000+

Tests B and M were designed to analyze the sensitivity of the modal split procedure to variations in economic status. The results show that the modal split procedure is relatively insensitive to changes in economic status. The number of transit passengers declined 2.4 and 4.5 percent, respectively, in relation to increases of 20.0 and 50.0 percent in median income.

Figure 4 illustrates five modal split curves (percent transit usage vs travel time ratio) for the five levels of economic status when the other variables were not changed; level of service was ratio 1.25 and cost ratio was 2.50. For time ratios favorable to transit—shown to the left of the vertical dashed line (travel time ratio of 1.00) in Figure 4—economic status 5 exhibits a higher split to transit than economic status groups 2, 3, or 4. As time ratios became less favorable for transit, the split to transit became inversely related to income level. In other words, the relationships developed indicate that people having higher incomes are more apt to use good transit than those having low incomes; conversely, people having high incomes are less apt to use poor transit than those having low incomes.

The characteristics noted of these particular modal split relationships tend to explain the relatively small areawide change in modal split in relation to large changes in median income. The modal split procedure indicates that for the zonal interchanges having time ratios favorable to transit, an increase in the split to transit usage occurs according to increases in economic status, as more zones fall into the economic status group 5. Conversely, for those interchanges having less favorable time ratios, a decrease in

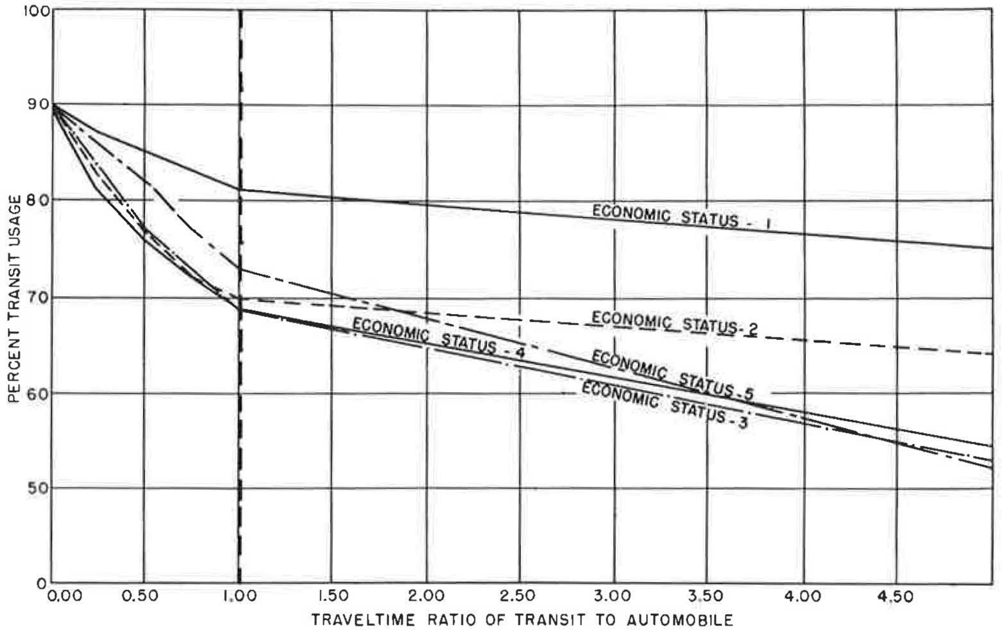

Figure 4.—Variation in modal split related to economic status.

transit usage occurs as median incomes increase. This finding was confirmed by the analysis showing the higher decline in non-CBD-oriented trips (15.4 percent) as opposed to the trips that were CBD-oriented (1.7 percent). These joint effects tended to cancel areawide variation in modal split caused by changes in median income. The modal split procedure appeared to be sensitive to changes in economic status on a zonal basis but not on an areawide basis.

Cost Ratio.—The cost ratio variable was the ratio of the out-of-pocket costs via each mode. Sensitivity tests A, E, and H were designed to evaluate the sensitivity of the modal split technique to the cost ratio. Tests A and H indicated that the range of sensitivity of the cost ratio is fairly narrow as a result of the mechanics of the cost ratio calculation. Four levels of cost ratio are specified by the modal split procedure. Between the first and the fourth levels, the cost ratios were, in effect, continuous because of interpolation between levels. However, cost ratios lower than those of the lowest level (0.25) or higher than the highest level (3.00) were considered to be equal to the high and low ratios. In other words, a cost ratio of 6.00 or 12.00 was considered to be no different than a cost ratio of 3.00.

Increases in transit fares had only a minor effect on the modal split. When a $0.15 increase in fares was applied to each zonal interchange—from an average base of $0.35—transit patronage dropped 5.0 percent overall. An examination of the cost ratios from this test indicated that the resultant ratios were predominantly on the maximum level. To prove this, fares were doubled for test H, and the decline in patronage from the base was 7.8 percent, or only 2.8 percent more than the decline caused by the $0.15 increase. This decline of 7.8 percent probably closely approaches the maximum decline in patronage caused by fare increases that the model would predict. When transit costs were held constant and parking costs in the downtown area were doubled (test E), estimates for transit trips to downtown increased 7.7 percent. The modal split procedure was sensitive to changes in the cost ratio only in a very limited range. From the drastic changes in the cost ratio variable—doubled transit fares to double parking costs—the number of estimated riders ranged only from 99,752 to 115,972.

Service Ratio.—The service ratio, also termed the excess time ratio, relates the service available by private automobile in terms of the portion of the trip time spent

Table 11.—Comparison of alternate estimates of transit waiting times

District	Transit waiting time estimates from—	
	Curve development	Test made with 1955 O-D data
1	1.2	3.9
6	2.7	4.0
11	3.0	4.7
16	4.6	4.2
22	4.0	2.0
27	7.2	5.6
32	1.7	4.1
37	7.8	8.5

outside the means of conveyance (automobile or transit). Tests C, D, and I were designed to evaluate the sensitivity of the modal split technique to changes in the level of service ratio. By factoring the waiting and transfer times for transit by 1.5 (test D), transit service was, in effect, reduced. For example, trains running on 10-min headways would have 15-min headways. This change caused a decline in the estimate for transit trips of 15.1 percent. To show the possible variation in estimates of this type, a comparison was made of selected district transit waiting time estimates developed for the 1980 application with estimates developed for the tests applying 1955 data (Table 11). Each of the estimates was made by the same person but at different times.

It is emphasized, however, that the estimates for the BPR test against 1955 O-D data were adjusted to the curve development estimates before their use for the test, as previously explained in the material on input factors. To test the sensitivity of the denominator of the service ratio, 1 min was added to both the automobile parking delay time and the walking time from parking place to ultimate destination (test C). This change had drastic effects; transit patronage estimates were increased by 32.7 percent. CBD-oriented trip estimates were increased by 10.3 percent. As the waiting and walking times for automobile trips to non-CBD areas were assumed to be 1 min each for all other tests, only CBD-oriented trips are discussed here.

Test C indicated such a high sensitivity of the procedure to automobile associated waiting and walking time that an additional test was designed. The parameters developed for these times in the test of the 1955 O-D survey data were substituted for the 1980 estimated times in test I. When these 1955 test parameters were used, the estimation for transit trips to the CBD declined 20.8 percent.

The results of these tests indicate that the modal split procedure is highly sensitive to the service ratio within the range of realistic input variables. Because of the relative difficulty in accurately estimating waiting and walking times, the procedure may be too sensitive to this parameter. A determination must be made as to whether walking and waiting times are as pivotal a factor in the choice of a mode of travel as indicated by the sensitivity test results.

As for the cost ratio, fixed limits for upper and lower levels were established for the service ratio. However, unlike the cost ratio, the range of percent transit usage was extremely broad between limits. For example, when the other parameters were held constant at given levels, the modal split might vary from 70 to 50 percent in relation to the maximum change in cost ratio. By varying the level of service ratio between its maximum and minimum values and holding all other parameters constant, a typical range in modal split might be from 70 to 30 percent.

Travel Time Ratio.—The travel time ratio consists of the portal-to-portal time via each mode, including waiting, walking, and transfer times. Sensitivity tests F, G, and J were designed to evaluate the sensitivity of the procedure to travel time ratio. A review of all three outputs showed that the model was adequately sensitive to changes in travel time. For trips in the less favorable time ratios, that is, those characterized by the non-CBD-oriented trips, the procedure was more sensitive to the travel time ratio than in the areas having ratios favorable to transit. The maximum areawide change of 13.8 percent in patronage estimates occurred when transit times were factored by 1.5. These output figures showed that the procedure was sensitive to travel time ratios but that the effects of minor time changes, such as varying speeds on a given route section, would be very hard to detect.

Combined Variables.—Sensitivity tests K and L were designed to determine the joint effect of varying several parameters at the same time. Changing an individual parameter provided a good picture of the relative sensitivity of the procedure to the change in the variable. However, because the modal split procedure exhibited different degrees of sensitivity over certain ranges, it was very difficult to evaluate the joint effect of changes in more than one parameter. For example, a 25 percent decrease in transit times might cause an 8 percent increase in the estimate for transit patronage if the average cost ratio were 1.5. The same decrease in transit time might have an entirely different effect if, because of changes in fare structure, the average cost ratio were 2.0.

When parameters used in the test of 1955 data for parking costs and automobile waiting and walking times were substituted (test K), the estimated transit usage of CBD-oriented trips dropped to 36.3 percent from the 1980 base estimate of 57.9 percent. It is difficult to draw conclusions from this particular test since the estimate for CBD-oriented transit usage dropped below the level reported in the 1955 O-D survey. In other words, despite the assumptions regarding improved transit, when the 1955 terminal parameters for automobiles were used, the 1980 estimated percent of transit usage was less than the actual 1955 level.

Test L, which contained more favorable assumptions regarding 1980 automobile travel conditions (higher automobile speeds, lower parking costs, and shorter walking times) showed a 25.5 percent areawide drop in estimated transit trips. Approximately one-half of this change can be related to the factoring of highway times because test G, in which the same highway time change was isolated, showed a patronage decline of 13.2 percent. Because the procedure is much more sensitive to the level of service ratio than the cost ratio, the bulk of the remaining decline can be related to the more favorable assumptions made regarding the walking time from the automobile at the destination.

The results of the analyses for combined variables showed the same key trends as the analyses of individual variables: (a) the level of service ratio far outweighs the other variables in importance; (b) cost ratio plays a minor role; and (c) travel time ratio exhibits adequate sensitivity over its entire range.

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Discussions

THOMAS B. DEEN, Acting Director, Office of Planning, National Capital Transportation Agency.—A rational and practical procedure for estimating the relative usage of private and public transportation systems has long been a pressing need in the urban transportation planning process. The modal split procedure developed for NCTA appears to be a significant step forward in filling this theoretical and methodological gap.

The Sosslau-Heanue-Balek report makes a valuable and necessary contribution to a fuller understanding of this procedure, to the implications involved in its application to specific planning problems, and to the subtle interrelationships of the variables affecting transit usage. The authors have treated this complicated and, unfortunately, controversial subject with objectivity and fairness.

Of fundamental importance as a test of its basic validity is the fact that the modal split procedure accurately reproduced the transit usage actually observed in 1955 as regards total areawide transit use, CBD transit use, interdistrict transit use, and transit trip length. It is axiomatic that public transit's greatest strength is in the delivery of work trips to and from the CBD. Estimating transit's ability then to attract CBD-bound workers is essential in proper planning of urban transit and highways systems. The modal split procedure estimated these trips as 75,678, missing the observed O-D survey by only 46 trips, an error so small that it must be considered at least partially coincidence. Total CBD trips estimated by the procedure were in error by only 1 percent.

The authors properly point out that non-CBD trips were not as precisely estimated, and follow with the suggestion of development of separate non-CBD modal split relationships and separate handling of such trips. As the model in its present state is a costly and time-consuming procedure, to complicate it further by additional stratification of the thinly sampled data and to raise the number of modal split curves above the present 160 might not be the most promising approach, particularly since factors other than the need for separate non-CBD modal split relationships may well be more important causes of the lesser accuracy of the non-CBD estimate. These factors would include the inadequate representation of zonal parameters such as walking distances and waiting times to employment areas in the larger nonsector zero zones. For example, walking distances to bus stops for each zone, CBD or non-CBD, were estimated so as to represent average conditions to and from trip generation points within the zone. For most nonsector zero zones, such points are primarily residential. However, walking distances to employment or commercial areas within these zones might be very different from those representing the residential trip generation points.

One disappointing aspect of the model's performance concerns the geographical bias observed in the synthesis of 1955 transit travel. The consistent underestimate of transit usage from the western side of the city and the overestimate on the eastern side are problems of real concern. However, the gravity model trip distribution process used in Washington has been observed to produce a similar bias (8). Work trips to the CBD from the western side of the city were consistently underestimated by the gravity model until adjustment factors were applied. This behavior by the gravity model has been considered a result of unequal distribution of income or other socio-economic factors between the eastern and western sides of the city. No such simple explanation suggests itself in the case of the modal split model because income is one of the input parameters.

The largest percentage of error for any corridor (as indicated by comparison of the 1955 actual and computed figures) was 22.6 percent. However, the largest absolute error was 1,473 trips over a 2.17-hour peak period. If 60 percent of these trips are assumed to occur during the peak hour and the observed peak hour downtown Washington car occupancy (1.8) is used, the error becomes $1,473 \times 0.60 \times 1/1.8 = 490$ vehicles per hour, less than one-third of that of a highway lane. Considering the limitations in our abilities to estimate future land use and trip distribution, this would appear to be well within limits acceptable for transportation planning.

The sensitivity tests are extremely interesting and if studied sufficiently can shed much light on the relative importance of the numerous factors affecting transit usage. I concur with the authors' findings that the model is sensitive to cost ratio only through a very limited range and to service ratios and travel time ratio through a much larger range. The limited cost ratio range is not an inherent characteristic of the procedure, however. If data can be found for a broader cost range, the observed results may be incorporated into this or a similar process.

One surprising element reported from the sensitivity tests is the high elasticity of transit use relative to auto terminal conditions, specifically to auto walk and delay times. I should like to make several comments in this regard:

1. One of the most attractive features of unrestricted auto travel which is almost impossible to duplicate with public transportation is that it begins where you want to begin and takes you directly to where you want to go. If, because of lack of properly located parking space, the auto trip must end some distance from the trip destination, then much of the auto convenience is lost, and public transportation is at once more competitive. Therefore, it is not unreasonable to suppose that auto walking time is, in fact, an important factor in modal split.

2. An equally attractive feature of auto travel is that it goes when you want to go. If significant delays are associated with unparking—from a parking garage, for instance—then auto convenience is reduced. Therefore, parking delay could reasonably be supposed to be an important modal split determinant.

3. Even if the preceding two points are accepted, the degree of sensitivity shown by the model to auto-walk-wait times would appear to justify careful scrutiny. Perhaps the problem lies in the use of a ratio to express the relative convenience of auto and transit travel. One of the characteristics of the service ratio is that the denominator is significantly smaller than the numerator. In fact, for the nonsector zero-destined trips, the denominator was 2 min and the numerator was usually 7 to 10 min or more. Thus, a 2-min increase represents a 100 percent increase in the denominator and a 50 percent decrease in service ratio. A 2-min decrease makes the service ratio infinite. The extreme effect of this on the modal split can be seen in test C where nonsector zero transit trips increased 120 percent as a result of adding 2 min to auto-walk-wait times. The same distorting influence is operating for sector zero trips, though to a lesser degree because the denominator for such trips is larger. Perhaps the problem could be solved by quantifying the convenience factors into time difference, transit excess time minus auto excess time, instead of a time ratio.

Some comment should be made concerning test K in which use of 1955 auto terminal values (parking costs, auto-walk-wait times) along with the other 1980 assumptions, including the proposed rail transit system, produced a modal split below the 1955 level. I concur with the authors that this test is difficult to interpret. However, before any interpretation can be made, certain other items must be fully understood:

1. Although in this test the proportion of peak hour commuters using transit to sector zero dropped below the 1955 level, the absolute volume of sector zero transit riders held about the same as in 1955.

2. The 1955 auto terminal conditions have long since disappeared. Average parking costs have gone up an estimated 100 percent since 1955, due in part to a 30 percent increase in commercial rates, but more importantly to an increase in the number of parkers using pay facilities and a corresponding decrease in the number parking free.

3. Test K, in addition to assuming an improved transit service, assumed a substantially improved highway system over 1955, with significant increases in auto travel speed. An intelligent appraisal of the real meaning of returning to 1955 auto terminal conditions in 1980 cannot be made without evaluation of the effects on auto speeds of the shift of such a large number of transit riders to the highway.

4. In fact, it can be fairly stated that the modal split at any moment is the result of a large number of conflicting factors that are in equilibrium. Change in any factor, for example, parking costs, causes a shift to auto travel. This in turn causes decreases in auto speed, which tend to shift travelers back to transit. Thus, the elasticity of modal split indicated in test K along with all the other tests must be viewed as somewhat artificial since the feedback required to reach equilibrium has not been accounted for.

In conclusion it must be noted that whereas the modal split procedure appears promising, there are many elements concerning its use that are as yet unknown. The sensitivity tests reported here indicate that within limitations the model responds in a reasonable way to changes in input conditions; the 1955 transit use synthesis indicates that the mechanics of the procedure, the method of inputting certain of the variables, and the otherwise questionable procedure of representing conditions within fairly large geographical areas by averages (for example, average walking distances and income) are adequate. But results of these tests indicate little about the relative importance of other factors that probably affect transit use, such as schedule adherence, air conditioning, riding comfort, vehicle esthetics, diesel fumes, subway claustrophobia, station shelters and parking facilities, and kiss-and-ride. Nor do we yet know much of the universality of the modal split relationships. Most important, we do not know if modal split relationships remain stable over a period of time. Finally, the entire approach ignores the effect of relative transit and auto use on trip distribution and generation, although logically it would appear that all these elements are interrelated, at least through land-use changes, and probably more directly. All things considered, there are many unknowns worthy of concern and further study. Yet, when viewed alongside the other unknowns in the field of urban planning, the modal split model is a significant advance contributing much to our understanding of the determinants of public transit usage.

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WILLIAM L. MERTZ, Technical Director, Tri-State Transportation Committee.—The modal split procedure evaluated by Sosslau, Heanue, and Balek has received widespread attention in the technical field. Also, the controversy over the future course of highway and transit development in the National Capital Region has assumed national proportions. I am concerned that the technician who reads this paper without more background and perspective might assume a more pessimistic view of the usefulness of the procedure than is warranted. I would, therefore, suggest that the other two papers, Development of a Model for Forecasting Travel Mode Choice in Urban Areas, by Von Cube and Hill, and Application of a Modal Split Model to Travel Estimates for the Washington Area, by Deen, Irwin, and Mertz, be studied in conjunction with this one.

The problem of mode choice is assuming greater proportions each year. Heretofore, the tools to deal with the problem have been skimpy indeed. The use of time ratio curves alone will no longer suffice. I suggest that the reader make a judgment as to whether the significant factors in modal choice have been incorporated into the procedure. By and large, I submit that they have. Because we need to know more about the effect of crowding—the standee problem—and other factors in quantifiable terms, more research is certainly needed.

If the position that the major significant variables have been incorporated is accepted, the next question to be answered is whether a proper description of the action and interaction of the variables has been found. This is the subject under discussion. A review of the article and an inspection of the curves will reveal the different sources of data and the portions of the curves for which there were no data at all, the dotted portions. There is always great difficulty in developing a common denominator base, both in time and geography, for data collected from different sources. This points to the need for the collection of more information in O-D surveys bearing on the mode choice problem. Also, changes of variables assumed to influence mode choice need to be made within functioning transit-highway systems and results must be carefully measured and evaluated. The Demonstration Grant Program could be the instrument for such studies.

The reader must also judge the conclusiveness of the test against the 1955 O-D data. The authors state that on a district-to-district basis "the variation between the O-D and model estimates is less than the variation in the survey." At the same time it is stated that the variation between corridor movements is a particularly critical weakness of the modal split technique. There have been several tests of transportation planning techniques against O-D data in the past. In all cases, the variation has been higher than we would like and leaves moot the question of how much variation is due to sampling and how much is due to a procedure's inability to describe an historical situation.

The sensitivity tests of the model are particularly interesting. It should be borne in mind that the sensitivity tests, by their very nature, extend the parameters into the dotted portions of the curves for which no data were available. The configuration and interaction between variables in these extended ranges, of necessity, were based on logic and intuition. Even so, it is not surprising that changes in fare proved to be less sensitive than, for example, automobile terminal conditions such as parking delay, walking time, and parking costs. I am encouraged that the authors stated that the model is "adequately sensitive to changes in travel time," which has been the backbone of mode selection procedures in the past.

A point that none of the three articles brings out clearly should be emphasized. One of the major objectives of this development was to create a modal split computer program to fit into and be compatible with so-called BPR battery of transportation planning programs. This was achieved. The modal split relationships (represented by tables) are input to the program just as travel time matrices, etc., are input. All of the discussion in the report concerns the evaluation of this input. Different sets of relationships were used for the work and nonwork purposes. The program is operational, is compatible, and is usable by any study. The tabular curve relationships should certainly be evaluated against data for the urban area in question and modified or completely reconstructed in the light of local conditions. This operational capability should not be overlooked.

GEORGE B. WICKSTROM, Deputy Director, Penn-Jersey Transportation Study.— When one is given the opportunity to comment on material that is in itself a comment on a previous paper, it is difficult to know where to begin. Comments could be directed to the problem (modal split), the method evaluated (diversion), or the evaluation of the modal test methods and results.

The major points of the conclusions as stated in the paper included: (a) CBD and non-CBD trips may require stratification; (b) certain input variables (notably excess time) are overly sensitive; and (c) further study is required.

Although it is difficult to disagree with these conclusions, I cannot help but feel that the basic approach taken to solve the problem of predicting modal split should also be examined. The approach investigated is a diversion approach; that is, it attempts to predict the percentage of travelers who choose transit rather than the auto. Although it may be possible mathematically to match observed transit choice behavior by this method with aggregates of O-D data available, how does one accurately predict the future total number of travelers between two O-D zones using all modes of travel from which to take a percentage? Isn't the ultimate answer desired not only the percentage on transit for each corridor, but also how many on transit or auto?

It would also seem that the data available from the O-D survey were overly stratified in an attempt to introduce as many of the factors influencing transit use as possible. A 5 or even 10 percent sample of CBD trips simply does not permit so many stratifications, as sample variability plays havoc. If home interview data are ill-suited for models of this type, shouldn't we collect data at the CBD end of the trip?

One of the major reasons for collecting home interview data throughout the metropolitan area is the present need to obtain a universe of household characteristics and trip interchanges. Although the day has not yet come when secondary source data and models have made these basic requirements obsolete, perhaps better models could be developed if data collection were intensified in several parts of the urban area to provide a statistically reliable sample for model development purposes, while collecting a slightly smaller uniform sample elsewhere.

If only conventional origin-destination data are available, one is forced to predict transit use on an area basis and usually to ignore or generalize the effects of changes in system characteristics. Modal splits are made before distributing trips rather than afterward.

There is also some question as to whether diversion curves can ever adequately predict modal split, since they usually tend to overemphasize system characteristics at the expense of more determining factors—such as whether or not the wife needs the family car. In this regard, I notice that the model tested did not directly deal with car ownership. Yet, the importance of this variable in estimating transit use is illustrated by the fact that only 14 percent of all trips and 9 percent of nonwork trips were made in the Philadelphia area in 1960 by persons in families owning one car. For trips by two-car families these low percentages were halved, and persons not owning a car made 76 percent of their trips by transit. It would seem that the apparent effect of car ownership is important enough not to be even partially ignored.

In the Philadelphia area, only 25 percent of all transit trips have origin or destination in the CBD. A CBD-derived relationship could not be readily used to explain the remaining behavior, since 75 percent of the trips would then be estimated on the basis of relationships derived from 25 percent of the trips.

These comments were not directed at criticizing the model, but rather at pointing up the difficulties inherent in deriving models of this type with conventional origin and destination survey data. The fact that the model behaved as well as it did underlines the need for continued study in this area. This is the only modal split model now available that has been derived and tested with O-D data from several cities and that deals directly with relative transportation system characteristics. If the excess time factor were modified or eliminated, the model would serve as an important interim tool while awaiting the results of the further research recommended.

The Sosslau-Heanue-Balek paper is an excellent example of the type of thorough, painstaking model evaluation required before the problem of modal split can be solved. The authors have done an excellent job.

A Research Program for Comparison of Traffic Assignment Techniques

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One purpose of this paper is to describe a computer program that has been prepared to compare techniques of assigning traffic to a transportation network. The program has been prepared principally as a research tool. However, one option permits a new type of assignment technique to be used involving the incremental loading of the network and the use of a generation curve function to revise input interzonal transfers in the event of excessive network overloading.

The program may be used as a research tool to perform a number of experiments on the same network and input data. These include assignment by minimum path trees, assignment by single paths using various increments of interzonal volume, assignment by a combined technique of trees and single paths, and investigation of effects of different random numbers.

•AN INCREMENTAL traffic assignment technique has been incorporated into a more general traffic assignment computer program, which can be used for the comparison of several current traffic assignment procedures. The more general traffic assignment program is termed a research tool as it is to be used in a project to develop a better understanding of the characteristics of both proposed and existing traffic assignment techniques and is not intended to be suitable for immediate use by operational groups for purposes such as large-scale transportation studies.

The more general research assignment program to be described includes the incremental technique as a special case. The research program is very flexible and may be used in a number of ways.

The paper discusses the difficulties inherent in the comparison of traffic assignment techniques and suggests some statistics of program performance as a basis for the comparison of one assignment technique with another.

To establish a framework of reference for consideration of the incremental technique to be described and to show the relevance of a quantitative comparison of assignment techniques, a brief review will be given of the development of traffic assignment and of the techniques now available.

DEVELOPMENT OF TRAFFIC ASSIGNMENT TECHNIQUES

During the development of transportation planning techniques, the use of an assignment procedure has become increasingly important. In the first use of assignment techniques, the volume of vehicles assigned to any particular link in the network often did not correspond with the flows occurring in the real network. However, the technique did provide the engineer with a general indication of the volumes to be expected and the level of service being provided by the network under evaluation. Most of the manipulation of the trips to be assigned was undertaken manually and the engineer was

Paper sponsored by Committee on Origin and Destination.

able to apply his own judgment at many stages. In 1952 the technique was summed up as follows:

> Traffic assignment is fundamental to the justification of a proposed highway facility and to its structural and geometric design, to spotting points for access and for advance planning of traffic regulation and control measures. As yet, traffic assignment is considered to be more of an art than a science. (12)

Since 1952, the large urban area transportation studies and other planning agencies have developed assignment procedures to the point where less and less emphasis is placed on personal judgment. There are probably three main reasons for this development of more formalized assignment techniques. First, the scale of problems attempted by planning studies has become very large, making manual methods too time-consuming and costly. Second, the general availability of high-speed electronic computers permits the engineer to use more involved approaches to problems for less cost and time than previously. And third, the attempts to formalize other phases of the transportation planning process are aimed at the development of an integrated set of prediction models for the evaluation of alternative combinations of land use and transportation facilities.

The result of this intensive development activity has been the creation of several different traffic assignment techniques. The first of these is the diversion curve technique in which the total number of trips between an origin and destination are divided between two routes, one of expressway characteristics and the other an arterial or equivalent highway (9, 10, 11). The technique originated as a solution to the problem of locating a single expressway relative to some existing highway. The diversion curve is based on data obtained from observations at some other location where two "similar" facilities exist. Curves have been developed for various parameters, such as time saved by using the expressway, ratio of time by expressway to time by alternative, and similar expressions for distance; in some cases curves have been developed relating the cost differences between using the expressway and some other facility. In each case, the curve indicates for a given value of the parameter used, such as time saved, the percentage of drivers who will use the expressway.

If suitable data can be found, the diversion curve approach is quite workable for a small network where only one additional expressway-type facility is being considered. However, in large networks, where the system effects are significant, other forms of assignment are required. Perhaps the first alternative to the diversion curve technique was the "all-or-nothing" or "desire" assignment technique used in the Detroit Transportation Study in 1958 (1). In this procedure, the total interzonal transfer is assigned to the minimum time path between a zone pair. No account is taken of the capacity of the system between a zone pair during the assignment. The technique is termed desire assignment since it shows the volumes that would occur if everybody could choose the shortest route through an unloaded or constant travel time system. Frequently in practice, this amount of capacity cannot be provided in one corridor and the procedure does not effectively utilize all facilities in the network. The results of this type of assignment are not particularly useful in evaluating the performance of economically feasible networks.

The next development was an attempt to account for the capacity of the system, which clearly restrains the number of vehicles that can use any particular corridor and, in fact, the whole system. Each program that has included this feature has done so in a different way, but all of the techniques are generally referred to as "capacity restrained." There are four techniques, each of relatively recent origin, so no attempt will be made to rank them in historical order.

In the U. S. Bureau of Public Roads assignment technique an all-or-nothing procedure is used without changing the link speeds during the execution of the assignment. On completion of one assignment the volume-capacity ratio is determined for each link, and the link speed is obtained from a function relating volume-capacity ratio to speed.

The assignment is then repeated using the revised link speeds and the new volume-capacity ratios computed. The procedure is repeated until the speeds at the beginning of an assignment approximately equal the speeds obtained from the volume-capacity ratio-speed curve at the conclusion of the assignment.

In the traffic assignment technique developed by the Chicago Area Transportation Study, the capacity restraint option operates on a zonal basis (2, 3). One zone is randomly selected from the possible loading zones, and the minimum path tree is determined from the selected zone to all other zones. All trips from the selected zone are then assigned to the minimum path defined by the tree. The network is then updated with new travel times calculated for the links in the minimum path tree according to a relationship between speed and volume. The procedure is now repeated with the random selection of one of the remaining loading zones and the computation of a new tree. The assignment is complete when each loading zone has been selected as the origin for a minimum path tree. The procedure does not involve any iteration since the network is updated before the computation of each tree, and the speeds will always be related to the link volumes. The Chicago technique also includes the computation of the interzonal transfer from the opportunity model.

Traffic Research Corporation has developed a traffic model incorporating both distribution and assignment phases (4, 5). An initial set of minimum path trees are computed for the network using travel times based on an unloaded network. These trees are then employed to make an initial trip distribution using the gravity model and an initial assignment using an all-or-nothing technique, keeping the link times constant during the execution of the assignment. A series of curves relating unit travel time in minutes per mile to volume in vehicles per hour is then employed to determine new link travel times from the assigned link volumes. The new link travel times are used for the computation of a revised set of minimum path trees. A new distribution of trips is computed and an assignment is made: trips are assigned to the original and revised minimum paths in proportion to the travel times over the two routes. At the completion of the second assignment, the link travel times are again revised using the unit travel time-volume relationship. These new link times will be used to repeat the whole procedure with up to four routes possible between each origin and destination. The assignment procedure is concluded when the total number of vehicle hours of travel in the system becomes approximately constant.

A technique developed at Wayne State University also involves a series of iterations (6). The first assignment is made using the all-or-nothing technique with travel times based on typical speeds for the facilities in the network. At the completion of the first assignment, the volume on each link is expressed as a percentage of the capacity of the link and used to modify the link travel time in the following expression:

$$V_i = e^{(R_i - 1)} V_o \tag{1}$$

where

V_i = travel time on link for a given iteration,

R_i = ratio of volume assigned (average from all previous iterations) to capacity; and

V_o = original travel time based on typical speed.

The second iteration of the assignment consists of computing new trees based on the revised travel times and assigning the traffic evenly over the old and new paths. At the end of the second iteration the travel times are revised using Eq. 1. Smock describes the continuation of the procedure as follows:

> For the third pass the same procedure is followed, and such passes can be repeated, dividing interzonal volumes over more and more paths, until capacity-adjusted speeds, on the average, come to approximately typical speeds. The two measures of speed will converge as assigned

volumes converge on capacities. This particular type of "convergence" will happen quickly when the network provides sufficient capacity exactly in the places where it is needed, and will never happen completely if the network does not contain sufficient capacity for the volumes assigned to it. (6)

It is evident from the foregoing brief summary that there are several traffic assignment techniques currently available. Each of the techniques that has included a capacity restraint has done so in a different way. Although a lot can be said, and has been said, about the different techniques in a qualitative manner, there is little, if any, quantitative data showing the results of using different techniques on the same problem. Arguments for or against a particular technique are often academic and philosophical in nature, and may leave the practicing engineer or planner confused. In the following sections of this paper we will describe an iterative assignment technique which, while of interest in itself, has been extended to a more general assignment program suitable for making a number of useful comparisons between some of the existing traffic assignment techniques.

AN INCREMENTAL TRAFFIC ASSIGNMENT TECHNIQUE

When an engineer uses traffic assignment, he is attempting to simulate the manner in which drivers will use the network under evaluation. An assignment technique must, therefore, be designed to reproduce the decision-making behavior of drivers choosing routes. At the present time there is not a complete understanding of the manner in which drivers make this decision. It is fairly evident that a number of factors are involved and, from the survey data available, travel time appears to be the most predominant factor. Hence, assignment techniques have been developed which assign all of the trips, between an origin and destination, to the shortest time path.

However, to assign all drivers to the minimum time path is often unrealistic in terms of our knowledge and experience of the operation of existing systems. As noted previously, there are two assignment techniques that use several alternate paths between an origin and destination. In essence, there is a conflict between using an assignment principle, that of minimum time, and obtaining results that correspond with the operation of a real network.

It seems likely that this conflict occurs because the assignment program is basically a static technique attempting to simulate a dynamic system. The driver about to make a trip must, consciously or subconsciously, assume that all other drivers have made their decisions as to which route to take, and base his own decision on his knowledge of the system in its present state. This knowledge will consist principally of his previous experience in the network. The behavior of the total population of drivers can perhaps be summarized as follows: each driver attempts to minimize his own travel time, given the state of the system as he sees it, but as drivers enter the system at various times, the state of the system is constantly changing. Therefore, at different times different routes will have the shortest travel time. From this initial statement one may further postulate that given these decision conditions, the travel time over all the reasonable alternatives, between any origin and destination, will be approximately the same for a system carrying a significant volume. If this were not so, then under the decision framework postulated, drivers would switch routes until this "equilibrium" condition was achieved. Several researchers have for some time felt that equilibrium condition of a network is true of real systems (7).

To reproduce this behavior exactly in an assignment technique would probably require more knowledge of the time distribution of trips than we have currently available and would involve a rather large computer program. However, the following incremental technique may, in fact, assign vehicles to a network in such a way that these conditions of network equilibrium are fulfilled. We would hasten to point out that it has not been proven that other assignment techniques do not fulfill this condition, since it is difficult to come to any rational conclusions without experimenting with the techniques themselves.

The incremental assignment procedure consists of five phases:

1. The random selection of a zone pair;
2. The determination of the minimum time path between the zone pair;
3. The use of a generation rate characteristic to determine the potential volume to be assigned between the zone pair;
4. The addition of a small increment of the potential volume to the minimum path; and
5. The use of a volume-delay characteristic to update the travel times of the links in the minimum path due to the increase in volume.

These five phases are continually repeated until, for each zone pair, the traffic assigned is equal to the interzonal potential volume determined from the generation rate characteristic. The procedure is summarized in Figure 1 and is described in detail in the following paragraphs.

The input assumed to be available for the program consists of five groups of data.

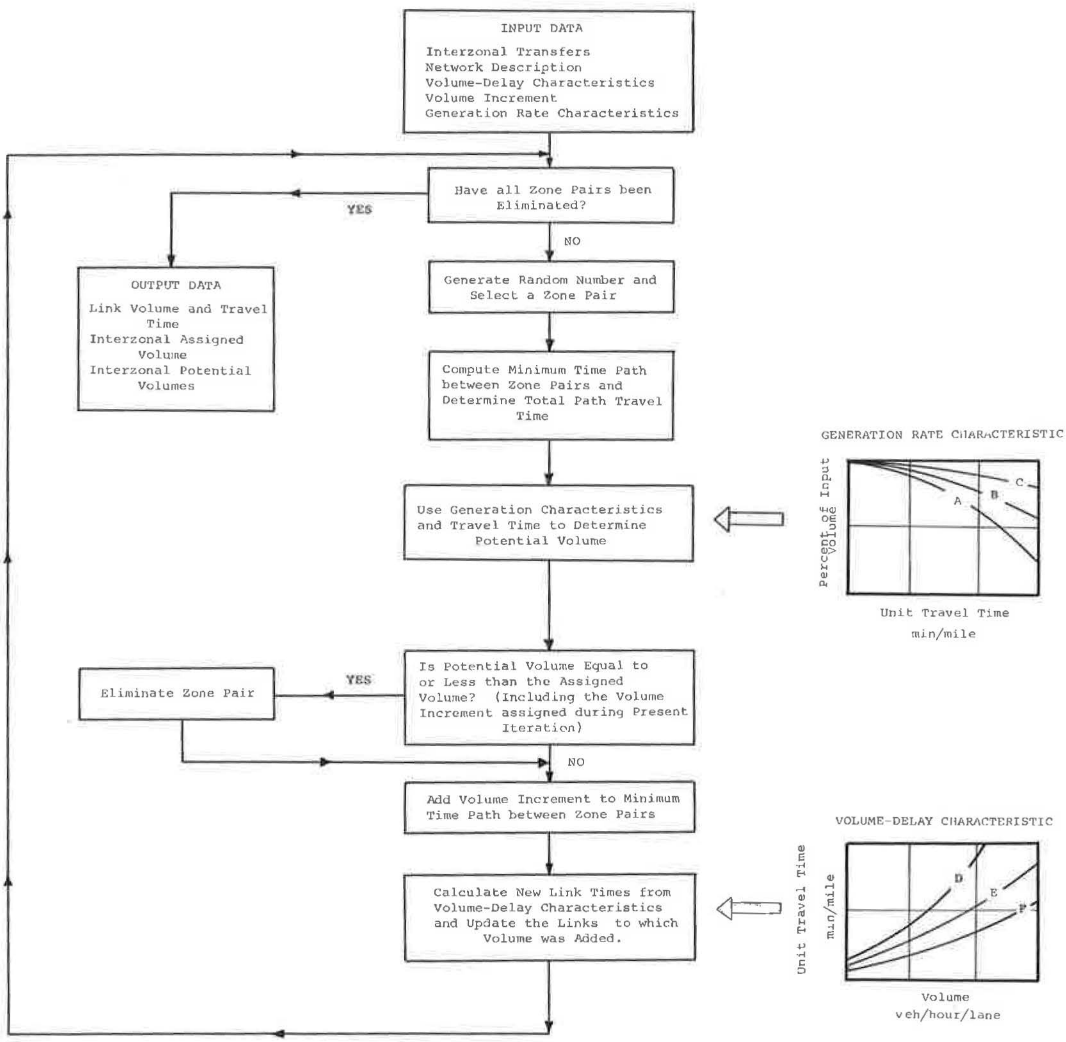

Figure 1. Summary of incremental assignment procedure.

1. Potential interzonal volumes—assumed to have been prepared by a distribution model such as the gravity model, using ideal travel times to measure the interzonal separation. They are termed potential volumes since they are based on ideal travel times which will change during the loading of the network. The potential volume will then also be changed.
2. Network description—includes the identification of links by node numbering, the lengths of the links, the number of lanes of road in each link, and the type of road each link represents.
3. Volume-delay characteristics--relationships between link travel time (min/mi) and link volume (veh/hr). There is a separate curve for each type of road designated in the network.
4. Volume increment—a variable set by the user, indicating either the percentage of an interzonal transfer to be assigned on each iteration of the program or the absolute number of vehicles to be assigned on each iteration of the program, for example, 200 vehicles.
5. Generation rate characteristics—indicating the percentage of the input interzonal potential volume that will be realized as a function of the unit travel time between zone pairs (which is an indicator of network congestion).

The procedure commences with the generation of a random number used to select a zone pair from a table indicating those zone pairs to be assigned. The minimum time path is then determined between the zone pair. This is not a complete minimum path tree, but just that portion required to determine the minimum path between the two zone pairs (8).

The minimum path time is used to compute the unit travel time (min/mi) between the zone pair. The generation rate characteristic is now entered with this time to obtain the percentage of the input interzonal potential volume that will be realized at the given level of network congestion. At the beginning of the assignment the figure will probably be 100 percent. Thus, if the input potential volume was 1,000 trips, the result of the generation rate curve inspection is that 1,000 trips are still to be assigned between the zone pair being considered. The procedure now continues, and a check is made to determine the volume that may have been assigned between the zone pair on previous iterations. Obviously, on the first iteration this will be zero, so the volume increment as specified by the input data will be added to the minimum path between the zone pairs. Thus, if the input had specified a 10 percent increment, 100 trips would be added to the minimum path. If the input had specified an increment of 200 trips, then 200 trips would be added to each link on the minimum path.

If the assignment procedure had already completed many iterations, it is quite likely that trips would have already been assigned between the zone pair, and it is also possible that the network has become relatively congested. Thus, reconsidering the previous example, the generation characteristic may have indicated that only 95 percent of the input interzonal potential volume should be assigned, i. e., 950 trips in this example. On inspection of the trips already assigned it is found that 800 of these 950 trips have been previously assigned. Thus, if the 10 percent increment is being used, a further 100 trips will be added to the current minimum path between the zone pair. If the 200-trip increment is being used, only 150 trips will be added to the minimum path; the zone pair will be considered fully assigned, and the corresponding entry will be removed from the table of zone pairs to be assigned.

After an increment of volume is assigned to the minimum path, the volume-delay characteristic is used to determine the new link travel time, corresponding to the link volume resulting from the addition of the increment. The volume-delay curve used will depend on the type of highway the link represents, as specified by the input data. It is, therefore, possible for several different curves to be used along the total length of a minimum path.

As soon as the network has been updated, the procedure returns to the initial phase, the generation of a random number for the selection of a zone pair. The procedure is repeated with zone pairs picked randomly from the table of available zone pairs. As zone pairs become fully assigned, their entry is removed from the table of available zone pairs and, therefore, the assignment is complete when the table is empty. Any one zone pair may be considered, and in general will be considered, several times during the course of the assignment.

To clarify the concept of the incremental technique further, the volume-delay characteristic, the incremental loading and the generation rate characteristic will each be discussed in more detail.

VOLUME-DELAY CHARACTERISTIC

The purpose of the volume-delay function is to relate the travel time over a link to the volume assigned to the link. At the beginning of an assignment the travel time over a link will correspond to the time required to travel the length of the link at the posted speed limit. As traffic is assigned to the link, the volume-delay function is used to increase the travel time over the link. For low volumes this increase is relatively small, although it may be enough to change the minimum path between a zone pair. As the volume reaches the operating capacity of the link, the travel time begins to increase significantly. If the volume exceeds the operating capacity of the link, the travel time will increase rapidly. The general form of the volume-delay curve is shown on the flow chart in Figure 1, where unit travel time (min/mi) is plotted vs volume (veh/hr/lane). The volume-delay characteristic is a link characteristic and will have a different shape, depending on the physical properties of the link and the form of traffic control.

INCREMENTAL LOADING

The incremental loading affects the operation of the procedure in several ways. Basically, it is an attempt to load the network in a balanced manner so that all regions of the network approach the fully loaded condition at the same time. The incremental loading permits several paths to be used between each origin and destination, makes the inclusion of the volume-delay characteristic more significant, and probably permits the network to be loaded in such a manner that the network equilibrium condition mentioned previously will be obtained.

These features can perhaps best be illustrated with the aid of a simple example. Let us consider two zones connected by three fairly direct routes: A, B and C. At the beginning of the assignment the travel times over the routes are as follows: A, 9 min; B, 11 min; and C, 12 min. As the assignment commences, the first increment of traffic will be added to the minimum path between the zone pairs, Route A. The volume-delay function is now used and the travel time over Route A increases to 10 min. When this zone pair is next considered it is very likely that because of traffic assigned between other zone pairs, the travel time over Route A has increased to 11.5 min. The next increment, therefore, will be added to Route B, and the travel time on Route B is increased to 12.5 min. Further increments might then be added to the original Route A, increasing the travel time to 13 min. Route C is now the shortest route between the zone pairs and will be used for any further increments until its travel time reaches or exceeds the next best route, B.

Two things can be noted from this simple example. First, the volume-delay function has more effect when small increments are added than when a very large, perhaps the total interzonal transfer, is added, which will mean that the link becomes immediately congested. Second, the alternative routes between a zone pair will be used in such a way that the travel times will tend to converge toward a common value. Since the same behavior will occur between each zone pair and the zone pairs are being selected at random, the rate at which volume is added will be approximately the same for the whole network. In assignment techniques where the complete interzonal transfer is added in one operation, it is possible for one section of the network to be congested and an adjacent section to have no loading at all.

GENERATION RATE CHARACTERISTIC

In all existing traffic assignment techniques, the total number of interzonal transfers put into the program will always be assigned to the network, regardless of the re-

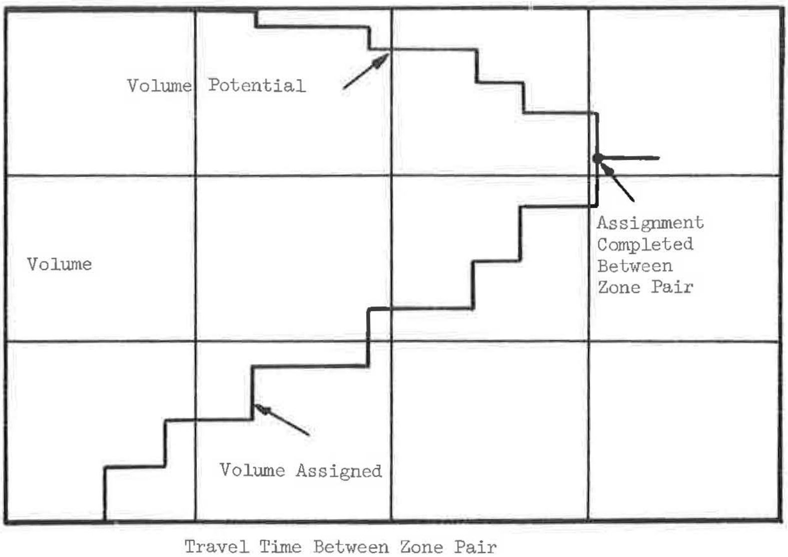

Figure 2. Curves showing combined effect of generation rate characteristic, volume-delay characteristic, and volume increment.

sulting state of the system. This procedure is adopted because it is assumed that the amount of travel is affected only by the land use and that the network controls only the actual routing of this travel. In effect, this says that the demand can be predicted, without considering any restrictions in the supply. This assumption is probably not true for any product and would certainly seem questionable in the urban transportation case. It is true that this factor has been considered in an intuitive manner when making the initial land-use predictions. However, until very recently there has been no attempt explicitly to consider the effect of the transportation network on the amount of travel predicted.

In the original formulation of the incremental assignment technique, an attempt was made to take into account the effect of the capacity and service restrictions of the transportation network on the amount of travel generated, by the introduction of the generation rate characteristic. The general form of the curve has been shown in the flow chart in Figure 1, where the percentage of the initial interzonal transfer that will be realized is shown plotted as a function of the unit travel time between a zone pair. As the unit travel time increases between the zone pair, and hence the network congestion increases, the percentage of the initial interzonal transfer realized is assumed to decrease.

No theoretical formulation can be given for the generation rate characteristics and as yet no attempt has been made to obtain any empirical data to determine their shape. In fact, at the present time the curves are more an interesting idea than a workable concept. However, if the effect of the generation rate characteristic, the incremental loading and the volume-delay function are considered together the results are interesting. If the volume assigned between a zone pair and the potential volume obtained from the generation rate characteristic are plotted as a function of the travel time experienced between the zone pair at different stages of the assignment, Figure 2 is obtained. The horizontal steps in the volume assigned curve indicate the increase in travel time due to the volume between the zone pair being considered, and the volume between other zones using common links. As the travel time increases between the zone pair, the potential volume is reduced by the generation rate characteristic, the volume assigned is increased by increments until it intercepts the potential volume curve. Figure 2 might be thought of as a crude supply and demand curve for travel between the zone pairs.

The implementation of the generation rate characteristics will clearly require more study, and it may even turn out that the development of more sophisticated land-use prediction techniques, which take account of the service characteristics of the transportation network, will eliminate the need for such a function. However, during the development of our ideas, another interpretation of the possible use of the generation rate characteristic has been considered.

In this second interpretation, the characteristic would be used at the end of an assignment to provide the engineer with more information about the deficiencies in the transportation network. At the present time, when the engineer is formulating a transportation network to be evaluated by a traffic assignment, he is limited by the available information and may not determine the best location and capacity of all facilities. By using the results of traffic assignments, the network layout can be modified before further assignments. However, the results of an assignment only indicate the links in the network which are overloaded. They do not provide any information about the origins and destinations of the trips involved. Furthermore, it is possible that the network congestion has resulted in the use of rather circuitous paths by some trips. It is thought that the generation rate characteristic could be used to provide the engineer with more information about the trips not served adequately and reduce the likelihood of circuitous paths being used.

This could be done in the following way. The generation curve would be based on the desired level of service required in different directions in the network, based on average speeds. As the network is loaded, the generation curve could be used to prevent the assignment of trips between a zone pair if the level of service was below that desired. This would also reduce the possibility of using circuitous routes in the network. At the end of the assignment the engineer could compare the input interzonal volumes with those actually assigned, and be able to determine immediately which zone pairs were not being served adequately. The engineer may now reduce the level of service desired by shifting the curves to the right, or provide additional capacity before the next assignment. Thus, the use of the curves in the program does not change, but the results themselves are given a different interpretation.

TRAFFIC ASSIGNMENT PROGRAM FOR RESEARCH

The incremental traffic assignment technique has many interesting possibilities. However, considerable experimentation is required before some of the features can be fully understood. This statement is also true of other traffic assignment techniques in use today and is, in fact, a general criticism of many of the models used in the various phases of the transportation planning process. The U. S. Bureau of Public Roads has recently been involved in a series of comparisons of the traffic distribution models as an initial step toward learning more about the characteristics of models in use. It became clear in the conduct of our work at M.I.T. that much could be learned from a quantitative comparison of several different assignment techniques, each applied to the same problem. It also seemed possible that the incremental technique could be the basis for the development of a more general traffic assignment program which could be used for the comparison of several existing techniques.

The operating procedure of the research assignment program is summarized in Figure 3 and is based on a development of the flow chart shown in Figure 1. The principal change in the procedure is the added flexibility obtained by revising the minimum path algorithm so that either single paths, as required in the incremental technique, or complete minimum path trees may be obtained. The remaining portions of the program have also been revised so that either of the options can be used.

The input to the program is basically the same as described for the incremental technique. The items added are for the procurement of additional data during the execution of an assignment to provide a better basis for the evaluation and comparison of the results from different techniques.

During the comparison of traffic assignment techniques, the generation rate characteristic can be set to a constant value of 100 percent so that it will have no effect. The volume increment and the volume-delay characteristic, together with the path or

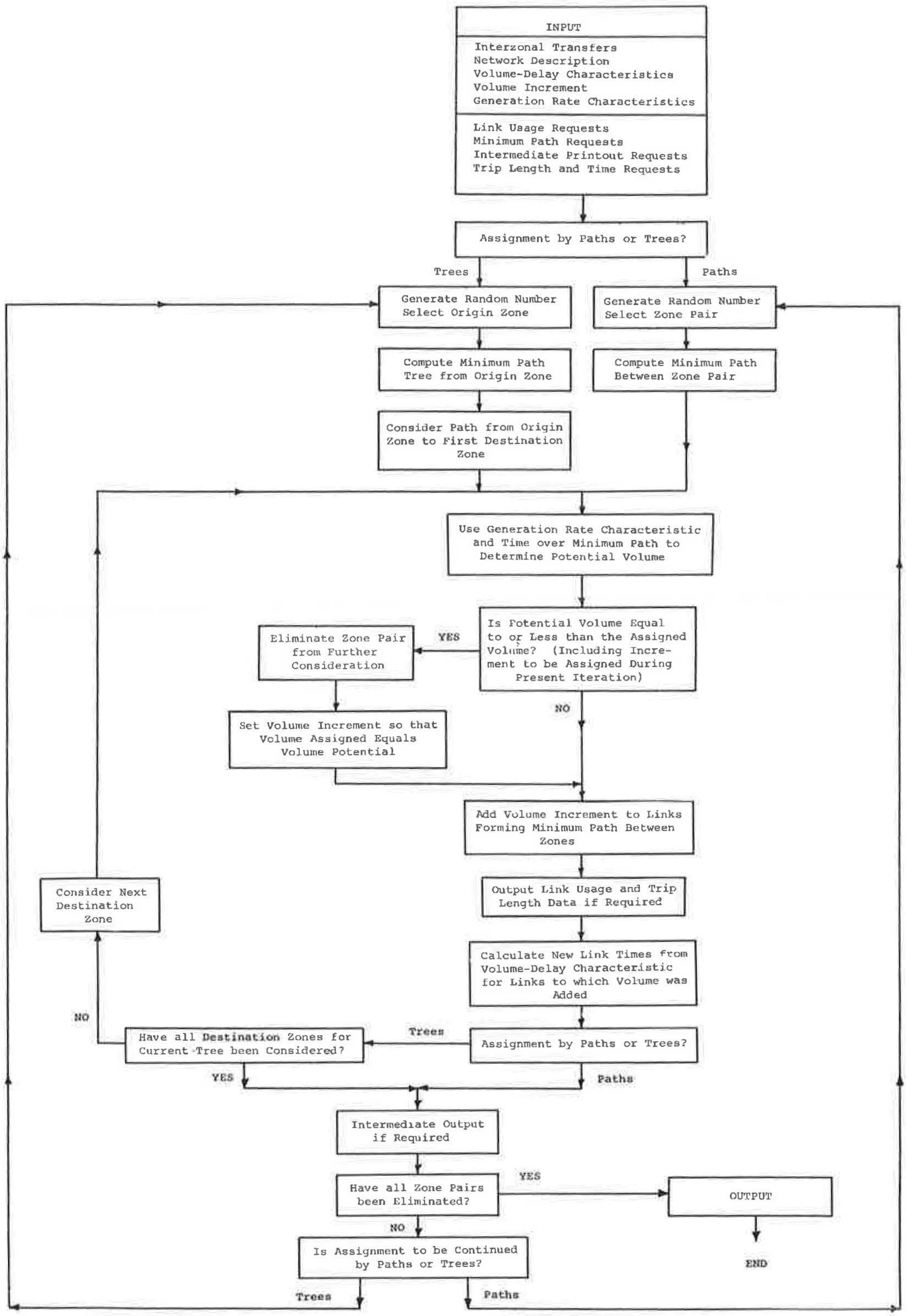

Figure 3. Flow chart of research traffic assignment program.

tree mode of operation, can be used to obtain a number of different assignment techniques.

Mode 1—all-or-nothing assignment using minimum path trees, without a capacity restraint (a desire assignment).

Mode 2—all-or-nothing assignment using minimum path trees and a capacity restraint, operative during the execution of the assignment. This is essentially the pro-

TABLE 1

DIFFERENCES IN OPERATING PROCEDURE TO OBTAIN VARIOUS MODES OF OPERATION OF ASSIGNMENT PROGRAM

Mode	Mode Specified on Initial Input	Volume-Delay Characteristic	Volume Increment	Procedures Required External to Main Program
1	Trees	Function for each type of facility represented by horizontal line equal to constant unit travel time required.	Must be 100 percent of interzonal transfer.	None
2	Trees	Volume delay function for each type of facility as generally shown in Figure 1.	Must be 100 percent of interzonal transfer.	None
3	Trees	Normal volume delay curve as in mode 2, or some other relationship.	Must be 100 percent of interzonal transfer.	Adjustment of link times according to volume-delay relationship.
4	Paths	Volume delay function for each type of facility as in mode 2.	May be a percentage of the interzonal transfer, or a constant increment.	None
5	Trees	Volume delay function for each type of facility as mode 2.	May be a percentage of the interzonal transfer, or a constant increment; if a percentage, should not be 100 percent if operation is to be distinguished from mode 2.	None

cedure used in the Chicago Area Transportation Study program with the capacity restraint option, but the Chicago program also included the computation of the interzonal transfers from the opportunity model. However, as a method of traffic assignment, the two programs are the same.

Mode 3—all-or-nothing assignment using minimum path trees and a capacity restraint operative at the end of a complete assignment cycle. This is the technique used by the U. S. Bureau of Public Roads. The adjustments of the link speeds or travel times would be done outside the structure of the program as shown in Figure 3.

Mode 4—incremental assignment by single paths using a capacity restraint during the execution of the program. This is the incremental technique described previously. A complete range of possibilities exists in the selection of the volume increment; an increment of 100 percent would be an all-or-nothing assignment by minimum paths. This mode of operation does not simulate the techniques used by Traffic Research Corporation and Wayne State University but is similar in as far as several routes are used between each origin and destination. However, in the research program, no iteration is involved.

Mode 5—incremental assignment commenced by minimum path trees and completed with single paths, using a capacity restraint during the execution of the program. This is an extension of the incremental technique as previously described, in which the first increment from each zone is made on a minimum path tree basis. However, remaining increments are added on an individual path basis. It is reasoned that this approach might produce essentially the same results as the original incremental technique with a saving of computer time.

Table 1 indicates the actual operational procedures required to use the program in each of these modes.

ANALYZING RESULTS OF RESEARCH PROGRAM

In analyzing the results of experiments with the research traffic assignment program, there are two basic questions to be answered: what type of input data should be used for the comparisons and how are the results of the various techniques going to be compared and evaluated?

The choice of a network and origin and destination data is a difficult problem. Because of the large quantities of data involved in traffic assignment and the limited resources of a research effort of this nature, very large network problems have to be avoided. On the other hand, it is likely that a very small problem would not give meaningful results in most practical situations. A desirable feature of the network used, at least in the initial comparisons, would be a completed expressway network, since these are the facilities most affecting the accessibility patterns and, therefore, are likely to cause the differences in assignment technique to stand out more clearly. Many medium-sized cities do not have completed expressway plans, other than on paper, and there are no field data describing the network flows. At the present time we have available a network of approximately 1,000 links and 250 nodes, with 60 loading zones, together with origin and destination data, for 1980 based on the predictions of two transportation studies. The advantage of the problem is that most of the desirable features are present and we know the existing network. The undesirable feature is, of course, the lack of network flow data.

For the initial comparisons it is expected that this network will be used, and in the meantime an effort will be made to locate a complete set of data for use in future comparisons. Ideally, comparisons should be made between techniques on a variety of cities with different network configurations and located in different parts of the United States.

The second question concerned the methods to be used for the analysis of the output of the research traffic assignment program. The problem is complex in the sense that the amounts of data involved are very large. The problem, therefore, is to summarize the large quantity of results obtained from several assignments so that the performance of a particular technique can be interpreted conveniently, without suppressing too much of the detail relevant to the comparisons. This problem was considered in formulating the research assignment program and is the reason behind much of the output obtained. There are five different sets of data available from the program output.

1. Link Usage Data. At the beginning of a run the user may specify any number of links so that each time one of the links is assigned traffic, the origin and destination and the number of trips is recorded. These link usage requests may be arranged so that detailed information is available about the vehicles assigned to certain key facilities such as tunnels and bridges, or a particular route such as a circumferential belt, or for the analysis of a particular screenline. The exact location of links referred to by link usage requests would depend on the individual network being used.

2. Trip Length and Trip Time Data. For each iteration of the program the user may obtain, on an optional basis, the trip length (mi), the trip time (min), and the number of trips assigned. This information can be used to construct a distribution of trip lengths and a distribution of trip times for vehicles assigned to the network. It will also be useful in comparing the performance of different techniques.

3. Minimum Path Data. The user can specify the output of minimum path data, between specified origins and destinations, during the execution of the program. These data can be used to obtain an indication of the number of different paths being used between specified origin and destinations.

4. Intermediate Network Data. The user may specify certain intervals during the execution of the program when the current status of the network will be output, in terms of link times, link volumes, the volumes assigned and the input volume between each zone pair. The intermediate network data can be used to study the manner in which the system is loaded by various techniques, and also may be used to obtain additional minimum path data.

5. Final Output Data. The final output data include the link times and link volumes, the volume assigned between each zone pair and the input volume between each zone pair. These data can be used to compute the following quantities: (a) total system vehicle-miles of travel; (b) total system vehicle-hours of travel; (c) vehicle-miles of travel by type of route, expressway, etc.; (d) vehicle-hours of travel by type of route; and (e) detailed analysis of the volumes assigned to a few selected routes. When field data are available, the total assignment can be compared with the real network flows and statistical measures can be developed indicating the variation.

It is anticipated that the preceding analysis would form the basis from which to make deductions about the characteristics of each technique and would provide some information of a comparative nature. Undoubtedly, as the comparisons are made and results are obtained, other forms of analysis may suggest themselves or be brought to our attention.

RESULTS WITH RESEARCH PROGRAM TO DATE

The principal effort so far has been the preparation of the research traffic assignment computer program. After several preliminary versions, the final program form is ready for the first series of comparisons. The results given here were obtained during the preparation of the program and the testing of earlier versions. They are included to give an indication of what might be expected from future use of the program, but since they are provisional in nature, no attempt will be made to describe them in detail.

The first set of results is based on tests made with a small network, using the incremental traffic assignment technique. Assignments were made using increments of 50, 100, 150, 200, 250, 300, 350, 400, 500, 600, 900 and 1,800 veh/hr. The increment of 1,800 veh/hr corresponds to a 100 percent increment in the problem used. The resulting total system vehicle-hours of travel for each assignment are shown in Figure 4. Table 2 gives the number of paths used between four zone pairs for each increment used.

The second test was made on a provisional form of the network to be used in the first series of comparisons, consisting of 1,000 links and 250 nodes, with 60 loading

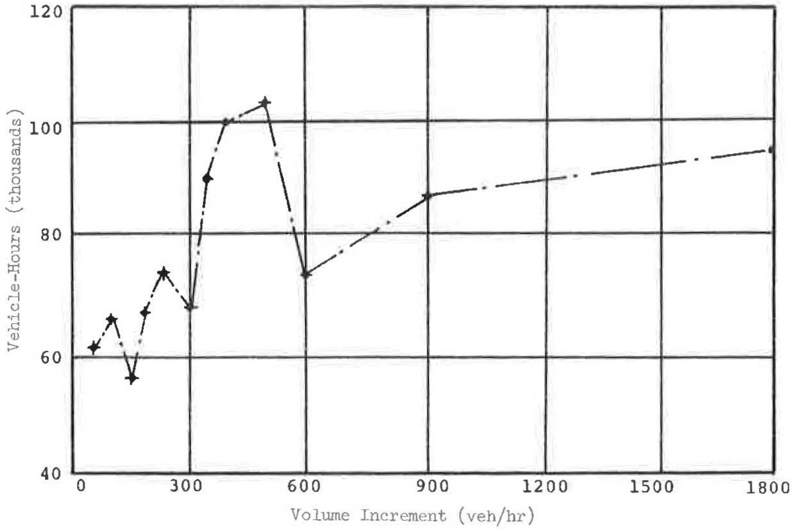

Figure 4. Total system vehicle-hours of travel as function of volume increment.

Number of Iterations	Travel Time For Different Paths in Minutes			
	1	2	3	4
0	12.01	13.08	13.55	14.73
373	13.58	14.14	14.34	15.77
693	16.79	15.00	15.33	16.66
994	18.98	17.16	15.99	17.54
1314	23.31	20.53	19.73	19.23
1603	31.43	24.67	35.78	23.68

Entry underlined indicates minimum

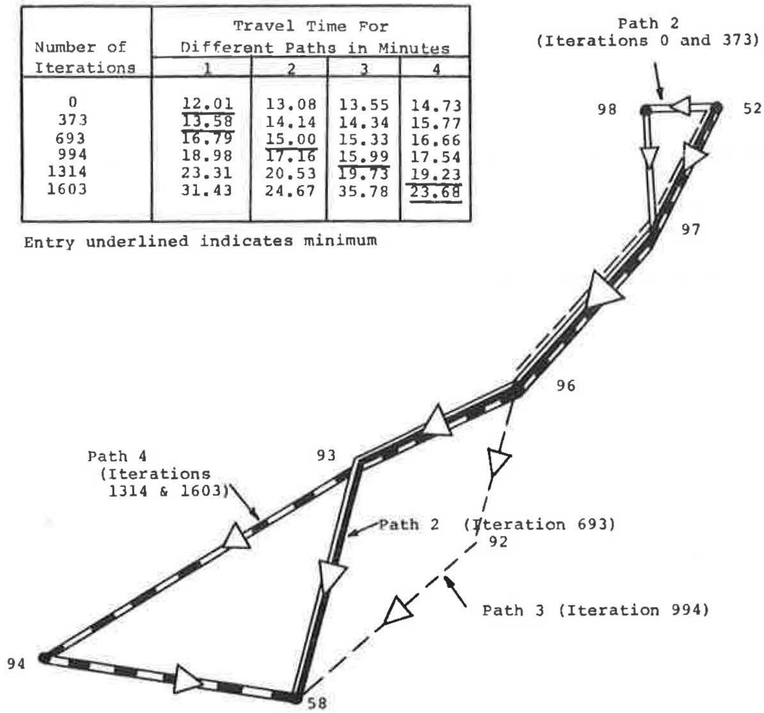

Figure 5. Variation in paths used between Zones 52 and 58.

TABLE 2

NUMBER OF DIFFERENT PATHS USED BETWEEN ZONE PAIRS IN TEST PROBLEM

Volume Increment	No. of Paths			
	Zone Pair 1	Zone Pair 2	Zone Pair 3	Zone Pair 4
50	4	3	5	2
100	3	4	4	2
150	4	2	2	1
200	4	3	4	2
250	3	2	4	1
300	4	2	3	1
350	2	2	2	1
400	3	2	3	2
500	4	4	5	1
600	2	1	2	1
900	2	1	2	2
1,800	1	1	1	1

TABLE 3

PERCENTAGE OF VEHICLE-HOURS AND VEHICLE-MILES OF TRAVEL ON DIFFERENT TYPE OF FACILITIES

Iteration No.	Expressways		Parkways		Arterials and Local Streets	
	Veh-Hr (%)	Veh-Mi (%)	Veh-Hr (%)	Veh-Mi (%)	Veh-Hr (%)	Veh-Mi (%)
373	43	62	5	5	52	33
693	35	58	4	4	61	38
994	26	56	3	4	71	40
1,314	23	54	4	5	73	41
1,603	27	52	4	5	69	43

points. The incremental assignment technique was used with an increment of 200 veh/hr. Figures 5 and 6 show the variation in travel time over several routes used between two zone pairs. The routes themselves are illustrated, but the remainder of the network is not shown. The intermediate output was analyzed and a summary of the results is given in Table 3, where the percentage of travel occurring on three types of facilities, at various points during the assignment, is indicated. (Note that the total system vehicle-miles and hours of travel increases with increasing iterations.)

Now that the program has been developed to an operational stage, we will begin the experimental program. Our purpose in presenting the paper at this time is to keep practicing engineers and other researchers aware of our work, so that we might benefit from their suggestions and opinions. Inquiries relating to the use of this computer program for research by others will be considered.

Number of Iterations	Travel Time For Different Paths in Minutes		
	1	2	3
0	8.31	8.63	13.29
373	9.00	9.15	14.37
693	10.73	9.74	15.07
994	14.48	11.54	15.60
1314	19.68	14.43	15.97
1603	25.02	23.43	20.26

Entry underlined indicates minimum

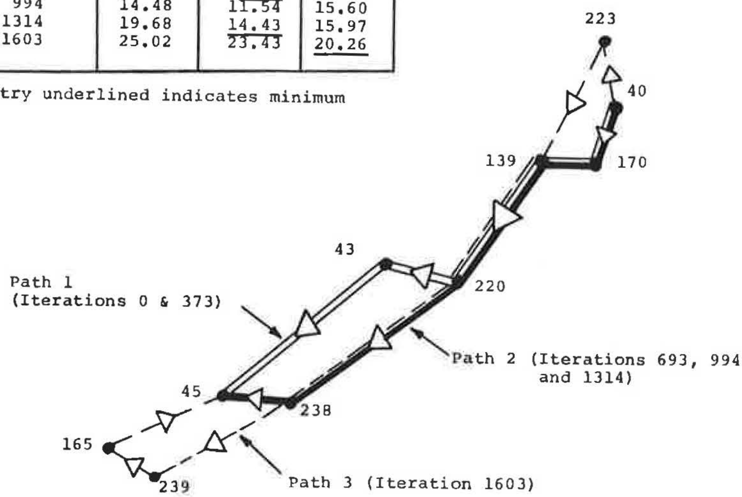

Figure 6. Variation in paths used between Zones 40 and 45.

ACKNOWLEDGEMENTS

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Gravity Model Theory Applied to a Small City Using a Small Sample of Origin-Destination Data

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The research was concerned with the use of the gravity model in a small city (Hutchinson, Kansas; 37,000 population) and was conducted to study the feasibility of using a small clustered sample of O-D interviews to estimate the gravity model parameters, trip production, trip attraction, and travel time factors. The model was calibrated using the estimations of trip productions and attractions and was compared to the trip distribution obtained from a complete O-D survey. In addition, a gravity model was calibrated using O-D productions and attractions and the resulting distribution was also used in the comparison of results.

The information utilized was obtained from interviews from 402 dwelling units in 14 selected zones; the complete O-D survey was made up of 2,528 interviews obtained from a 20 percent sample of dwelling units from the 83 zones in the survey area. The study was limited to consideration of auto-driver trips which were internal in nature. Three trip purposes—home-work, home-other, and non-home based—were studied in detail.

The study was concerned with present-day traffic rather than with the estimation of future traffic and although the research was not specifically aimed at future estimation, the data used in the development of estimating equations for attractions and productions were those which could be expected to be quickly and economically obtainable and to estimate reasonably well for the future.

The method of using the clustered sample (reduced sample size in the 14 zones) enables adequate estimation of existing zonal trip productions. The estimates of attractions and non-home productions, although not as good as the estimates of home-based trip production, appear to be adequate for use in the planning process. On the basis of experience in Hutchinson, it should be possible to develop for smaller cities excellent estimating equations for both trip productions and attractions using the data from a complete O-D interview study. The travel time factors were satisfactorily estimated using data from the clustered sample study. Analysis of the results of the gravity model distribution, using productions, attractions, and travel time factors based on the clustered sample, indicates that the existing trip distribution as measured by the complete O-D survey data can be adequately reproduced.

•SINCE the end of World War II, the growth of urban areas and the increase in automobile ownership have created new and involved transportation problems. A large number of transportation studies have been made in the last ten years to make available factual data which would describe existing problems and serve as a basis for estimating future problems. These studies have resulted in general agreement that urban traffic patterns are a function of (a) the type and extent of the transportation

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facilities available in the area; (b) the pattern of land use in an area, including the location and intensity of use; and (c) the various social and economic characteristics of the people who make trips (1). A significant effort has been made to develop a transportation planning process which uses these interrelationships to provide quantitative information on the travel demands created by alternate land-use patterns and transportation systems in any urban area. This information can be used by various agencies to make decisions concerning improvements in transportation networks to satisfy present and future travel demands and to promote desirable land development patterns.

The planning process must be capable of estimating, within limits of acceptable accuracy, the zonal trip interchanges for the alternate land-use patterns and transportation systems which might reasonably be expected to develop in an area. The information obtained from home interview origin-destination surveys coupled with information on the existing land-use configuration and transportation system gives an adequate picture of the existing travel patterns in an area. However, it is the future travel demands with which we are most interested and the present-day data must in some way be extrapolated to the future.

Studies of travel habits have led to the development of mathematical formulas or "traffic models" which can satisfactorily reproduce zonal trip interchange estimates from comprehensive home interview traffic studies. If present-day zonal interchanges can be estimated within acceptable limits of accuracy and these interchanges are dependent on measurable characteristics of the urban area, it follows, that if it is possible to estimate future urban characteristics (intensity and type of land use, the distribution of job opportunities, and the economic status of the residents), it should be possible to estimate future zonal interchanges. This is subject, of course, to the possibility that, for a given set of identical circumstances for the present and the future, higher or lower trip generation rates may result because of a change in the amount of travel per vehicle. Several formulations of traffic models have been developed for the estimation of future interchanges, particularly in large metropolitan areas, but much additional research is needed to evaluate and verify the various models in cities of all sizes.

The mathematical traffic model offers estimates of likely consequences in terms of traffic patterns for various alternative land-use configurations and transportation systems. There are a number of different traffic models currently being used in transportation studies but the most widely used model to date is the so-called gravity model. This model is based on the adaptation to the movements of human beings of Newton's law of gravity, which states that the gravitational force exerted between two bodies in space is in direct proportion to the masses of the two bodies and inversely proportional to the square of the distance between them. To apply the gravity model theory to a given city, it generally is considered necessary to conduct, as a minimum, a comprehensive origin-destination (O-D) survey and to calibrate or adjust the model to reproduce, at an acceptable level, the trip distributions found in the O-D survey. The model is then used to distribute trips with various configurations of land use and transportation alternatives that would logically be expected to develop in the future.

PURPOSE AND SCOPE

This research was concerned with the use of the gravity model in a small city and was conducted to study the feasibility of using a small sample of home interviews taken in selected O-D zones to estimate the gravity model parameters of trip production, trip attraction and travel time factors. One gravity model was calibrated using the estimations of trip productions and attractions obtained from the small sample and another was calibrated using those obtained from the comprehensive home interview O-D survey. The resulting distributions were compared.

In the sample study, information obtained from interviews from 402 dwelling units in 14 zones was used. The comprehensive O-D study consisted of 2,528 interviews obtained from a 20 percent sample of dwelling units from all 83 zones in the survey area.

The study was limited to the consideration of auto-driver trips which had both origin and destination within the survey area shown in Figure 1. The auto-driver trips

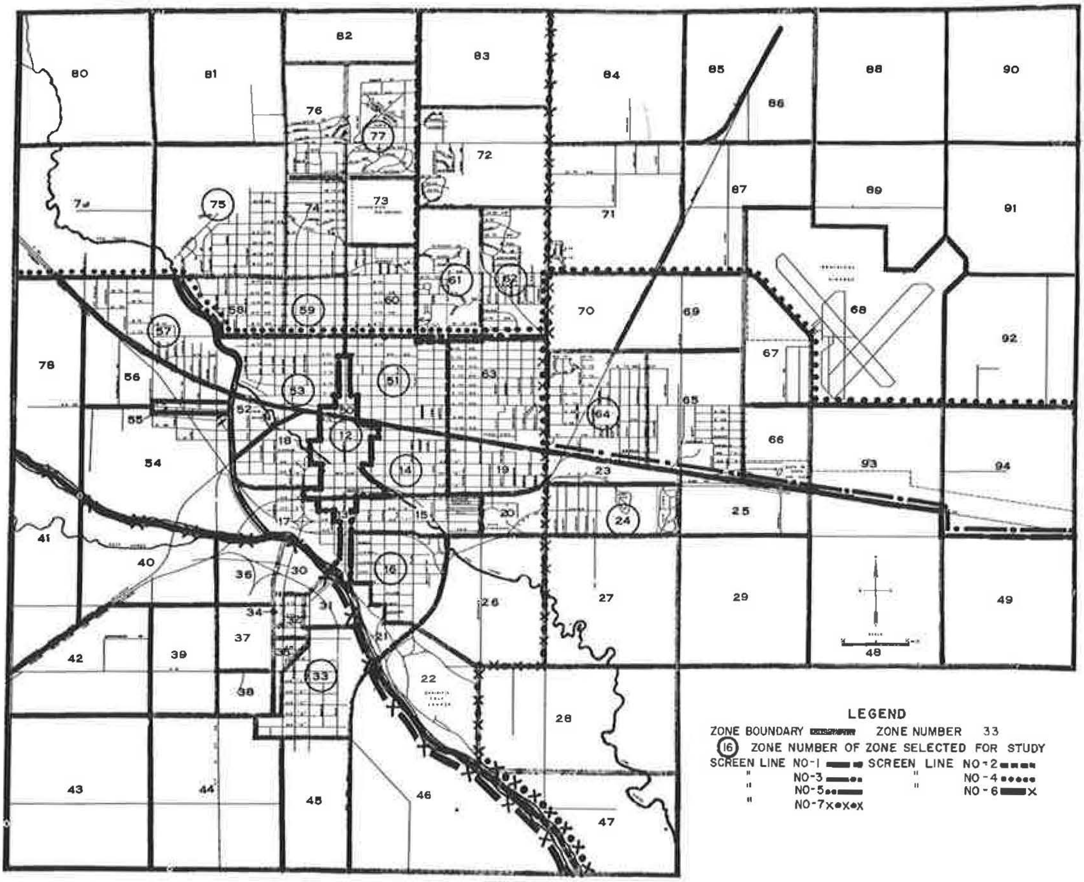


Figure 1. Hutchinson, Kans., metropolitan area zone map showing screenlines and selected zones for study.

were classified according to trip purpose, three of which (home-work, home-other, and non-home-based) were studied in detail.

The study was concerned with present-day traffic rather than with the estimation of future traffic. However, the data used in the development of estimating equations for attractions and productions could be obtained quickly and economically and could be expected to estimate reasonably well for the future.

GRAVITY MODEL THEORY AND USE

The gravity model theory as proposed by Voorhees (2) stated that the trip interchange between zones is directly proportional to the relative attraction for trips of each of the zones and inversely proportional to some function of the spatial separation between zones.

Stated mathematically, the gravity model formulation as used in its earlier applications is as follows:

$$T_{i-j} = P_i \frac{\dfrac{A_j}{\left(d_{i-j}\right)^b}}{\dfrac{A_i}{\left(d_{i-i}\right)^b} + \dfrac{A_j}{\left(d_{i-j}\right)^b} + \dots \dfrac{A_n}{\left(d_{i-n}\right)^b}} \tag{1}$$

where

T_{i-j} = trips produced by zone i and attracted to zone j;

P_i = trips produced by zone i;

A_j = trips attracted by zone j;

d_{i-j} = spatial separation between zones i and j, generally expressed as total travel time between zones i and j; and

b = an empirically determined exponent expressing average areawide effect of spatial separation between zones on amount of trip interchange.

Early research by Voorhees and others indicated that the exponent, b, varied between 0.6 and 0.8 for work trips in areas of different population size (3).

In response to studies indicating a need for a variable exponent and other refinements, the form of the gravity model formula was changed to the following in which the distribution is generally handled on a basis of various trip purposes:

$$T_{i-j} = \frac{P_i A_j F_{i-j} K_{i-j}}{\sum_{x=1}^{n} A_x F_{i-x} K_{i-x}} \qquad (2)$$

where

T_{i-j} = trips produced in zone i and attracted to zone j;

P_i = trips produced by zone i;

A_j = trips attracted by zone j;

F_{i-j} = an empirically derived travel time factor expressing average area wide effect of spatial separation on trip interchange between zones (The measure of distance or spatial separation between zones is usually the total travel time between the centroids of zones i and j. The use of this factor to express the effect of distance between zones on the zonal trip interchange, rather than the previously used inverse exponential function of time, greatly simplifies the computational requirements of the model and provides for the consideration that the effect of spatial separation generally increases as the separation increases, particularly for some trip purposes);

K_{i-j} = a specific zone-to-zone adjustment factor to allow for incorporation of effect on travel patterns of defined social or economic linkages not otherwise accounted for in gravity model formulation; and

n = total number of zones.

In dealing with the gravity model, confusion often exists among the terms productions, attractions, origins, and destinations. With the exception of trips classified as non-home-based, the number of trips produced refers to the number of trips originating in and returning to a given zone; the number of trips attracted refers to the number of trips arriving at and departing from a given zone. For non-home-based trips, origins and destinations are, respectively, productions and attractions. The gravity model, in the determination of T_{i-j}, deals with trip interchange between zones with no reference to the direction of movement. The trip interchange between zones is often referred to as non-directional or two-way, as opposed to directional trips or trips which start in zone i and end in zone j. Some models use the one-way trip and deal with origins and destinations. Figure 2 is a schematic diagram of the process of determining zonal trip productions and attractions.

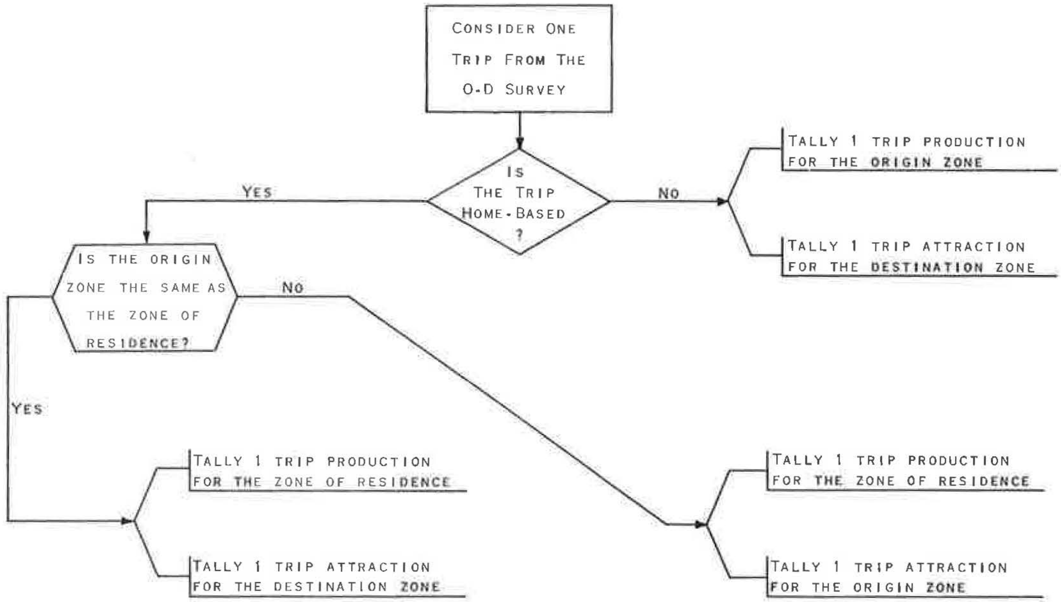


Figure 2. Schematic diagram of process of determining zonal trip productions and attractions.

STUDY PROCEDURE

To carry out the objectives of the research, the metropolitan area of Hutchinson, Kansas, was chosen for the study. In 1961, the city had a population of 37, 873 and the metropolitan area a population of approximately 41, 000 persons. At the initiation of this project this was the only smaller city in Kansas in which both an internal origin-destination survey as well as a land-use study had been made. Origin-destination and some land-use data were available for Topeka, Wichita and Kansas City, Kansas, but these were the three largest metropolitan areas in Kansas and were not typical in size of smaller Kansas cities. Table 1 indicates all cities in Kansas with a population over 10, 000. There were 24 cities outside of metropolitan areas with a population between 10, 000 and 50, 000 and only 3 cities with a population over 50, 000. It was believed that the results of the study, if aimed at these smaller cities, would be of greatest value in Kansas since they so outnumber the larger metropolitan areas.

In 1959, the Kansas State Highway Planning Department, in cooperation with the U. S. Bureau of Public Roads and the City of Hutchinson, conducted a comprehensive home interview O-D survey and a complete land-use study in the Hutchinson metropolitan area. The O-D survey was conducted in accordance with standard procedures prescribed by the Bureau. The internal survey was made by the home interview method in which a 1 in 5 (20 percent) dwelling unit sample was taken. The data gathered in the internal O-D survey and the land-use study were used in this research.

Among the data collected for each surveyed dwelling unit in the internal O-D survey were number of persons, number of employed persons, number of cars owned, age groups, number of vehicular trips, trip purposes at origins and destinations, and mode of travel for each trip. The land-use study recorded the following major groupings of land use by zone in 1, 000's of square feet: residential; manufacturing; retail trade; wholesale and warehouse; transportation; construction; personal, business, repair services and office; government and utility; other open space (streets, alleys, rivers, and lakes); and recreation and institution. The land-use categories recorded within each major grouping were as given previously (10, Appendix C).

The IBM 1620 computer and various allied tabulating equipment were extensively used in this study. A list of computer programs written for and used in this research

TABLE 1

CITIES OF KANSAS HAVING POPULATION OVER 10,000[a]

City	Population
Wichita	247,557
Kansas City[b]	126,236
Topeka	120,799
Salina	43,090
Overland Park[b]	40,796
Hutchinson	37,873
Prairie Village[b]	26,873
Lawrence	26,132
Leavenworth	23,707
Manhattan	21,410
Junction City	20,944
Pittsburg	18,737
Great Bend	17,885
Coffeyville	17,030
Emporia	16,763
Liberal	14,806
Newton	14,704
Arkansas City	14,696
Dodge City	13,303
Parsons	13,014
El Dorado	12,614
Garden City	12,575
Hays	12,301
Atchison	12,126
Independence	11,387
Shawnee[b]	11,387
Ottawa	11,237
Olathe	10,776
Chanute	10,666
Winfield	10,522

[a]Populations as of Jan. 1, 1962; reported by county assessors and compiled by Kansas State Board of Agriculture.
[b]Included within Kansas City, Kansas, metropolitan area.

was published previously (10, Appendix B). A write-up of each such program developed can be obtained from the Kansas Highway Commission.

Preparation of O-D Survey Data

The information obtained from the internal O-D survey (hereafter referred to as the O-D data or O-D survey data) was, for the most part, transferred to tabulating machine punch cards and was available to the researcher from the beginning of the project. The cards were of two general types. Card 1, the dwelling unit card (only one card 1 existed per sampled dwelling), contained information on the zone in which the dwelling unit was located, the number of persons living in the dwelling unit, the number of cars owned by these persons, and information on the number of trips made on the day (the trip day) before the interview. Card 2, referred to as the trip card, contained information on the location zone of the home (or dwelling unit), the zone of origin and the zone of destination of the trip, the land-use category at both destination and origin of the trip, mode of travel, the number of persons in the car, and the purpose of travel of each end of the trip. There was a card 2 for each trip recorded at a sampled dwelling unit.

Classification of Trips by Purpose.— In most model studies the trips have been studied by grouping them into a number of trip purposes. After an examination of the O-D survey data, it was initially decided that the five trip purpose groupings (home-work, home-social-recreation, home-shopping, home-miscellaneous, and non-home) would be studied instead of the O-D survey trip purpose categories (work, business, medical-dental, school, social-recreation, change travel mode, eat meal, shopping, home, and serve passenger). Eventually it was found more satsifactory to use only three trip purpose categories, however, because of the small numbers involved.

In an origin-destination survey, one trip ends and another begins every time a person changes his mode of travel, a driver stops to serve a passenger, or a trip maker reaches a destination. In the first two cases, if each of these trips were analyzed separately, the relationships among the actual starting point, the destination and the purpose of the trip would be lost. It would also be difficult to relate the type and intensity of trip making to the type and intensity of land use. Consequently, it is desirable to combine or link those trips which have a change travel mode or serve passenger purpose in order to preserve the relationship between the purpose of the trip and the destination of the trip.

Trip linking may not be necessary in all cases. In many small cities where change travel mode trips may be small in number because of lack of transit facilities and where serve passenger trips may also be small in number because of the absence of car pools, trip linking may be unnecessary (1). However, in studying the Hutchinson data it was found that although change travel mode trips were negligible, the serve passenger trips made up approximately 23 percent of all auto driver trips. Consequently, it was considered necessary to link those trips. In this case, it was judged more expedient to link by hand than to prepare a computer program for the process, although trip linking in a large metropolitan survey area would, no doubt, be most efficiently carried out by the use of a high-speed computer. The U. S. Bureau of Public Roads, in fact, has a trip linking program for use on the IBM 1401.

In the linking process for Hutchinson about 2,400 trips were lost. That is, there were 2,400 trips that made up a part of a journey but were not meaningful to the major trip purpose. With the serve passenger trips linked or converted into meaningful purposes, the original ten trip purposes were combined into five categories.

Because of the numbers of trips involved and the differences in treatment of trip productions and attractions, two general classifications of trips are usually made: (a) the trips in which one end is the home (home-based trips), and (b) the trips in which neither end is the home (non-home-based trips). Data in Tables 2 and 3 indicate that the major purposes of home-based trips were work, shopping, and social-recreation.

Using these three categories and combining all other home-based trips into one category and all non-home-based trips into another resulted in the trip purpose groups with percentages of trips in each group as shown in Table 4. During the processes of developing estimating equations for trip productions and attractions and calibrating model by purpose, the relatively small numbers of trips in the home-based social-recreation, shopping and miscellaneous trips appeared to be responsible for much of the variability of results. Therefore, the trip purpose groups were further combined into home-work, home-other, and non-home trips as shown in Table 4. The discussions throughout the remainder of this report relate to these three groups.

Additional Data Obtained.—The number of employed persons per dwelling unit was determined from the home interview sheets and was placed in each dwelling unit card.

TABLE 2

AUTO-DRIVER TRIPS BY RESIDENTS OF INTERNAL AREA, SHOWING O-D SURVEY RECORDED PURPOSE OF TRIP

From \ To		(1) Work	(2) Business	(3) Medical-Dental	(4) School	(5) Social Recreation	(6) Change Travel Mode	(7) Eat Meal	(8) Shopping	(0) Home	Total
Work	(1)	2,497	615	51	128	593	21	2,609	802	8,788	16,104
Business	(2)	656	903	31	51	394	5	57	742	1,861	4,700
Medical-Dental	(3)	31	31	5	5	52	-	10	127	295	556
School	(4)	432	77	20	167	233	-	259	148	1,879	3,215
Social Recreation	(5)	422	252	26	66	1,505	16	103	736	5,678	8,804
Change Travel Mode	(6)	31	10	5	-	21	-	5	31	97	200
Eat Meal	(7)	2,446	73	15	217	140	-	5	107	352	3,355
Shopping	(8)	328	468	31	98	640	10	114	1,685	5,813	9,187
Home	(0)	9,395	2,226	387	2,523	5,332	128	339	4,786	5	25,121
Total		16,238	4,655	571	3,255	8,910	180	3,501	9,164	24,768	71,242

TABLE 3

PERCENT AUTO-DRIVER TRIPS BY RESIDENTS OF INTERNAL AREA, SHOWING O-D SURVEY RECORDED PURPOSE OF TRIP

From \ To	(1) Work	(2) Business	(3) Medical-Dental	(4) School	(5) Social Recreation	(6) Change Travel Mode	(7) Eat Meal	(8) Shopping	(0) Home	Total
Work (1)	3.51	0.86	0.07	0.18	0.83	0.03	3.66	1.13	12.34	22.61
Business (2)	0.92	1.27	0.04	0.07	0.55	0.01	0.08	1.04	2.61	6.59
Medical-Dental (3)	0.04	0.04	0.01	0.01	0.07	0	0.01	0.18	0.41	0.77
School (4)	0.61	0.11	0.03	0.23	0.33	0	0.36	0.21	2.64	4.52
Social Recreation (5)	0.59	0.35	0.04	0.10	2.11	0.02	0.14	1.03	7.97	12.35
Change Travel Mode (6)	0.04	0.01	0.01	0	0.03	0	0.01	0.04	0.14	0.28
Eat Meal (7)	3.43	0.10	0.02	0.30	0.20	0	0.01	0.15	0.49	4.70
Shopping (8)	0.46	0.66	0.04	0.14	0.90	0.01	0.16	2.37	8.16	12.90
Home (0)	13.19	3.12	0.54	3.54	7.48	0.18	0.48	6.72	0.01	35.26
Total	22.79	6.52	0.80	4.57	12.50	0.25	4.91	12.87	34.77	

Persons classified as non-gainfully employed workers (including housewives and other unpaid home-workers, retired workers, persons permanently incapacitated for any gainful employment, and students) were not included in the employed persons totals. Also placed in each dwelling unit card was the net area of residential land use per dwelling unit. This was determined by dividing the area of residential land in a given zone less the vacant land zoned residential by the number of dwelling units in the zone. The area was recorded in 1,000's of square feet per dwelling unit.

The driving time from the centroid of each zone to the central business district (CBD) was determined to the nearest 0.1 min from the minimum driving time paths developed from a travel time study in Hutchinson.

Before the development of estimating equations for work trip attractions, it was decided, as was found in an Iowa study (4), that the number of jobs in a zone would be expected to be a potent indicator of home-work trip attractions. Information on various categories of employment in each zone was therefore collected. An attempt was made to determine the employment in the various zones as it existed at the time the O-D survey was made, but only major changes in employment could be determined. However, a very good correlation of total number of jobs in the survey area with the 1960 Census data was obtained.

The employment study was made in the Hutchinson office of the Kansas State Employment Service. The excellent cooperation of the employment service personnel enabled completion of the survey within 3 days with two persons collecting most of the data. The number of self-employed persons and the number of employees in each of the following types of business and industry were tabulated by zone: agricul-

TABLE 4

DISTRIBUTION OF AUTO DRIVER TRIPS BY PURPOSE OF TRIP

Purpose	Initial Category No.	Initial Category %	Final Category No.	Final Category %
Home-work	18,183	25.53	18,183	25.53
Home-social-recreation	11,010	15.45	-	-
Home-shopping	10,599	14.88	-	-
Home-miscellaneous[a]	10,092	14.16	-	-
Home-other[b]	-	-	31,701	44.49
Non-home	21,358	29.98	21,358	29.98
Total	71,242	100.00	71,242	100.00

[a]Includes business, medical-dental, school, change travel mode and eat meal.
[b]Includes social-recreation, shopping and miscellaneous.

ture and forestry; mining; construction; manufacturing and processing; transportation, communications and public utilities; wholesale, retail, finance and insurance; personal services; amusement and recreation; professional; and government.

Selection of Zones for Reduced Sample Study

Zones were selected for the reduced sample survey to reflect a range in zonal characteristics such as residential density, car ownership rate, population density, distance from CBD and distance to the nearest large employment center. An investigation of the Hutchinson data showed that the principal CBD zone, 12, was, in fact, the large employment center in the city. A zonal map (Fig. 1) was used in selecting the zones. The number of dwelling units, cars owned by residents of the zone, total number of persons residing in the zone, cars per dwelling unit, and persons per dwelling unit were noted on a zone map for each zone having any significant number of dwelling units.

The selection of zones was further based on opinions of those familiar with the nature of residential areas in Hutchinson so that zones of varying economic status or value of residence would be chosen. After consultation with statisticians it was decided that a minimum of 14 zones would be required if an estimating equation with as many as seven terms were to be used. Data from 14 zones, giving 14 pieces of information, were judged to give a satisfactory statistical estimate of the predictive power of the estimating equation. A minimum of seven degrees of freedom was judged to be required. Zones 12, 14, 16, 24, 33, 51, 53, 57, 59, 61, 62, 64, 75, and 77 were chosen for the study.

Development of Equations for Estimating Zonal Productions

Early attempts were made to develop estimating equations based on groups of samples within each of seven initially selected zones. It was hoped that interviews obtained in a single zone could be grouped into small subsamples that would give good estimates of the productions and attractions of that particular zone.

Information concerning the assessed evaluation per dwelling unit in zone 75 (Fig. 1) was obtained in a two-day study of the city records in Hutchinson. The evaluation data were tested for value as an economic indicator in the production of trips. The results were inconclusive since the trip production based on the subsamples showed great variability. Examination of the evaluation study indicated that such a study for each zone in the area would probably not produce data of significant aid in the estimation of zonal trip productions and attractions.

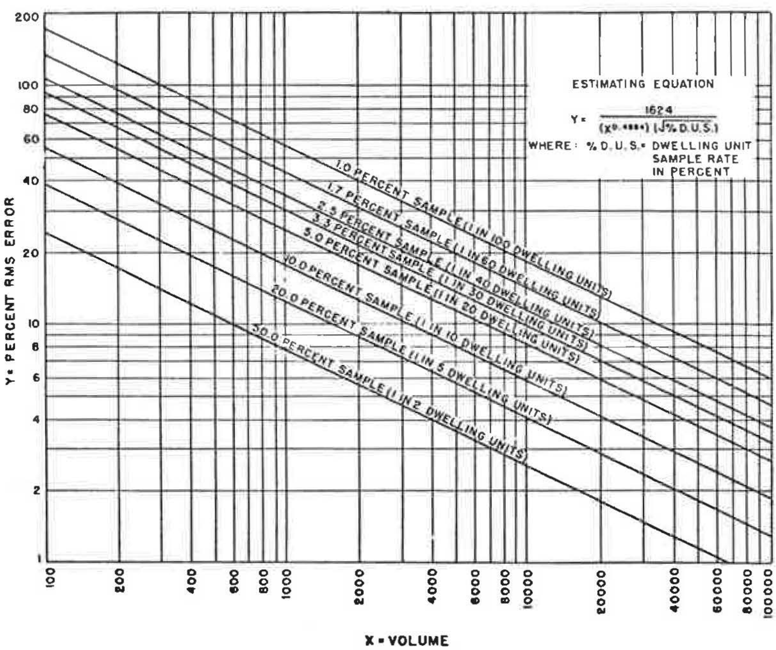
It was also believed that the number of employed persons per dwelling unit might be a better indicator of work trip production than persons per dwelling unit. To test this hypothesis, four sets of regression equations were developed using, among the variables, either persons per dwelling unit or employed persons per dwelling unit. The data used were from the comprehensive survey of the 22 zones containing more than 125 dwelling units. There was less than one percent difference between the value of R^2, the coefficient of determination, for each pair of equations. It was concluded, therefore, that employed persons per dwelling unit was no better indicator of work trip production than persons per dwelling unit.

Due to the great variability among subsamples as well as the problems anticipated in gathering data on zonal characteristics in such small areas, the estimation of productions was carried out using zonal averages of such information as cars and persons per dwelling unit, area of residential land per dwelling unit and distance to the CBD in minutes. The development of the estimating equations was carried out using the multiple regression technique in which the form of an equation is estimated and the coefficient of each term is obtained from the least squares best fitting curve. The measure of fit was obtained as an output of the computer program used (7). The SCRAP "Sixteen-twenty Card Regression Analysis Progam" used in this research is one of a number of such programs available in most computing centers.

Two sets of estimating equations of trip production were developed. One was based on zonal characteristics obtained from each of 22 zones as a result of sampling 20 percent of the dwelling units in each zone. The 22 zones were those in which over 25 dwelling units were sampled. In essence, the 22 zones represented the universe of zones of substantial size. The second set of equations was based on zonal characteristics obtained from each of the previously mentioned 14 selected zones. However, in this case, a sampling rate was established for each zone.

To estimate the total number of non-home-based trip productions, non-home-based trips were treated precisely as home-based trips. These productions represented only the number of non-home trips made by the residents of each zone and did not distribute the trips according to location of trip end. A regression analysis, similar to that used for home-based productions, was made on these trips with the resulting equation, as expanded to the entire area, giving the total number of non-home trip productions or attractions. This number was later used in expanding the non-home-based productions to this estimated total.

Selection of Reduced Samples.—The selection of the reduced sample size in the 14 zones was made in accordance with research conducted by Sosslau and Brokke (8). To use Figure 3, it is necessary to estimate the number of trips per zone and to find an acceptable root-mean-square (RMS) error before selecting the appropriate rate of sampling. A level of accuracy yielding an expected RMS error of zonal trip production of 15 percent or less was acceptable in this case. The estimation of trips produced per zone was made and the citywide average was found to be about five auto-driver trips per dwelling unit. Where an estimate of this average is not available for a city, studies



$$\text{Dwelling unit sample rate in percent} = \left[\frac{1{,}624}{\left(\text{percent RMS error}\right)\left(\text{volume}^{0.4884}\right)}\right]^2$$

Figure 3. Relation of percent root-mean-square error and volume for various dwelling unit sample rates (8).

of trip-making characteristics of similar cities should suffice for this estimate.

Figure 3 was entered with X, the estimated volume of trips in a given zone, and the 15 percent RMS error line indicated the minimum percentage of dwelling units to be sampled in that zone. The subsample was drawn from the O-D sample and selected by a computer program.

The subsample in zone 12 was selected as follows:

1. Estimated trips = 5 x 270 dwelling units = 1,350.
2. Enter Figure 3 with 1,350 and intersect the horizontal 15 percent RMS error line.
3. Read 15 ± percent sample.
4. A 15 percent sample is equivalent to three-fourths of a 20 percent sample (the existing sample size).
5. The computer program was devised to select the dwelling unit and trip cards for every n th sampled dwelling unit and in this case a random selection of a number from 1 to 4 was made to indicate the starting sample and thereafter every fourth dwelling unit sample was selected. This group was discarded and the remaining three-fourths of the original 20 percent sample was taken. The original expansion factors were multiplied by the ratio of the original number of sampled dwelling units to the reduced number of sampled dwelling units and this new expansion factor was placed in the dwelling unit and trip cards for the reduced samples.

Table 5 shows the sample size selected in each of the 14 zones. There were 402 dwelling units in the reduced samples in the 14 selected zones. The comprehensive O-D survey consisted of 1,359 interviews obtained from a 20 percent sample of dwelling units in the same 14 zones.

Development of Equations for Estimating Zonal Attractions

The SCRAP regression analysis program (7) was used in developing two sets of estimating equations for trip attractions by trip purpose. One set was obtained using the attractions as distributed according to the data from the reduced sample in the 14 selected zones. The second set was obtained using data from the comprehensive O-D survey for all zones having 40 or more trips attracted for each of the three purpose groupings.

For the first set of equations, even though trips produced by only 14 zones were used, the attraction ends of the trips were distributed to many zones. For example, assume that 10,000 trips of a given purpose were produced by the 14 zones and of these 200 were attracted to zone 1, 300 to zone 4, 1,000 to zone 12, 2,000 to zone 20, 1,500 to zone 50, etc. The total of all trips attracted would be 10,000. The trips attracted

TABLE 5

REDUCED SAMPLE SELECTION IN 14 SELECTED ZONES

Zone	Estimated Auto Driver Trips per Zone[a]	% Sample Size to Obtain 15% RMS Error	Fraction of Orig. 20% Sample	No. of Interviews Selected	O-D Expansion Factor	No. of Dwelling Units, Orig. Sample	Expansion Factor, Reduced Sample[b]
12	1,350	15	3/4	35	5.32	46	6.99
14	3,760	5	1/4	32	5.21	126	20.51
16	2,160	7	1/3	25	5.11	77	15.74
24	1,350	11	1/2	24	5.11	49	10.43
33	1,490	10	1/2	29	4.98	57	9.79
51	7,360	2.5	1/8	29	5.34	233	42.90
53	4,820	3.3	1/6	27	5.18	164	31.46
57	1,570	10	1/2	26	5.19	53	10.58
59	3,010	5	1/4	26	5.29	102	20.75
61	1,785	9	1/2	29	5.03	58	10.06
62	2,060	7	1/3	25	5.05	76	15.35
64	2,870	6	1/3	35	5.13	105	15.39
65	3,490	5	1/4	30	5.21	123	21.36
77	2,470	7	1/3	30	5.16	90	15.48

[a] 5 × No. of dwelling units per zone. [b] O-D expansion factor × No. of dwelling units in original sample/No. of interviews selected.

to each zone were divided by 10,000, the total of trips produced, giving the proportion of all trips attracted to a given zone. Thus zone 1 would attract 0.02 trips per trip produced, zone 4 would attract 0.03, zone 12 would attract 0.10, zone 20 would attract 0.20, and zone 50 would attract 0.15.

Based on such zonal characteristics as various types of land use in 1,000's of square feet, numbers of jobs of various classifications and total number of persons and dwelling units in the zone, an equation was developed for each trip purpose that estimated the trip attractions in the various zones. The dependent variable was the number of trips attracted per trip produced.

A similar procedure was followed in developing equations based on the 20 percent sample obtained in the O-D survey. The estimating equation for the non-home productions was developed in the same manner as that for trip attractions.

In the case of home-work attractions, it was discovered that the best predictor of trips attracted was the total employment in a zone. Since the SCRAP program would not handle a problem with a single independent variable, the equation was developed using a computer program which fitted a polynomial to the data by the method of least squares.

The equation for trip attractions, along with non-home productions, had to be multiplied by the total number of trips produced in the study area to give total attractions per zone. Thus, zonal estimates of trip attractions (and non-home productions) were the product of two estimates and, in general, were less satisfactory than estimates of home-based productions.

Development of Travel Time Factors

The calibration of the gravity model (Eq. 2) was carried out using the three trip purposes (home-work, home-other and non-home) and consisted principally of the determination of travel time factors which resulted in a trip length frequency distribution comparing satisfactorily to that of the surveyed population. Two sets of travel time factors for each trip purpose were determined, one from zonal productions and attractions from the comprehensive O-D survey and the other from those obtained from the reduced sample size in the 14 selected zones.

The gravity model formula as used requires input parameters of zonal trip productions, attractions, travel time factors, and zone-to-zone adjustment factors. The zone-to-zone adjustment factors were used as unity throughout this study because of no apparent effect on travel patterns of defined zonal characteristics.

The travel times used for determination of the corresponding travel time factors for use in the gravity model were made up of the terminal time on each end of the trip plus the zone-to-zone driving time. The zone-to-zone minimum driving time was obtained from the "time trees" or minimum driving time paths developed from travel time study data. The driving time for intrazonal trips (those trips with both ends in a given zone) was not available from the time trees and was estimated at 1 min for each zone after inspection of interzonal times for all adjacent zones. The interzonal times of adjacent zones were, in all cases, slightly less than 2 min. The maximum intrazonal time was also about 2 min and a reasonable average time was believed to be 1 min. Other methods of determining intrazonal times have been previously discussed (1).

The terminal time of one end of a trip may be made up of the time spent in looking for a parking space, the time spent waiting before a vehicle can be parked and the time spent walking from the parking place to the actual destination. The terminal time of the other end of the trip may consist of the time spent walking from home to garage or parking lot and the driving time from garage or parking lot to the street. The initial estimates of terminal times for the zones in Hutchinson were made after consultation with personnel who were familiar with Hutchinson. The CBD, zones 12, 13 and 50 (Fig. 1), were each given terminal times of 3 min and each of the zones adjacent to the CBD was given a terminal time of 1.5 min. Some changes in these terminal times resulted in better trip end balance for some zones and some trip purposes. Table 6 shows the final sets of terminal times used in the study.

TABLE 6

FINAL TERMINAL TIMES BY ZONE AND TRIP PURPOSE

Terminal Time (min)	Trip Purpose		
	Home-Work	Home-Other	Non-Home
3.0	12, 13, 50[a]	None	12, 13, 50
2.5	14, 15, 16, 17, 18, 51, 52, 53[b]	None	14, 15, 16, 17, 18, 51, 52, 53
2.0	19, 58, 59, 60, 61, 63[c]	12, 13, 14, 15, 16, 17, 18, 19, 50, 51, 62, 53, 58, 59, 60, 61, 63	19, 58, 59, 60, 61, 63
1.5	All others[d]	All others	All others

[a]CBD zones. [b]Zones adjacent to CBD. [c]Other highly developed zones.
[d]Relatively undeveloped zones.

The interzonal travel time between any two zones was made up of the terminal time of the production zone plus the driving time between the zones plus the terminal time of the attraction zone. Intrazonal travel time for a given zone was made up of twice the zonal terminal time plus the intrazonal driving time for that zone.

A set of travel time factors using the comprehensive O-D zonal productions and attractions was developed. An initial set of travel time factors was assumed and the trip interchanges between all zones were computed. The trip length frequency distribution of the trip interchanges was determined by finding the number and the percentage of trips falling in each 1-min increment of driving time. The estimated trip length frequency was then compared to the actual trip length frequency distribution obtained from the O-D data. The comparison was made in three ways: (a) both distributions expressed as percent trips for each 1-min driving time should, when plotted, be relatively close to one another; (b) the average trip length, in minutes, for both sets of data should be within ±5 percent of each other; and (c) the person hours of travel for both sets of data should be within ±5 percent of each other (1). The average trip length was determined by multiplying the number of trips of each incremental trip length by the length of trip (driving time) in minutes and dividing this product by the total number of trips. The vehicle-hours of travel were obtained by multiplying the number of trips of each incremental trip length by the length of trip in minutes and dividing the product by 60. Computer programs were written to determine the trip length distributions as well as the average trip length and vehicle-hours of travel.

If the comparisons were not within the limits cited, an adjustment was made in the initially assumed set of travel time factors for each trip purpose. The travel time factors were adjusted manually by a procedure which follows from the question: "What must be done to the travel time factor at each travel time increment to bring the gravity model estimated percentage of trips, in each travel time increment, into closer agreement with the surveyed trips at each increment?" The actual adjustment was made for each travel time increment by multiplying the initial travel time factor for each increment by the ratio of the percentage of surveyed trips to the percentage of estimated trips for the respective time increments. The adjusted travel time factors (for each 1 min of travel time) were then plotted against the respective travel time increments on log-log graph paper in most cases and straight-line graph paper in others. The second set of travel time factors was then determined from a hand-fitted line of best fit to the adjusted factors. The gravity model was then run using the second set of travel time factors and the comparisons of trip length frequency, etc., were repeated. This process was continued until satisfactory agreement among the comparisons was reached.

In the case of home-work trips, 12 sets of adjustments were required before acceptable agreement was reached. Better estimates of initial travel time factors would have resulted in fewer iterations being required. This was graphically illustrated by home-other trips when the Iowa travel time factors (4, 9) were used for the initially estimated factors; only four iterations were required. In addition, much time was spent in adjusting to the trip length frequency curve. The Iowa travel time factors (4, 9) are shown in Table 7.

The second set of travel time factors was developed in a similar manner except that productions and attractions obtained from data from the 14 zones with the reduced sample size were used. The trip length frequency, average trip length and vehicle-hours of travel, against which comparisons were made, were those resulting from the O-D data obtained from the reduced sample size in the 14 zones. The Iowa travel time factors (4, 9) were used as the first estimate of the factors used for each trip

TABLE 7

CEDAR RAPIDS, IOWA, TRAVEL TIME FACTORS[a]

Travel Time (min)	Travel Time Factors by Purpose: Work	Non-Home Based	Other-Home Based	Travel Time (min)	Travel Time Factors by Purpose: Work	Non-Home Based	Other-Home Based
1	2.00	3.00	5.00	28	0.33	0.07	0.10
2	2.00	2.25	3.66	29	0.31	0.06	0.09
3	2.00	1.80	2.20	30	0.29	0.05	0.08
4	1.50	1.40	1.45	31	0.27	0.04	0.06
5	1.25	1.15	1.20	32	0.25	0.03	0.04
6	1.10	1.00	1.00	33	0.23	0.02	0.03
7	1.00	0.90	0.90	34	0.21	0.01	0.02
8	0.93	0.80	0.80	35	0.19	0.01	0.01
9	0.87	0.70	0.70	36	0.17	-	-
10	0.84	0.62	0.62	37	0.15	-	-
11	0.80	0.56	0.56	38	0.14	-	-
12	0.76	0.49	0.50	39	0.13	-	-
13	0.72	0.43	0.45	40	0.12	-	-
14	0.68	0.38	0.41	41	0.11	-	-
15	0.64	0.34	0.38	42	0.10	-	-
16	0.61	0.30	0.35	43	0.09	-	-
17	0.58	0.27	0.32	44	0.08	-	-
18	0.55	0.24	0.30	45	0.07	-	-
19	0.52	0.22	0.27	46	0.06	-	-
20	0.49	0.20	0.25	47	0.05	-	-
21	0.47	0.18	0.23	48	0.04	-	-
22	0.45	0.16	0.21	49	0.04	-	-
23	0.43	0.14	0.19	50	0.04	-	-
24	0.41	0.12	0.17	51	0.03	-	-
25	0.39	0.10	0.15	52	0.03	-	-
26	0.37	0.09	0.13	53	0.02	-	-
27	0.35	0.08	0.11				

[a]Source: (4, 9).

TABLE 8

TRAVEL TIME FACTORS BY TRIP PURPOSE

Travel Time (min)[a]	Travel Time Factors: Home-Work		Home-Other		Non-Home	
	F.S.[b]	R.S.[c]	F.S.[b]	R.S.[c]	F.S.[b]	R.S.[c]
4	2.78	2.12	1.74	2.70	1.40	3.00
5	2.40	1.70	1.22	1.84	1.15	2.25
6	2.20	1.41	0.94	1.23	1.00	1.80
7	1.97	1.20	0.78	0.91	0.90	1.40
8	1.78	1.06	0.65	0.68	0.80	1.15
9	1.58	0.93	0.56	0.51	0.70	1.00
10	1.43	0.84	0.49	0.41	0.62	0.90
11	1.32	0.76	0.43	0.34	0.56	0.80
12	1.20	0.70	0.39	0.28	0.49	0.70
13	1.12	0.65	0.35	0.23	0.43	0.62
14	1.04	0.60	0.32	0.19	0.38	0.56
15	0.96	0.56	0.30	0.17	0.34	0.49
16	0.90	0.53	0.28	0.14	0.30	0.43
17	0.85	0.49	0.25	0.12	0.27	0.38
18	0.80	0.46	0.23	0.11	0.24	0.34
19	0.76	0.44	0.21	0.10	0.22	0.30
20	0.72	0.43	0.20	0.09	0.20	0.27

[a]No travel time of less than 4 min was possible for any trip.
[b]F.S. - Model input: full sample O-D productions-attractions, all zones.
[c]R.S. - Model input: reduced sample O-D productions-attractions, 14 zones.

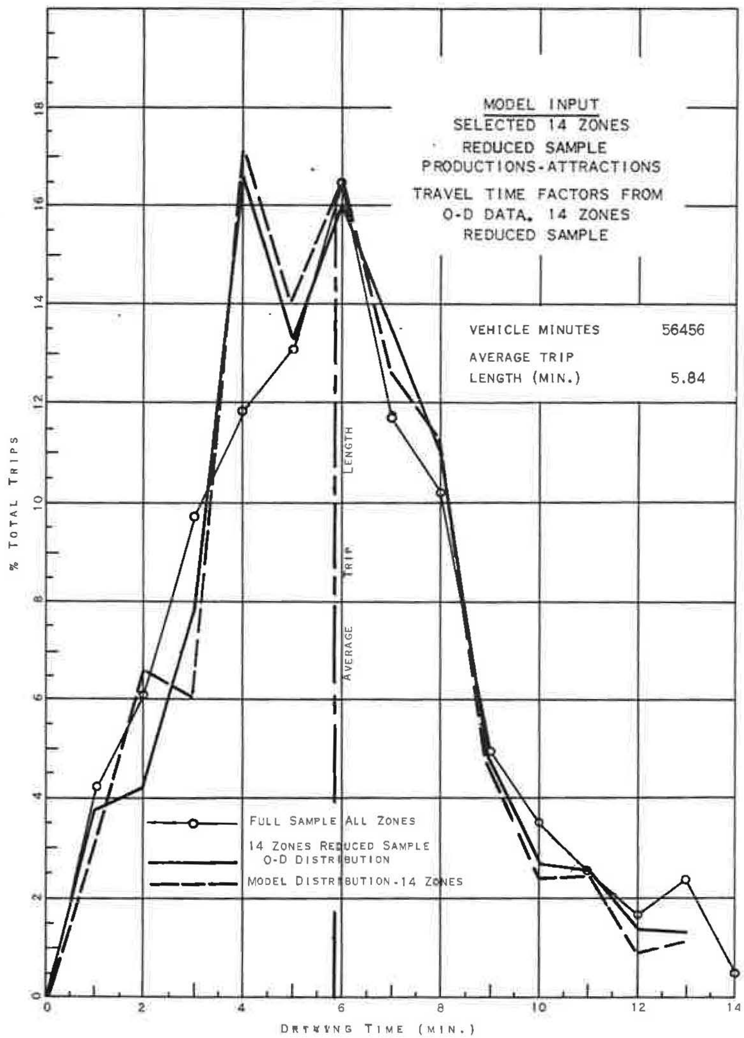


Figure 4. Comparison of trip length frequency using O-D and model data, home-work trips.

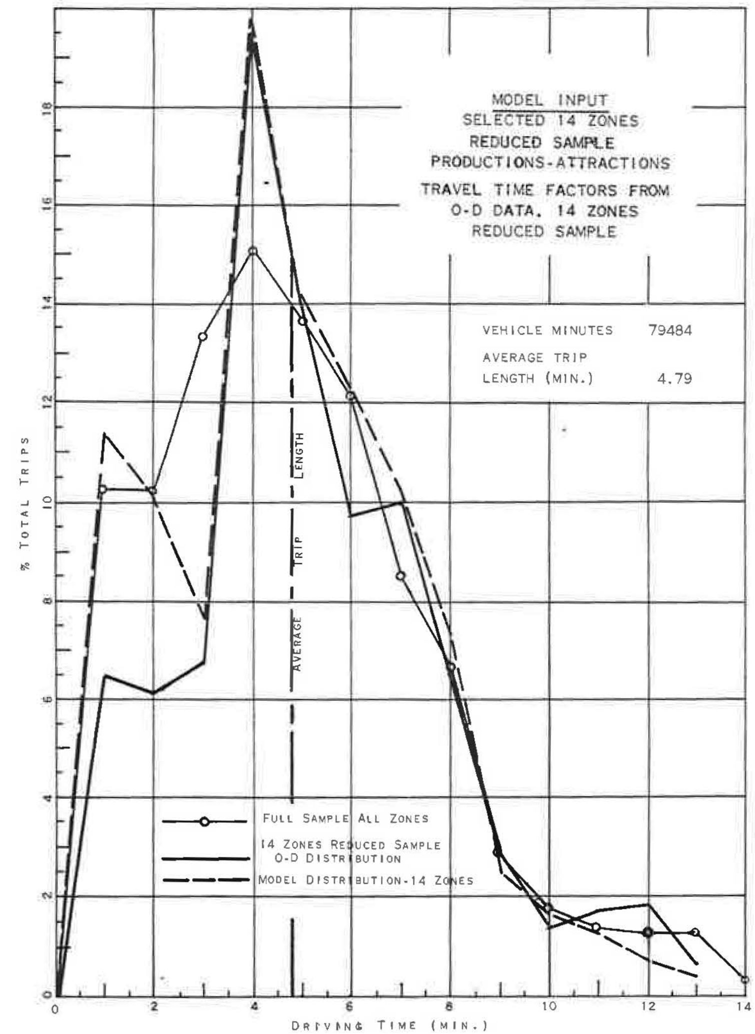


Figure 5. Comparison of trip length frequency using O-D and model data, home-other trips.

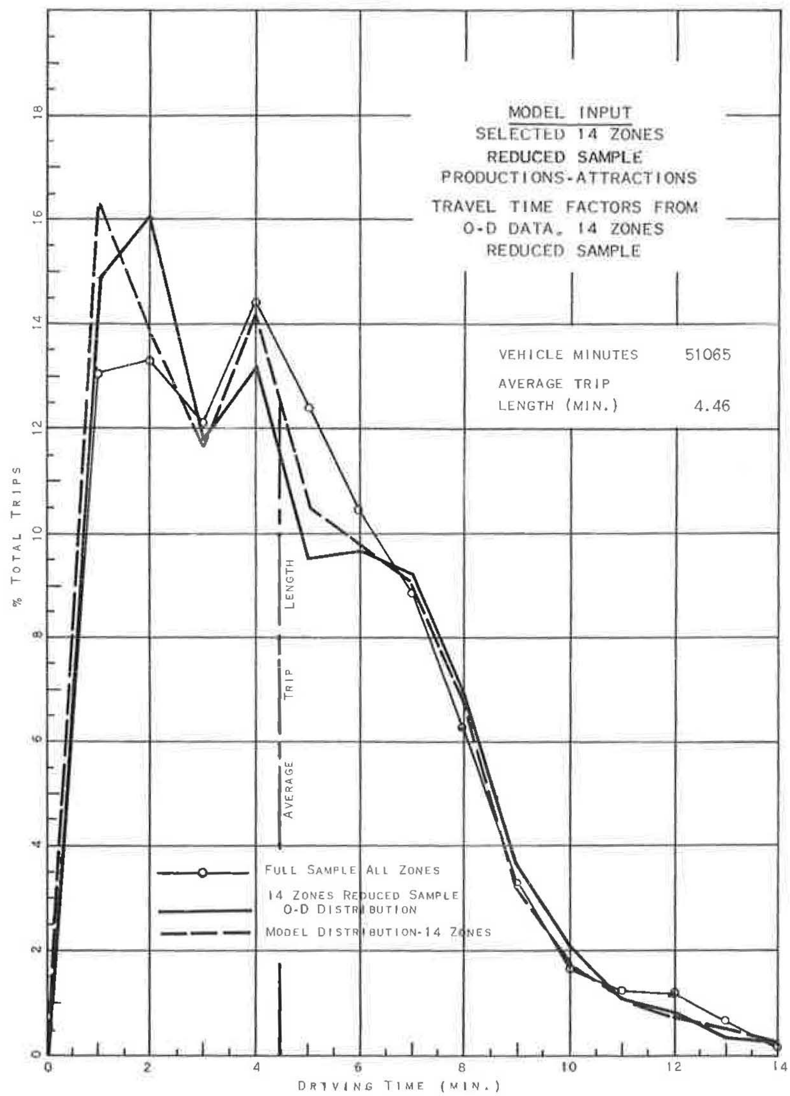


Figure 6. Comparison of trip length frequency using O-D and model data, non-home trips.

purpose. From three to seven iterations were necessary to arrive at acceptable factors. The computer time was much reduced because of the great reduction in number of trips to be distributed. Figures 4, 5, and 6 show the comparison of trip length distributions as obtained for the 14 zones, reduced sample O-D data vs the model distribution using the second set of travel time factors. Table 8 shows the best set of travel time factors developed in each case.

The trip-length frequency data were developed on the basis of driving time rather than travel time. An examination of the computational procedures indicates that, with little difficulty, the distribution could have been made on the basis of travel time if terminal times were introduced as input data. The results of the calibration process probably would have been more satisfactory had this been done.

ESTIMATING EQUATIONS

The following estimating equations for trip productions and attractions were developed using the multiple regression analysis technique.

Trip Production

OSP 22030--home-work, full sample:

$$Y = -5.78775 + 10.25491\,(\text{cars/DU}) + 1.52715\,(\text{pers./DU}) - 0.70627\,(\text{CBD dist.}) - 2.66103\,(\text{cars/DU})\,(\text{pers./DU}) + 0.30996\,(\text{pers./DU})\,(\text{CBD dist.}) - 0.039634\,(\text{CBD dist.})^2$$

Y = trips/dwelling unit. (3)

RSP 14030--home-work, reduced sample:

$$Y = -0.54297 - 0.96297\,(\text{cars/DU}) + 0.79424\,(\text{pers./DU}) + 0.13594\,(\text{CBD dist.}) + 0.31954\,(\text{cars/DU})\,(\text{pers./DU}) - 0.10496)\,(\text{pers./DU})\,(\text{CBD dist.}) + 0.018626\,(\text{CBD dist.})^2$$

Y = trips/dwelling unit. (4)

OSP 22039—home-other, full sample:

$$Y = -5.92767 + 11.60937\,(\text{cars/DU}) + 1.39224\,(\text{pers./DU}) - 1.20225\,(\text{CBD dist.}) - 2.26609\,(\text{cars/DU})\,(\text{pers./DU}) + 0.29830\,(\text{pers./DU})\,(\text{CBD dist.}) + 0.007200\,(\text{CBD dist.})^2$$

Y = trips/dwelling unit. (5)

RSP 14039--home-other, reduced sample:

$$Y = 4.56907 - 6.09284\,(\text{cars/DU}) - 1.69056\,(\text{pers./DU}) + 0.58893\,(\text{CBD dist.}) + 2.98149\,(\text{cars/DU})\,(\text{pers./DU}) - 0.29073\,(\text{pers./DU}\,(\text{CBD dist.}) + 0.042162\,(\text{CBD dist.})^2$$

Y = trips/dwelling unit. (6)

NHP 04514—non-home, full sample:

$$Y = -2.398094 - 0.0051391\,(LU_1) - 0.017017\,(LU_5) + 0.054498\,(LU_6) + 0.058424\,(\text{jobs}) + 0.048989\,(\text{pers./zone}) - 0.084438\,(\text{tot. DU/zone}) - 0.017802\,(\text{cars/zone}) + 0.0000005793\,(LU_1)^2 + 0.000003317\,(LU_5)^2 + 0.00052392\,(LU_6)^2 - 0.000023462\,(\text{jobs})^2 - 0.000023616\,(\text{pers./zone})^2 + 0.000089245\,(\text{tot. DU/zone})^2 + 0.000060598\,(\text{cars/zone})^2$$

Y = trips/zone/1,000 trips produced in 14 selected zones. (7)

NRP 04514—non-home, reduced sample:

$$Y = -6.22386 - 0.0046915\,(LU_1) + 0.043900\,(LU_5) + 0.045839\,(LU_6) + 0.070971\,(\text{jobs}) + 0.058497\,(\text{pers./zone}) - 0.15106\,(\text{tot. DU/zone}) + 0.038259\,(\text{cars/zone}) + 0.0000005283\,(LU_1)^2 - 0.00020223\,(LU_5)^2 + 0.00064132\,(LU_6)^2 - 0.00002833\,(\text{jobs})^2 - 0.00002883\,(\text{pers./zone})^2 + 0.00013757\,(\text{tot. DU/zone})^2 + 0.00002562\,(\text{cars/zone})^2$$

Y = trips/zone/1,000 trips produced in 14 selected zones. (8)

Trip Attraction

Work trip attraction--home-work, full sample (adj. jobs):

$$Y = 1.109 + 0.0624\,(\text{jobs})$$
$$Y = \text{trips/zone/1,000 trips produced in 14 selected zones.} \qquad (9)$$

RS 460--home-work, reduced sample (zone 12 omitted):

$$Y = 1.092802 + 0.058113\,(\text{jobs})$$
$$Y = \text{trips/zone/1,000 trips produced in 14 selected zones.} \qquad (10)$$

MRA 51409--home-other, full sample:

$$\begin{aligned} Y = {} & -0.62306 - 0.048951\,(LU_6) + 0.005561\,(LU_9) - 0.0052420\,(\text{pers./zone}) \\ & + 0.035644\,(\text{tot. DU/zone}) - 0.050611\,(\text{who.-ret. jobs}) + 0.06504\,(\text{pers. serv. jobs}) + 0.064090\,(\text{prof. jobs}) - 0.012982\,(\text{grouped jobs}) \\ & + 0.32256\,(LU_{220}) + 1.95827\,(LU_{240}) + 1.63904\,(LU_{250}) + 0.39525\,(LU_{280}) \\ & + 0.00017289\,(LU_6)^2 - 0.00000037908\,(LU_9)^2 - 0.0000001466\,(\text{pers./zone})^2 + 0.000018689\,(\text{tot. DU/zone})^2 - 0.0000094125\,(\text{who.-ret. jobs})^2 \\ & - 0.00061319\,(\text{prof. jobs})^2 + 0.0001369\,(\text{grouped jobs})^2 - 0.0032360\,(LU_{220})^2 - 0.054781\,(LU_{240})^2 \\ & - 0.0055373\,(LU_{280})^2 \qquad (11) \end{aligned}$$
$$Y = \text{trips/zone/1,000 trips produced in 14 selected zones.}$$

RSA 51309--home-other, reduced sample:

$$\begin{aligned} Y = {} & -0.021097 - 0.080372\,(LU_6) + 0.0045021\,(LU_9) + 0.0078854\,(\text{pers./zone}) \\ & - 0.013214\,(\text{tot. DU/zone}) - 0.049754\,(\text{who.-ret. jobs}) \\ & + 0.26185\,(\text{pers. serv. jobs}) - 0.018923\,(\text{prof. jobs}) \\ & - 0.0041486\,(\text{grouped jobs}) + 0.35568\,(LU_{220}) \\ & + 0.88353\,(LU_{240}) + 2.63884\,(LU_{250}) \\ & + 0.35530\,(LU_{280}) + 0.00017385\,(LU_6)^2 \\ & - 0.0000003212\,(LU_9)^2 - 0.000003921\,(\text{pers./zone})^2 \\ & + 0.000059441\,(\text{tot. DU/zone})^2 \\ & - 0.000024614\,(\text{who.-ret. jobs})^2 \\ & - 0.00003059\,(\text{prof. jobs})^2 \\ & + 0.000078437\,(\text{grouped jobs})^2 \\ & - 0.0031158\,(LU_{220})^2 - 0.032500\,(LU_{240})^2 \\ & - 0.0043047\,(LU_{280})^2 \end{aligned}$$
$$Y = \text{trips/zone/1,000 trips produced in 14 selected zones.} \qquad (12)$$

NHA 04714--non-home, full sample:

$$\begin{aligned} Y = {} & -0.722068 - 0.004496\,(LU_1) - 0.055532\,(LU_5) + 0.052999\,(LU_6) \\ & + 0.045612\,(\text{jobs}) + 0.02664\,(\text{pers./zone}) - 0.0314071\,(\text{tot. DU/zone}) \\ & - 0.009572\,(\text{cars/zone}) + 0.0000005513\,(LU_1)^2 + 0.00012975\,(LU_5)^2 \\ & + 0.00045254\,(LU_6)^2 - 0.000019178\,(\text{jobs})^2 - 0.000016506\,(\text{pers./zone})^2 \\ & + 0.000061364\,(\text{tot. DU/zone})^2 + 0.000044775\,(\text{cars/zone})^2 \end{aligned}$$
$$Y = \text{trips/zone/1,000 trips produced in 14 selected zones.} \qquad (13)$$

NRA 04714--non-home, reduced sample:

$$\begin{aligned} Y = {} & -3.03559 - 0.0073974\,(LU_1) - 0.024895\,(LU_5) - 0.0027639\,(LU_6) \\ & + 0.056735\,(\text{jobs}) + 0.062327\,(\text{pers./zone}) - 0.11725\,(\text{tot. DU/zone}) \\ & - 0.014188\,(\text{cars/zone}) + 0.0000014912\,(LU_1)^2 + 0.000048958\,(LU_5)^2 \\ & + 0.00063131\,(LU_6)^2 - 0.00002446\,(\text{jobs})^2 - 0.00002917\,(\text{pers./zone})^2 \\ & + 0.00014079\,(\text{tot. DU/zone})^2 + 0.000049897\,(\text{cars/zone})^2 \end{aligned}$$
$$Y = \text{trips/zone/1,000 trips produced in 14 selected zones.} \qquad (14)$$

OSP 14034--non-home, full sample:

$$Y = 3.34575 - 6.39670\,(\text{cars/DU}) - 0.52092\,(\text{pers./DU}) + 0.000120\,(\text{CBD dist.}) + 2.52203\,(\text{cars/DU})\,(\text{pers./DU}) - 0.35194\,(\text{pers./DU})\,(\text{CBD dist.}) + 0.13654\,(\text{CBD dist.})^2$$

Y = trips/dwelling unit. (15)

RSP 14034--non-home, reduced sample:

$$Y = 3.75602 - 6.31798\,(\text{cars/DU}) - 1.19446\,(\text{pers./DU}) + 0.46274\,(\text{CBD dist.}) + 2.76797\,(\text{cars/DU})\,(\text{pers./DU}) - 0.45012\,(\text{pers./DU})\,(\text{CBD dist.}) + 0.13799\,(\text{CBD dist.})^2$$

Y = trips/dwelling unit. (16)

In these equations, LU_x indicates 1,000's of square feet of land use; x, if a single digit, indicates major group land use; and x, if three digits, indicates land-use categories within major group land uses. The land-use codes have been published previously (10, Appendix A).

In Eqs. 3, 4, 5, 6, 15, and 16:

DU = dwelling units which responded to the O-D interview;
pers. = persons; and
CBD dist. = distance from the zone centroid in question to the centroid of zone 12, in minutes.

In Eqs. 7 through 14:

tot. DU/zone = total number of dwelling units per zone;
grouped jobs = total jobs in wholesale, retail, finance, personal services, amusement, recreation, professional government, and self-employed;
jobs = total of all jobs;
who.-ret. jobs = total jobs in wholesale, retail, finance and insurance;
pers. serv. jobs = total jobs in personal service; and
prof. jobs = total jobs in professional area.

Equations 15 and 16 were used only for the estimation of numbers of non-home productions or attractions.

ANALYSIS OF RESULTS

Estimates of Trip Production and Attraction

The coefficients of correlation, R, for the estimating equations were obtained from the SCRAP regression analysis program and are shown in Table 9. The squared correlation coefficient or coefficient of determination, R^2, is a measure of the amount of variation about the mean that the estimating equation explains. Although many of the R^2 values were quite high, this coefficient did not necessarily indicate the predictive power of the various equations. For the same data, however, higher values of R^2 did indicate better predictive power of the form of equation being used.

A more meaningful statistical test of the estimating power of the equations was felt to be the calculation of RMS errors. The RMS error for each equation was computed by summing the squares of the differences between the estimated and surveyed values of production or attraction and dividing the total squared differences by the number of zoned productions or attractions and finding the square root of the quotient:

$$\text{RMS error} = \sqrt{\frac{(Y - Y_{est})^2}{N}} \qquad (17)$$

TABLE 9

COEFFICIENTS OF CORRELATION AND DETERMINATION FROM REGRESSION ANALYSIS

Eq. No.	R	R^2
3	0.936	0.876
4	0.952	0.907
5	0.918	0.843
6	0.912	0.831
7	0.995	0.990
8	0.991	0.982
9	-[a]	-[a]
10	-[a]	-[a]
11	0.994	0.989
12	0.992	0.984
13	0.995	0.990
14	0.986	0.972
15	0.968	0.937
16	0.961	0.923

[a] Not determined, equation developed in "polynomial best fit" program (see Table 10 for RMS error comparisons).

TABLE 10

RMS ERRORS OF ESTIMATING EQUATIONS

Eq. No.	Avg. Trips per Zone	RMS Error	% RMS Error[a]
3	302	65	21
4	297	118	40
5	545	137	25
6	545	171	31
7	306	71	23
8[b]	306	218	71
8[c]	307	146	48
9	219	39	18
10[b]	219	88	40
11	452	208	51
12[b]	411	208	51
13	297	65	22
14[b]	306	220	72
14[c]	306	162	53

[a] % RMS error = 100 (RMS error)/average trips per zone.
[b] Using estimated total non-home productions to expand to zonal totals.
[c] Using O-D total non-home productions to expand to zonal totals.

where

Y = surveyed value,

Y_{est} = value estimated from regression equation, and

N = number of values.

The RMS error indicates the limits within which about two-thirds of the deviations between the observed and the estimated values will fall. The RMS errors, shown in Table 10, for the developed estimating equations were smallest when the regression equation was based on data obtained from the comprehensive O-D survey. The recorded RMS error, in most cases, appears to be reasonable when one considers that this is equivalent to stating that two-thirds of the time the estimated zonal productions or attractions can be expected to be within one RMS error of the actual value. The estimating power of Eqs. 8, 10, 12, and 14 were much improved when O-D survey productions were used to expand to zonal values. A plot of the estimated values vs O-D values of zonal productions or attractions provided an excellent graphical portrayal of the goodness of fit of the estimating equations. Figures 7 through 12 show the comparison of O-D trips per zone by purpose to the estimated zonal trips as obtained from Eqs. 4, 6, 8, 10, 12, and 14. Comparisons for all equations have been previously published (10). If the estimated value was equal to the O-D value, the plotted point fell on the 45° line. The plot of the O-D value ± RMS error vs the O-D value indicates a band within which one would expect the estimated values to fall about two-thirds of the time.

Gravity Model Distribution

As noted, two sets of travel time factors were developed. One set, F_1, was based on the O-D productions, attractions and trip length frequency distribution as obtained from the comprehensive O-D data in all zones; the other, F_2, was based on productions,

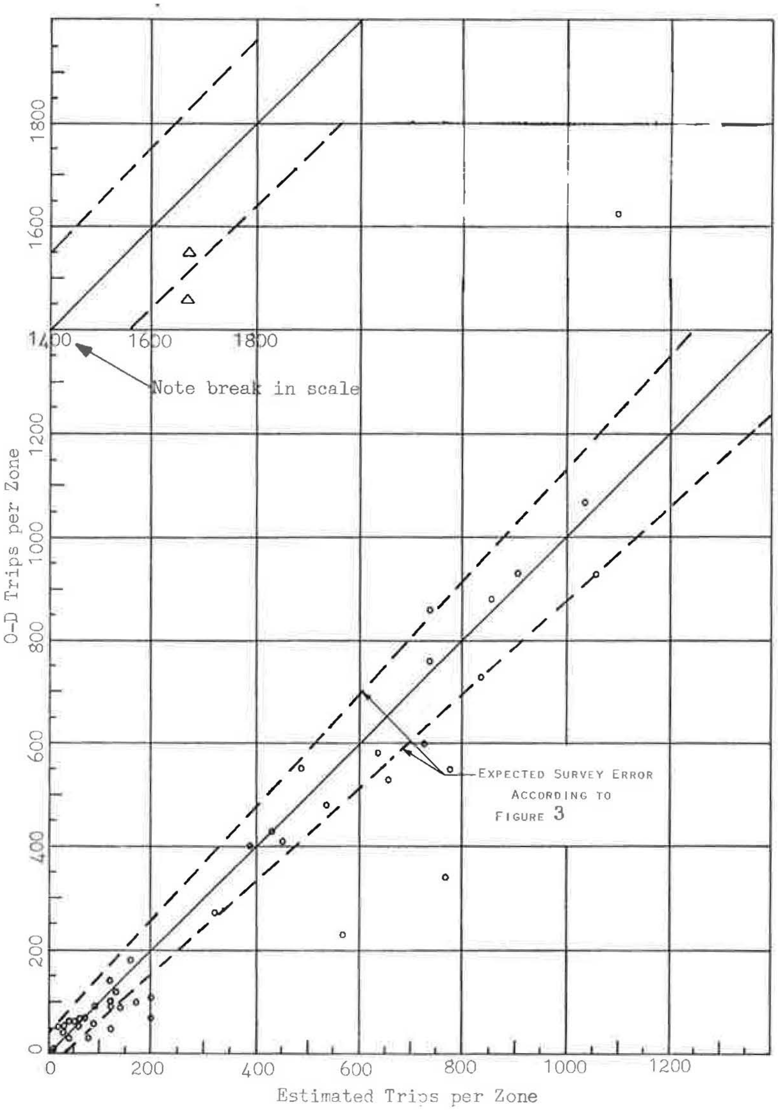


Figure 7. Comparison of home-work trips produced (Eq. 4).

attractions, and the trip length frequency distribution obtained from the reduced sample in the 14 selected zones. Table 8 shows the developed travel time factors. The trip distribution of the model was analyzed using the following four combinations of model parameters:

Combination 1—O-D productions, attractions, and travel time factors, F_1;
Combination 2—O-D productions, attractions, and travel time factors, F_2;
Combination 3—estimated productions, attractions, and travel time factors, F_1; and
Combination 4—estimated productions, attractions, and travel time factors, F_2.

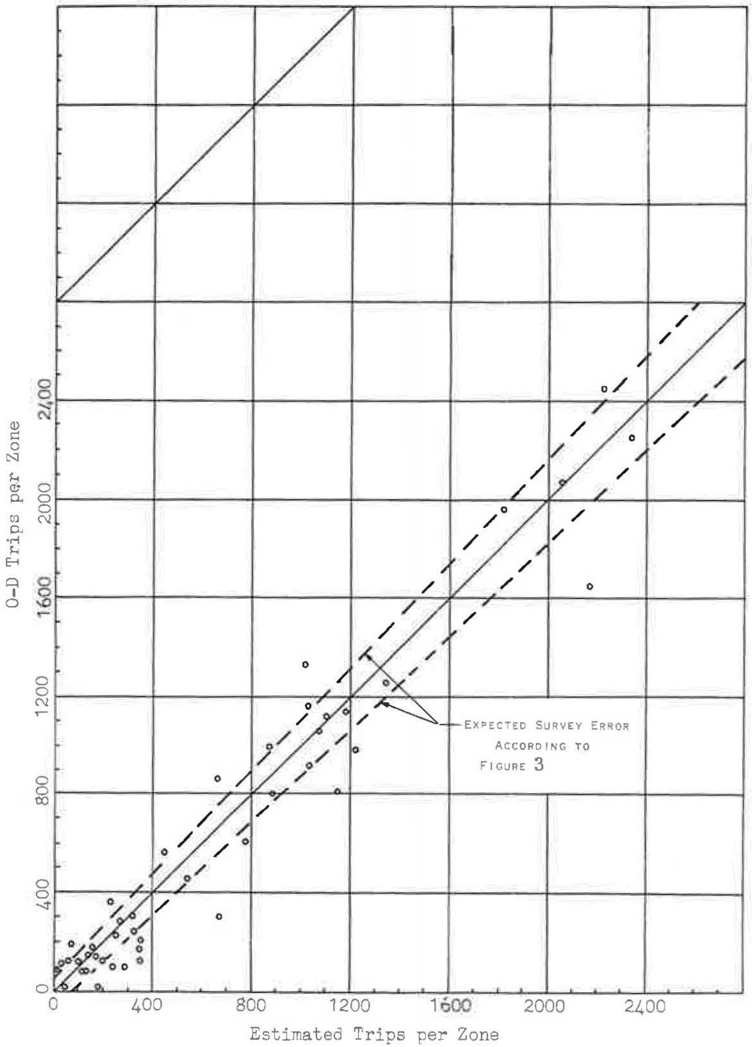


Figure 8. Comparison of home-other trips produced (Eq. 6).

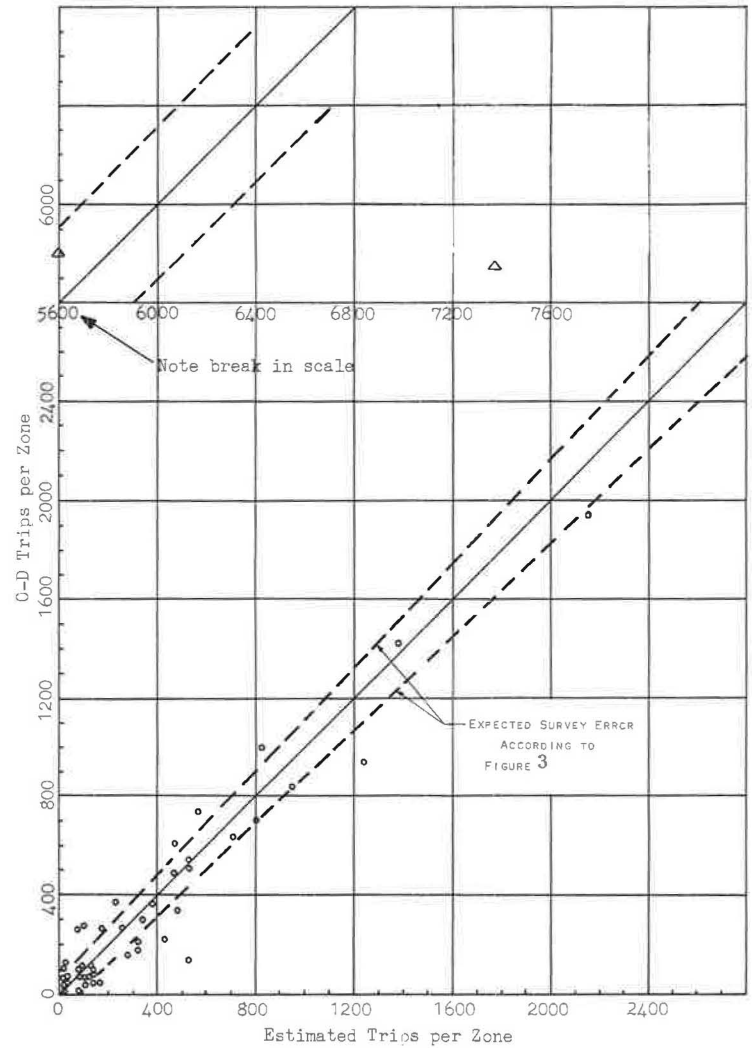


Figure 9. Comparison of non-home trips produced (Eq. 8).

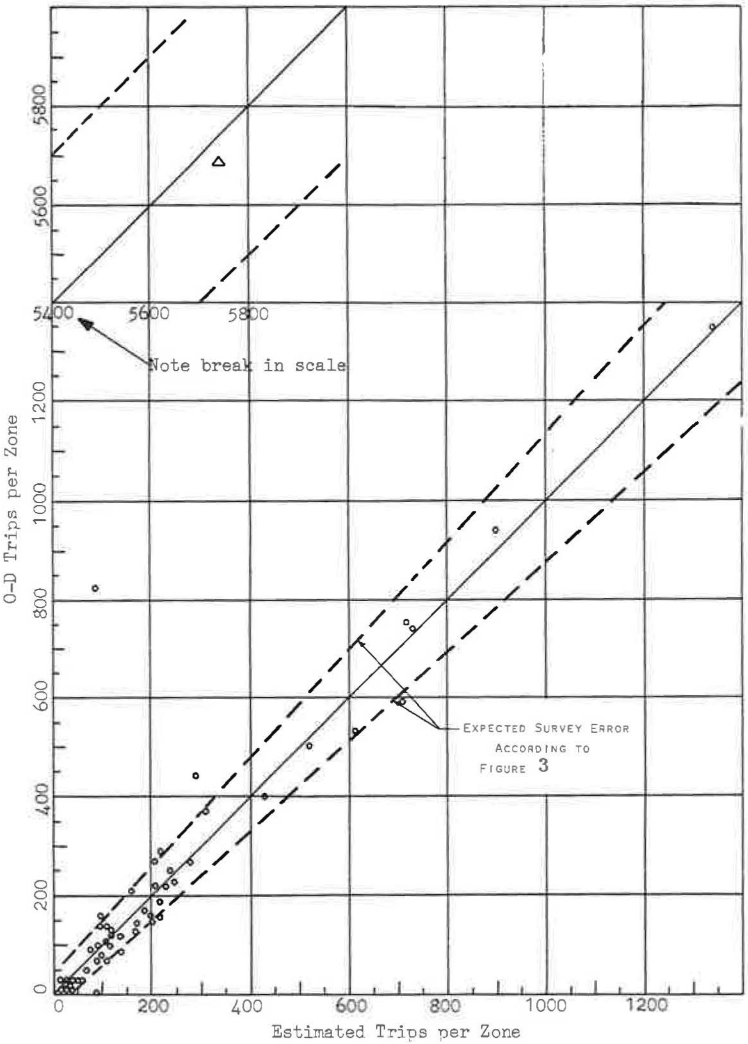


Figure 10. Comparison of home-work trips attracted (Eq. 10).

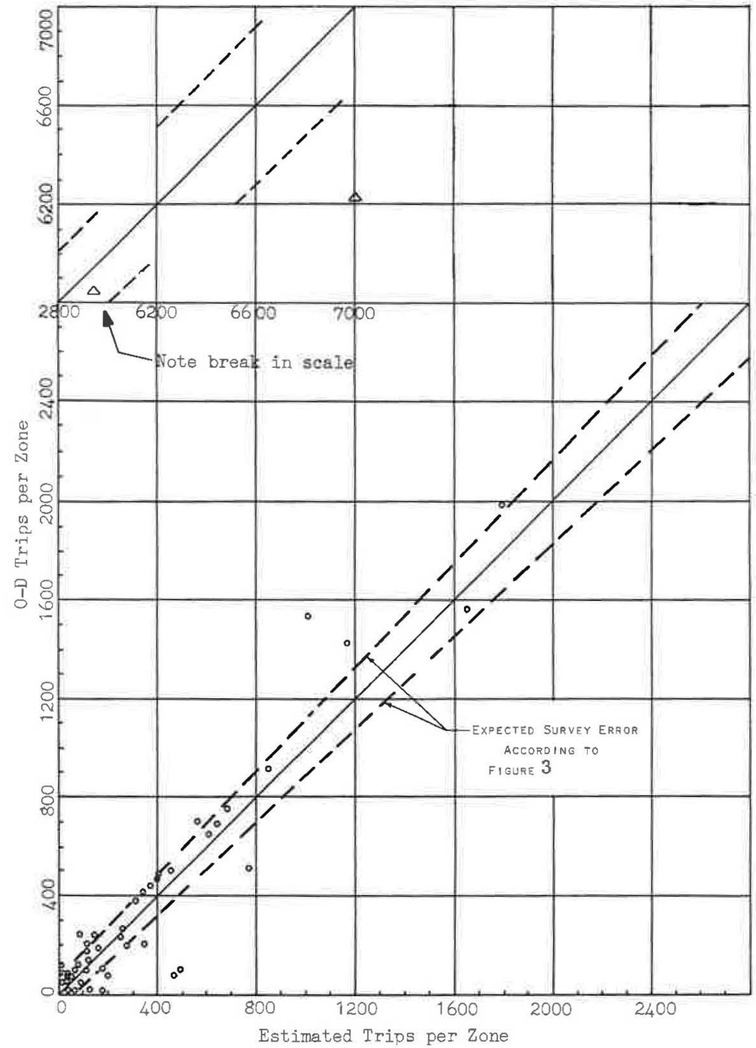


Figure 11. Comparison of home-other trips attracted (Eq. 12).

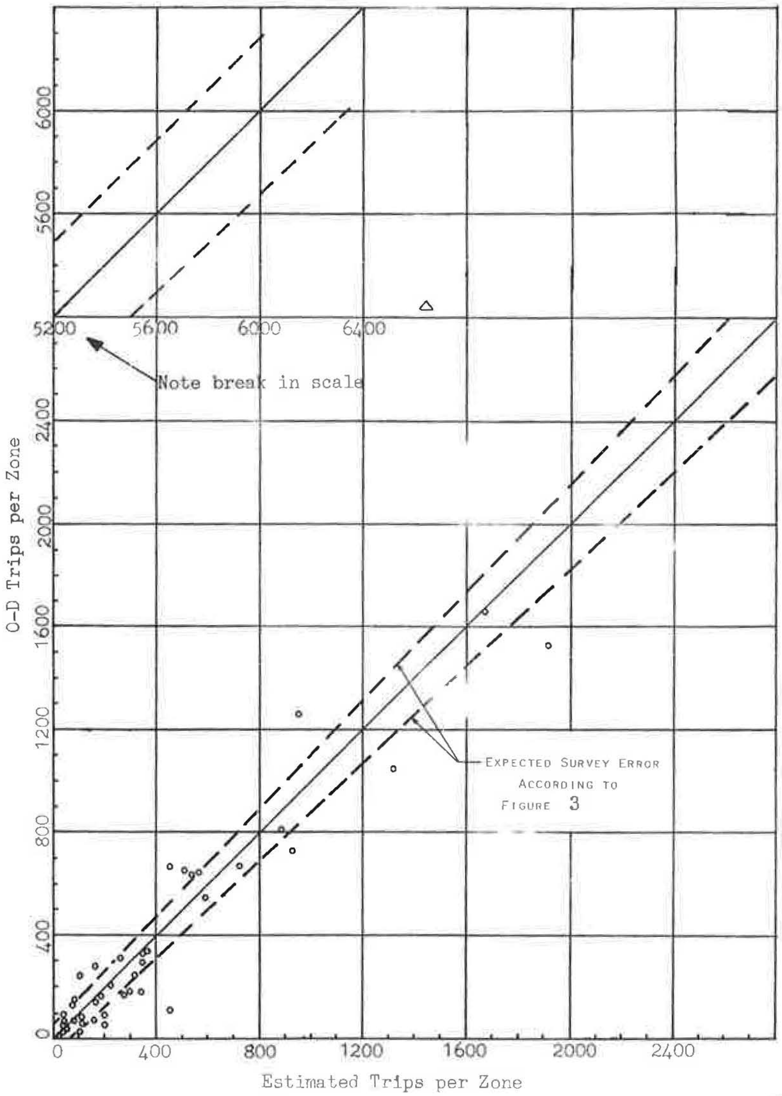


Figure 12. Comparison of non-home trips attracted (Eq. 14).

Screenline Comparison.—Seven screenlines were chosen for a comparison of crossings using the O-D data and those obtained from the gravity model with the various combinations of parameters. The location of the various screenlines is shown in Figure 1. Crossings of screenline 6 showed the largest percent difference; however, the number of trips crossing the line was very small, making it difficult to obtain a close agreement in percent. It is believed, however, that this did indicate some geographical bias in the model and could probably have been remedied by increasing the terminal times in the zones south of screenline 6 or by applying zone-to-zone k factors. The total number of trips involved, however, did not appear to warrant such adjusting procedures. The various screenline crossings are compared in Table 11.

Trip Length Comparison.—It was felt that the comparison of the total amount of travel and average trip length as obtained from the various model distributions would serve as measurements of the adequacy of the model. Figures 13 through 15 show the

TABLE 11

COMPARISON OF SCREENLINE CROSSINGS USING O-D AND MODEL DATA

Screen-line[a]	Crossings from Complete O-D Survey	Full Sample[b]				Reduced Sample[e]			
		Model F_1[c]	Model/O-D (%)	Model F_2[d]	Model/O-D (%)	Model F_1[c]	Model/O-D (%)	Model F_2[d]	Model/O-D (%)
(a) All Trips									
1	27,564	27,478	99.7	29,924	108.6	27,861	101.1	29,884	108.4
2	20,557	20,946	101.9	21,930	106.7	21,157	102.7	22,212	108.1
3	27,656	26,439	95.6	28,248	102.1	26,678	96.5	28,505	103.1
4	24,530	24,008	97.9	25,299	103.1	24,240	98.8	25,473	103.8
5	26,828	24,765	92.3	28,643	106.8	26,419	98.5	28,536	106.4
6	4,202	5,156	122.7	5,720	136.1	5,095	121.3	5,704	135.7
7	10,028	9,682	96.5	11,302	112.7	9,734	97.1	11,755	117.2
Total	141,365	138,474	98.0	151,066	106.9	141,184	99.9	152,069	107.6
(b) Home-Work Trips									
1	8,507	8,731	102.6	9,537	112.1	8,793	103.4	9,438	110.9
2	6,140	6,229	101.4	6,762	110.1	6,328	103.1	6,990	113.8
3	8,908	8,245	92.6	8,427	94.6	8,320	93.4	8,565	96.1
4	7,714	7,535	97.7	7,566	98.1	7,609	98.6	7,642	99.1
5	7,844	7,644	97.5	8,339	106.3	7,642	97.4	8,007	102.1
6	1,235	1,427	115.5	1,838	148.8	1,450	117.4	1,839	148.9
7	3,596	3,440	95.7	3,672	102.1	3,522	97.9	4,194	116.6
Total	43,944	43,251	98.4	46,141	105.0	43,664	99.4	46,675	106.2
(c) Home-Other Trips									
1	9,959	9,916	99.6	10,275	103.2	10,007	100.5	10,332	103.7
2	9,002	9,182	102.0	9,784	108.2	9,292	103.2	9,840	109.3
3	11,694	11,289	96.5	12,518	107.0	11,450	97.9	12,634	108.0
4	10,509	10,342	98.4	11,464	110.8	10,500	99.9	11,569	110.1
5	9,785	9,388	95.9	9,840	100.6	9,605	98.2	10,073	102.9
6	1,731	2,130	123.1	2,274	131.4	2,128	122.9	2,256	130.3
7	4,239	4,077	96.2	4,971	117.3	4,045	95.4	4,902	115.6
Total	56,919	56,324	99.0	61,126	107.4	57,027	100.2	61,606	108.2
(d) Non-Home Trips									
1	9,098	9,055	99.5	10,112	111.1	9,061	99.6	10,114	111.2
2	5,415	5,535	102.2	5,385	99.4	5,538	102.3	5,383	99.4
3	7,054	6,905	97.9	7,304	103.5	6,908	97.9	7,306	103.6
4	6,309	6,131	97.2	6,271	99.4	6,131	97.2	6,262	99.3
5	9,198	9,181	99.8	10,465	113.8	9,172	99.7	10,456	113.7
6	1,235	1,515	122.7	1,608	130.2	1,518	122.9	1,609	130.3
7	2,193	2,165	98.7	2,660	121.3	2,167	98.8	2,659	121.2
Total	40,502	40,487	100.0	43,805	108.2	40,495	100.0	43,789	108.1

[a]See Figure 1 for the locations of screenlines. [b]Using productions and attractions from the complete O-D survey.
[c]Using travel time factors developed with model input productions and attractions from the complete O-D survey.
[d]Using travel time factors developed with model input productions and attractions from the 14 zones with a reduced sample size. [e]Using productions and attractions obtained from the regression estimating equations developed from the reduced sample in the 14 selected zones.

trip length frequency distribution, by purpose, of the O-D data vs the model with input from the small sample data. These comparisons show good agreement of the model and O-D data. Additional comparisons are found in the earlier report (10). The average lengths of trip in minutes and total vehicle-hours of travel as compared in Table 12 are also in close agreement.

Since there were few diagonal streets in Hutchinson, the distance, in miles, between zone centroids was measured by determining the L distance (sum of map coordinate differences); the total vehicle-miles of travel was taken as the product of the zone-to-zone interchange and the L distance between the zone centroids in question with the summation being made over all zones. The average trip length in miles was taken as the total vehicle-miles of travel divided by the total number of trips. The comparisons of the average length of trip in miles and total vehicle-miles of travel are given in Table 13 and again indicate close agreement.

Comparison of District-to-District Movements.—A comparison was also made of the district-to-district movements given by both the model and O-D data. The comparison was originally made using zone-to-zone movements but the small numbers of trips gave results having little stability. The RMS errors for the various volume groups and trip purposes, as shown in Tables 14 through 16, indicate that two-thirds of the time the difference between district interchanges, as given by the model and O-D data, is expected to be equal to, or less than, the value of the RMS error.

District-to-district trip interchanges can be used in determining interchange volumes between the CBD and various corridors. This can provide a check on the geographical bias of the model. However, in this analysis, it was felt that the screenline checks gave a dependable test for bias.

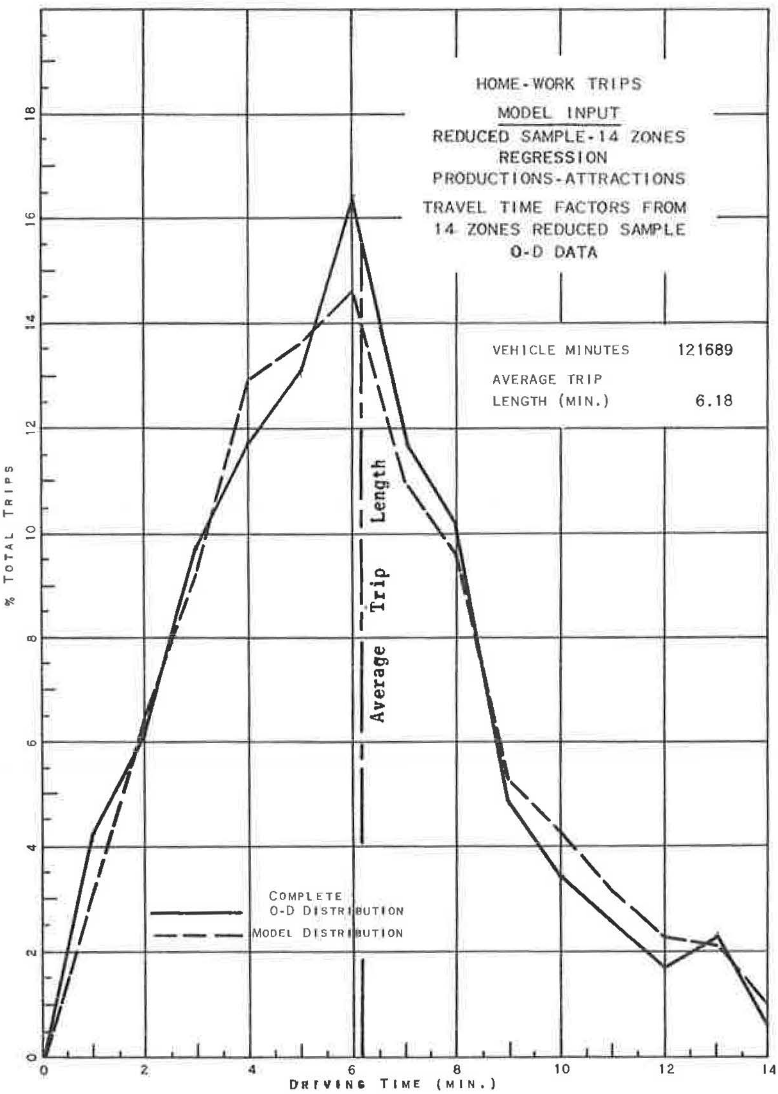


Figure 13. Comparison of trip length frequency using O-D and model data, home-work trips, combination 4 parameters.

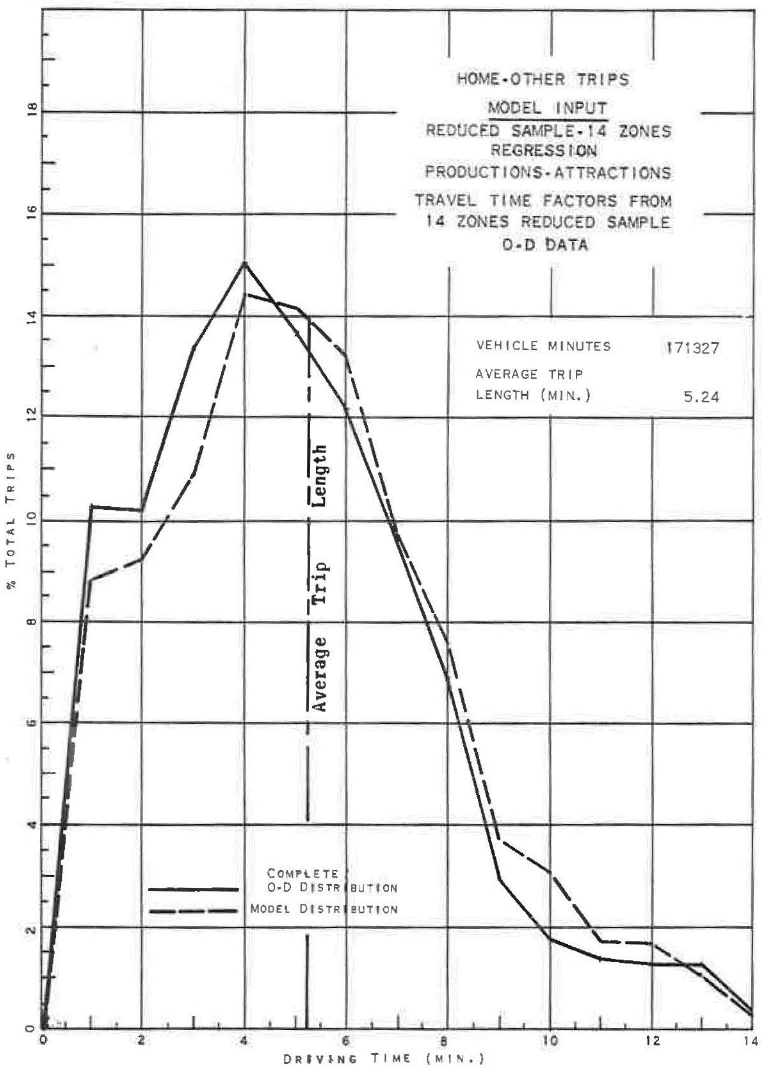


Figure 14. Comparison of trip length frequency using O-D and model data, home-other trips, combination 4 parameters.

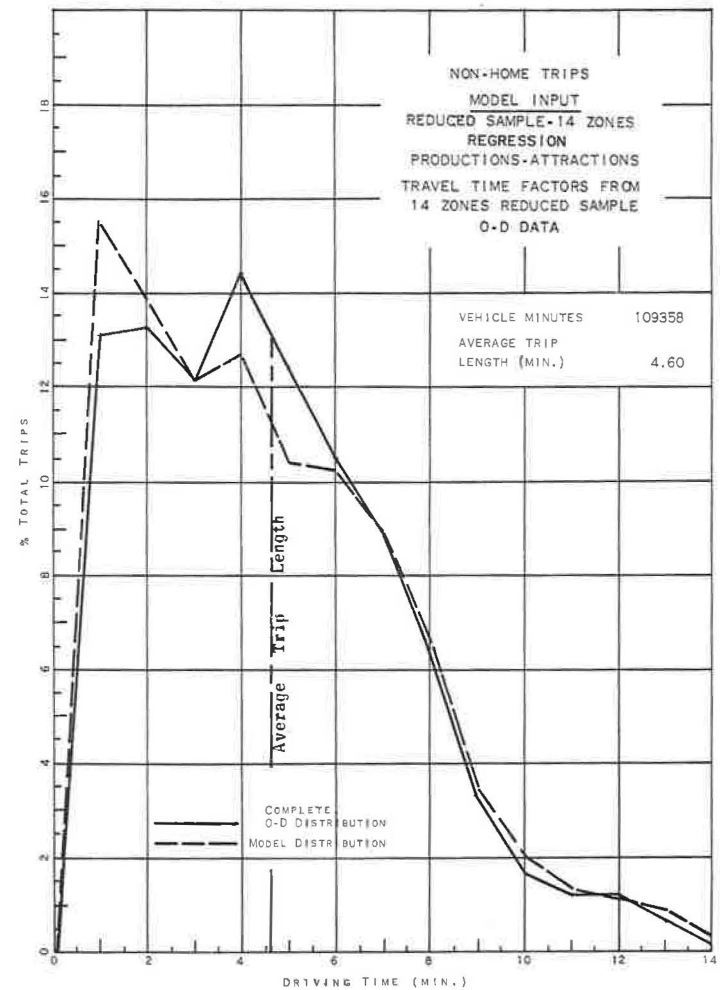


Figure 15. Comparison of trip length frequency using O-D and model data, non-home trips, combination 4 parameters.

TABLE 12

VEHICLE-HOURS OF TRAVEL AND AVERAGE TRIP LENGTH FROM O-D AND MODEL DATA

Purpose	Complete O-D Survey Data		Full Sample				Reduced Sample			
			O-D Prod.-Attract.		Regression Prod.-Attract.		O-D Prod.-Attract.		Regression Prod. Attract.	
	Veh-Hr	Avg. Trip Length (min)	Veh-Hr	Avg. Trip Length (min)	Veh-Hr	Avg. Trip Length (min)	Veh-Hr	Avg. Trip Length (min)	Veh-Hr	Avg. Trip Length (min)
Home-work	1,831	6.06	1,823	6.03	1,970	6.01	1,842	6.09	2,028	6.18
Home-other	2,584	4.91	2,610	4.95	2,845	5.22	2,627	4.98	2,855	5.24
Non-home	1,597	4.48	1,657	4.64	1,823	4.60	1,657	4.64	1,823	4.60

TABLE 13

VEHICLE-MILES OF TRAVEL AND AVERAGE TRIP LENGTH FROM O-D AND MODEL DATA

Purpose	Complete O-D Survey Data		Full Sample				Reduced Sample			
			O-D Prod.-Attract.		Regression Prod.-Attract.		O-D Prod.-Attract.		Regression Prod.-Attract.	
	Veh-Mi	Avg. Trip Length (mi)	Veh-Mi	Avg. Trip Length (mi)	Veh-Mi	Avg. Trip Length (mi)	Veh-Mi	Avg. Trip Length (mi)	Veh-Mi	Avg. Trip Length (mi)
Home-work	35,331.6	1.946	35,325.6	1.947	38,327.3	1.948	35,765.0	1.971	40,007.6	2.033
Home-other	48,248.2	1.527	49,193.3	1.552	54,894.9	1.680	49,454.6	1.563	54,882.0	1.679
Non-home	30,755.6	1.438	30,630.7	1.431	33,731.9	1.419	30,636.7	1.431	33,717.9	1.418

TABLE 14

ANALYSIS OF DISTRICT-TO-DISTRICT MOVEMENTS[a]

Volume Group	Freq.[b]	Total Trips		Mean Diff.	Std. Dev.	RMS Error	% RMS Error
		O-D	Model				
0-99	33	1,858	2,491	19	49	52	93
100-199	32	4,648	6,219	-49	76	90	62
200-299	32	7,875	8,831	-29	89	93	38
300-399	14	4,891	6,075	-84	132	157	44
400-499	8	3,476	4,024	-68	109	129	29
500-599	2	1,089	582	253	158	298	54
600-699	4	2,576	2,883	-76	234	247	38
700-799	4	2,943	2,608	83	143	165	22
800-899	2	1,641	1,800	-79	162	180	22
900-999	2	1,896	1,735	80	77	111	11
1,000-1,499	10	12,750	12,558	19	328	329	25
1,500-1,999	4	6,753	6,659	23	289	290	17
2,000-2,999	4	9,581	10,739	-289	411	503	21
3,000-3,999	1	3,549	4,837	-1,288	-	1,287	36
4,000-4,999	-	-	-	-	-	-	-
5,000-5,999	1	5,199	3,795	1,404	-	1,403	27
6,000-6,999	-	-	-	-	-	-	-
7,000-7,999	-	-	-	-	-	-	-
8,000-8,999	-	-	-	-	-	-	-
9,000-9,999	-	-	-	-	-	-	-
10,000-999,999	-	-	-	-	-	-	-
Total		70,725	75,836				

[a]All trips, full sample, regression productions-attractions, travel time factors from reduced sample O-D data.
[b]Number of district-to-district movements within volume group.

TABLE 15

ANALYSIS OF DISTRICT-TO-DISTRICT MOVEMENTS[a]

Volume Group	Freq.[b]	Total Trips		Mean Diff.	Std. Dev.	RMS Error	% RMS Error
		O-D	Model				
0-99	33	1,858	2,554	-21	48	52	93
100-199	32	4,648	5,907	-39	83	92	63
200-299	32	7,875	8,752	-27	88	92	37
300-399	14	4,891	6,034	-81	137	160	45
400-499	8	3,476	3,923	-55	116	129	29
500-599	2	1,089	611	239	164	290	53
600-699	4	2,576	2,970	-98	250	269	41
700-799	4	2,943	2,653	72	164	180	24
800-899	2	1,641	1,815	-87	118	147	17
900-999	2	1,896	1,725	85	78	116	12
1,000-1,499	10	12,750	12,603	14	309	309	24
1,500-1,999	4	6,753	6,714	9	303	303	18
2,000-2,999	4	9,581	10,923	-335	374	502	20
3,000-3,999	1	3,549	4,846	-1,297	-	1,296	36
4,000-4,999	-	-	-	-	-	-	-
5,000-5,999	1	5,199	3,780	1,419	-	1,418	27
6,000-6,999	-	-	-	-	-	-	-
7,000-7,999	-	-	-	-	-	-	-
8,000-8,999	-	-	-	-	-	-	-
9,000-9,999	-	-	-	-	-	-	-
10,000-999,999	-	-	-	-	-	-	-
Total		70,725	75,810				

[a]All trips, full sample, regression productions-attractions, travel time factors from full sample O-D data.
[b]Number of district-to-district movements within volume group.

TABLE 16

ANALYSIS OF DISTRICT-TO-DISTRICT MOVEMENTS[a]

Volume Group	Freq.[b]	Total Trips		Mean Diff.	Std. Dev.	RMS Error	% RMS Error
		O-D	Model				
0-99	33	1,858	1,965	-3	39	39	70
100-199	32	4,648	5,041	-12	60	61	42
200-299	32	7,875	8,389	-16	99	100	40
300-399	14	4,891	4,915	-1	90	90	25
400-499	8	3,476	3,638	-20	78	81	18
500-599	2	1,089	506	291	85	303	55
600-699	4	2,576	2,517	14	91	92	14
700-799	4	2,943	3,001	-17	196	197	26
800-899	2	1,641	1,757	-58	29	65	7
900-999	2	1,896	1,662	117	85	145	15
1,000-1,499	10	12,750	12,433	31	294	296	23
1,500-1,999	4	6,753	6,399	88	251	256	15
2,000-2,999	4	9,581	10,498	-229	159	279	11
3,000-3,999	1	3,549	3,868	-319	-	318	8
4,000-4,999	-	-	-	-	-	-	-
5,000-5,999	1	5,199	4,018	1,181	-	1,180	22
6,000-6,999	-	-	-	-	-	-	-
7,000-7,999	-	-	-	-	-	-	-
8,000-8,999	-	-	-	-	-	-	-
9,000-9,999	-	-	-	-	-	-	-
10,000-999,999	-	-	-	-	-	-	-
Total		70,725	70,607				

[a]All trips, full sample, complete O-D productions-attractions, travel time factors from full sample O-D data.
[b]Number of district-to-district movements within volume group.

CONCLUSIONS

1. Current zonal trip productions and attractions were adequately estimated from mathematical models developed from a small sample of home interviews (8) taken in a sample of the origin-destination zones. Best estimates resulted for home-based trip productions but estimated non-home-based trip productions and all trip attractions appeared to be adequate for planning purposes.

2. Mathematical models developed from current comprehensive O-D or reduced sample data should be of great value in estimating future zonal trip productions and attractions.

3. Only three trip purposes (home-work, home-other, and non-home) were found to be practical divisions of all trips for prediction of zonal trip productions and attractions from mathematical models based on comprehensive or reduced sample O-D data.

4. For home-work trip attractions, the number of jobs in a zone was the only important factor.

5. For home-work trip productions, the number of employed persons per dwelling unit was not found to be a more important factor than persons per dwelling unit.

6. For all trip productions, the number of persons and the number of cars per dwelling unit were found to be very important factors. Other factors of importance for trip productions were distance to the CBD for home-work and home-other trips, area of various land uses, and number of jobs for non-home trips.

7. For trip attractions other than the home-work trip, the number of persons per zone, the number of types of jobs in the zone, and the areas devoted to various land uses were found to be important factors.

8. Travel time factors for distribution of trips by the gravity model were satisfactorily estimated by calibrating the gravity model with trip length frequency data developed from a small sample of home interviews taken in a sample of the O-D zones.

9. The travel time factors which were developed varied in value for the different trip purposes for the same travel time separation.

10. The gravity model using trip productions and attractions and travel time factors developed from a small sample of home interviews taken in a sample of O-D zones distributed trips among all zones to give an adequate reproduction for planning purposes of the trip distribution obtained in a comprehensive O-D survey.

11. The gravity model using trip production and attractions and travel time factors developed from a comprehensive O-D survey distributed trips among all zones to give a good reproduction of the trip distribution obtained in the comprehensive survey.

ACKNOWLEDGMENT

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Adequacy of Clustered Home Interview Sampling For Calibrating a Gravity Model Trip Distribution Formula

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•INCREASED USE of the gravity model formulation in transportation planning has brought about a wide variation in study procedures, many of which, developed without the benefit of research, are characterized by a reduction in travel data accumulated for model calibration. In several instances, urban planning engineers have advocated the use of a reduced sample home interview survey, clustered in selected zones, to supply the basic data for model calibration (1, 2, 3).

A clustered sample may best be described by contrasting it with the typical systematic sample normally used in home interview origin-destination surveys. In a systematic sample every nth dwelling unit in each zone in the entire study area is surveyed. In clustered home interview sampling, a systematic sample is conducted, but only in selected zones. In other words, every nth dwelling unit is interviewed in the selected zones, but none are interviewed in the remaining zones. Each cluster, therefore, consists of a systematic sample in a selected zone.

The selected zones are generally chosen to reflect a range in the urban characteristics known to be correlated with travel habits. For example, residential density, car ownership, income level, and distance from the central business district (CBD) are among the variables which might be utilized as criteria for determining zones to select for the clustered sample.

The objective of the clustered sampling technique is to reduce study time and costs by reducing the total number of home interviews required. This objective is successfully achieved only if the clustered sample data are sufficient to develop a travel model which can then be used to estimate trip distribution patterns for the entire study area.

This paper reports the results of a research study designed to evaluate the use of clustered home interview samples as the basic source of data for developing a gravity model that will accurately synthesize areawide travel patterns. The study was initiated by the Urban Planning Division of the U. S. Bureau of Public Roads with the financial assistance of the Pennsylvania Department of Highways and in cooperation with the Pittsburgh Area Transportation Study (PATS).

THE GRAVITY MODEL

The gravity model theory may be simply described as follows. The trips produced in any zone will distribute themselves to other zones in the study area in direct proportion to the trip opportunities or attractions in the other zones and in inverse proportion to some function of the spatial separation between the zones.

The gravity model equation used in this research is stated as follows:

$$T_{(i-j)} = \frac{P_i \, A_j \, F_{(t_{i-j})} \, K_{(i-j)}}{\sum_{x=1}^{n} A_x \, F_{(t_{i-x})} \, K_{(i-x)}} \quad (1)$$

Paper sponsored by Committee on Origin and Destination.

where

$T(i-j)$ = trips produced in zone i and attracted to zone j;
P_i = trips produced in zone i;
A_j = trips attracted to zone j;
(t_{i-j}) = travel time in minutes between zone i and zone j;
$F(t_{i-j})$ = empirically derived travel time factor expressing average areawide effect of spatial separation on trip interchange between zones that are (t_{i-j}) apart; and
$K_{(i-j)}$ = specific zone-to-zone adjustment factor to allow for incorporation of effect on travel patterns of defined social or economic linkages not otherwise accounted for in the gravity model formulation.

The travel time factor $F(t_{i-j})$ is approximately equivalent to the more traditional $1/t^n$. The use of a set of travel time factors to express the effect of spatial separation on zonal trip interchange, rather than the traditional inverse exponential function of time, simplifies the computational requirements of the model. It also allows more complex mathematical functions (for example, with n varying by t) to be conveniently represented.

Trip production (P_i) and trip attraction (A_j) take on specific definitions when considered in the gravity model formulation. First, consider home-based trips. Home-based trip productions per zone are all those trips made by residents of the zone originating at or destined to their homes. Home-based trip attractions per zone are the nonhome trip ends of home-based trips arriving at or departing from the nonhome zone. For example, a person living in zone 1 who travels from his home to zone 2 and home again makes two trips. Zone 1 is credited with having produced two home-based trips; zone 2 is credited with having attracted two home-based trips.

Nonhome-based trips are those trips having neither end at the residence of the trip maker. Nonhome-based trip productions are the origins of nonhome-based trips and, accordingly, nonhome-based attractions are the destinations.

Data Sources

Basic trip data sources for this research were the 1958 standard origin-destination (O-D) home interview survey conducted in the 226 internal zones of the Pittsburgh study area and a special high sample rate clustered home interview survey conducted in 1960 in 13 selected zones of the same study area. Both of these home interview surveys were conducted by the staff of PATS.

The 1958 survey consisted of a systematic 4 percent sample of all the dwelling units in the study area, providing over 16,000 completed interviews (4, 5, 6). The 1960 clustered survey was designed with a sample rate varying by zone from 10 to 33 percent, yielding a total of 4,250 interviews. The variable sample rate was designed to provide trip data of approximately the same degree of accuracy from each of the selected zones. Previous research by Sosslau and Brokke on the statistical accuracy of home interview O-D data was used as the basis for the selection of the sample rates (7).

The 13 zones chosen for the 1960 survey were selected from among the 226 internal zones in the study area as a result of an examination of certain land-use and socio-economic characteristics tabulated from the 1958 survey data. Principal factors examined were net residential density, car ownership, and distance from the CBD, which in Pittsburgh is the Golden Triangle. The 13 zones were selected to yield a range in these characteristics and hopefully to reflect the full range of income levels. Income data were not available from the 1958 survey; however, some preliminary studies had shown income level to be highly correlated with trip production and a question on this subject was included in the 1960 survey.

Figure 1 illustrates the geographical location of the 13 selected zones and the area encompassed by the 1958 study. North, south, and east zones noted later are referenced to the three rivers.

The basic data sources for land-use and socio-economic data were the land-use survey conducted during the PATS study which summarized land area measurements

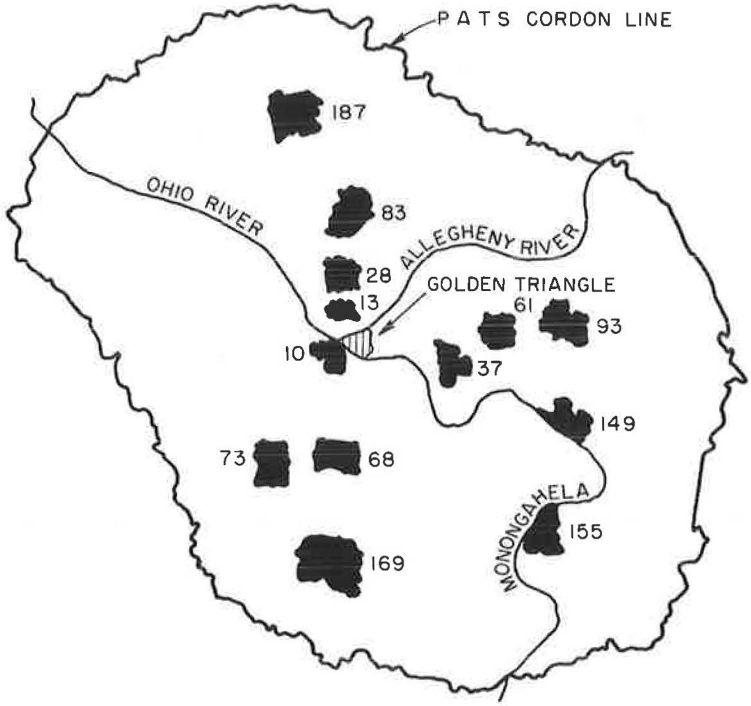

Figure 1. Location of 13 selected analysis zones used in Pittsburgh research project.

by two digit classification and the 1958 home interview survey which obtained population and car ownership statistics by zone.

Objectives

The study was designed to answer four basic questions.

1. Were the trip data from the 13-zone clustered survey sufficient to develop a set of travel time factors, $F(t_{i-j})$, representative of the effect of zonal separation on trip making for the entire study area?
2. Did the limited survey contain enough trip information so that trip productions (P_i) and trip attractions (A_j) could be related to specific land-use and socio-economic data through the use of regression analyses and thereby expanded to every zone in the study area?
3. How accurate, when compared to the 1958 O-D survey, was a gravity model developed solely through the use of the 13-zone survey trip data and all available land-use and socio-economic data when applied to the total study area?
4. How accurate, when compared to the 1958 O-D survey, was a gravity model developed by making use of the full 1958 O-D survey and the same land-use and socio-economic data?

Procedures

To provide answers to these questions the work of the study was organized into three major phases: (a) gravity model calibration, (b) trip production and attraction estimates, and (c) combined analysis—trip production, attraction and distribution. Each of these major phases was in turn divided into two subphases, one relating to the 13-zone clustered survey and the other to the total study area survey.

Gravity Model Calibration.—Travel time factors were developed using only the 13-zone survey trip data. These were representative of the effect of spatial separation on trip making as expressed by the clustered survey data. Travel time factors were then developed using the 1958 total study area trip data and were representative of the effect of spatial separation on trip making for the entire study area. Deviations between the clustered survey data factors and the total area data factors were analyzed for significance.

Trip Production and Attraction Estimates.—Regression analysis was used to develop trip production estimating equations from the 13-zone survey trip productions and the available land-use and socio-economic data. These equations were then solved for every zone in the study area to develop trip production estimates for each of the 226 internal zones. Regression analysis was also used in an attempt to develop trip attraction estimating equations from the 13-zone data.

Trip productions and trip attractions from the 1958 total study area survey were related to the available land-use and socio-economic data through the use of regression analysis.

Combined Analysis.—The trip production and attraction estimates, the calibrated travel time factor estimates developed using only 13-zone survey trip data, and the available land-use and socio-economic data were used as input to a total study area gravity model and a trip distribution was calculated. The accuracy of this distribution when compared to the 1958 O-D survey trip data was then determined.

Trip production and trip attraction estimates and the travel time factors developed using the 1958 O-D total study area trip data and the available land-use and socio-economic data were used to calculate another gravity model trip distribution. The accuracy of this distribution when compared to the 1958 O-D survey trip data was also determined.

A detailed analysis was then made of the accuracy of the alternate gravity model distributions. Each of the gravity model trip distributions was compared statistically to the 1958 O-D trip distribution. Selected movements were isolated and compared to measure geographical bias.

GRAVITY MODEL CALIBRATION

The basic calibration procedure and descriptions of the IBM 1401 and 7090 computer programs used for both the 13-zone and total study area phases of this study have been fully documented (8).

Data Processing

The initial data processing work was similar for both the 13-zone and the total study area survey analyses. The data necessary for use in the calibration process consisted of the following: (a) trip productions (P_i) and trip attractions (A_j) by purpose and zone; (b) minimum path travel times (t_{i-j}) between all zones; and (c) trip length frequency distributions by purpose for the O-D trip data.

Tables of expanded zone-to-zone person trip movements were first developed by purpose from the home interview survey data. A byproduct of the trip table building program was a zonal summary of trip production and trip attraction.

The trip tables and trip production and attraction summaries were tabulated for six trip purpose categories. The five home-based trip purposes were work, shop, school, social-recreational, and miscellaneous. The home-based trip purpose definitions were taken directly from the standard home interview questionnaire classifications, with the exception of miscellaneous which is a grouping of personal business, medical-dental, and eat meal trips. The sixth purpose category, nonhome-based trips, included all those trips where neither the purpose to nor purpose from was home.

Change mode and serve passenger trip purpose classifications had previously been eliminated when these trips were linked. In trip linking, certain segmented trips in the previous classifications are connected or linked to assign more meaningful origins, destinations, and purposes.

The trip tables were then used with the minimum path travel times between all zones to develop trip length frequency distributions by purpose. The minimum path travel time between any two zones is made up of the minimum path driving time between the zones and the terminal times in the zones of production and attraction. The minimum path driving times, more commonly called trees, were calculated by the traffic assignment process. To develop the driving times for use in this study, the PATS base network of coded link distances and times was recoded to fit the BPR tree building program format. The driving times on the PATS coded network were developed from a limited number of operating speed studies.

Terminal times were estimated by the research staff to allow for the effect of differences in cruising, parking, and walking times as caused by differences in congestion and availability of parking facilities. Terminal times, ranging from 1 min in suburban residential areas to 6 min in downtown areas, were added to the driving times to develop a more realistic measure of the actual spatial separation between zones. The same travel times were used to develop the trip length frequency distributions and as input to the gravity models.

For the gravity model travel time factor calibration runs, both trip productions and trip attractions were taken directly from the home interview survey results. The actual P_i and A_j from the survey were used rather than estimates to prevent error from this source from affecting the travel time factor calibrations. This is standard practice when calibrating gravity models.

13-Zone Gravity Model Calibration

Due to the limitations of the clustered survey data, an abbreviated trip distribution was utilized in the 13-zone gravity model calibration. For both the clustered survey data and the gravity model, home-based trip productions occurred in only 13 of the 226 internal zones, whereas trip attractions occurred in all 226 internal zones, 46 external analysis zones, and at the 8 external stations. Nonhome-based trip productions and attractions occurred in all 280 analysis units. For each of the trip purposes, the total of the trip productions equaled the total of the trip attractions.

For a first approximation of travel time factors, a set of values previously developed for Washington, D. C., was used (9, 10). Using these travel time factors and the clustered survey trip productions and attractions, the gravity model program was used to calculate a first trip distribution.

The trip length frequencies of the resultant distribution were plotted by purpose along with the O-D trip length frequencies. The trip length frequency distributions were not in agreement and the initial travel time factors were therefore modified by using the relationship between the percent O-D trips per 1 min of time interval and the percent gravity model trips per time interval (8). The gravity model program was then rerun using the adjusted travel time factors, and the plotting and adjustment procedures were repeated. This iterative process was continued until a satisfactory agreement was reached between the O-D and gravity model trip length frequency distributions for each purpose. In addition to the basic agreement in the closeness of fit of the curves, the total person hours of travel and mean trip length were continually checked by purpose. When all three parameters were in close agreement, the model was said to be calibrated. Figure 2 shows the plot of the trip length frequency distributions for all trip purposes of the 13-zone O-D vs the 13-zone calibrated gravity model along with the relationship between the total person hours and mean trip lengths. The set of travel time factors that resulted in an acceptable trip length distribution comparison was, therefore, that set which best approximated the effect of spatial separation on trip interchange as exhibited by the 13-zone survey data.

Trips from each of the 13 zones to the Golden Triangle were isolated for both the O-D selected zone survey trips and the 13-zone calibrated gravity model distribution to determine if there was any geographical bias inherent in the gravity model distribution. Table 1 presents these data. Several attempts were made to relate the gravity model's deviation from the O-D to selected socio-economic data. Figure 3 shows the results obtained when the ratios of gravity model to O-D Golden Triangle-oriented movements were plotted vs zonal income. Although the plot shows a slight correlation between the ratios of the movements and zonal incomes, the correlation ($r = -0.71$) was not considered significant enough to form the basis for the development of adjustment factors.

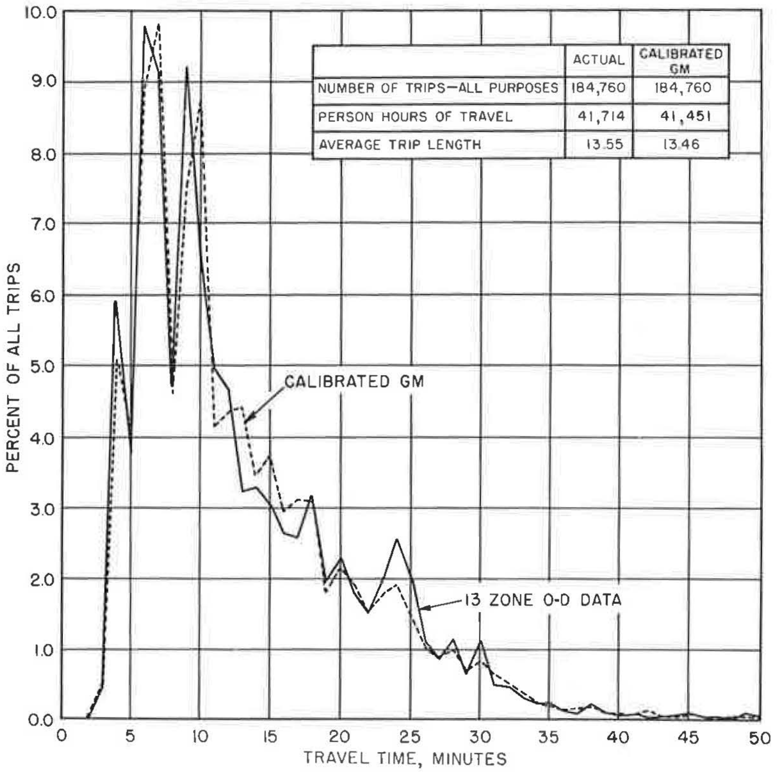

Figure 2. Trip length frequency for all trips, 13-zone data.

TABLE 1

SELECTED MOVEMENTS TO GOLDEN TRIANGLE; 13-ZONE GRAVITY MODEL DATA VS CLUSTERED SURVEY DATA

Zone of Origin	Home-Based Trips (No.)		Difference	
	Clustered Survey	Model	No.	%
10	2,409	3,375	966	40.1
13	2,450	3,595	1,145	46.7
28	1,324	2,136	812	61.3
37	2,086	1,983	-103	-4.9
61	2,471	1,319	-1,152	-46.6
68	2,161	1,364	-797	-36.9
73	2,353	932	-1,421	-60.4
83	593	418	-175	-29.5
93	1,092	711	-381	-34.9
149	764	642	-122	-16.0
155	282	453	171	60.6
169	835	433	-402	-48.1
187	320	261	-59	-18.4
Total	19,140	17,622	-1,518	-7.9

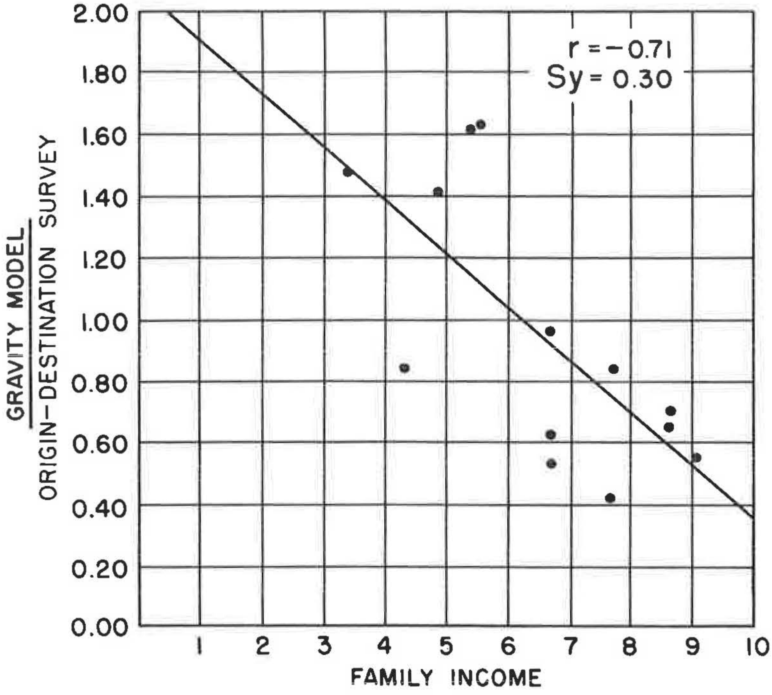

Figure 3. Differences in observed and estimated home-based trips from 13 selected zones to Golden Triangle related to mean family income per zone.

TABLE 2

SELECTED MOVEMENTS, CALIBRATED 13-ZONE GRAVITY MODEL DATA VS CLUSTERED SURVEY DATA

From	To	Home-Based Trips (No.)		Difference	
		Clustered Survey	Model	No.	%
South zones	North zones	1,962	1,981	19	1.0
North zones	South zones	2,650	3,135	485	18.3
South zones	East zones	13,114	11,217	-1,897	-14.5
East zones	South zones	6,017	6,298	281	4.7
East zones	North zones	2,138	2,476	338	15.8
North zones	East zones	8,907	11,269	2,362	26.5
North zones	North zones	21,281	18,434	-2,847	-13.4
South zones	South zones	33,169	35,047	1,878	5.7
East zones	East zones	66,239	65,620	-619	-0.9
North zones	Golden Triangle	4,687	6,410	1,723	36.8
South zones	Golden Triangle	7,758	6,104	-1,654	-21.3
East zones	Golden Triangle	6,695	5,108	-1,587	-23.7
Internal zones	External zones	4,501	4,337	-164	-3.6

If geographic bias, which showed a more direct numeric relationship to specific land-use or socio-economic characteristics, had been found, it would have been eliminated through the use of adjustment factors. These factors are represented by $K_{(i-j)}$ in the gravity model formulation (Eq. 1).

A comparison of selected movements was made to determine the accuracy of the model and to see if a time barrier was needed to bring river crossings into agreement with O-D data. Table 2 gives these data. The gravity model river crossing trips were not systematically high or low when compared with the O-D data and no time barrier was used. Several previous studies in other cities have shown the need for such a time barrier over rivers (10, 11).

Total Study Area Model Calibration

The total study area trip distribution for both the O-D and the gravity model had trip productions in all of the 226 internal zones and trip attractions in all of the 280 analysis units. The travel time factors developed using the 13-zone data were applied to total study area data. To eliminate error from other sources, the trip productions and attractions for all zones were taken directly from the 1958 O-D reportings. A new trip distribution was calculated and the trip length characteristics of this distribution were then compared with the 1958 O-D trip length characteristics. Figure 4 depicts the trip length distribution comparison for all trip purposes combined. The trip length curves were similar but the analysis indicated a definite need for further travel time factor calibration. This meant that the travel time factors developed from the clustered survey data were not sufficiently accurate when applied to the total study area.

A statistical comparison of district-to-district movements, given in Column (d) of Table 3, indicated significant differences between the 1958 O-D data and the clustered

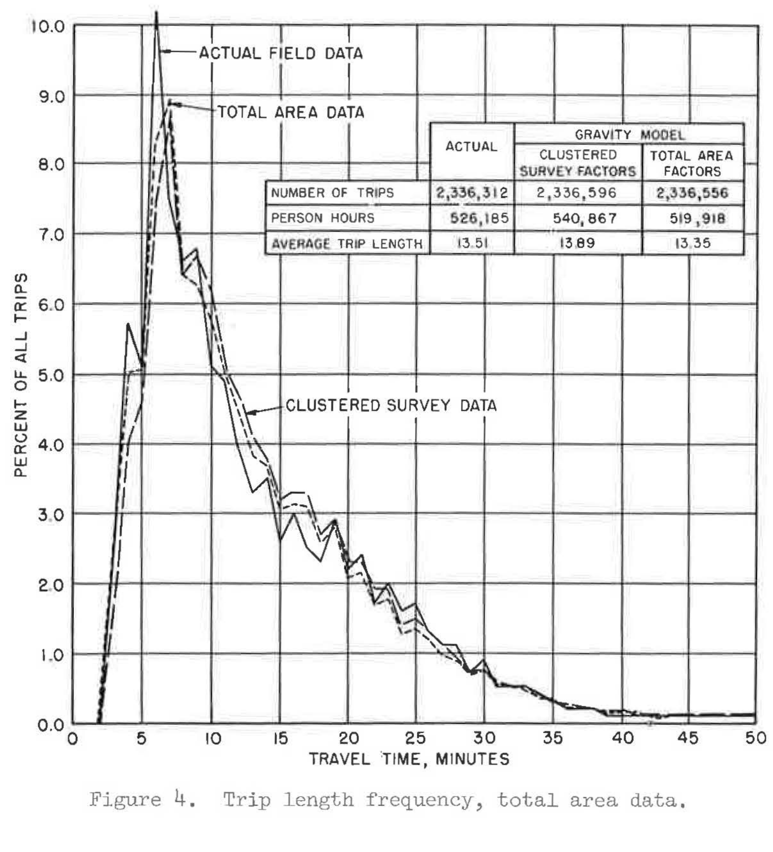

Figure 4. Trip length frequency, total area data.

TABLE 3

DISTRICT-TO-DISTRICT MOVEMENTS, PITTSBURGH, PA.

1958 Survey Data All Purposes			Percent RMS Error[a]				
			Trip Ends Based on				
			1958 Survey Data	1958 Survey Data	13-Zone Regression Est.	226-Zone Regression Est.	226-Zone Adj. Regression Est.
			Travel Time Factors Based on				
Volume Group	Mean of Volume Group	Frequency	13-Zone Study	226-Zone Study	13-Zone Study	226-Zone Study	226-Zone Study
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
0- 499	141	2,121	107.09	99.29	118.44	134.04	104.96
500- 999	698	261	53.72	50.72	65.90	62.46	53.72
1,000- 1,999	1,476	143	52.10	48.78	54.47	59.89	49.19
2,000- 2,999	2,451	81	42.80	42.15	40.43	47.00	41.33
3,000- 3,999	3,437	37	34.27	34.45	34.97	39.80	33.28
4,000- 4,999	4,373	21	38.74	40.04	47.82	39.42	42.35
5,000- 5,999	5,539	17	35.28	33.16	37.39	49.86	36.18
6,000- 7,999	6,797	20	28.83	29.56	29.66	50.62	30.74
8,000- 9,999	8,843	11	27.98	26.19	29.05	39.30	27.62
10,000-14,999	11,882	18	23.74	23.62	27.18	39.51	24.66
≥15,000-	31,159	22	21.07	16.08	21.83	26.08	17.89

[a]Percent RMS error $= 100 \left(\frac{\sqrt{\frac{\Sigma (\text{diff.})^2}{n}}}{\bar{x}} \right)$

where

diff. = difference between surveyed and estimated movements;
n = number of district-to-district movements; and
$\bar{x}$ = mean of survey volume.

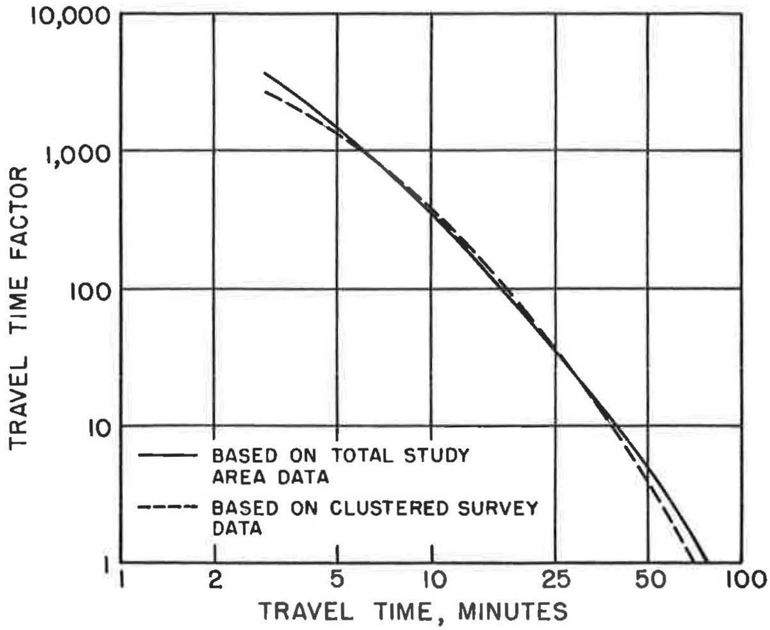

Figure 5. Home-based work travel time factors.

survey model results. The travel time factors were, therefore, adjusted using the trip data from the comprehensive 1958 O-D survey. The model calibration process was repeated until an acceptable relationship existed between the O-D and the gravity model trip length curves, mean trip lengths, and person hours of travel.

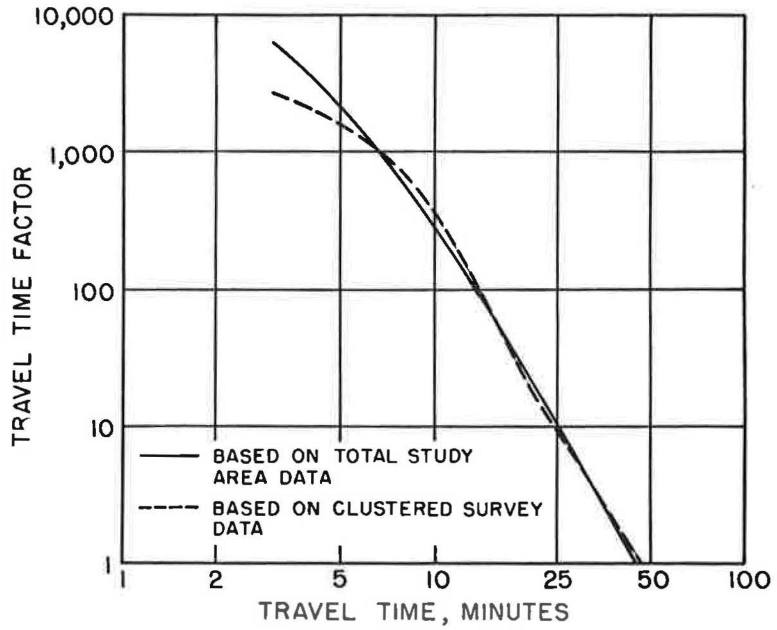

Figure 6. Home-based other travel time factors.

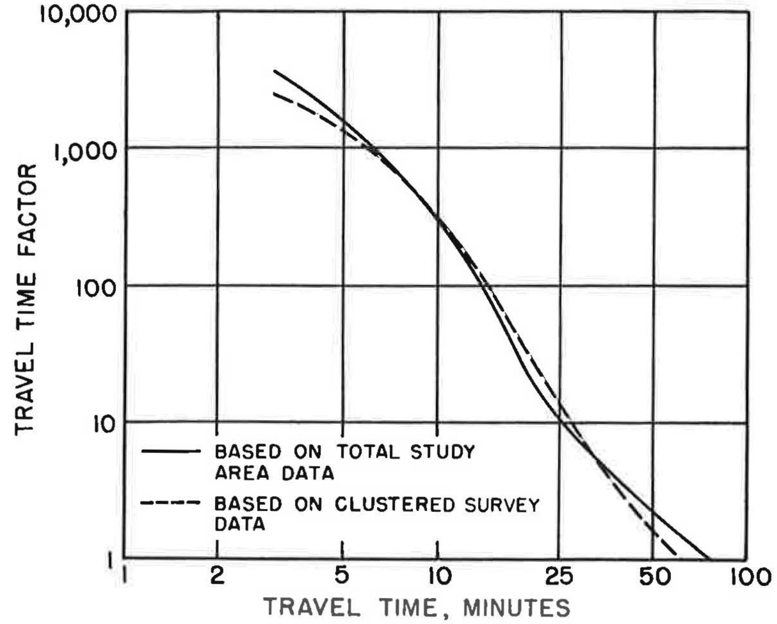

Figure 7. Home-based social and recreation travel time factors.

The travel time factors developed using 13-zone data and the revised set developed using total study area data are reflected in the curves in Figures 5 through 10. The significance of the differences between the two curves in each figure will be discussed later in this paper.

Figure 4 also illustrates the final agreement in trip length characteristics between the calibrated total area gravity model and the 1958 origin-destination survey data.

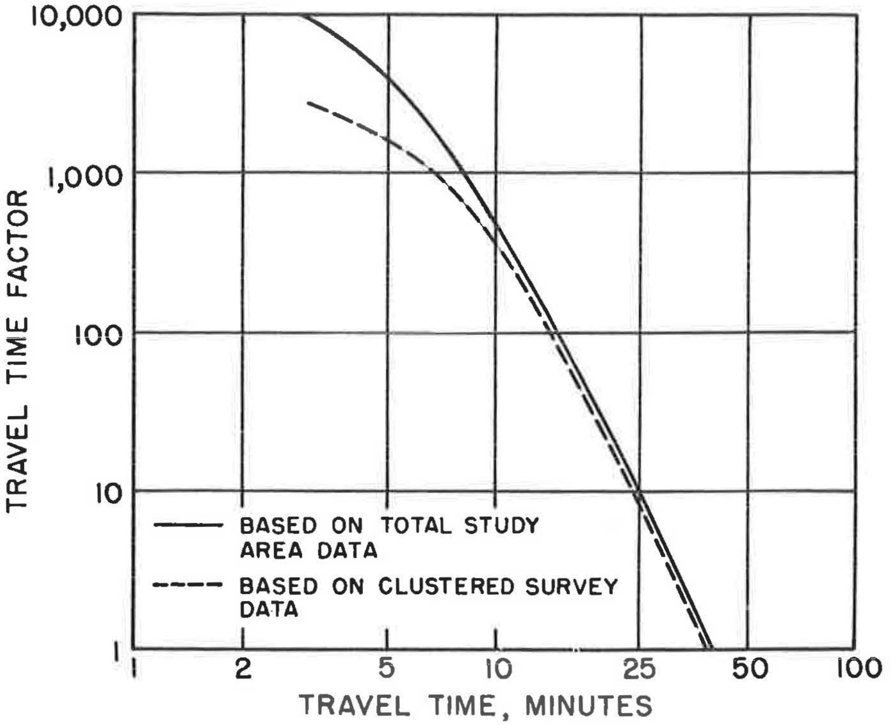

Figure 8. Home-based shop travel time factors.

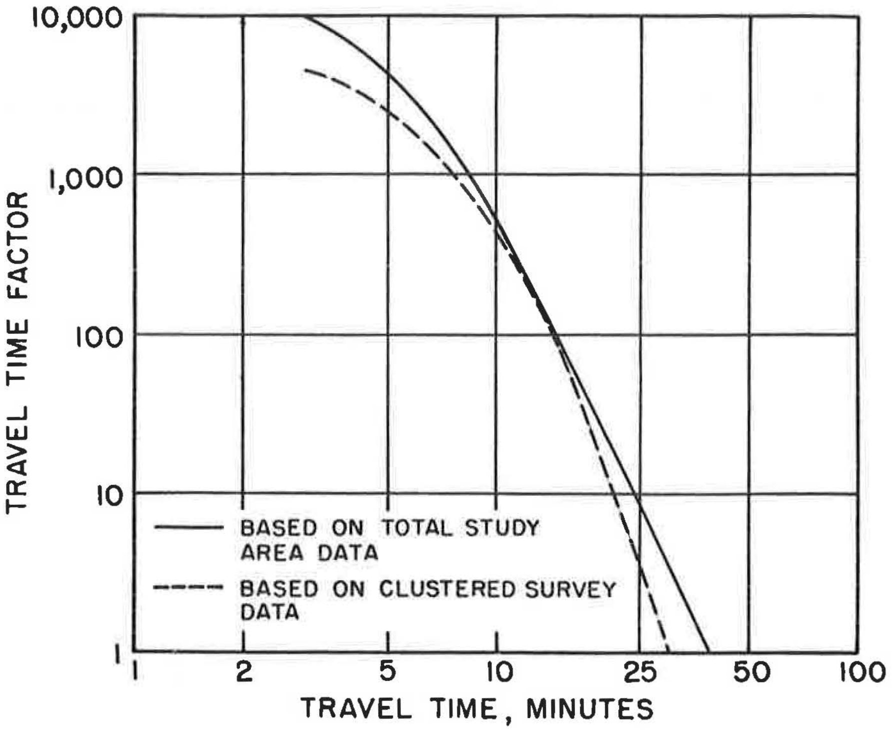

Figure 9. Home-based school travel time factors.

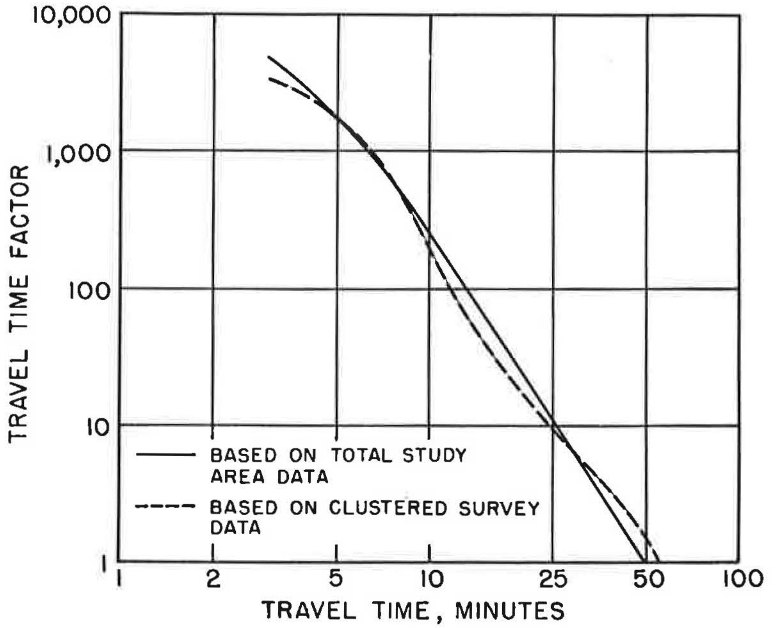

Figure 10. Nonhome-based travel time factors.

TABLE 4

SELECTED MOVEMENTS, CALIBRATED GRAVITY MODEL DATA VS 1958 HOME INTERVIEW DATA[a]

From	To	Total Trips (No.)		Difference	
		·1958 Survey	Model	No.	%
South zones	North zones	44,651	53,962	9,311	20.9
North zones	South zones	35,558	46,344	10,786	30.3
South zones	East zones	228,330	230,975	2,645	1.2
East zones	South zones	77,409	99,172	21,763	28.1
East zones	North zones	46,389	61,513	15,124	32.6
North zones	East zones	113,762	133,869	20,107	17.7
North zones	North zones	310,937	280,272	-30,665	-9.9
South zones	South zones	631,193	619,037	-12,156	-1.9
East zones	East zones	848,183	811,452	-36,731	-4.3
North zones	Golden Triangle	52,755	57,754	4,999	9.5
South zones	Golden Triangle	107,660	94,999	-12,661	-11.8
East zones	Golden Triangle	95,291	91,476	-3,815	-4.0
Golden Triangle	North zones	4,919	4,709	-210	-4.3
Golden Triangle	South zones	5,887	4,290	-1,597	-27.1
Golden Triangle	East zones	13,100	14,853	1,753	13.4
External zones	Internal zones	10,254	7,002	-3,252	-31.7
Internal zones	External zones	90,451	92,288	1,837	2.0
All zones	All zones	2,336,412	2,336,596	184	0.0

[a]Based on total study area data.

A statistical comparison of the differences in the district-to-district movements between the 1958 O-D and the calibrated gravity model is given in Column (e) of Table 3.

An analysis of selected movements for the O-D and the calibrated gravity model is given in Table 4. These values do not represent the maximum accuracy the total area model could attain. No attempt was made at this stage to perform a full river crossing or $K_{(i-j)}$ factor analysis. The calibration process was stopped because of the previously noted differences in the clustered survey and total area travel time factors.

TRIP PRODUCTION AND TRIP ATTRACTION ESTIMATES

Because trip productions and trip attractions are two of the key gravity model inputs, considerable time was spent in preparing these estimates and in subjecting them to statistical analyses. Indicators of zonal trip production such as residential density, car ownership, family size, and distance from the CBD were used for estimating trip production.

The trip attraction portion of the research study, however, was hampered by the fact that no data were available on zonal employment, school enrollment, or retail sales from either the 1958 or 1960 studies. These factors provide a basis for specifying nonresidential land-use intensity. They allow for a differentiation between, for example, a downtown office building, shopping area, or school and their suburban counterparts. Land area measurements alone do not reflect intensity of use. For example, a downtown office building on a 10,000-sq ft site may be 10 stories high and fill the entire site, whereas a two-story suburban office building may be located on a site of the same size and fill only one-half the site. Land area measurements would rate these sites equally.

One method by which trip attractions may be related to land use without a direct measure of intensity is through the use of a trip attraction rate analysis. For example, ratios of work trips attracted per acre of industrial land would be developed by individual zone or group of zones. These ratios are, in effect, measures of intensity. By making assumptions with respect to the stability of the ratios over time, these and similar ratios for other land-use activities could then be used to determine future trip attraction. The attraction estimate, therefore, would be based on a future land-use plan which would specify the projected areas of land-use types.

The PATS trip generation analysis did not require detailed measures of land-use intensity as it consisted of a study of land-use trip generation rates as the basis for trip end estimates. A study of trip generation rates, as opposed to a regression study, does not lend itself to a statistical analysis of its accuracy. It also requires an extensive knowledge of the study area. For example, large or specialized employment centers may be isolated for detailed analysis.

For these reasons, regression analysis was selected as the tool best-suited to the development of trip estimates for this research. In some of the trip attraction analyses, however, it was necessary to use modified ratio procedures because meaningful correlations could not be developed by regression analysis on the available data. Certain of these ratio trip attraction estimates, which exhibited high error when compared with O-D survey data, were arbitrarily adjusted to within preset limits of accuracy to make the final trip distribution analysis more meaningful. These preset limits were designed to yield trip attraction estimates with a level of accuracy that could be obtained had the land-use data been more complete and the research staff's knowledge of the study area more extensive. An indication of the type of accuracy to be expected was gained from analysis of data from other cities.

An alternative to either regression or ratio analysis is a procedure sometimes referred to as the synthetic procedure. This is particularly applicable when the trip attraction data are weak but the land-use data are reliable and extensive. In these instances, certain land-use or socio-economic indicators may be used directly as trip attractions. For example, total employment can be used to indicate work trip attraction, school enrollment for school trip attraction, and retail sales for shopping trip attraction. However, procedures such as these would require a detailed zonal analysis to account for such items as walk-to-work trips, school bus policy, and type of shopping center. Although the accuracy of this procedure is difficult to evaluate, it is more reliable than a regression analysis when data on trip attractions are insufficient.

The adjustment of the unsatisfactory attraction estimates was, in part, an attempt to match the type of accuracy that could be obtained by substituting selected land-use statistics (had they been available) directly for estimated trip attractions.

This portion of the research study made extensive use of the Bureau of Public Roads 1401 Regression Analysis Programs, consisting of a basic regression program, an equation solver, and a root-mean-square (RMS) error program. The latter program was used to calculate the accuracy of the 13-zone trip end estimates when applied to the total study area and of total study area estimates that were adjusted to eliminate negative trip production or trip attraction values.

Total Area Estimates Based on Study of 13 Zones

Trip Production.—Due to the high sampling rates, stable values of actual trip production by home-based purposes were available from the 1960 selected zone survey for each of the 13 zones. Regression analysis was used to relate these trip production values to land-use and socio-economic data for the zones. Six basic land-use and socio-economic variables, available for each of the 13 zones as well as for all remaining zones, were selected in a preliminary correlation analysis for use in this phase of the study. These were population, automobiles owned, residential acreage, nonwhite population, airline distance in miles from the CBD, and dwelling units. The number of variables was increased to 10 by using combinations and transformations of the basic variables.

Five equations were developed for each purpose by using varying combinations of independent variables. Two of these equations were then solved for each trip purpose using land-use and socio-economic data for all 226 internal zones. One set of equations had two independent variables and the other five. The five-variable equations had the lower standard errors of estimate based on the 13-zone dependent variable trip data but they showed higher RMS errors when applied to all 226 zones. The following two-variable equations were therefore selected for use in estimating trip production for each of the 226 zones:

$$\begin{aligned} Y_1 &= 2.6817 - 0.5045\,X_1 - 0.3812\,X_2 \\ Y_2 &= 1.5843 - 0.6584\,X_1 + 0.1205\,X_2 \\ Y_3 &= 0.7119 - 0.3503\,X_1 + 0.5374\,X_2 \\ Y_4 &= 1.7773 - 0.8095\,X_1 - 0.2639\,X_2 \\ Y_5 &= 0.7186 - 0.4638\,X_1 + 0.2154\,X_2 \end{aligned} \qquad (2)$$

where

Y_1 = home-based work trips produced per dwelling unit;
Y_2 = home-based other trips produced per dwelling unit;
Y_3 = home-based social-recreational trips produced per dwelling unit;
Y_4 = home-based shop trips per dwelling unit;
Y_5 = home-based school trips per dwelling unit;
X_1 = log of residential density; and
X_2 = car ownership.

The accuracy with which the selected equations estimate total trip production by purpose when compared to the O-D totals is given in Table 5. Although the total areawide home-based trip production estimate was 3.4 percent higher than the O-D value, the percent error by purpose varied from -20.5 to +21.6. The precision of the zonal estimates by trip purpose both before and after adjusting is given in Table 6.

It was not possible to develop nonhome-based trip production estimates by zone using the 13-zone data. The total nonhome-based productions from the 13-zone study amounted to 29,283 or slightly more than 100 trips per zone since they were produced in all

TABLE 5

PRECISION OF TOTAL HOME-BASED TRIP PRODUCTION ESTIMATES DEVELOPED FROM 13-ZONE DATA AND APPLIED TO TOTAL STUDY AREA

Trip Purpose	Trip Productions		Difference	
	1958 Survey	Clustered Survey Est.	No.	%
Work	796,646	813,761	17,115	2.1
Other	423,226	439,911	16,685	3.9
Social-rec.	292,195	355,226	63,031	21.6
Shopping	283,555	303,976	20,421	7.2
School	231,092	183,674	-47,418	-20.7
Total	2,026,714	2,096,548	69,834	3.4

TABLE 6

PRECISION OF ZONAL HOME-BASED TRIP PRODUCTION ESTIMATES DEVELOPED FROM 13-ZONE DATA AND APPLIED TO TOTAL STUDY AREA

Trip Purpose	1958 Survey Data		RMS Error[a]			
			Unadjusted		Adjusted	
	Mean	Std. Dev.	Abs.	%	Abs.	%
Work	3,525	2,698	735	20.85	723	20.51
Other	1,873	1,360	578	30.86	572	30.54
Social-rec.	1,293	997	661	51.12	543	42.00
Shopping	1,255	901	430	34.26	419	33.39
School	1,023	726	530	51.81	489	47.80

[a]Percent RMS error = $100 \left(\frac{\sqrt{\frac{\Sigma\,(\text{diff.})^2}{n}}}{\bar{x}} \right)$

where

diff. = difference between surveyed and estimate productions;
n = number of zones; and
$\bar{x}$ = mean of survey volume.

zones in the study area. A regression analysis showed that the 13-zone O-D nonhome-based trips were correlated with the 1958 O-D nonhome-based trips, as indicated by the correlation coefficient of +0.83. An examination of the data, however, showed that much of the variation in the two sets of data was due to bias in the vicinity of the 13 zones. Each of the 13 zones and the zones immediately surrounding them had a higher percentage of nonhome-based trip productions than shown by the total study area O-D data. Conversely, zones located at some distance from any of the 13 zones had a lower percentage of the nonhome-based trip productions. An alternate procedure was therefore developed which made use of the nonhome-based trip data from the 1958 O-D survey. Total areawide nonhome-based trips can be estimated from the 13-zone O-D data by relating these trips to the characteristics of the trip maker's zone of residence. A separate analysis must then be used to determine the zones of origin of these trips.

Trip Attractions.—Due to the lack of land-use or socio-economic data on zonal employment, school enrollment, or retail sales, etc., it was impossible to develop reliable trip attraction estimates using regression analysis. This was true even when the trip attraction data from the 1958 O-D survey were substituted for the 13-zone survey trip attraction data.

A further discussion of the 13-zone survey attraction data is warranted, however, since even if the land-use data had been sufficient the trip data would still present problems. The 13-zone trip attractions occur in all study area zones and are of low statistical significance numerically. More importantly, the distribution of trip attractions among the zones is highly biased by the location of the 13 zones. Therefore, a set of trip attraction estimates developed from the total area survey was substituted for the 13-zone trip attraction estimates.

Estimates Based on Study of All Zones

Trip Production.—This phase of the study made use of all available data, including 1958 O-D survey trips and all of the various land-use and socio-economic information. Regression analysis was used to estimate trip productions for all trip purposes. Several equations were developed and analyzed for each trip purpose. The selected equations and their standard errors of estimate (designated as ± values) are as follows:

$$\begin{aligned}
Y_1 &= -489.4913 + 0.2753\,X_1 + 0.3773\,X_2 + 0.6729\,X_3 \pm 521.0435\\
Y_2 &= 61.1273 + 0.0351\,X_1 + 0.0214\,X_2 + 0.8878\,X_3 \pm 551.5152\\
Y_3 &= 64.9557 + 0.0281\,X_1 - 0.0465\,X_2 + 0.6561\,X_3 \pm 542.6655\\
Y_4 &= 32.6220 + 0.0946\,X_1 - 0.3636\,X_2 + 0.7680\,X_3 \pm 379.1923\\
Y_5 &= 307.6413 + 0.1083\,X_1 - 0.6711\,X_2 + 0.7782\,X_3 \pm 491.8209\\
Y_6 &= 352.8010 - 0.4573\,X_1 + 2.0154\,X_2 + 0.0432\,X_3 \pm 1010.1590 \qquad (3)
\end{aligned}$$

where

Y_1 = home-based work trips produced per O-D zone;
Y_2 = home-based other trips produced per O-D zone;
Y_3 = home-based social-recreational trips produced per O-D zone;
Y_4 = home-based shop trips produced per O-D zone;
Y_5 = home-based school trips produced per O-D zone;
Y_6 = nonhome-based trips per O-D zone;
X_1 = population per O-D zone;
X_2 = dwelling units per O-D zone; and
X_3 = cars owned per O-D zone.

The precison of the estimates developed from these equations both before and after adjusting for the elimination of negative estimates is given in Table 7.

Trip Attraction.—A regression analysis was made using the available land-use data yielding estimates with standard errors of estimate given in Table 7. Because these standard errors of the regression estimates were unacceptably high, even after the estimates were adjusted for negative values, rates of trip attraction per unit of service acreage were developed by trip purpose for each district in the study area. The correlation analysis had shown that service acreage was the best single variable for estimating trip attraction for each of the six trip purposes. These attraction rates developed for each district were then applied to each zone in the district. These estimates were also very poor and were arbitrarily adjusted to within ±30 percent of the O-D values. The accuracy of these estimates both before and after adjustment is shown in Table 8.

TABLE 7

PRECISION OF TOTAL STUDY AREA REGRESSION ESTIMATES

Trip Purpose	1958 Survey Data		RMS error[a]			
			Unadjusted		Adjusted	
	Mean	Std. Dev.	Abs.	%	Abs.	%
			(a) Productions			
Home-based						
Work	3,525	2,698	521	14.78	509	14.44
Other	1,873	1,360	552	29.47	546	29.15
Social-rec.	1,293	997	543	42.00	537	41.53
Shopping	1,255	901	379	30.20	371	29.56
School	1,023	726	492	48.09	476	46.53
Nonhome-based	1,326	1,534	639	48.19	385	29.03
			(b) Attractions			
Home-based						
Work	3,355	6,721	3,745	111.62	3,200	95.38
Other	1,817	2,257	1,112	61.20	883	48.60
Social-rec.	1,191	1,254	690	57.93	587	49.29
Shopping	1,245	2,381	1,471	118.15	723	58.07
School	958	1,094	863	90.08	888	92.69
Nonhome-based	1,321	1,440	600	45.42	513	38.83

[a]RMS error of unadjusted regression estimates is equal to standard error of estimate.

TABLE 8

PRECISION OF TOTAL STUDY ATTRACTION RATE ESTIMATES[a]

Trip Purpose	1958 Survey Data		RMS Error			
			Unadjusted		Adjusted	
	Mean	Std. Dev.	Abs.	%	Abs.	%
Home-based						
Work	3,355	6,721	3,900	116.24	583	17.38
Other	1,817	2,257	1,252	68.90	497	27.35
Social-rec.	1,191	1,254	740	62.13	250	20.99
Shopping	1,245	2,381	1,520	122.09	246	19.76
School	958	1,094	974	101.67	212	22.13
Nonhome-based	1,321	1,440	650	49.21	269	20.36

[a]Estimates per origin-destination district based on 1958 trips per acre of land used for nongoods-handling activities serving both individuals and business.

COMBINED ANALYSIS—TRIP PRODUCTION, ATTRACTION AND DISTRIBUTION

The objectives of this phase of the study were (a) to evaluate the amount of error introduced into a gravity model trip distribution by the use of trip production and trip attraction estimates in the gravity model formulation, rather than trip production and trip attraction values taken directly from O-D data; and (b) to provide statistical measures of the accuracy of gravity model trip distributions calculated with parameters developed from 13-zone clustered survey trip data and from total study area trip data.

13-Zone Data

Two levels of areawide gravity model trip distribution accuracy for travel time factors were developed with 13-zone survey trip data.

1. The calibrated gravity model previously described used O-D trip ends (i.e., trip productions and trip attractions). The accuracy of this trip distribution when compared to the 1958 O-D on a district-to-district movement basis is given in Column (d) of Table 3.
2. A new gravity model trip distribution was calculated using the same travel time factors but with modified trip end input. The five home-based trip production purpose estimates were developed as previously described, using only 13-zone trip data and related land-use data for the entire study area. To develop nonhome-based trip productions and all trip attractions, it was necessary to use trip data from the 1958 survey. The accuracy of the trip production and trip attraction estimates is given in Tables 6 and 8, respectively.

The results of the gravity model trip distribution calculated with the travel time factors developed from 13-zone data and the trip end estimates developed partially from 13-zone data are given in Column (f) of Table 3. The increased error of the second distribution—Column (d) vs Column (f)—may be related entirely to the decreases in the accuracy of the trip production and trip attraction estimates.

Total Study Area Data

Three levels of trip distribution accuracy using the travel time factors were developed with total study area trip data and alternate trip production and trip attraction estimates.

1. The calibrated gravity model, which used O-D trip ends, was described previously. The accuracy of this trip distribution when compared to the 1958 O-D district-to-district movements is given in Column (e) of Table 3.
2. A gravity model was next run which used the same total study area travel time factors but with unadjusted regression estimates of trip production and trip attraction. Column (g) of Table 3 gives the accuracy of these estimates. This run was made to analyze the effect on trip distribution of trip attraction estimates that were significantly in error. The trip production estimates were satisfactory, but the trip attractions exhibited a high standard error. In addition, the error was biased with contiguous zones such as the CBD all under- or overestimated. The error in this trip distribution was the highest of any of the gravity models.
3. The trip attraction estimates used as input to the last run were adjusted by zone for the reasons previously discussed. The accuracy of these adjusted trip attraction estimates is given in Table 8.

The gravity model trip distribution was recalculated using as input parameters the total study area travel time factors, the regression trip productions, and the adjusted trip attractions. The accuracy of this distribution with respect to the O-D is given in Column (h) of Table 3.

SUMMARY

Trip Production and Trip Attraction Estimates

Home-based trip productions were estimated by zone for the entire study area using the clustered survey trip data. These estimates showed relatively minor losses in accuracy when compared to the regression estimates based on the 1958 O-D survey data. The percent RMS error of the zonal estimates of home-based trips developed from the clustered survey data was, on the average, approximately 5 percent greater than the percent RMS error of the zonal estimates based on trip data from the 1958 O-D survey. Areawide, total home-based trips were overestimated by 3.4 percent based on the clustered survey analysis. A statistical analysis of the total study area trip data showed that a random sample of the same size as the cluster sample would have estimated total study area trips within +1.7 percent (12).

Trip attractions for any purpose or the distribution of nonhome-based trip productions cannot be estimated from the clustered survey data. It must be assumed that if a clustered survey is used as the sole source of trip calibration data for a gravity model, synthetic trip end measures must be utilized. That is, specific land-use and socio-economic variables must be used as indices for the zonal distribution of trip attractions and for nonhome-based trip productions.

With a comprehensive survey, it might possibly be shown that the accuracy of these synthetic procedures is very high. However, the main disadvantage of these procedures is that there is no accurate means of checking the estimates without a complete home interview survey.

Travel Time Factor Calibration

Travel time factors developed with the 13-zone clustered survey trip data show significant differences when plotted and compared with the factors developed from the total study area data (Figs. 5 through 10). The differences are particularly significant for travel time values of less than 10 min. This portion of the travel time factor curve is used primarily to determine the number of intrazonal trips. A special analysis was made on intrazonal trips which showed that these trips were underestimated by 8.0 percent using only the 13-zone trips, but when the 13-zone factors were applied to the total study area, intrazonal trips were underestimated by 32.2 percent. In addition to variation in the upper portions of the curves, there was slope variation that was difficult to evaluate, but, in general, the total study area factors had steeper slopes.

Trip Distribution Accuracy

When the travel time factors developed using the 13-zone clustered survey data were applied to the total study area there was a loss in accuracy of the trip distribution as indicated in Table 3, Column (d) vs Column (e). The loss in accuracy was not significant enough to draw negative conclusions on the adequacy of clustered surveys, but it was significant enough to point up the value of the more accurate calibration data. The percent RMS error was 5 percent greater (21.07 vs 16.08) for trip volumes of 15,000 and over when the 13-zone factors were used as opposed to the total study area factors.

Socio-Economic Adjustments

The gravity model calibrated with the 13-zone data did not show a specific need for the use of socio-economic adjustment factors, $K_{(i-j)}$. However, if these factors had been necessary, there were not sufficient trip data from the clustered survey to establish them. The 1958 O-D trip data were extensive enough for a full $K_{(i-j)}$ factor analysis and for a meaningful river crossing analysis.

Full Gravity Model Trip Estimation

The combined analysis demonstrated that over the range of the larger trip volumes there was very little difference in the accuracy of the gravity model trip distributions when either O-D trip ends or trip end estimates were used as trip production and trip attraction. The analysis did demonstrate that when poor trip end estimates, such as the unadjusted regression attractions, were used as model input, a very significant decrease in accuracy resulted.

Adequacy of Clustered Samples

The clustered sample provided very stable trip volumes but did not provide good calibration data. An evaluation of the many study analyses would seem to indicate that one reason for the inadequacy of the clustered survey data is inherent in clustered sampling itself. The clustered survey trip attractions were biased by the location of the 13 zones. This bias had a direct effect on the travel time factors. The travel time factors developed from the total study area when compared directly with the 13-zone factors (Figs. 5 through 10) show higher travel time factors for the low time increments. If other parameters of the model remain fixed, these higher time factors mean that the total study area data place a higher weight on short trips than do the 13-zone data. If it is considered that the total study area data present a greater range of potential attractions, then it may be hypothesized that the travel time factors at the lower time intervals would have to be greater to keep the correct proportion of short trips.

The 13 zones selected for clustered sampling were chosen with the utmost care. During the course of the research work there was no reason to criticize the selection or to feel that a different set of 13 zones would have been more representative of the entire study area. The basic problem seemed to be the bias created by the fact that the clustered survey zones amounted to such a small portion of the total zones in the study area.

Further Research

The authors recommend that further research be undertaken on the reduction of data requirements for travel model calibration. They suggest that the most promising approach to this research would be to examine the adequacy of small systematic or random samples. This suggestion is not derived from any specific study finding, but rather from the general impression that any clustered survey data will be biased by the location of the selected zones. To eliminate this bias, the number of zones selected for interviewing would have to be increased to a point where the clustered sample would take on the characteristics of a systematic sample.

CONCLUSIONS

1. The clustered survey did provide sufficient trip data for the development of zonal estimates of trip production.
2. The clustered survey did not provide enough trip data for the development of trip attraction estimates.
3. The travel time factors developed from the clustered survey were significantly different from those developed with the total study area data.

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An Evaluation of Simplified Procedures for Determining Travel Patterns in a Small Urban Area

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This report presents the results of research aimed at calibrating and testing the gravity model for a small urban area. The first part deals with application of the gravity model theory to travel patterns in Sioux Falls, S. Dak. (population 62,000). A gravity model trip distribution formula was calibrated from comprehensive information on the area's travel patterns and related characteristics. The ability of this model to simulate the trip distribution patterns was investigated by comparing the gravity model movements with movements obtained from a standard origin-destination survey. In addition, investigations were made to check the effects of balancing trip attractions (as is customary in all traffic forecasting procedures) and to determine how many purpose categories are required in a small city to simulate adequately the existing travel patterns with a gravity model.

The second part of the report deals with investigation into the minimum amount of data required to calibrate a gravity model in a small urban area. For the past three years small sample home interview data have been used increasingly for calibrating traffic models in urban areas. Sample sizes ranging from 0.1 to 1 percent have been used in several transportation studies. Users of these small samples feel that the data collected provide sufficient information about an area's travel patterns for calibrating traffic models. They believe that these data can be used to develop the total universe of trips in an area, as well as the percentage of trips for each of the several trip purpose and travel mode categories. Furthermore, they think that these data yield sufficient information concerning the lengths of urban trips, an important parameter in the development of traffic models. However, in developing a traffic model, specific information on the numbers and types of trips beginning and ending in each zone of the study area must also be known. This information cannot be obtained from a small sample home interview. Consequently, some assumption must be made as to how the total universe of trip productions and trip attractions distribute themselves on a zonal basis. This research examines the validity of these various assumptions. The ability of several sample sizes (as low as 200 home interviews) to provide the needed parameters for calibrating traffic models is investigated and the minimum sample size required is calibrated. The ability of simplified procedures to establish zonal productions and attraction values from areawide trip production values obtained from the small sample surveys is also investigated. The paper then reports the results of using the minimum sample size and the estimated production and attraction values to calibrate a gravity model for Sioux Falls. All validity tests are made using comprehensive home interview survey data of large sample size.

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•SINCE THE early 1940's transportation planning studies have been conducted in urban areas throughout the country in an increasingly comprehensive manner. In most of these areas basic data on travel patterns, social and economic characteristics of trip makers, and the uses of land have been collected, and the type and extent of transportation facilities have been determined. The interrelationships between these various kinds of data have in turn been analyzed to the point that today several theories on urban travel are emerging. These theories are in the form of traffic models, or equations, composed of the various parameters which influence the generation and distribution of urban trips as well as the routes which these trips will traverse. One of the most widely used theories on urban travel is the gravity model theory which utilizes a gravitational concept to describe the distribution of trips between various parts of an urban area.

With the advent of travel models, the theory has been advanced that the need for basic data on travel patterns may be less now than before these models were developed. In the past four years, interest has grown in the use of small sample home interview data for calibrating traffic models, particularly the gravity model, in urban areas. For example, the Hartford Area Traffic Study (1) collected travel data from only 200, or 0.1 percent, of the dwelling units within the study area. The Southeast Area Traffic Study (2) collected such data from 1,384 or 2.0 percent of the dwelling units within its study area. Several other studies (3, 4) have used similar sampling rates. Although theories have been advanced concerning travel patterns and the desirability of reducing the amount of travel data to be collected, little has been done to quantify their accuracy and validity.

This research had two principal objectives. The first was to examine the ability of a calibrated gravity model to reproduce the trip distribution patterns in a particular small urban area. To achieve this objective, full use was made of comprehensive origin-destination survey data in calibrating the gravity model for the urban area under study. The ability of this calibrated gravity model to simulate the area's trip distribution patterns was then investigated by comparing the gravity model movements against movements from the O-D survey.

The second objective was to evaluate simplified procedures for calibrating a gravity model trip distribution formula for the same urban area. Instead of calibrating with all the available data, only that trip information available from the external cordon survey and from a subsample of the original home interview survey was used. Simplified procedures were used to determine productions and attractions from detailed socio-economic data. The ability of this calibrated gravity model to simulate the area's travel patterns was then investigated by comparing the resultant gravity model movements against the movements obtained from the standard O-D survey of the area.

The small urban area selected for this research was Sioux Falls, S. Dak. (population, 62,000). In 1956, a comprehensive home interview O-D survey was conducted in 12.5 percent of the area's nearly 20,000 dwelling units (5), the rate recommended by the U.S. Bureau of Public Roads (6) for urban areas of this size. The standard external cordon and truck and taxi surveys (5) were also conducted, as were surveys of the land use and the type and extent of the area's transportation facilities. Unpublished data on the capacity and level of service characteristics of Sioux Falls transportation facilities, retail sales figures by zone, and certain employment and labor force statistics were supplied by the South Dakota Department of Highways. Also available were the results of a 1960 parking survey (9). The study area was divided into 74 traffic zones with 10 external stations. For summary and general analysis, these zones and stations were combined into 28 districts (Fig. 1).

GRAVITY MODEL THEORY

The gravity model theory, its mathematical statement, and the five parameters for calculating trip interchanges from this statement have been discussed in detail by Bouchard and Pyers (11, p. 2). However, the results of the present study indicate that there is no need for the application of the zone-to-zone adjustment factors, $K_{(i-j)}$, in the case of Sioux Falls. The need for these factors seems to be more pronounced

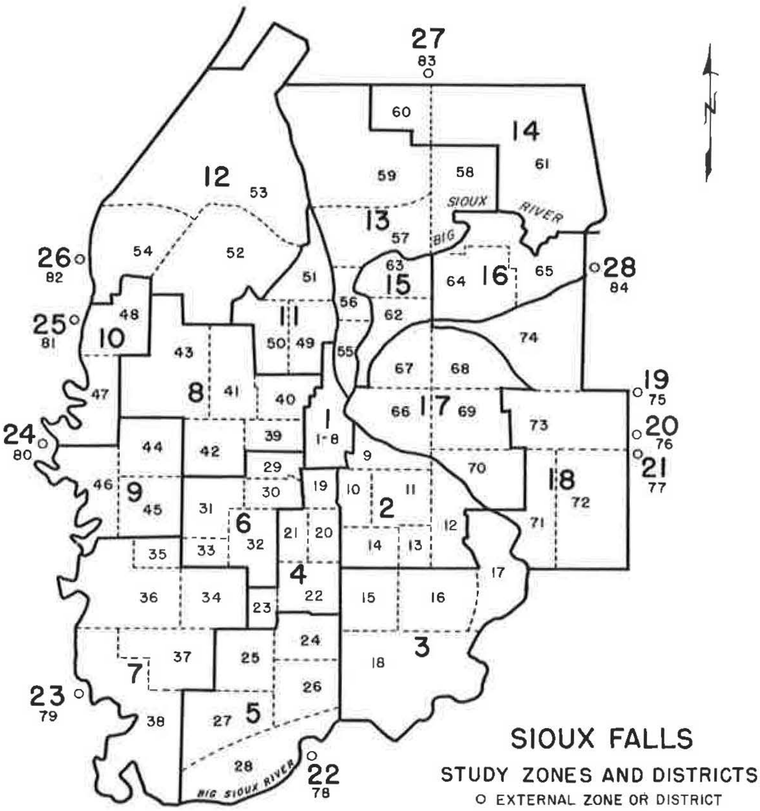

Figure 1. Zonal and district boundaries, Sioux Falls, S. Dak., study area, 1956.

in large urban areas where the range in various social and economic conditions of the residents is large.

TESTING THE GRAVITY MODEL THEORY FOR A SMALL URBAN AREA

This phase of the research deals with calibrating a gravity model from data obtained in the Sioux Falls O-D survey and testing the ability of this calibrated model to simulate the travel patterns found in the O-D survey. The steps involved in this phase were identical to those which have been completely documented in two recent publications by the U. S. Bureau of Public Roads (7, 8). These were essentially:

1. Processing basic data on the area's travel patterns and transportation facilities to provide three of the basic inputs to the gravity model formula, i. e., zonal trip production and attraction values and the spatial separation between zones;
2. Developing travel time factors, $F_{(t_{i-j})}$, to express the effect of spatial separation on trip interchange between zones;
3. Balancing zonal attraction factors, A_j, to assure that the trips attracted to each zone by the gravity model formula were in close agreement with those shown by the O-D survey data;
4. Examining these estimated trip interchanges to determine the need for adjustments to reflect various factors not directly accounted for in the model; and
5. Comparing the final gravity model trip interchanges with those from the home interview survey to test the ability of the model to simulate the 1956 travel patterns in the Sioux Falls area.

For this research, the total daily vehicular trips with either origins or destinations in the study area were used. Excluded from the study were trips which had neither their origins nor their destinations within the cordon (through trips) and all transit trips. The trips were stratified into the following categories: (a) home-based auto-driver work trips, (b) home-based auto-driver nonwork trips, and (c) nonhome-based vehicular trips.

The measure of spatial separation between zones (t_{i-j}) was composed of the off-peak minimum path driving time between zones plus the terminal time in the production and attraction zones connected with the trip. Terminal times were added to driving times at both ends of the trip to allow for differences in parking and walking times in the zones as caused by differences in congestion and available parking facilities.

Basic Data

All information from the home interview, external cordon, and truck and taxi surveys had previously been verified, coded and punched in cards. This information was made compatible as to meaning and location on the cards. The records were edited to insure that all pertinent information had been recorded correctly, and the edited records were then separated into the three trip purpose categories previously described. A table of zone-to-zone movements was then prepared for each trip purpose category. Each trip record was examined and all trips from each zone of production to every zone of attraction were accumulated. During this accumulation process the total number of trips produced by and attracted to each zone in the study area was also determined. These zonal trip production and attraction values were used to calculate trip interchanges with the gravity model formula. The zone-to-zone movements were subsequently used in testing the ability of the gravity model to simulate the 1956 travel patterns in Sioux Falls.

The data from the transportation facilities inventory had to be processed in the same way. This allowed the computation of the spatial separation between zones. Interzonal

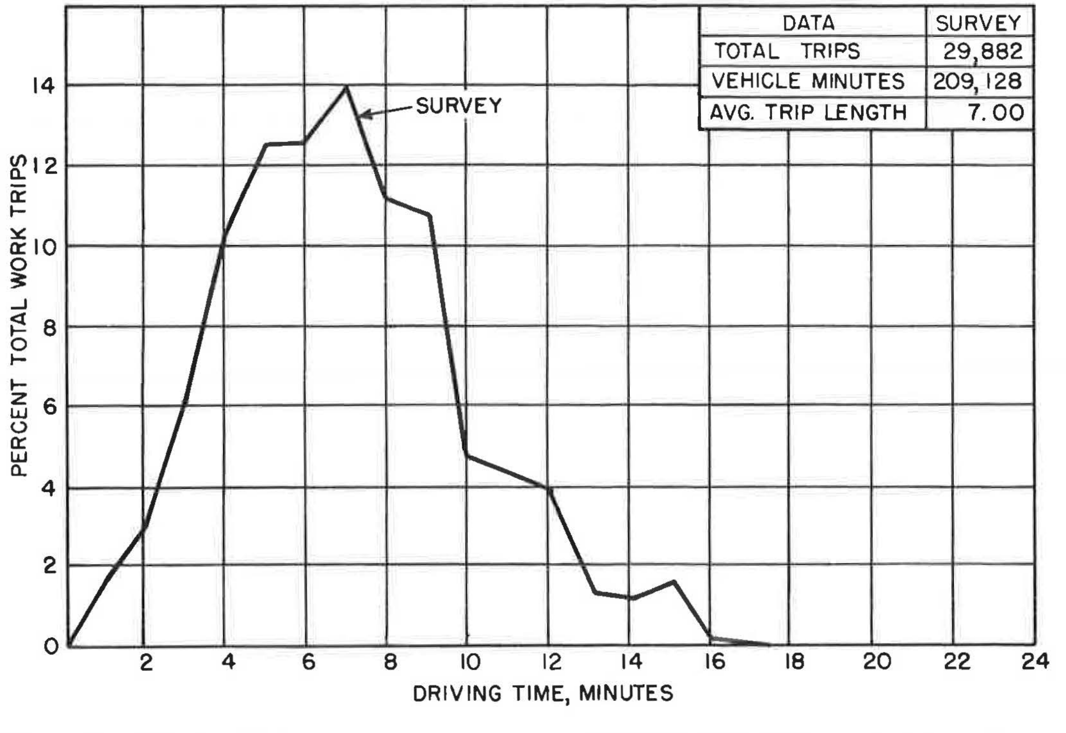

Figure 2. Trip length frequency distribution, home-based auto-driver work trips, Sioux Falls, 1956.

driving times were obtained from a description of the major street system in the area using a standard tree-building computer program. Intrazonal driving times were determined from an examination of the speeds on the highway facilities in each zone of the study area. Terminal times in each zone were determined by analyzing the results of the 1960 parking survey (9), which indicated to some extent the congestion and available parking facilities in each zone; central business district (CBD) zones were allocated 3 min and all other zones were allocated 1 min of terminal time.

Developing Travel Time Factors

The best set of travel time factors associated with each trip purpose was determined through a process of trial and adjustment. To determine travel time factors by this procedure, information is needed which reflects the effect of trip length on trip making. A useful summary of such information was obtained by determining the number and percent of trips for every minute of driving time for each trip purpose category. From the data on travel patterns, information was available on interzonal trips, and from the data on transportation facilities on driving times between zones. The trip length frequency distribution was obtained by combining the number of trips between each zone with the minimum path travel times between the zone pair, and repeating this process for all possible zone pairs. The resulting curve for work trips is shown in Figure 2. Table 1 summarizes this pertinent information for all trip purpose categories.

The procedure used was to assume a set of travel time factors for each trip purpose and to calculate trip interchanges using the gravity model formula, zonal trip productions and attractions and zonal separation information, obtained as previously described. The initial estimate of trip interchanges was then combined with the minimum time paths to obtain an estimated trip length frequency distribution for each trip purpose category. A comparison of the actual and the estimated trip length frequency distributions and the average trip length figures indicated close agreement. However, the discrepancies between the actual and the estimated figures were larger than desired by the research staff (±3 percent on average trip length with the frequency curves closely paralleling each other). Consequently, a revised gravity model estimate was made.

To make a revised estimate, new sets of travel time factors were calculated for each trip purpose category. The percentage of survey trips occurring during each minute of driving time was divided by the percentage of gravity model trips occurring during the same time increment, and the results of this division were multiplied by the initial factor. An example of this procedure is given in Table 2. These new factors were then plotted on log-log graph paper for the appropriate 1-min intervals for each trip purpose category, as shown in Figure 3. A line of best fit was drawn (by judgment) through the plotted points to obtain a smooth curve for travel time factors (Fig. 3).

TABLE 1

DISTRIBUTION OF VEHICULAR TRIPS BY PURPOSE
SIOUX FALLS, 1956

Purpose	No. of Trips	Veh-Min of Travel	Avg. Trip Length
Home-based work	29,882	209,128	7.00
Home-based nonwork	65,759	404,749	6.15
Nonhome-based	63,280	360,736	5.70
Total	158,921	974,613	6.13

TABLE 2

TRAVEL TIME FACTOR ADJUSTMENT PROCESS, WORK TRIPS

Driving Time	Percent Trips (Actual)	Travel Time Factor 1	Percent Trips (Est. No. 1)	Adj. Travel Time Factor[a]	Travel Time Factor 2[b]
1	1.68	162	1.24	219	220
2	2.93	152	2.12	210	210
3	6.09	142	4.88	177	185
4	10.28	132	10.32	131	150
5	12.61	122	13.49	114	125
6	12.57	112	13.62	103	110
7	13.91	102	13.26	107	100
8	11.22	092	11.26	92	085
9	10.91	082	11.42	78	079
10	4.20	072	6.04	50	067
11	4.40	062	5.33	51	061
12	3.98	052	3.52	59	057
13	1.53	042	1.56	41	050
14	1.34	032	1.09	39	048
15	1.70	022	0.74	51	045
16	0.04	012	0.08	06	010
17	0.01	0	0.04	0	002
18	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0

[a]From $\frac{\text{\% trips (actual)}}{\text{\% trips (est. No. 1)}}$ x travel time factor 1.

[b]From Figure 3.

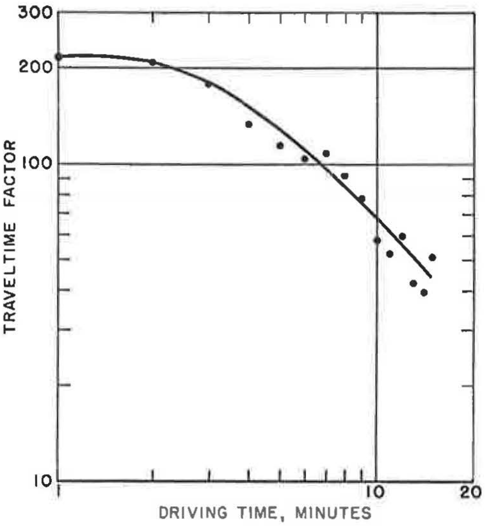

Figure 3. Determining revised travel time factors, work trips.

These new sets of travel time factors were then used in the same manner as in Calibration 1 to obtain a new estimate of trip interchanges with the model. New estimated trip length frequency curves, person hours of travel, and average trip length figures were developed and compared with the survey data. This comparison indicated that the gravity model estimates were within the established criteria. Consequently, the second estimate of travel time factors was judged to describe adequately the effect of spatial separation on trip interchange between zones in Sioux Falls. These final travel time factors are given for each trip purpose in Table 3.

Adjustment of Zonal Trip Attractions

The number of trips distributed by the gravity model to any given zone does not generally equal that shown by the O-D surveys as actually attracted to the zone,

TABLE 3

FINAL TRAVEL TIME FACTORS BY TRIP PURPOSE, SIOUX FALLS, 1956

Driving Time	Work	Nonwork	Nonhome-Based
1	220	280	300
2	210	260	270
3	185	220	210
4	150	160	120
5	125	130	100
6	110	090	080
7	100	085	070
8	085	070	060
9	079	060	055
10	067	050	044
11	061	039	038
12	057	035	032
13	050	027	030
14	048	025	026
15	045	021	023
16	010	016	014
17	002	000	005
18	000	000	000
19	000	000	000
20	000	000	000

because the gravity model formula does not have any built-in adjustment to insure such results. This variation in zonal attractions is a difficulty inherent in all currently available trip distribution techniques. Therefore, the trip attractions (A_j) for each zone were adjusted to bring the number of trips assigned to a given zone into balance with the trip attraction of that zone as determined by the survey.

Prior to balancing attractions, the estimated trip attractions resulting from Calibration 2 were compared with the actual attractions as shown by the survey to determine the differences. The two items of information for each zone were plotted for each trip purpose. An example for work trips is shown in Figure 4. A technique developed by Brokke and Sosslau (10) was used to judge the adequacy of the estimated figures. This earlier work established a reasonable approximation of the error that can be expected to result from O-D surveys of various sample rates, depending on the volume of trips measured. Curves developed to show the error in the survey volumes in terms of the root-mean-square (RMS) error, which is

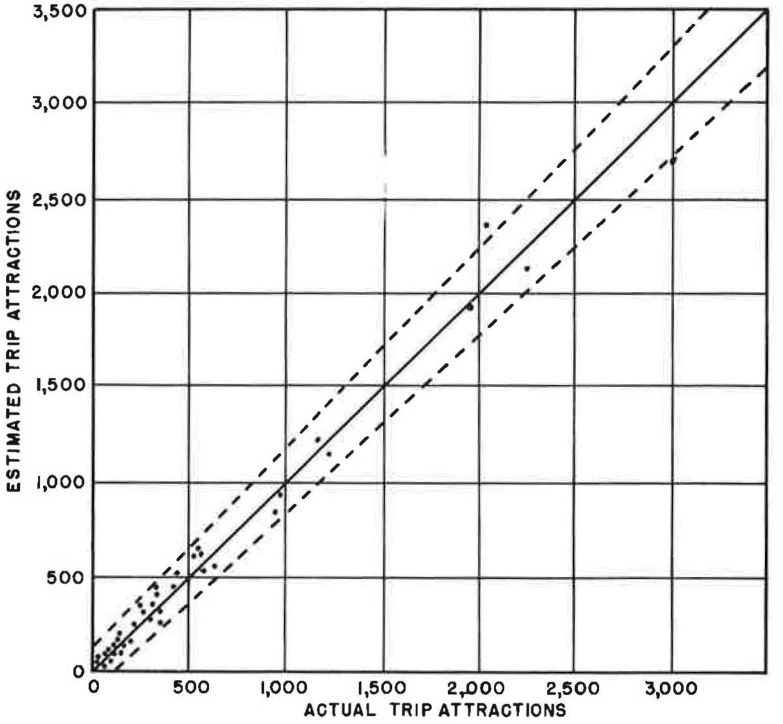

Figure 4. Comparison of work trip attractions, Calibration 2, Sioux Falls, 1956.

similar to the standard deviation, have been shown by Smith (16, Fig. 3). Two-thirds of the time (68.2 percent) the error in the origin-destination survey data, for a particular sample rate and volume group, will fall within one RMS error. Over 95 percent of the time, the recorded volumes will be within two RMS errors, and so forth. To determine the reliability (the degree of acceptability of the gravity model estimates) of the number of trips attracted to each zone in the study area, the RMS error for each volume group for the 12.5 percent sample rate was plotted as shown in Figure 4 and the points were connected by the dashed lines. If two-thirds of the points fall within these dashed lines, no adjustments are required. However, if less than two-thirds fall within these lines, all zonal attraction values should be adjusted. An examination of the results shown in Figure 4 indicated that the variations were small and entirely within the limits just described. The other two trip purposes showed similar results. Nevertheless, for purposes of this research, the zonal attraction values for each trip purpose were adjusted to obtain a more realistic measure of the error in the actual distribution of the trips. The adjustment was made by dividing the zonal trip attraction from the O-D survey by the trips attracted to each zone as developed by the gravity model and then multiplying the result by the original zonal trip attraction factor developed from the O-D survey. The amount of adjustment required for each trip purpose was relatively small. In most zones the adjustment was less than 10 percent and in no case was the adjustment greater than 20 percent. There was no discernible pattern in the required adjustment.

The gravity model interchanges were then recalculated using the adjusted zonal attraction values. The slight differences in this information between Calibrations 2 and 3 indicated that the zonal attraction factor adjustment had very little effect on the variation. Part of this, of course, can be explained on the basis of the rather small adjustments which were required to balance the zonal adjustment factors for each trip purpose. The results of this third and final calibration in terms of the trip length frequency distribution and the average trip length for work trips are shown in Figure 5.

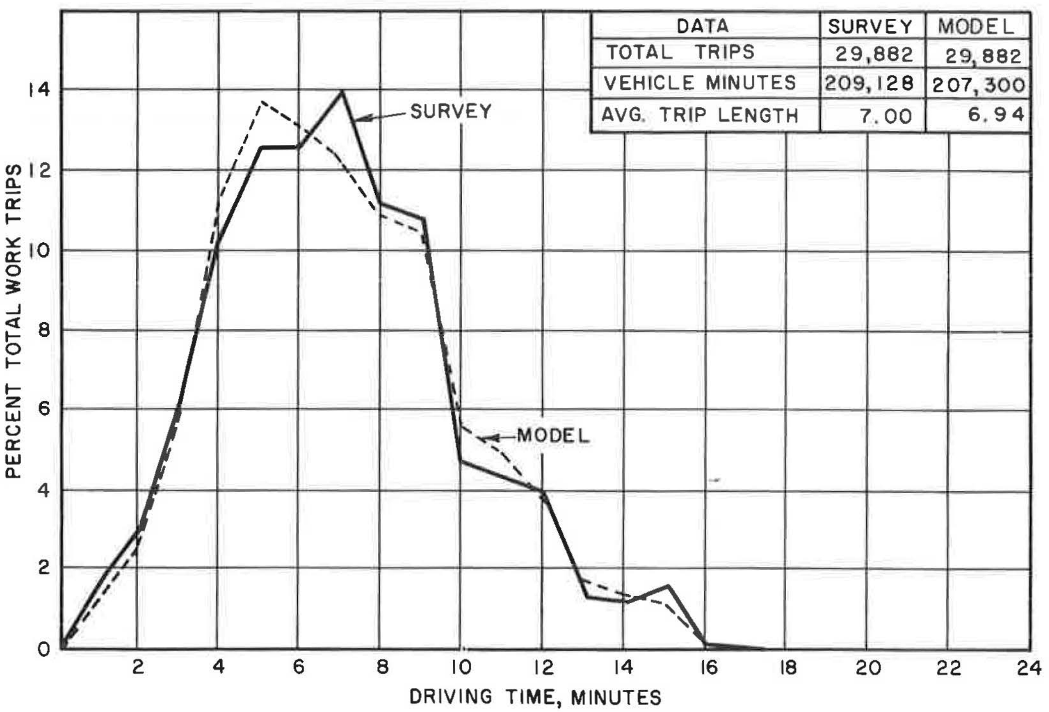

Figure 5. Trip length frequency distribution, home-based auto-driver work trips, Sioux Falls, 1956.

To investigate the effect of the zonal attraction factor adjustment on actual trip interchanges, the district-to-district movements were examined for both the second and third calibrations. District-to-district movements, rather than zone-to-zone movements were used in this analysis to obtain a more meaningful accumulation of trips. The results of this analysis for work trips, shown in Figure 6, were quite similar for the other two trip purposes although the dispersion was somewhat more pronounced. However, in no case was the dispersion greater than 15 percent. An examination of this information indicated that the attraction adjustment procedure had only a small effect on trip interchanges.

Checking Model for Geographical Bias

In using the gravity model, several researchers have discovered the need for various adjustment factors to account for special conditions within an urban area which affect travel patterns but are not accounted for in the model. For example, a recent study in Washington, D. C., indicated that the Potomac River had some influence on trip distribution patterns (11). A study in New Orleans, La., indicated similar problems connected with river crossings (12). A study in Hartford, Conn., indicated that toll bridges crossing the Connecticut River also had an effect on travel patterns (1). In each of these cases, the effects of these conditions were indicated to the gravity model by time penalities on those portions of the transportation system for which discrepancies in the model were observed. In addition, some studies have indicated geographical bias caused by factors other than topographical barriers. For example, the Washington, D. C., study showed the need for adjustment factors to account for a rather unique relationship existing in that area. Before incorporating the adjustment factors into the gravity model formula, the estimated trip interchanges were significantly biased in

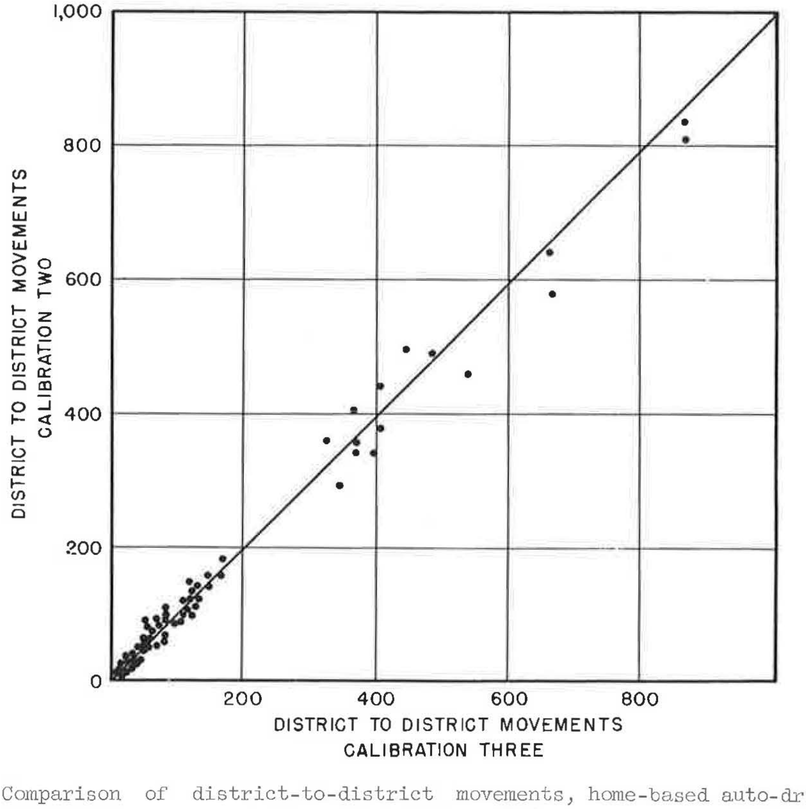

Figure 6. Comparison of district-to-district movements, home-based auto-driver work trips, Sioux Falls, 1956.

that the model did not adequately account for the fact that medium income blue collar workers residing in certain parts of the Washington area had no job opportunities within the central parts of the area. If work trips had been further stratified, perhaps the need for adjustment factors would have been reduced.

Several tests were conducted on the results of Calibration 3 to determine the need for adjustment factors such as those just described. One of these tests involved the Big Sioux River which bisects the Sioux Falls area as shown in Figure 1. For those trips crossing the Big Sioux River, the total trip interchanges as shown by the home interview survey were compared directly with the results of the gravity model. In addition, both of these items were compared with volume counts taken on all the bridges crossing this river. As indicated in Table 4, there is a very close agreement between these three sources of information; this indicates that the Big Sioux River is no barrier to travel.

Another test for geographical bias was conducted for trips to the CBD of Sioux Falls. Trips from each district to the CBD, by trip purpose, as shown in Calibration 3 of the gravity model were compared directly with the same information from the O-D survey. These results are shown in Figures 7, 8, and 9. An analysis of these figures indicates that no significant bias is present in the model and, furthermore, the gravity model estimates are close to the O-D survey.

Final Results

The total trips resulting from the final calibration of the gravity model and from the O-D survey were assigned to the transportation network. An examination of the results of these two assignments was made by comparing the number of trips crossing a very comprehensive series of screenlines. Figure 10 shows this comprehensive series of screenlines and also identifies each screenline. Table 5 compares the actual and estimated trips crossing each of these screenlines. An examination of the absolute and the percent differences between the actual and the estimated screenline crossings indicated only four differences larger than 10 percent and none which have absolute volume discrepancies large enough to affect design considerations.

One final test was made to determine the statistical significance of the differences between the gravity model estimates and the O-D survey data. The results of this test are given in Table 6. When these results were compared with the O-D survey error (10), the gravity model estimates had almost the same degree of reliability as the O-D survey data.

TABLE 4

COMPARISON OF TOTAL VEHICULAR TRIPS CROSSING BIG SIOUX RIVER, SIOUX FALLS, 1956

Facility	Trips (No.)		
	Vol. Count	O-D Survey	Gravity Model
Cherry Rock Ave.	1,511	1,640	1,660
Cliff Ave., S.	9,132	8,420	9,444
Tenth St.	14,842	16,296	16,648
Eighth St.	8,606	6,612	6,080
Sixth St.	3,864	2,900	3,576
McClellan St.	3,069	2,596	2,032
Cliff Ave., N.	4,699	4,156	3,904
Totals	45,723	42,620	43,344
Percent from Vol. Count	-	-6.8	-5.2
Percent from O-D Survey	+7.3	-	+1.7

The tests and comparisons shown in this section of the report indicate that the calibrated three purpose gravity model adequately simulates the trip distribution patterns shown by the O-D survey. Nevertheless, it is desirable to have a measure of the differences in the results which would have been obtained for lesser and higher degrees of trip stratification than the three purposes used in this research. To date, little has been done to investigate these differences. The analysis to be outlined is not conclusive, but it does shed considerable light on the subject.

The analysis procedure was as follows. Gravity models were calibrated for the following trip purpose stratifications:

1. One purpose model—total vehicular trips; and
2. Six purpose model—home-based auto-driver work trips, home-based auto-

driver shop trips, home-based auto-driver miscellaneous trips, home-based auto-driver social-recreation trips, nonhome-based vehicular trips, and truck and taxi trips.

The same techniques and the same number of calibration runs were made in these two models as were made in calibrating the three purpose model. The same tests were also performed on these models as on the three purpose model with about the same degree of accuracy. Table 5 gives the absolute and percentage differences between the model and survey trips crossing the comprehensive series of screenlines (Fig. 10) for one purpose, three purpose, and six purpose models. Results indicate that the three purpose model is better than the one purpose model, but the increased accuracy obtained with a six purpose model is only slightly greater than with a three purpose model.

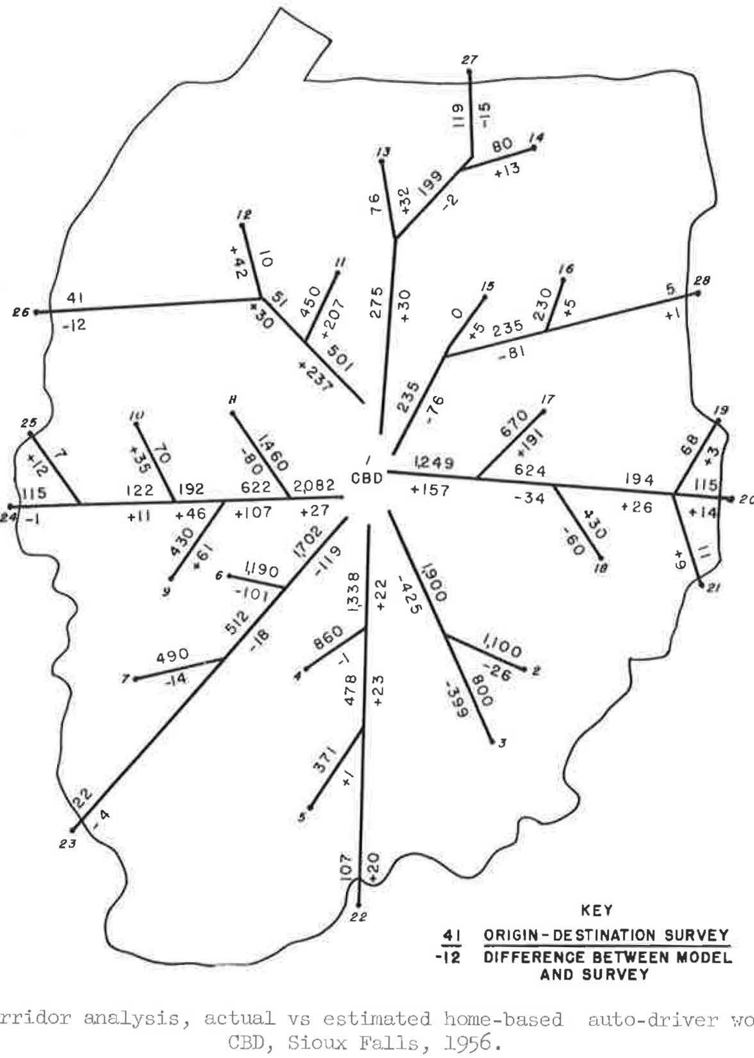

Figure 7. Corridor analysis, actual vs estimated home-based auto-driver work trips to CBD, Sioux Falls, 1956.

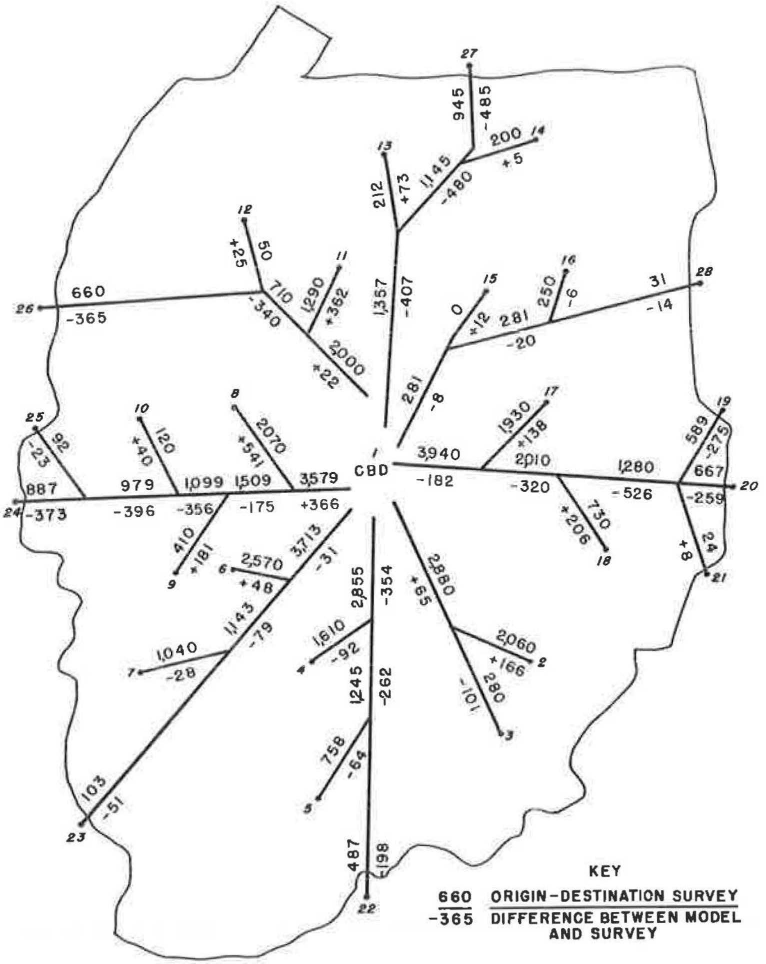

Figure 8. Corridor analysis, actual vs estimated home-based auto-driver nonwork trips to CBD, Sioux Falls, 1956.

USE OF SIMPLIFIED PROCEDURES FOR DETERMINING TRIP DISTRIBUTION PATTERNS IN A SMALL URBAN AREA

The previous phase of this research illustrated that the gravity model formula can be used to simulate trip distribution patterns in a small urban area when comprehensive home interview data are available for use in developing the model to fit the area's travel patterns. The research reported in this section examines the feasibility of reducing the amount of data necessary to develop the gravity model. Since in developing the gravity model for Sioux Falls, no significant geographical bias was observed, it was not necessary to make use of all the data available for the area. This led to an exploration of smaller samples of data for calibrating the gravity model. This phase of the research was accomplished in the following steps.

1. The minimum sample size of home interview survey required to provide the information necessary to develop the gravity model formula for Sioux Falls was determined. Since the previous phase of this research illustrated that information on zonal trip production and attraction and a trip length frequency distribution of trips, by trip

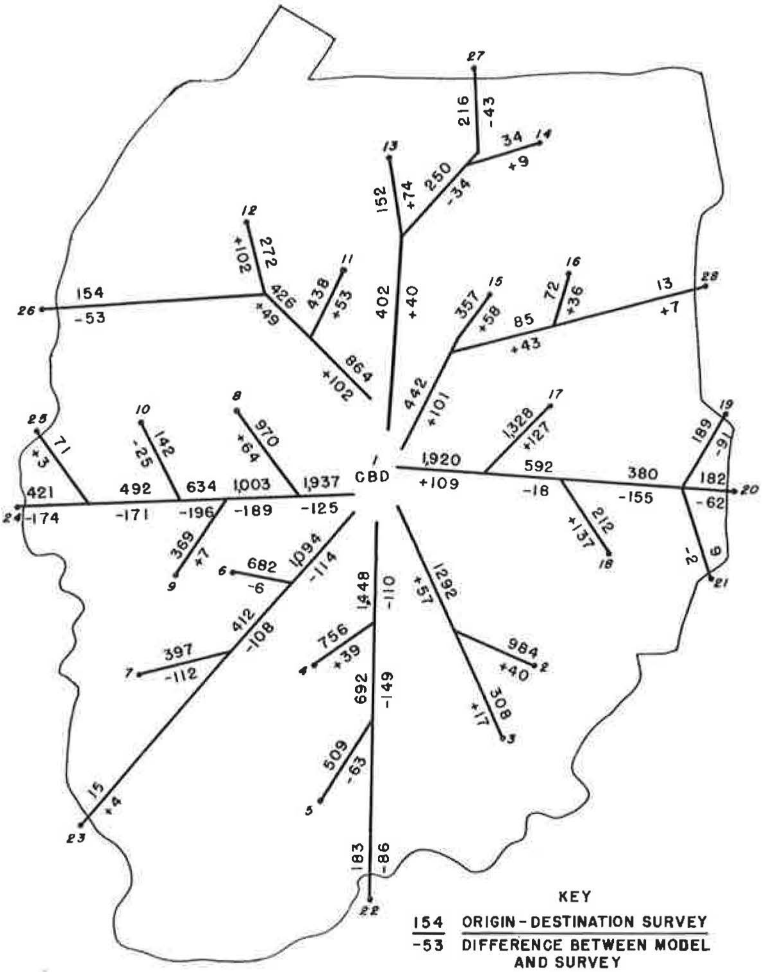

Figure 9. Corridor analysis, actual vs estimated nonhome-based vehicular trips to CBD, Sioux Falls, 1956.

purpose, was all that was required for a gravity model calibration, the small sample data must provide sufficient information to develop these parameters. This step involved an analysis of subsample data from several urban areas and the development of curves that could be used to determine the relative error which would occur for different size samples.

2. Zonal trip production and trip attraction values for each trip purpose were estimated using the total trips expanded from the small sample, their split among the various purposes, and certain social and economic characteristics of each individual zone. Zonal trip production and attraction values were developed in this manner because they are not available from small sample data, and they were compared directly with the data from a comprehensive O-D survey to determine the reliability of the techniques used.

3. Trip interchanges for each trip purpose were determined using the results of the previous two steps and the gravity model formula. The synthetic trip distribution patterns were then compared directly with the O-D survey results.

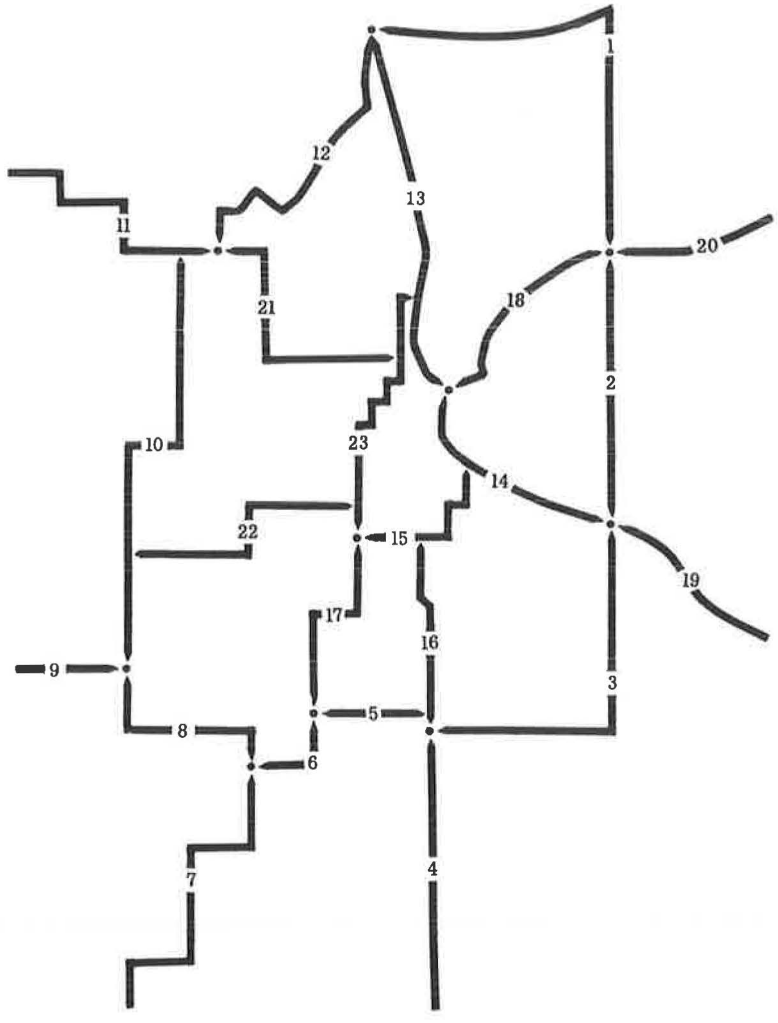

Figure 10. Location and identification of comprehensive series of screenlines, Sioux Falls, 1956.

Determining Overall Travel Characteristics from Small Sample

It has been reported by studies using small sample home interview surveys that the data collected in such surveys are adequate for calibrating a gravity model (1, 2). Those using small sample home interview surveys in the past have reported that the resulting data can be used to develop the total number of trips in the area, as well as the percentage of trips for each of the several trip purposes and travel mode categories. Furthermore, they indicated that these data gave sufficient information concerning the length of urban trips, an important parameter in the development of travel models.

There is some evidence available to substantiate these reports. For example, a recent study by the Connecticut Highway Department compared the total universe of trips as well as the percentages of trips for each of three trip purposes for subsamples of 153 and 592 home interviews. These subsamples were drawn from an original field sample of 1,384 home interviews taken in the Southeast Area Traffic Study. Some of the results of this study, given in Table 7, indicate that samples as low as 600 interviews may give approximately the same results for total trips by trip purpose as the

TABLE 5

TOTAL TRIPS CROSSING SCREENLINES, SIOUX FALLS, 1956

Screenline No.	O-D Survey Vol.	One Purpose Model		Three Purpose Model		Six Purpose Model	
		Vol.	Diff. from O-D (%)	Vol.	Diff. from O-D (%)	Vol.	Diff. from O-D (%)
1	7,952	6,996	-12.0	7,344	- 7.6	7,440	- 6.4
2	21,012	20,580	- 2.1	20,460	- 2.6	20,552	- 2.2
3	13,516	14,216	+ 5.2	13,900	+ 2.8	13,222	- 2.2
4	11,384	12,344	+ 8.4	12,060	+ 5.9	11,956	+ 4.2
5	9,744	9,332	- 4.2	9,252	- 5.0	9,336	- 5.0
6	8,784	9,500	+ 8.2	9,392	+ 6.9	9,444	+ 7.5
7	6,280	6,788	+ 8.1	6,824	+ 8.7	6,852	+ 9.1
8	6,568	6,984	+ 6.3	7,032	+ 7.1	7,152	+ 8.9
9	2,264	2,772	+22.4	2,676	+18.2	2,648	+17.0
10	17,448	17,808	+ 2.1	17,592	+ 0.8	17,668	+ 1.3
11	5,868	6,468	+10.2	6,532	+11.3	6,704	+14.2
12	5,592	6,484	+16.0	6,412	+14.7	6,392	+14.3
13	13,656	13,660	0.0	14,840	+ 8.7	13,924	+ 2.0
14	22,908	25,096	+ 9.6	23,040	+ 0.6	22,720	- 0.8
15	33,220	31,400	- 5.5	32,144	- 3.2	34,005	+ 2.4
16	10,032	10,736	+ 7.0	10,012	- 0.2	10,120	+ 0.8
17	13,424	14,016	+ 4.4	13,760	+ 2.5	14,012	+ 4.4
18	9,724	10,324	+ 6.2	10,276	+ 5.7	10,424	+ 7.2
19	10,060	11,352	+12.8	11,044	+ 9.8	11,092	+10.3
20	5,332	5,240	- 1.7	5,420	+ 1.6	5,556	+ 4.2
21	8,496	9,056	+ 6.6	9,136	+ 7.5	9,200	+ 8.3
22	13,332	14,612	+ 9.6	14,504	+ 8.8	14,672	+10.0
23	41,500	40,660	- 2.0	41,852	+ 0.8	39,995	- 3.6

1,384 interviews originally made in the field. The 1,384 sample, used as a base, is small and it must be realized that it contains inherent sampling error. This same study also compared the trip length frequency distributions and average trip lengths for the same trip purposes and sample sizes. The results for work trips (Fig. 11) show that the trip length frequency distributions and mean trip lengths are very similar for the 1,384 and 592 sample sizes, with the 592 interviews being about as adequate as the 1,384 interviews. The same data for the 153 samples show significant error.

A recent study in North Carolina (14) compared the total trips and trip percentages for three trip purposes for subsamples of 192, 196, 248, 383, and 742 home interviews drawn from an original field sample of 1,457 home interviews taken in Fayetteville, N.C. Some of the results of this study (Table 8) indicate that samples as low as 600 might give approximately the same results for total trips by purpose as the 1,457 original interviews. This study also compared the trip length frequency distributions (Fig. 12) and mean trip lengths. These figures were very similar for the 1,457 and 742 sample sizes. A sample size greater than 383 was necessary for an adequate mean trip length reproduction.

A similar study, recently completed by the Urban Planning Division of the U.S. Bureau of Public Roads, examined the variation in total trips, purpose split, average trip lengths, and trip length frequency distributions for subsamples of 2,021 and 404 interviews. These subsamples were from an original field survey of 16,169 home interviews taken during the Pittsburgh Area Transportation Study. Table 9 gives the total sample figures and the results of the comparisons of total trips and purpose split for each subsample. Figure 13 illustrates the trip length frequency distributions and the mean trip length figures for one of the six purposes in each of the sample rates tested. This information indicates that small samples yield adequate data on these overall travel characteristics, but the minimum sample rate shown by the Pittsburgh study appears to be around 2,000 interviews, as compared with about 600 interviews in the Connecticut and North Carolina studies. The Pittsburgh analysis used person

TABLE 6

COMPARISONS OF DISTRICT-TO-DISTRICT MOVEMENTS[a]

Volume Group	O-D Survey Trip		RMS Error	
	Mean	Freq.	Abs.	Percent
(a) Home-Based Auto-Driver Work Trips				
0- 99	21	400	17	80.95
100- 199	133	40	47	35.34
200- 299	259	13	87	33.59
300- 499	402	13	85	21.14
500-1,499	920	8	166	18.04
(b) Home-Based Auto-Driver Nonwork Trips				
0- 99	27	423	24	88.89
100- 199	136	53	83	61.03
200- 299	239	28	87	36.40
300- 499	380	22	112	29.47
500- 999	728	22	231	31.73
1,000-2,999	1,711	9	276	16.13
(c) Nonhome-Based Auto-Driver Trips				
0- 99	25	473	22	88.00
100- 199	144	62	63	43.75
200- 299	241	30	100	41.49
300- 499	385	33	101	26.23
500- 999	773	9	119	15.39
1,000-4,999	1,695	9	263	15.52

[a]1956 O-D survey data vs gravity model estimates, relative difference measured in terms of percent RMS error:

$$\text{Percent RMS error} = 100\left(\frac{\sqrt{\frac{\Sigma\,(d)^2}{n}}}{\bar{x}}\right)$$

where

d = difference between surveyed and estimated,
n = number of district-to-district movements, and
$\bar{x}$ = mean of surveyed trips.

trips, whereas the other two studies used auto-driver trips. The results appear consistent since the Pittsburgh analysis stratified trips six ways and the Connecticut and North Carolina analyses used only three trip stratifications.

Several subsamples of the Sioux Falls home interview data were also examined for their ability to yield accurate figures on total trip productions, average trip lengths, and trip length frequency distributions by trip purpose. The results of these analyses for 599 and 199 dwelling unit subsamples and the original 2,399 field samples appear in Table 10 and Figures 14, 15, and 16. These results reinforce the findings of the previously mentioned studies which indicate that samples as small in number as 600 can be used to determine the overall average characteristics of travel in a small urban area, when three trip stratifications are used.

The results for the Sioux Falls analytical subsamples were analyzed to see if general curves could be developed to approximate the error which would occur in mean trip length and total trips by trip purpose and trips per dwelling unit for various sample sizes. The curves which were developed from the relationship between the standard deviation of the mean and the square root of sample size are shown in Figures 17 and 18. They give the expected error which would occur in the indicated parameters for various sample sizes, based on the known variance in the trip data.

A statistical analysis of the ability of small samples to adequately estimate trip production and average trip length characteristics in the Pittsburgh, Pa., study area has also been made. The results of this analysis, shown in Figures 19 and 20, indicate the reliability of small sample home interview surveys in determining the overall travel characteristics of an urban area.

The research discussed in the next section of this report is based entirely on the sample size analyses. It utilizes the results of the 599 subsample of the Sioux Falls home interview survey and the standard external cordon survey in calibrating a synthetic gravity model.

Determining Zonal Trip Production and Attraction Values

As stated earlier, two of the basic parameters required to estimate trip interchanges by the gravity model formula are the number of trips produced by each zone and the number of trips attracted to each zone for each trip purpose category. This information cannot be obtained directly from a small sample home interview. Consequently, some assumption has to be made as to how the total number of trip productions and trip attractions distribute themselves on a zonal basis.

TABLE 7

COMPARISON OF TOTAL TRIP PRODUCTIONS FOR VARIOUS SAMPLE SIZES, SOUTHEAST AREA TRAFFIC STUDY, 1962

Trip Purpose	1,384 Sample[a]			592 Sample[b]			153 Sample[c]		
	Sample Trips	Percent Total Trips	Diff. (%)	Expanded Trips	Percent Total Trips	Diff. (%)	Expanded Trips	Percent Total Trips	Diff. (%)[d]
Home-based work	2,067	32.9	0	2,006	30.9	-3.0	1,936	32.6	-6.3
Other home-based	3,218	51.3	0	3,446	53.1	+7.1	3,139	52.9	-2.5
Nonhome-based	990	15.8	0	1,040	16.0	+5.1	859	14.5	-13.2
Total	6,275	100.0	0	6,492	100.0	+3.5	5,934	100.0	-5.4

[a]Sample rate, 2.4 percent.
[b]Sample rate, 1.1 percent.
[c]Sample rate, 0.3 percent.
[d]Percent difference from 2.4 percent sample.

The assumptions made and procedures used to obtain zonal trip production and attraction values in this research are very similar to previously reported synthetic procedures (1, 4). These procedures make use of detailed socio-economic data in developing productions and attractions for use with the gravity model trip distribution technique. For example, labor force can be used to indicate work trip production, employment can be used for work trip attraction, and retail sales for nonwork trip attraction.

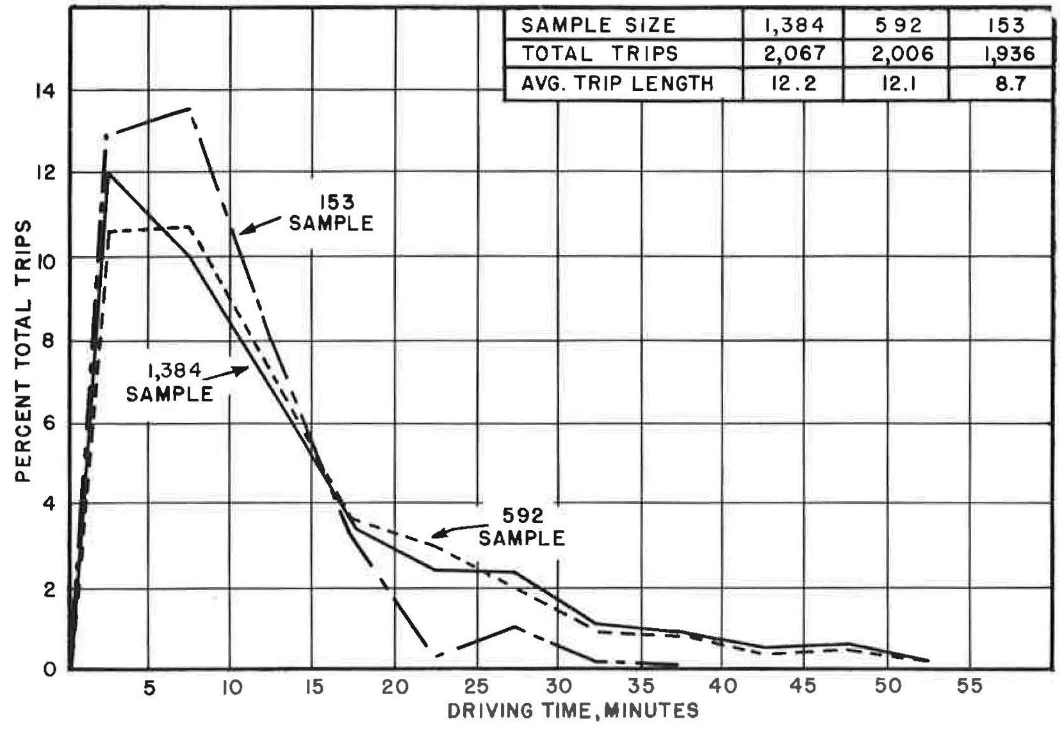

Figure 11. Trip length frequency distribution, home-based auto-driver work trips, southeast Connecticut, 1960.

TABLE

COMPARISON OF TOTAL TRIP PRODUCTIONS FOR SELECTED SAM

Trip Purpose	1,457 Sample			742 Sample			196 Sample	
	Expanded Trips	Percent Total Trips	Diff. (%)a	Expanded Trips	Percent Total Trips	Diff. (%)a	Expanded Trips	Percent Total Trips
Home-based work	26,207	38.9	0	25,781	38.6	-1.6	26,080	39.0
Other home-based	27,760	41.2	0	27,887	41.7	+0.5	27,101	40.5
Nonhome-based	13,437	19.9	0	13,194	19.7	-1.8	13,720	20.5
Total	67,404	100.0	0	66,862	100.0	-0.8	66,901	100.0

[a]Percent difference from total sample.

Table 11 indicates that there was a total of 7.18 trips made for every car owned by the persons who were interviewed; 1.36 of these were work trips, 2.84 were nonwork trips, and 2.98 were nonhome-based trips. By applying these rates to the total number of automobiles in the area, a total number of trips, by trip purpose, can be obtained. The total number of automobiles in the study area can be obtained from several sources such as census data (only for the census year), state, county, or city auto registration records, or special surveys. In this study the information was obtained from the 1956 comprehensive home interview survey. The resulting estimates of total trip production for each trip purpose are given in Table 12. Since total trip productions for the

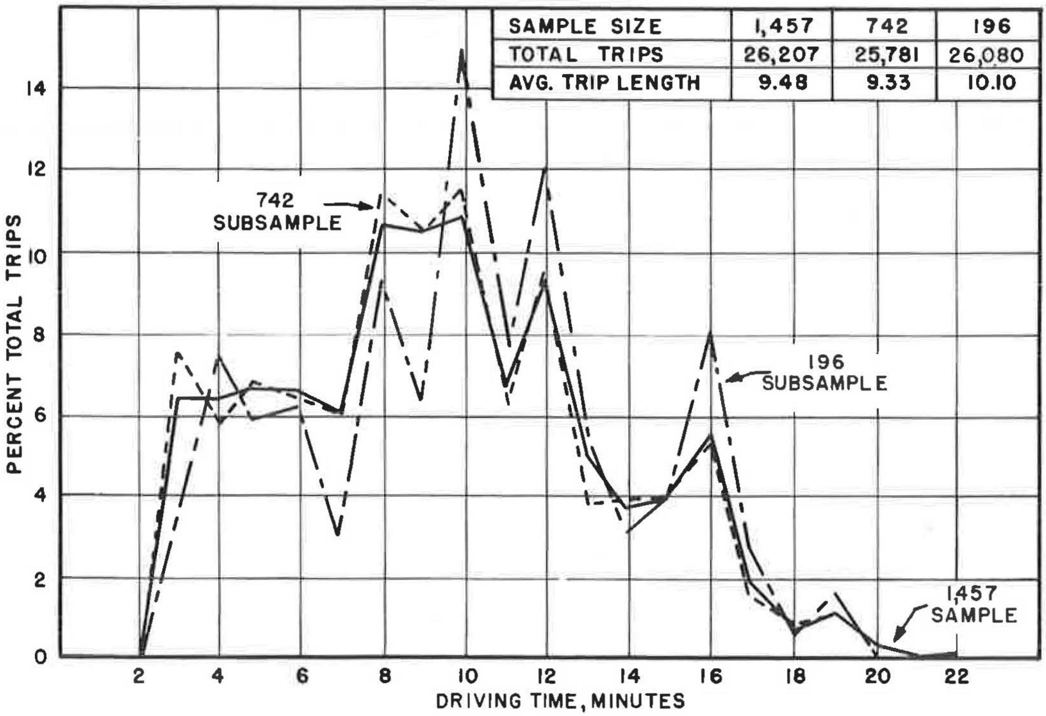

Figure 12. Selected trip length frequency distributions, home-based auto-driver work trips, North Carolina study, 1963.

8

PLE SIZES, NORTH CAROLINA RESEARCH PROJECT N, 1963

	383 Sample			248 Sample			192 Sample		
Diff. (%)a	Expanded Trips	Percent Total Trips	Diff. (%)a	Expanded Trips	Percent Total Trips	Diff. (%)a	Expanded Trips	Percent Total Trips	Diff. (%)a
-0.5	24,382	38.5	-7.0	25,920	40.0	-1.1	27,498	39.3	+4.9
-2.4	27,983	44.2	+0.8	27,896	43.0	+0.5	26,637	38.1	-4.0
+2.1	10,991	17.3	-18.2	11,053	17.0	-17.7	15,802	22.6	+17.6
-0.8	63,356	100.0	-6.0	64,869	100.0	-3.8	69,937	100.0	+3.8

entire study area must equal total trip attractions for the entire study area in each trip purpose category, estimates of total trip attractions are also available from this procedure and are given in Table 12.

Home-Based Auto-Driver Work Trips. —As one might suspect, work trips are closely associated with labor force and employment; these were the basic socio-economic data used to determine zonal production and attraction values for this trip purpose.

Zonal Trip Productions. —These values for the 74 internal zones for this trip purpose were derived from zonal information on the labor force. Labor force data are generally available from sources such as census reports, labor statistics, and reports. In this research, the information for each zone was taken from data available for Sioux Falls. From studies in other areas (1, 4), it has been found that there are about 0.80 daily work trips produced (one-way) for each person in the labor force. This figure differs from 1.0 work trips (one-way) because some persons in the labor force are unemployed, on vacation, walk to work, etc. An examination of the survey data in the Sioux Falls area indicated similar trip rates. Consequently, to determine the total number of work trip productions by auto and transit in each zone, the labor force in each internal zone was first multiplied by 0.80.

To determine transit usage, the information given in Table 13 was used. This information was developed from survey data in Chicago, Ill. By entering this table with the zonal information on car ownership and net residential density, an index of transit usage is obtained. The resulting zonal indices were then totaled and equated to the work trip transit usage for the Sioux Falls study as determined from the small sample home interview survey. A correction factor was developed which, when applied to the

TABLE 9

COMPARISON OF TOTAL TRIP PRODUCTIONS FOR VARIOUS SAMPLE SIZES, PITTSBURGH, PA., 1958

Trip Purpose	16,169 Sample[a]			2,021 Sample[b]			404 Sample[c]		
	Expanded Trips	Percent Total Trips	Diff. (%)d	Expanded Trips	Percent Total Trips	Diff. (%)d	Expanded Trips	Percent Total Trips	Diff. (%)d
Home-based work	796,195	34.1	0	792,576	33.9	-0.5	765,480	33.3	-3.9
Home-based other	425,074	18.2	0	440,784	18.8	3.7	436,920	19.0	2.8
Home-based soc-rec.	288,047	12.3	0	293,752	12.6	2.0	311,280	13.5	8.1
Home-based shop	286,883	12.3	0	276,416	11.8	-3.6	289,640	12.6	1.0
Home-based school	232,875	10.0	0	218,264	9.3	-6.3	191,920	8.4	-17.6
Nonhome-based	306,915	13.1	0	318,688	13.6	3.8	303,520	13.2	-1.1

[a]Sample rate, 4.0 percent.
[b]Sample rate, 0.5 percent.
[c]Sample rate, 0.1 percent.
[d]Percent difference from 4 percent sample.

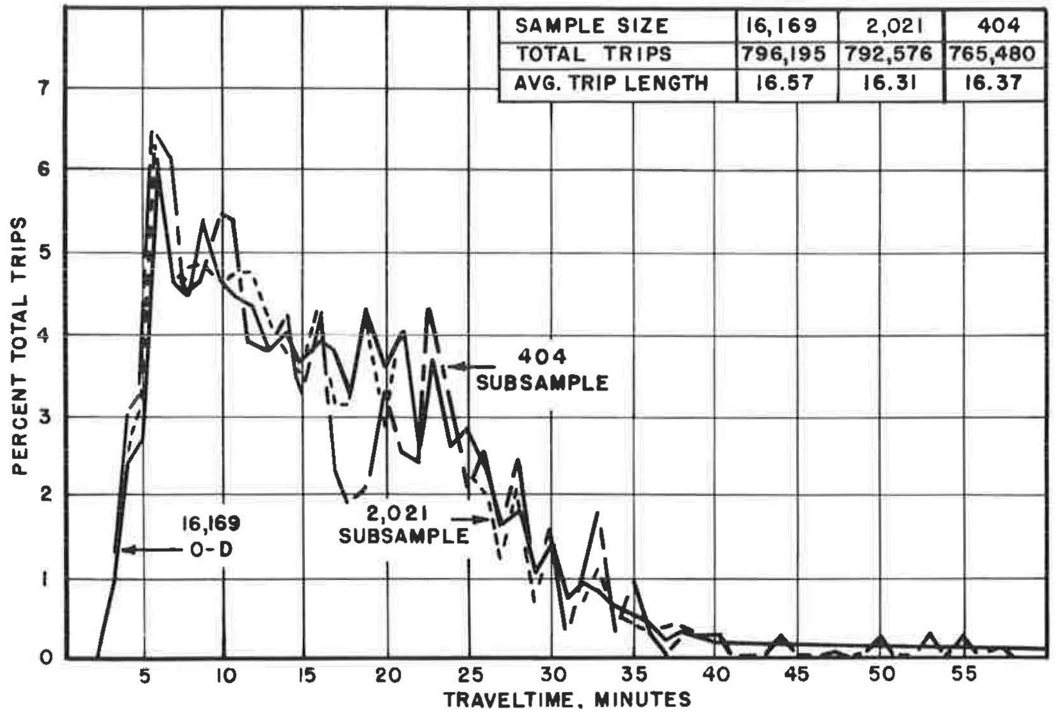

Figure 13. Trip length frequency distributions, home-based person work trips, Pittsburgh, Pa., 1958.

previously developed indices, would yield figures on zonal work trip transit usage; these figures, when totaled, would agree with that shown for the total study area by the small sample. The application of this correction factor was based on the assumption that a three-dimensional plot of the characteristics of variation in transit usage would maintain the same form and shape from one city to another. This correction factor for Sioux Falls was 0.5, and when applied to the zonal indices, it brought the total estimated work transit trips into agreement with the total from the small sample. The number of person work trips made by auto for each zone was then obtained by subtracting

TABLE 10

COMPARISON OF TOTAL TRIP PRODUCTION FOR VARIOUS SAMPLE SIZES, SIOUX FALLS, 1956[a]

Auto-Driver Trip Purpose	2,399 Sample[b]			599 Sample[c]			199 Sample[d]		
	Expanded Trips	Percent Total Trips	Diff. (%)[e]	Expanded Trips	Percent Total Trips	Diff. (%)[e]	Expanded Trips	Percent Total Trips	Diff. (%)[e]
Home-based work	25,161	24.2	0	26,564	24.4	5.6	26,292	26.4	4.5
Home-based nonwork	50,782	48.9	0	53,848	49.4	6.0	47,232	47.4	-7.0
Nonhome-based	27,924	26.9	0	28,516	26.2	2.1	26,040	26.2	-6.8
Total	103,867	100.0	0	108,744	100.0	4.6	101,496	100.0	-2.4

[a]These figures are from internal home interview person trip data only and do not include information available from the truck, taxi, and external cordon survey. Auto-driver trip data from both of these sources were used in developing trip interchanges synthetically as described in text and given in Table 12.
[b]Sample rate, 12.5 percent.
[c]Sample rate, 3.1 percent.
[d]Sample rate, 1.0 percent.
[e]Percent difference from 12.5 percent sample.

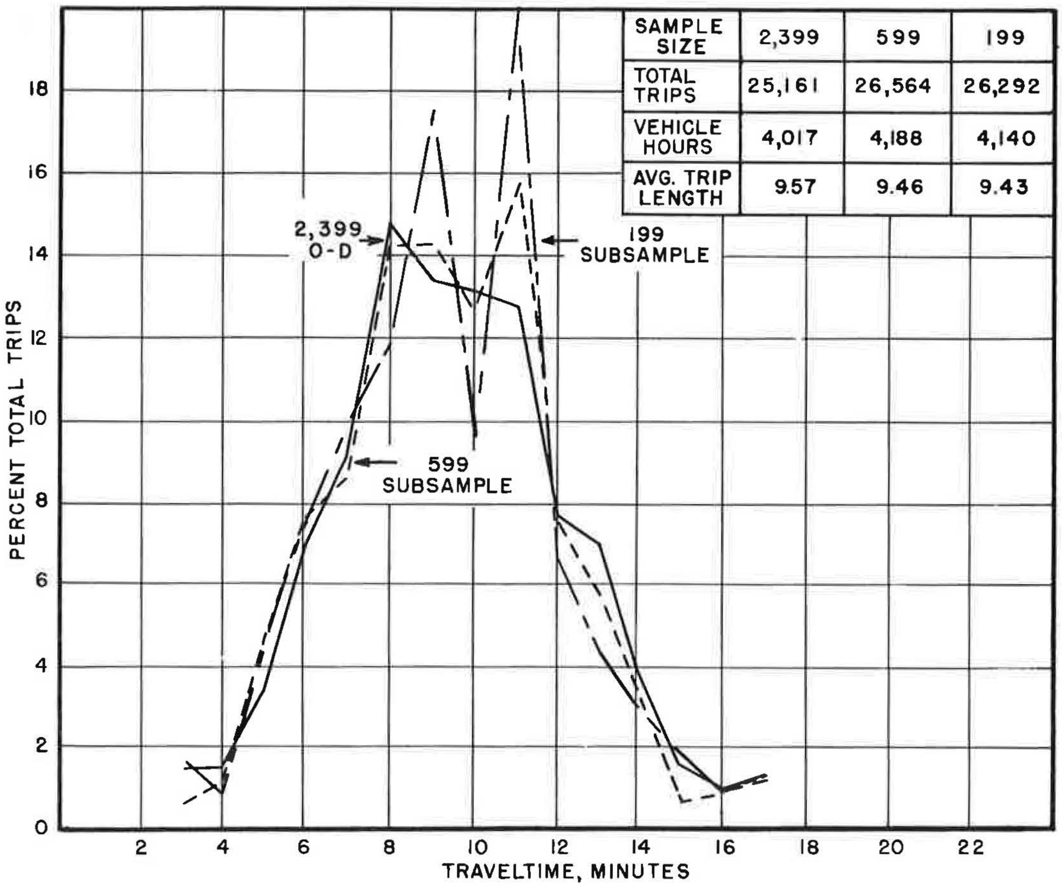

Figure 14. Trip length frequency distributions, home-based auto-driver work trips, Sioux Falls, 1956.

these transit work trips from the total person work trips for each zone. To correct for car occupancy and to arrive at auto-driver work trips, the information from Table 14 was applied to the total automobile work trips previously developed for each zone. Table 14 shows the relationship between car ownership and car occupancy, as developed from data in the Chicago area. Assuming that the relationship between car occupancy and car ownership is relatively stable from urban area to urban area, the information in Table 14 is also usable in Sioux Falls.

For each of the 10 external stations in Sioux Falls, the number of automobile work trips produced by each station was estimated as a percentage of the adjusted total trips for all purposes recorded at all stations during a standard external cordon survey. The adjusted total trips for all stations were obtained by deducting the through trips from the total external station trips and analyzing the remaining trips. The adjusted total station trips consisted of auto and taxi trips between the external stations and the zones. The percentage of automobile work trips produced by the 10 external stations was determined to be 20 percent of this adjusted external station volume.

To determine the accuracy of these procedures, the auto-driver work trip productions estimated for each zone were compared with those shown by the 1956 comprehensive O-D survey. The results are shown in Figure 21. These comparisons were also analyzed using the RMS error criteria described earlier, and the analysis indicated very close agreement between the actual and the estimated values. The limits of one RMS error are shown as dashed lines in Figure 21.

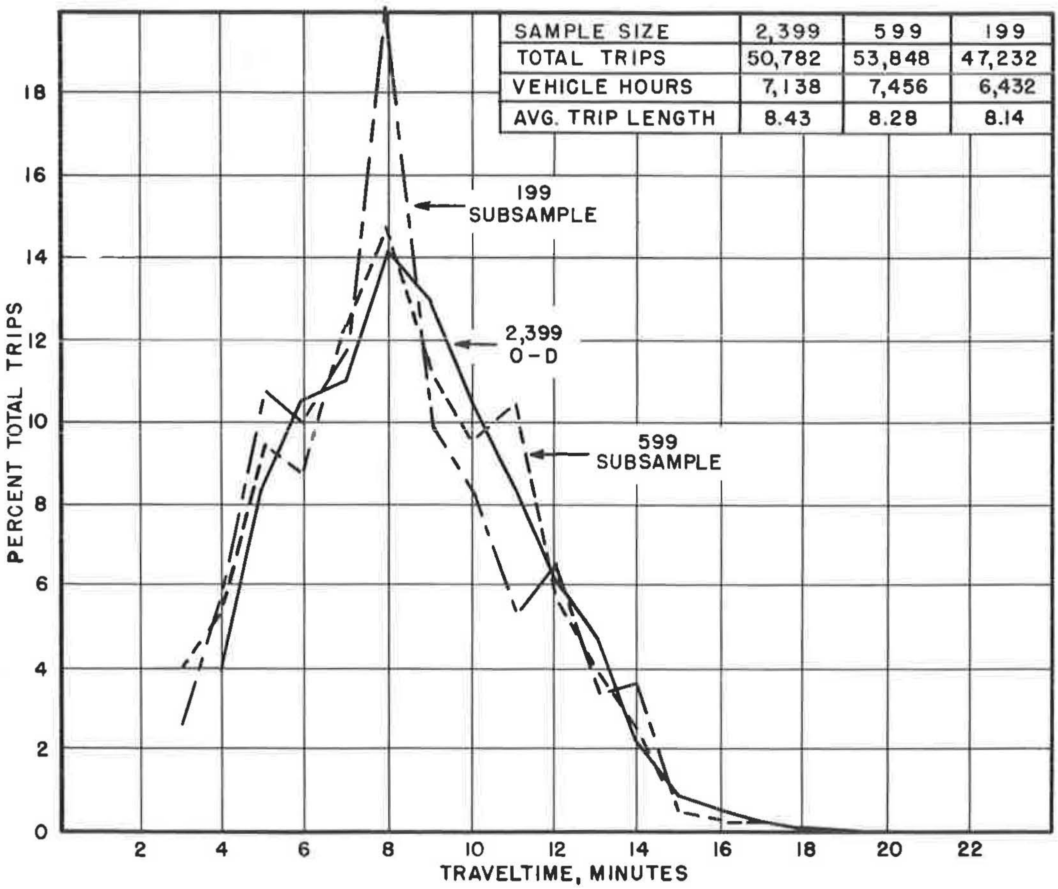

Figure 15. Trip length frequency distributions, home-based nonwork trips, Sioux Falls, 1956.

Zonal Trip Attractions.—These values for each of the 74 internal zones were developed from zonal employment information. Information on the number of people employed in each zone was available from employment statistics and also from information collected in a special survey by the Sioux Falls Chamber of Commerce. From an analysis of the data, it was determined that each employee in Sioux Falls attracted about 0.83 person work trips per day. The remaining employees were not recorded as making work trips because of illness, vacations, and walk to work trips. Consequently, to obtain an estimate of the total person work trips attracted to each zone, zonal employment figures were multiplied by 0.83. Corrections were then made for transit usage and car occupancy by using the information in Tables 13 and 14, as previously described for work trip productions, to arrive at auto-driver work trip attractions. In addition to these two corrections, a control figure for work trips to the CBD was also applied. Essentially, the estimated auto-driver work trips to the CBD were factored to meet the number indicated by the small sample and the external survey. All non-CBD zones were then factored in a similar manner so that the total auto-driver work trips remained the same.

For each of the 10 external stations, auto-driver work trip attractions were determined in the same manner as external station auto-driver work trip productions. The percentage of total station auto-driver trips (minus through trips) which were attracted by the external stations was determined to be 6.0 percent.

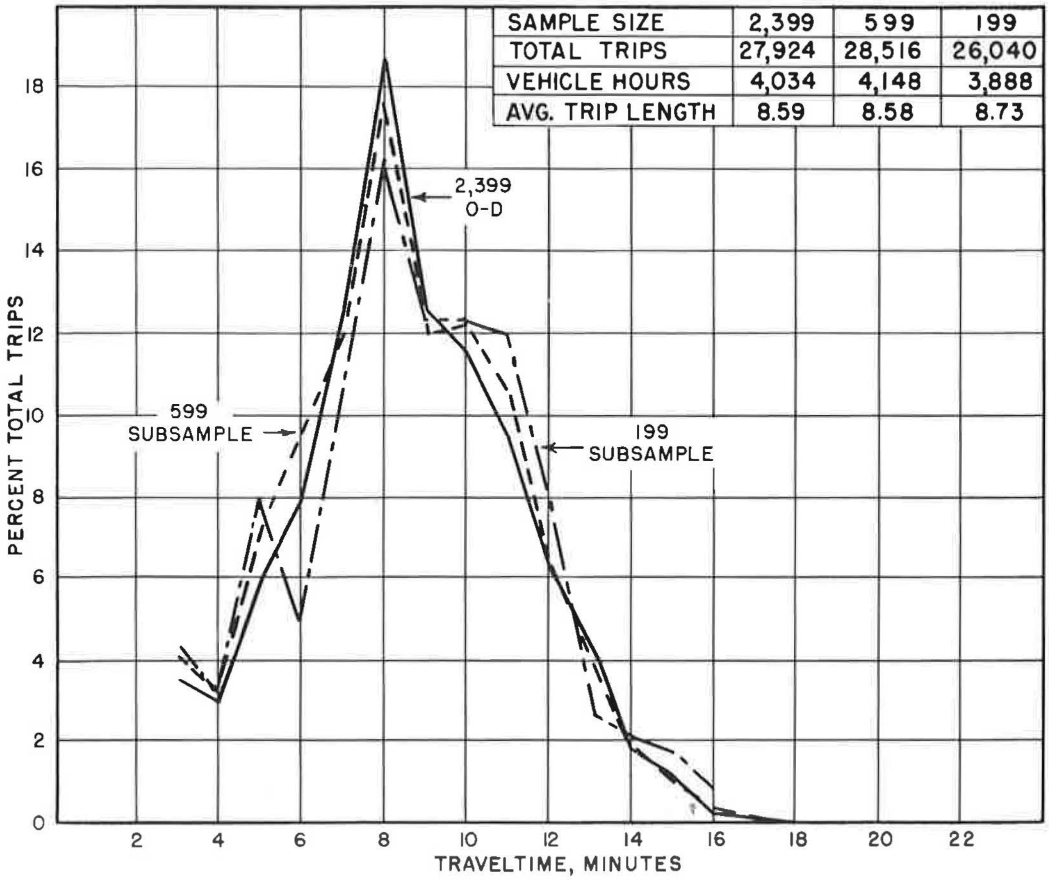

Figure 16. Trip length frequency distributions, nonhome-based trips, Sioux Falls, 1956.

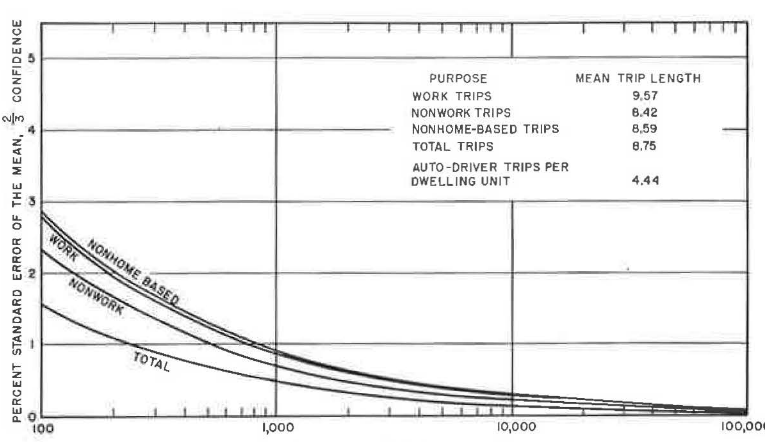

Figure 17. Percent standard error of mean trip length vs sample size in dwelling units, Sioux Falls, 1956.

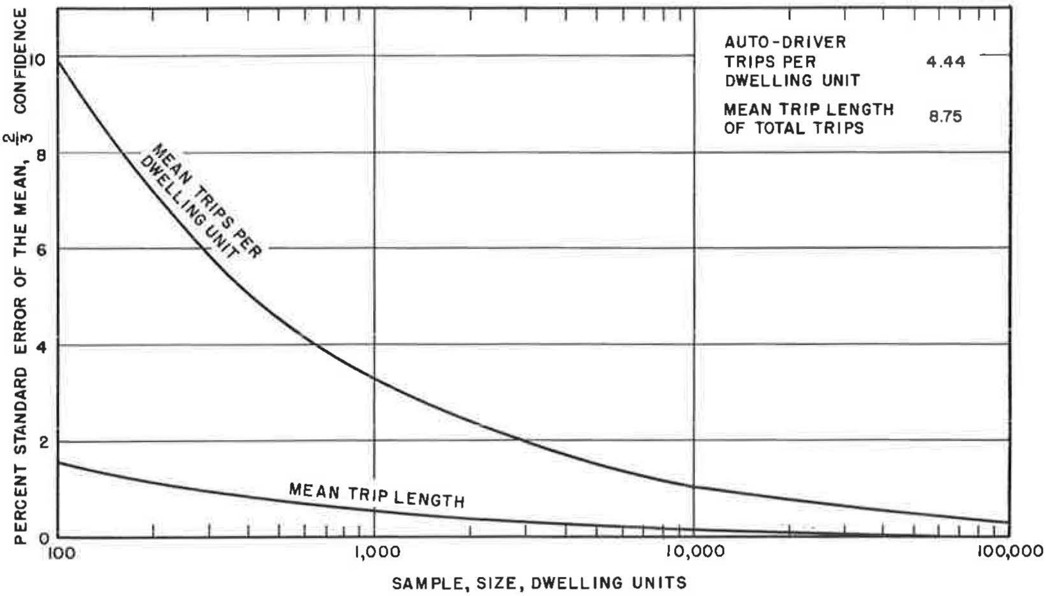

Figure 18. Percent standard error vs sample size in dwelling units for mean trip length and trips per dwelling unit, Sioux Falls, 1956.

To determine the accuracy of these procedures, the auto-driver work trip attractions estimated for each zone were compared with those shown by the 1956 comprehensive O-D survey. The results are shown in Figure 22. These comparisons were analyzed in the same manner as the work trip productions and the analysis indicated very close agreement between the actual and the estimated values.

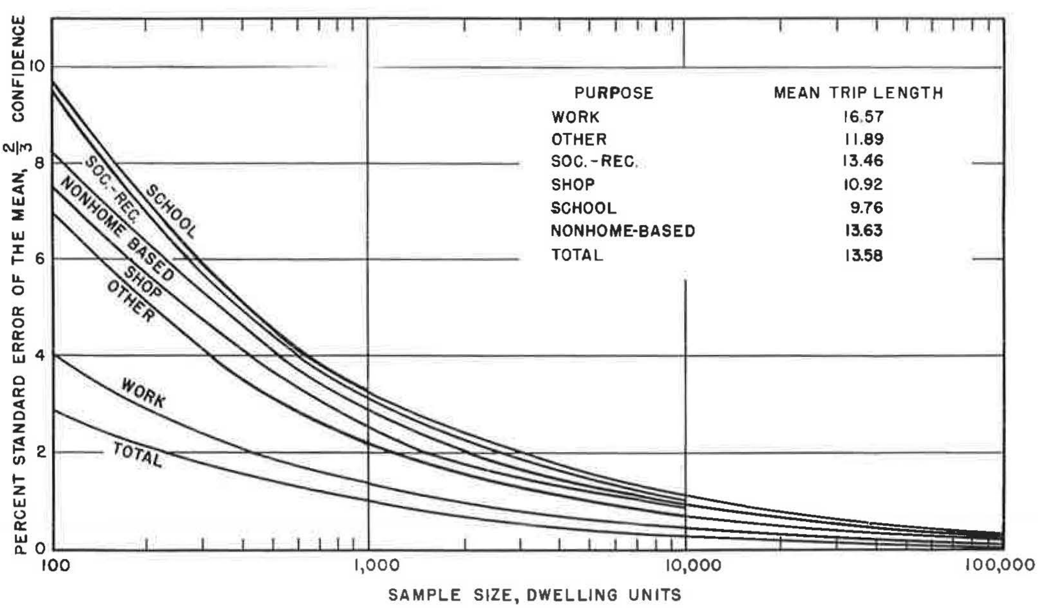

Figure 19. Percent standard error of mean trip length vs sample size in dwelling units, Pittsburgh, Pa., 1958.

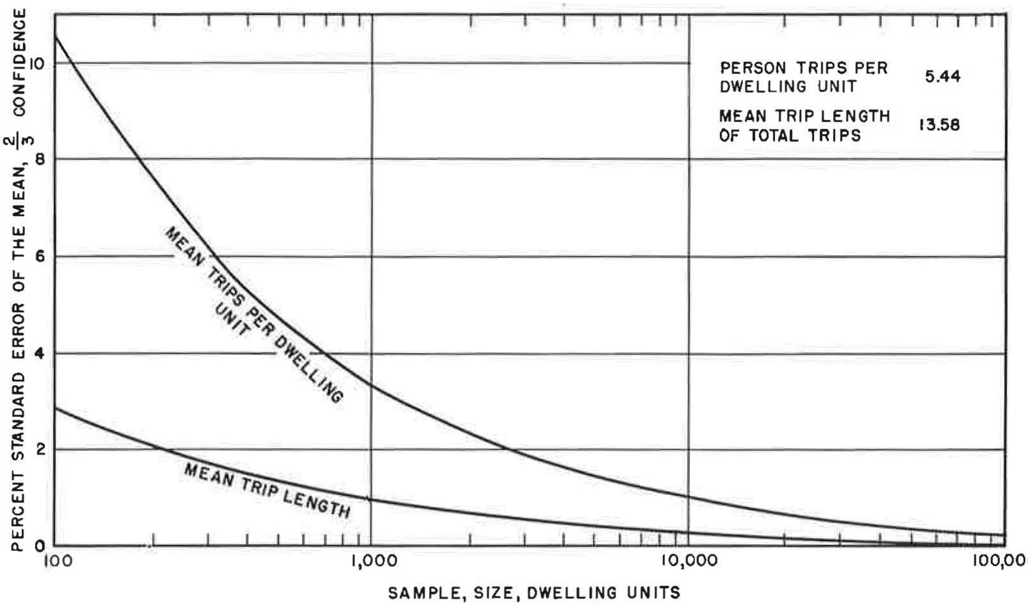

Figure 20. Percent standard error vs sample size in dwelling units for mean trip length and trips per dwelling unit, Pittsburgh, Pa., 1958.

TABLE 11

TOTAL INTERNAL VEHICULAR TRIP PRODUCTION RATES BY TRIP PURPOSE, SIOUX FALLS, 1956[a]

Trip Purpose	Trips per Car
Home-based work trips	1.36
Home-based nonwork trips	2.84
Nonhome-based trips	2.98
Total vehicular trips	7.18

[a]Information included in this table includes travel data from both the 599 home interview sample and the truck and taxi surveys.

Home-Based Auto-Driver Nonwork Trips. —Zonal trip productions for the 74 internal zones for this purpose of trip were derived from zonal data on car ownership obtained from the O-D survey. As previously pointed out, however, car ownership data are also generally available from several other sources. Table 11 indicates that there are 2.84 home-based auto-driver nonwork trips per car. This figure was applied to the number of cars owned by the residents of each of the internal zones to determine trip production values for this trip purpose. For the 10 external stations, the nonwork trip

TABLE 12

TOTAL VEHICULAR TRIP PRODUCTIONS AND ATTRACTIONS BY TRIP PURPOSE, SIOUX FALLS, 1956

Trip Purpose	Productions			Attractions		
	Internal[a]	External[b]	Total	Internal[a]	External[b]	Total
Work	27,475	2,175	29,650	28,212	1,438	29,650
Nonwork	57,219	8,010	65,229	60,123	5,106	65,229
Nonhome-based	59,966	4,956	64,922	59,847	5,075	64,922
Total	144,660	15,141	159,801	148,182	11,619	159,801

[a]These figures obtained by multiplying trip rates given in Table 11 by total cars owned by residents of study area.
[b]These figures from standard external cordon survey.

TABLE 13

PERCENTAGE OF ALL WORK TRIPS MADE BY TRANSIT (17)

Cars per 1,000 Persons	Work Trips by Transit (%)					
	Net Land per Family					
	10,000 Sq Ft	5,000 Sq Ft	2,500 Sq Ft	1,200 Sq Ft	600 Sq Ft	300 Sq Ft
500	5	7	11	19	33	65
450	7	9	13	21	35	67
400	9	11	15	23	37	69
350	11	13	17	25	39	71
300	13	15	19	27	41	73
275	14	16	20	28	42	74
250	15	17	21	29	43	75
225	16	18	22	30	44	76
200	17	19	23	31	45	77
175	18	20	24	32	46	78
150	19	21	25	33	47	79
125	20	22	26	34	48	80

productions were obtained in the same manner as described for external station auto-driver work trip productions. Nonwork trip productions were determined to be 30 percent of the total station volume. To test the accuracy of these procedures, the auto-driver nonwork trip productions estimated for each zone were compared with those shown by the 1956 comprehensive O-D survey. The results are shown in Figure 24. These comparisons were analyzed and the results indicated very close agreement between the actual and the estimated values.

Zonal trip attractions for the 74 internal zones for this trip purpose were derived from zonal data on population and retail sales. By dividing the total internal auto-driver nonwork trip attractions into the total population of the area, the population per attraction for this purpose was obtained. By repeating this process for the total retail sales in the area, the unit of sales per attraction was also obtained. By dividing the larger of these rates (population) by the smaller (retail sales) it was found that 1.69 units of retail sales were required to attract each nonwork trip, whereas 1.00 units of population were required to attract each nonwork trip. By using this technique a weighting factor equal to population + 1.69 × retail sales was established as an indicator of the auto-driver nonwork trip attractions in each zone. Consequently, the total number of attractions for this purpose were prorated to the zones using this weighting factor. As in the case of the auto-driver work trip attractions, nonwork trip attractions were factored to insure that the CBD attraction values are equal to those shown by the

TABLE 14

RELATIONSHIP BETWEEN CAR OCCUPANCY AND CAR OWNERSHIP FOR TOTAL WORK TRIPS (17)

Cars per 1,000 Persons	Persons per Car
500	1.20
450	1.23
400	1.27
350	1.30
300	1.33
250	1.40
200	1.46
150	1.52
100	1.65

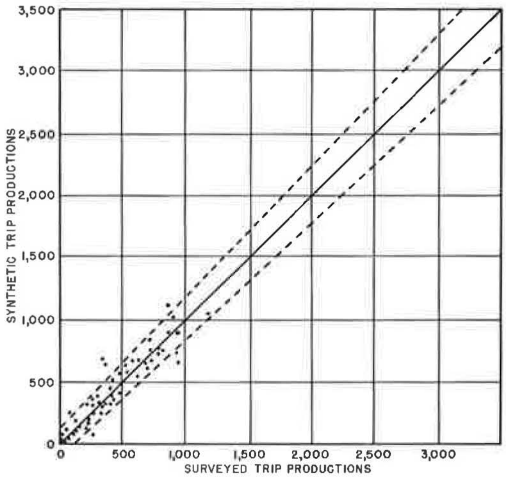

Figure 21. Synthetic vs surveyed auto-driver home-based work trip productions, Sioux Falls, 1956.

small sample survey data. The non-CBD attractions were then adjusted accordingly to keep the total attractions the same as shown by the small sample.

For the 10 external stations, trip attractions for this trip purpose were obtained in the same manner as described for external station auto-driver work trip productions. The percentage of total station auto-driver trips (minus the through trips) which were nonwork trips was determined to be 20 percent.

To test the accuracy of these procedures, the auto-driver nonwork trip attractions estimated for each zone were compared with those shown by the 1956 comprehensive O-D survey. The results, shown in Figure 24, were analyzed and indicated reasonable agreement between the actual and estimated values.

Nonhome-Based Auto-Driver Trips.—Several studies have reported that auto-driver nonhome-based trip production is associated with car ownership (1, 4). Because by definition the trip productions are equal to trip origins and trip attractions are equal

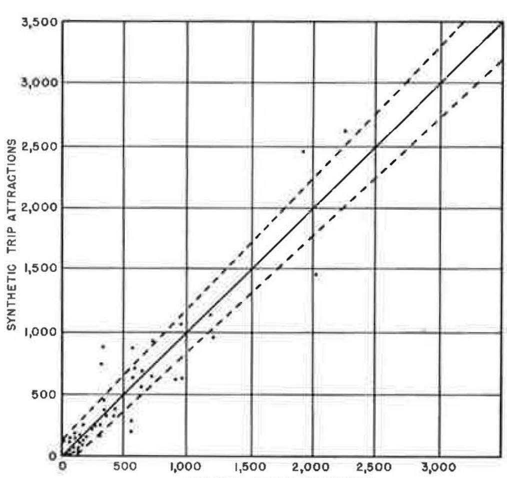

Figure 22. Synthetic vs surveyed auto-driver home-based work trip attractions, Sioux Falls, 1956.

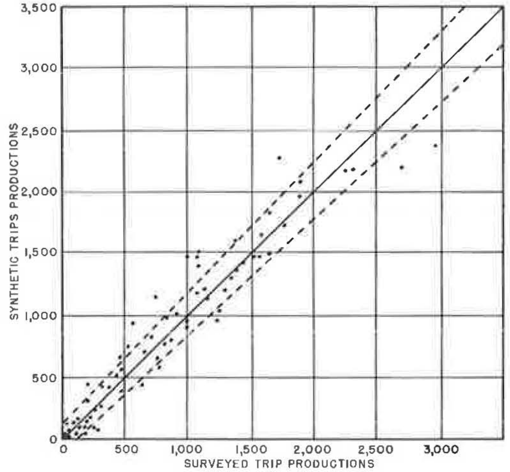

Figure 23. Synthetic vs surveyed auto-driver home-based nonwork trip productions, Sioux Falls, 1956.

to trip destinations for nonhome-based trips, production and attraction values should be equal on a zonal basis as well as on a study area basis. Since origins should closely agree with destinations on a zonal basis during the 24-hr day, productions must also agree closely with attractions. This information was used in determining zonal trip productions and attractions for nonhome-based auto-driver trips in this research project. Zonal trip productions and attractions for the 74 internal zones for this trip purpose were derived from zonal data on car ownership, which in this research was obtained from the origin-destination survey. Table 11 indicates that there are 2.98 nonhome-based vehicular trips per car. This figure was applied to the number of cars owned in each internal zone to determine trip production values for this trip purpose.

For the 10 external stations, trip productions and attractions were obtained in the same manner as described for external station auto-driver work productions. The percentages which were nonhome-based auto-driver productions and attractions were determined to be 18.5 and 19.0, respectively.

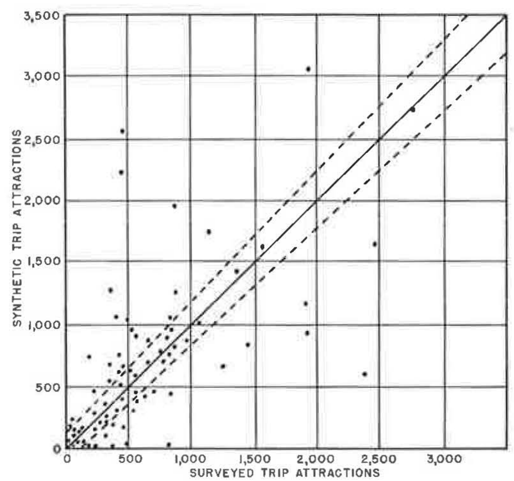

Figure 24. Synthetic vs surveyed auto-driver home-based nonwork trip attractions, Sioux Falls, 1956.

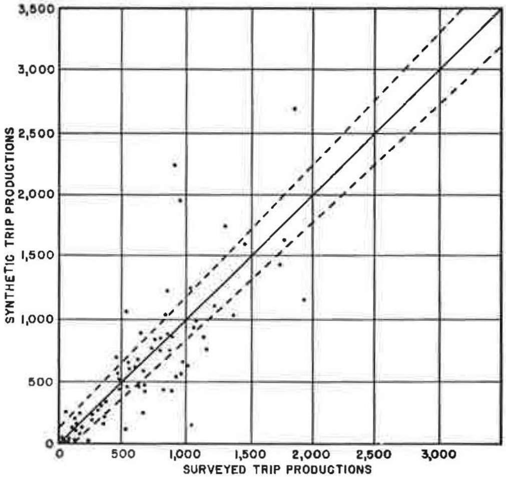

Figure 25. Synthetic vs surveyed nonhome-based vehicular trip productions, Sioux Falls, 1956.

To test the accuracy of these procedures, the auto-driver nonhome-based trip productions and attractions estimated for each zone were compared with those shown by the 1956 comprehensive O-D survey. An analysis of the results shown in Figures 25 and 26 indicated rather poor agreement between the actual and estimated values. An examination of the internal nonhome-based trip productions and attractions from other studies showed similar agreement for these values.

Determining Trip Distribution Pattern

The previously described procedures provided zonal trip production and attraction values for each of the trip purpose categories. However, before interchanges can be calculated using the gravity model formula, some measure of spatial separation between the zones must be developed. For the purpose of this phase of the research, the minimum path driving times between zones, the intrazonal times, and the terminal

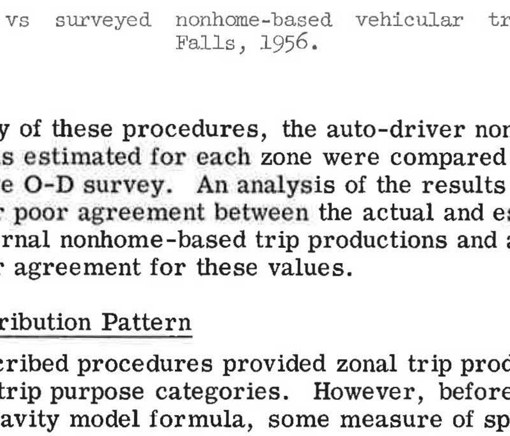

Figure 26. Synthetic vs surveyed nonhome-based vehicular trip attractions, Sioux Falls, 1956.

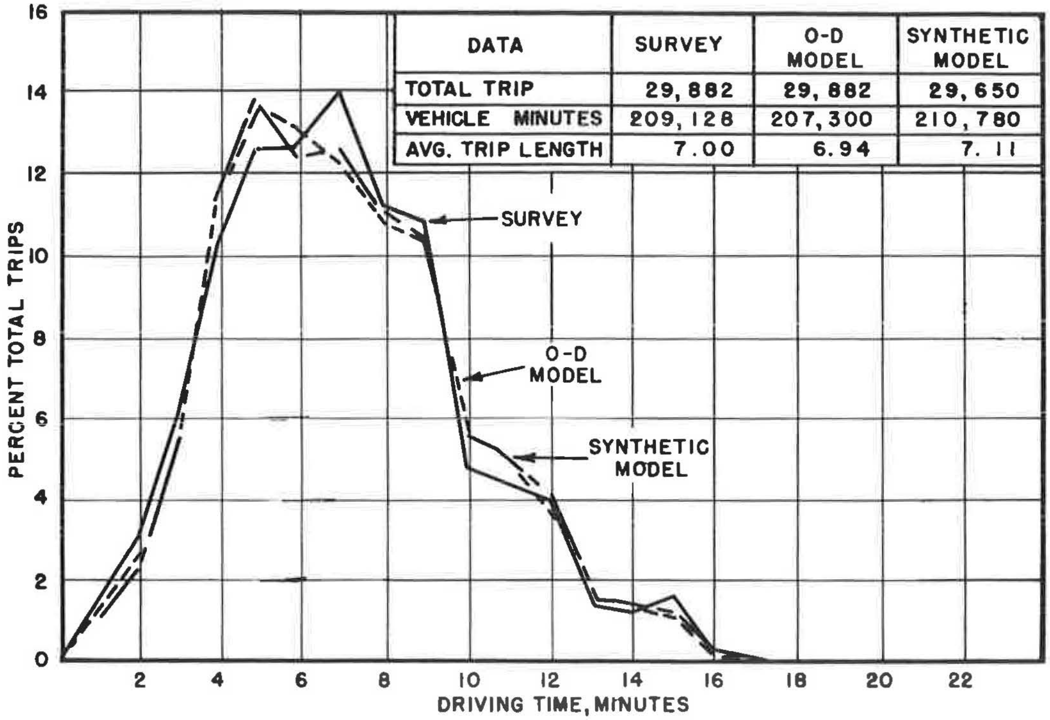

Figure 27. Trip length frequency distributions, home-based auto-driver work trips, Sioux Falls, 1956.

times used were as developed for the previous phase of this work. In addition, some measure of the effect of this spatial separation on trip interchange between zones, $F_{(t_{i-j})}$, is also required. In this phase of the research, full use was made of the travel time factors already developed for each trip purpose during the previous phase

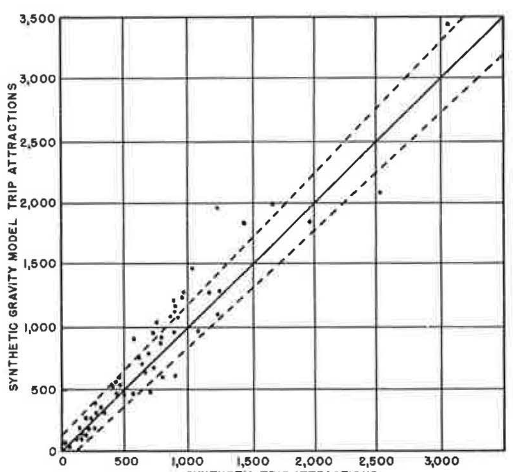

Figure 28. Synthetic vs synthetic gravity model home-based auto-driver nonwork trip attractions, Sioux Falls, 1956.

TABLE 15

COMPARISON OF TOTAL VEHICULAR TRIPS CROSSING BIG SIOUX RIVER, SIOUX FALLS, 1956

Facility	Vol. Count	O-D Survey	Syn. Gravity Model
Cherry Rock Ave.	1,511	1,640	1,512
Cliff Ave., S.	9,132	8,420	9,208
Tenth St.	14,842	16,296	16,832
Eighth St.	8,606	6,612	6,752
Sixth St.	3,864	2,900	4,564
McClellan St.	3,069	2,596	1,972
Cliff Ave., N.	4,699	4,156	2,048
Totals	45,723	42,620	42,888
Percent Diff. from Vol. Count		-6.8	-6.2
Percent Diff. from O-D Survey	+7.3		+0.6

TABLE 16

TOTAL TRIPS CROSSING SCREENLINES, SIOUX FALLS, 1956

Screenline No.	O-D Survey Vol.	Syn. Gravity Model	
		Vol.	Diff. from O-D (%)
1	7,952	7,280	-8.5
2	21,012	21,120	+0.5
3	13,516	13,224	-2.2
4	11,384	10,428	-8.4
5	9,744	8,516	-12.6
6	8,784	8,440	-3.9
7	6,280	6,520	+3.8
8	6,568	6,100	-7.1
9	2,264	1,980	-12.5
10	17,448	18,420	+5.6
11	5,868	4,836	-17.6
12	5,592	3,872	-30.8
13	13,656	15,280	+10.6
14	22,908	23,584	+2.9
15	33,220	33,204	0.0
16	10,032	10,996	+9.6
17	13,424	14,220	+5.9
18	9,724	12,200	+25.5
19	10,060	10,720	+6.6
20	5,332	5,476	+2.7
21	8,496	8,364	-1.5
22	13,332	14,192	+6.5
23	41,500	41,468	-0.1

of the research. This was done because the trip length frequency curves for the 599 subsample were so similar to those for the total sample which was used to develop the travel time factors. The values of these factors are shown in Table 3.

With all the required parameters available, the gravity model calculations were made to obtain a synthetic trip distribution pattern. This pattern was then compared to the O-D survey data to determine the accuracy and, consequently, the ability of the simplified procedures described in this report to supply the necessary information for adequately simulating trip

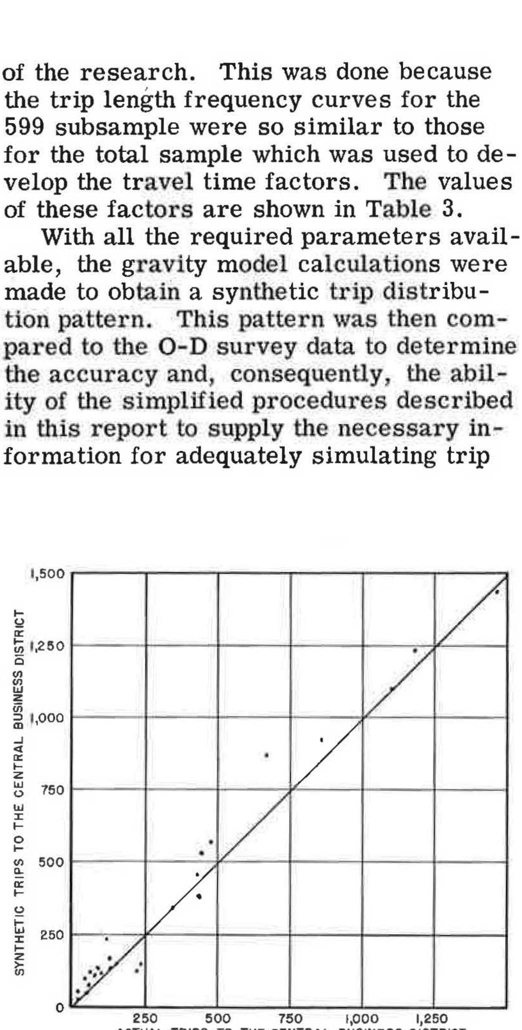

Figure 29. Actual vs synthetic model nonhome-based vehicular trips to CBD, Sioux Falls, 1956.

distribution patterns. Several tests were involved in the comparisons.

First, the synthetic trip length frequency distributions and average trip lengths were compared with those from the O-D survey for each trip purpose category. The results for work trips are shown in Figure 27; the other two purposes also exhibit very close agreement. The results of this test indicated that the decision to use the travel time factors from the previous phase of this research was a correct one. If an initial set of travel time factors had been assumed and the normal trial and adjustment process utilized, the final result would have been travel time factors identical to those shown in Table 3.

Tests were made comparing the trips attracted to each zone by the gravity model with those shown by the synthetic procedures for each trip purpose. The results for all purposes indicated an accuracy within one RMS error. Figure 28 shows the results for nonwork trips which had the largest scatter.

Another test was made of the number of synthetic trips crossing the Big Sioux River. These figures were compared with

TABLE 17

COMPARISONS OF DISTRICT-TO-DISTRICT MOVEMENTS[a]

Volume Group	O-D Survey Trip		RMS Error	
	Mean	Freq.	Abs.	Percent
(a) Home-Based Auto-Driver Work Trips				
0- 99	21	400	20	95.24
100- 199	133	40	58	43.61
200- 299	259	13	119	45.95
300- 499	402	13	98	24.38
500-1,499	920	8	186	20.22
(b) Home-Based Auto-Driver Nonwork Trips				
0- 99	27	423	28	103.70
100- 199	136	53	83	61.03
200- 299	239	28	103	43.10
300- 499	380	22	166	43.68
500- 999	728	22	282	38.74
1,000-2,999	1,711	9	343	20.05
(c) Nonhome-Based Auto-Driver Trips				
0- 99	25	473	24	96.00
100- 199	144	62	82	56.94
200- 299	241	30	122	50.62
300- 499	385	33	157	40.78
500- 999	773	9	289	37.39
1,000-3,999	1,311	8	457	34.86

[a]1956 O-D survey data vs synthetic gravity model estimates, relative difference measured in terms of percent RMS error (see footnote to Table 6).

those from the O-D survey and again, the differences were small (Table 15).

Synthetic trips to the CBD, for each trip purpose, were also compared with the same movements from the total sample. The results for work trips (Fig. 29), indicate that there is no geographical bias present in the synthetic interchanges and that the discrepancies between the two sets of information are quite small.

Synthetic trip interchanges for total trips were then assigned to the minimum path driving time network. The expanded trips from the full O-D sample were also assigned. These two sources of information were then compared by analyzing the differences over the comprehensive series of screenline crossings shown in Figure 10. The results of the comparisons are given in Table 16.

Finally, a statistical comparison of the actual and the estimated trips was made for each trip purpose (Table 17). An analysis of the comparisons indicated acceptable results for all purposes when compared with similar studies (12, 13, 15) and with the comparisons resulting from the first phase of this research (Table 6).

SUMMARY AND CONCLUSIONS

The application of the gravity model theory in a particular small urban area was investigated and, because it was the theory of the gravity model which was being tested, the model was developed using all of the travel information normally collected during a comprehensive O-D survey obtained by using the dwelling unit sample size recommended in the Public Roads Home Interview Manual (6). The home interview survey provided the data on trip production, trip attraction, and trip length distribution needed for developing the model, as well as information on the zonal trip interchanges used to test the gravity model results.

A three purpose gravity model was calibrated following the procedures outlined in this paper but more fully detailed previously (8). The calibrated gravity model was then thoroughly tested against the O-D trip distributions and volume counts. These tests revealed that the gravity model formulation adequately simulated trip distribution patterns for the Sioux Falls area.

Having determined that the three purpose model was adequate, when based on the data from the full O-D survey, we then investigated the question of reducing the O-D survey sample necessary to develop the model. To determine the appropriate sample sizes to investigate, the results of studies of small samples in other cities were collected and analyzed. Comparisons were made with the full field sample, by trip purpose, of total trips, average trip lengths, and trip length frequency distributions for each of several subsamples. From the tests made in Sioux Falls and from an analysis of other studies, it was determined that about 600 home interview samples in combination with the standard external cordon survey provided adequate data for obtaining, by purpose, total trips, trip length frequency distributions, and average trip lengths.

Since a small sample does not yield stable data on zonal trip productions and attractions by trip purpose, these items of information must be obtained by other techniques. Synthetic procedures based on detailed socio-economic data were used for this purpose. The results of the synthetic procedures were compared to the O-D survey productions and attractions, and the procedures were shown to be satisfactory for computing productions and attractions for Sioux Falls.

Finally, the synthetic productions and attractions were combined with the travel time factors that reflected the 599 home interview sample to determine a trip distribution pattern for each trip purpose. The results were compared with the O-D survey distribution and the patterns agreed closely.

With these separate analyses completed, the following conclusions appear warranted:

1. The gravity model formula provided an adequate framework for determining trip distribution patterns for Sioux Falls.
2. A three purpose trip stratification of home-based work, nonwork, and nonhome-based trips was sufficient in the small urban area.
3. For Sioux Falls, a 599 home interview sample used in combination with detailed socio-economic data and the standard truck, taxi, and external cordon surveys provided sufficient data for a three purpose gravity model calibration. Sioux Falls is a self-contained urban area with a single center and no strong travel linkages to other urban areas. This city does not exhibit any social or economic factors which might have a significant effect on travel patterns, and which might require adjustments to the gravity model trip distributions. The findings for Sioux Falls may not apply to cities exhibiting different characteristics.
4. The synthetic procedures used in this research to compute zonal trip productions and attractions are satisfactory for this small urban area when used in combination with detailed socio-economic data and with limited travel data from a small sample survey.

Further research should be conducted to determine if the findings for this small urban area can have wider application.

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Method for Estimating Potential Increases in Traffic Volumes Based on O-D Survey Data from a Mid-Western City

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An attempt is made to estimate the possible increase in trip generation which could occur in a community if the number of households remained constant over a period of time during which the vehicle ownership by households and/or the intensity of vehicle use by households increased. The information is based on the data secured in the home interviews of an origin-destination survey conducted in Champaign-Urbana in the spring of 1958.

The study was based on the assumption that households or families are the basic traffic-generating units in a community. The averages for household characteristics were correlated by zones with the average number of vehicular trips per zone. The validity of the procedure was supported by the results of a variance analysis which indicated that the differences between zones were significantly greater statistically than the differences within zones in respect to traffic generation. The fact that the family is a significant unit of traffic generation was shown in the findings that two-car families on the average made only 40 percent more trips than one-car families. Increasing the number of vehicles in families already owning vehicles, therefore, does not proportionately increase the number of vehicular trips.

A statistical factor analysis was made of about 30 variables reported in the home interview which conceivably might be linked to traffic generation by households in the survey zones. Four major factors associated with trip generation were derived—a traffic volume factor, a trip purpose factor, a distance factor, and a time-of-trip factor. The fact that the traffic volume factor most clearly included socio-economic traits of households was accepted as a demonstration that socio-economic influences are the basic source of variations between zones of a community in production of traffic.

The proportion of potential trip makers in households who make trips appeared to be the best measure of the differences between zones in the production of traffic. On the basis of this criterion, three types of survey zones each with a different trip generating potential were determined. The zones with lowest potential were generally close to the CBD, were often inhabited by minority or low-ranked occupational groups, or were areas of changing land use. The zones with the highest potential were either very high on the occupational-economic scale or at extreme distances from the CBD. The medium or average potential zones were average in economic criteria of households and tended to be average distances from the CBD. Socio-economic level and proportion of land use devoted to single-family residence seem to be the principal criteria associated with trip-generating potential of zones.

A socio-economic scale combining occupational level and proportion of land use in single-family residence was developed. Values for types of zones correlated well with measures of trip generation by zones. It was estimated on the basis of the growth of the gross national product for the past decade that a community might increase the level of its socio-economic scale value about 20 percent between 1960 and 1970. If this estimate of a 20 percent increase in

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community socio-economic level were applied to the Champaign-Urbana data, then assuming no increase in the number of households in the community from 1960 to 1970, the number of vehicles would increase by 8 percent and trips by 24 percent. This disproportionate increase in the number of trips represents the greater intensity of vehicular use by households at higher socio-economic levels.

•A NUMBER of studies have used the origin-destination survey data to determine the attributes of persons and communities associated with local traffic generation. In all of these studies the number of vehicles found in a community correlates most highly with vehicular trip generation (1-5). However, there has been little systematic consideration of factors underlying a long-run trend in the relation between number of vehicles and the volume of trips produced by these vehicles. The present report, part of a larger study dealing with the social factors in traffic generation, attempts to estimate the possible increase in trip generation which would be associated with increased ownership of vehicles and more intensive use of vehicles.

This report is based on the data obtained in the home interviews of an O-D survey conducted in Champaign-Urbana in the spring of 1958 (6). The study was based on the assumption that households or families are the basic traffic-generating units in a community. There were a total of 4,400 households in the sample, but the analysis was made largely in terms of the 2,000 which were classified as non-student households since it was felt that understanding traffic generation by student households would not be particularly useful for estimating vehicular trips in most other communities. The original internal survey area contained over 50 zones, but of these only 41 reported 10 or more non-student households in the sample. Therefore, the present study was made in terms of these 41 zones.

DEFINITIONS OF TECHNICAL AND STATISTICAL PROCEDURES

The following definitions of techniques and devices used or referred to in the text are included to clarify the discussion.

Variance—the statistical term for the sum of the squares of the deviations from the mean value of a numerical distribution divided by the number of cases in the distribution. The variance as a measure gives an indication of the range of values of the cases in the distribution.

Analysis of variance—the statistical comparison of two or more numerical distributions normally with the purpose of determining whether or not these distributions are alike or different in respect to some criterion. In the report, analysis of variance was used to compare the relation of the number of vehicles per zone to the number of trips to determine if the variance in respect to this relation was greater within the survey zones or between the survey zones.

F-test—a statistical measure to determine if the differences between a criterion for two numerical distributions are significant or could simply be a product of sampling error or random probability. The F-test was used in the report to show that variance between and within survey zones in respect to the number of vehicular trips was significant.

Factor analysis—a statistical method for determining a smaller number of underlying dimensions or factors which exist in the correlations between a larger number of specific variables. Normally a factor analysis begins with a matrix of product-moment correlations and then reduces them a number of patterns which account for the pattern of correlations. In the report, factor analysis begins with a matrix showing the intercorrelations of 30 variables involving trip generation and household traits by survey zone. Through mathematical manipulation this matrix was reduced to five dimensions or axes which account for a good part of the actual number of correlations secured. The factors, therefore, show which variables tend to cluster together. The largest single cluster in terms of association of traits was the factor which showed the association between trip generation and socio-economic traits.

Cumulative or Guttman scaling—a statistical technique for ordering observations of objects so that the order numerically describes variations in some common property shared by all the objects. For example, if a boy can be seen to climb to the top of very tall trees, it can be assumed that he can climb to the top of small and medium trees. If, however, a boy is seen to climb only small trees, it cannot be assumed that he can climb to the top of tall trees. In this situation it would be possible to create a cumulative scale whereby boys observed climbing to the top of tall trees are given scale value of 3, those to the top of medium trees the value 2, and those up in small trees the value of 1. In this way it is possible to prepare numerical measures of properties of phenomena which cannot normally be given such a numerical ranking. In the report this procedure was applied to occupations so as to measure the occupational level of survey zones and to measure land use in terms of the variations in single-family, multi-family and commercial use. These two scales were then combined into one scale of socio-economic ranking of zones.

VARIANCE ANALYSIS TEST OF VALIDITY OF INDICES USED

The statistical procedure was to correlate zone averages for the number of passenger or vehicular trips by household with the zone averages by household of such traits as occupation, number of cars per household, and age of drivers. The statistical relationships, therefore, are measures representing the statistical correlations of the averages of the 41 zones. There are certain problems inherent in using averages as the basis of correlations, but it was assumed that the statistical variance in respect to any of the traits studied was less within than between zones. If the validity of this assumption could be demonstrated, the method of product-moment correlations would appear to be a correct device for establishing statistical relations between traits represented as zone averages. It was, therefore, decided to make a variance analysis by zones of the relationship between the number of vehicles and the number of passenger trips for each zone. By applying the F-test to the results of the analysis, it would be possible to estimate whether the variance in this key relationship was mainly within or between zones. In a sense this test is also an estimation of the homogeneity of the survey zones as indices of traffic generation. The results of the variance analysis, shown in Table 1, indicate that there is a very high probability that the statistical relation between the number of vehicles in zones and the rate of traffic generation by zones, as established by this O-D survey, is due to actual differences between the zones themselves and not to differences within the zones.

FACTOR ANALYSIS OF TRAFFIC GENERATION

The demonstration of this point, therefore, gave strong support to the effort to prepare product-moment correlations between a number of indices based on the Champaign-Urbana survey data as they might pertain to traffic generation. The technique utilized to develop this point was that of factor analysis. Intercorrelations between some 30 averages of indices for the zones, including five which concerned traffic generation, were computed. The matrix of intercorrelations thus secured was then factor analyzed to a centroid solution and rotated to an orthogonal solution according to the Illiac programs of the University of Illinois. The results of these procedures produced five factors, four of which showed a clear relation of zone indices to traffic generation. The results of this analysis and the identification of the factors secured are shown in Table 2.

These four factors account for almost 55 percent of the variance in the correlations among 28 variables which described either qualities of traffic generation or socio-economic indices of survey zones.

TABLE 1
SUMMARY OF ANALYSIS OF VARIANCE[a]

Source	Sum of Squares	Deg. of Freedom	Variance Est.	F-Ratio
Between zones	4,600.286	53	86.797	2.355[b]
Within zones	60,404.036	1,639	36.854	
Total	65,004.322	1,692		

[a]Regression relation between number of vehicles per zone and passenger trips per zone. [b]Significant at better than 0.01 level.

TABLE 2

FACTOR ANALYSIS OF TRAFFIC GENERATION—URBANA-CHAMPAIGN

Factor No.	Description	% of Tot. Var.[a]	Interpretation
1	Traffic volume	21.9	Economic and occupational measures of zones correlate most highly with measures of number of trips by zones.
2	Trip purpose	14.6	Trip purpose associated with driver characteristics such as age and length of residence.
3	Time of trip	9.0	Times at which trips are made during day are associated with distance which driver lives from CBD.
4	Household size and value of residence	8.8	Non-traffic factor indicates that large households live in lower value residences.

[a]Accounted for by factor.

What is important in the findings given in the table is that three of the four major factors are made of variables which are attributes of traffic and also of socio-economic indices of zones. The importance of Factor 4 is that it provides confirmation that the relationships of traffic with other indices, at least in this body of data, are valid and not merely a reflection of the manner in which the data were assembled. Attributes of traffic such as volume, purpose, and time of trip cluster with certain socio-economic indicators.

Factor 1 is significant because it indicates that traffic volume in a community is most closely linked to occupational-economic traits of zones. Also, the amount of variance accounted for by this factor suggests that the association of socio-economic traits with the amount of traffic is one of the most significant statistical clusters which can be found in the information derived from a typical O-D survey. It was this finding that prompted investigation of the question of how variations in the occupational-economic averages of zones were associated with variations in the volumes of trip generation. The aim of this approach was to estimate how much increases in the occupational-economic status of zones would increase the traffic generation of such zones if no other influences were operating in a community. The actual model of the research design was one of zones in which changes in socio-economic factors alone were operating. The fundamental question was what effect such change would have on rates of traffic generation.

CONDITIONS UNDER WHICH RATE OF TRAFFIC GENERATION MIGHT CHANGE WITHOUT CORRESPONDING CHANGE IN NUMBER OF HOUSEHOLDS

Assuming that the number of households in the zones of a community were fixed, changes in the community rate of vehicular or passenger traffic generation would presumably be a result of the change in the intensity of vehicle use by the household or of change in the number of vehicles in the household. The patterns of community traffic generation, however, reflect the differential generation by zones. The variation between zones in the number of vehicular trips generated can be accounted for by zone in terms of (a) the number or proportion of households owning cars, (b) the number of cars owned, on the average, by households, and (c) the intensity of the use of vehicles by households. The attempt to account for the influence of changes in economic-occupational traits on traffic generation must, therefore, be seen in terms of its influence on all three of these indices.

Although occupational-economic traits as a cluster of attributes seem most closely associated with the number of trips generated by the zones, no single occupational-

TABLE 3

COEFFICIENTS OF CORRELATION OF MEDIAN NUMBER OF PASSENGER TRIPS WITH SOCIAL AND ECONOMIC CHARACTERISTICS OF ZONE[a]

Characteristics	Correl. Coeff.	Std. Error of Est.	Slope b
Avg. No. of cars per household	0.797	1.198	6.215
Distance from CBD	0.461	1.758	0.118
Socio-economic status	-0.495	1.652	-0.989
Avg. length of residence	000	-	-
Median year of cars	-0.262	-	-
Avg. make of cars	0.187	-	-
Avg. value of structure	-0.453	-	-0.096
Percentage of potential trip makers making trips	0.733	1.350	0.137
Avg. No. of trips per household, having 2 cars	0.249	1.707	0.281
Having 1 car	0.802	1.184	1.406

[a] n = 41 for all of calculations.

economic trait shows as close a correlation with the number of trips generated by zones as the correlation between number of cars and number of trips in zones. The data in Table 3 demonstrate this point.

In view of the relatively low values of correlations, it appeared that an analytic technique other than statistical correlation would offer a clearer preliminary insight into the manner in which economic-occupational measures are associated with change either of vehicular ownership by households or of intensity of vehicular use. The technique used was that of analytic types based on the frequency distribution by zones of percentage of potential trip makers making trips. The data in Table 3 indicate this trait to be highly correlated with trip generation; its distribution frequency approaches that of a normal curve, making it appropriate for the derivation of analytic types of zones classified by potential trip makers who make trips. The frequency distribution of this trait is given in Table 4.

On the basis of this distribution, it was possible to derive three types of zones, one low in potential trip making, one average, and one high in this trait. The average zones, eight in number, were those which were either the mean or median values in the distribution. The low zones were one standard deviation below the mean and included seven zones in which 45 percent or less of potential trip makers made trips. The high zones were one standard deviation above the mean and included the seven in which 65 percent or more of trip makers made trips. The types, therefore, included one-half of the actual cases located at the extreme and central points of the distribution.

TABLE 4

PERCENTAGE OF POTENTIAL TRIP MAKERS MAKING TRIPS BY ZONE

Percent	No. of Zones
< 34	1
35-39	2
40-44	2
45-49	6
50-54	5
55-59	14
60-64	4
65-69	5
70-74	2
Total	41

When a number of variables associated with traffic generation are arranged by these types, several significant points become apparent, as can be seen in Table 5. This table depicts the marked differences between types of zones in their capacity or propensity to produce trip volumes. The high zones which altogether contain only slightly more households than the low zones produce almost $2\frac{1}{2}$ times as many vehicular trips and almost 5 times as many trips among households owning two cars. This decisive differential suggests how great an increase might possibly occur in local traffic volumes if existing households which are low in traffic genera-

TABLE 5

TRAITS RELATED TO TRAFFIC GENERATION OF ZONES[a]

Trait	% of Pot. Trip Makers Making Trips		
	Low Zone	Medium Zone	High Zone
% of households in tot. sample	14.7	26.6	17.3
% of veh. owned	12.6	26.2	19.8
% of all veh. trips	9.7	26.4	23.0
% of trips made by 1-car families	9.9	27.2	19.9
% of trips made by 2-car families	5.0	27.3	32.6
Veh. trips per developed acre	0.87	2.11	1.35
Occupational level	3.9	2.5	1.4

[a]Percentages are of totals for all zones.

tion were raised to the level of households which are high in this quality. The average type of zone is also of interest because it produces trips of all categories in almost exact proportion to its number among all households.

As might be expected, each type shows variation in certain general characteristics. One of the important factors in such differentiation is the predominant land use established by the local zoning code. When the possible land use is more varied, the rate of trip making is lower. Also when the proportion of single-family residences or the occupational level is higher, the rate of trip making is greater. In general, the trip-making rate is lower in areas closer to the CBD, but these areas also tend to be more heterogeneous in land use, lower in proportion of areas devoted to single-family residency, and lower in occupational level. In addition, zones at extreme distances from the CBD may be low in the occupational level, but high in the rate of trip making. In short, it appears that the influences associated with zones as they affect trip making appear to be multiple in number and not necessarily constant in effect. Zones with high occupational levels and with a high proportion of single-family residences, however, appear to represent a complex of traits leading to high traffic production. It is assumed that this complex represents a socio-economic way of life which calls for a high rate of traffic production.

INFLUENCE OF MULTIPLE-VEHICLE OWNERSHIP ON TRIP GENERATION

To estimate how changes in characteristics of households are correlated with changes in traffic volumes, some attention should be given to the influence exercised by multiple-vehicle ownership on trip production. Increase in multiple-car ownership does not proportionately increase the number of vehicular trips made by the household; for example, a two-car household does not make, on the average, twice the number of trips of a one-car household. The complicating element here, however, is that zones having a high proportion of two-car families are also those in which the use of all vehicles is intensive. This point will be treated later. The data in Table 6 demonstrate the influence of multiple-car ownership on trip production and suggest several points concerning the effect of household characteristics on trip production. First, about 15 percent of the sample of local families own no vehicles and approximately the same proportion own two. Of interest is the fact that trips with only the driver in the car are more than twice as frequent as those with driver and passenger. This is equally true of both one- and two-car-owning households, which is somewhat surprising as it had been hypothesized in households with two cars, that there would be considerably more trips made with only the driver in the car. Most pertinent, perhaps, is the fact that two-car households produce about 25 percent of vehicular trips

TABLE 6

AVERAGE NUMBER OF VEHICULAR TRIPS PER FAMILY AND PER VEHICLE

No. Cars/Family	No. Families	No. Vehicular Trips			No. Trips/ Family (avg.)	No. Trips/ Car (avg.)
		Driver Only	Driver and Passenger(s)	Total		
0	321	0	0	0	0	0
1	1,365	5,134	2,508	7,642	5.6	5.6
2	301	1,664	718	2,382	7.9	4.0
Total	1,987	6,798	3,226	10,024		

although they account for only 15 percent of households. These conditions, obviously, must be considered in the estimation of the potential increase in traffic generation which might be introduced by changing the characteristics of households.

A number of the relationships between trip generation by two-vehicle households and other criteria associated with vehicular trips were explored. First, as indicated in Table 3, the correlation between the average number of trips per zones and the average number of trips of two-vehicle households by zone is very low. This fact would seem to suggest that pattern of trip production by multi-vehicle households diverges from that of single-vehicle households. However, correlation of the differences between average number of trips made by single-vehicle and two-vehicle households in each zone with the average number of trips by two-vehicle households per zone shows that this is not the case. A plot of these two series as a scattergram indicated that there was a high and consistent relationship among them. Computation of the regression equation between them by Eq. 1 gave the following results:

$$Y = a + bX$$

$$Y = -5.51 + 1.01X \qquad (1)$$

where

X = average number of vehicular trips by two-vehicle households per zone; and
Y = difference between average number of vehicular trips for one- and two-vehicle families per zone.

This equation can be interpreted as meaning that an increase of one unit in the average number of trips by two-vehicle households implies an increase of one unit in the difference between the average number of vehicular trips by one- and two-vehicle households. It suggests that since the average number of vehicular trips by zone for two-vehicle households does not correlate with total vehicular trips by zone, the average generation of trips by households increases at a different rate than that of total trips by zones. This conclusion can be related to vehicular trip production by stating that in zones of high trip production both single- and two-vehicle households produce relatively more trips since the differences between these groups is constant. The only exception to this statement is the case of multi-vehicle households in zones which are lowest in trip production. In other words, the production of vehicular trips by two-vehicle households is not independent of the trip production of the zone in which the two-vehicle household is located. This conclusion is in agreement with the implications of the findings in Table 1, although it might be hypothesized, without the evidence presented thus far, that when a household enters the status of multi-vehicle ownership, its pattern of trip production may vary considerably from the other households in its survey zone. As noted, the only apparent actual exception is for the zones at the lowest level of trip production by resident households.

ESTIMATING INFLUENCE OF INCREASES IN SOCIO-ECONOMIC STATUS ON TRIP GENERATION

To estimate how much influence an increase in the socio-economic status of households would have on trip generation, it was necessary to establish some index of socio-economic status. The research staff decided that such a measure should include three criteria which appeared to be correlated with trip generation by zones and which also were apparently indices of the socio-economic way of life of households as it influenced the typical pattern of trip generation. These criteria were (a) the average occupational level, (b) the dominant pattern of land use of the zone as defined by local zoning ordinances, and (c) extreme distances of zones from the CBD which included areas outside the city limits of the Champaign-Urbana community. This last item was considered because households in this category were unique in their combination of socio-economic traits and patterns of trip generation.

TABLE 7

WEIGHTED SCALE OF OCCUPATIONS BY ZONES[a]

Composition	Criteria	Scale Type[b]	Weight	No. of Zones
Order (1 2 3) 1. Laborers and unskilled 2. Craftsmen, foremen, and skilled or clerical, sales and kindred workers 3. Professions and semi-professions or managers and officials	A category receives a "1" if the percent in the zone who work in that occupation is equal to or greater than the median percent for all zones (a "0" is received if this percent is less than the median); 0 percents are included in the determination of the median.	001 011 010 111 110 100	1 2 3 4 5 6	4 8 3 2 2 3

[a]Source of data: occupation of driver reported in household survey.
[b]When there are two industries in any single category, the category receives a "1" if either or both industries placed in that category qualify for a score of "1" which indicates a proportionately prevalent number of workers in that industrial category.

The index developed was a Guttman-type scale which combined only the average occupational level of zones and prevailing legal land use. Extreme distance of zone from the CBD did not appear to be a dimension of this scale, but allowance was made for this trait by independently estimating its influence on traffic generation. The primary scale developed was regarded as a measure of the average socio-economic level of households in a zone. The occupational index for each zone was derived from the occupations reported on the No. 2 card of the household survey. These occupations were scaled according to the prestige and income rankings of occupation as reported in a study of the National Opinions Research Center (7). A 6-point scale was devised which when applied to the 22 zones represented in Table 5 gave the results indicated in Table 7.

The second dimension of socio-economic status included in the scale was based on the predominant land use of zones as defined by the local zoning code of Champaign-Urbana. The proportions of the land area of each zone devoted to legally permitted categories of land use were determined by studying local zoning maps. The community as a whole appeared to have a distribution of land use roughly comparable to other communities of this size. The distribution for the whole community is given in Table 8.

A scale was developed representing the predominant land use of each zone in terms of the proportions of the zone represented by the land-use categories in Table 8. This scale was applied to the 22 sample zones. The distribution of these zones on a 3-point scale and the criteria of the scale are given in Table 9.

These two dimensions were then combined in a Guttman-type scale for the 22 zones as indicated in Table 10. The resulting scale distribution had a coefficient of reproducibility of 0.89 with a relatively broad distribution across a 6-point scale. Despite the small sample of zones, this scale appears to be a measure of a uni-dimensional trait representing the socio-economic status of the local community. It is important to note that the two dimensions of the scale were developed from independent bodies of data and therefore the high degree of association is not an artifact of the household survey itself.

The scale in Table 8 provides a relatively simple measure of the socio-economic differences of the zones. The next problem in the investigation was to determine the extent to which these differences were associated with differences in the three types of zones representing different proportions of trip makers. When the occupation scale is applied to these three types, as in Table 11, clearly discernible differences are apparent in the socio-economic status of the types of zones as defined in terms of their traffic-generating

TABLE 8

LAND-USE DISTRIBUTION, CHAMPAIGN-URBANA COMMUNITY

Description	Acreage	Percent Total Acreage
Single family use	4,074	49.2
Multi-family	1,237	14.9
Commercial	492	5.9
Industrial	921	11.1
Public[a]	1,557	18.8
Total urbanized acres[a]	8,281	100.0

[a]Does not include street acreage included in each category which constitutes approximately 30 percent of total acreage.

TABLE 9

LAND-USE TYPES

Scale Type	Description	Definition	No. of Zones
I	Single-family dwellings	> 50 percent acreage in residence but ≥ 60 percent of total acreage in single-family dwellings.	9
II	Multiple-family dwellings	> 50 percent acreage in residence but < 60 percent in single-family dwellings.	8
III	Commercial—mixed	< 50 percent residential and combination of public land and industrial, railroad and commercial ≥ 50 percent of developed acreage.	5

TABLE 10

SOCIO-ECONOMIC STATUS OF SAMPLE ZONES[a]

Scale Value[b]	No. of Zones
2	4
3	5
4	5
5	6
6	3

[a]Based on Guttman-type scale combining occupation and prevailing land use.
[b]The lower the scale value, the higher the socio-economic status.

TABLE 11

RANKINGS OF ZONES DISTINGUISHED BY TRAFFIC-GENERATING POTENTIAL

Type of Zone[a]	Socio-Economic Avg. of Zones
Low	4.6
Medium	3.6
High	2.3[b]

[a]From Table 5. [b]Does not include zones extending outside city limits.

potential. The differences between these zones, if we can assume that the 6-point scale of Table 7 roughly represents the total socio-economic range, is approximately 20 percent. In other words, the socio-economic level of the medium traffic potential type is 20 percent above the low traffic potential type and that of the high type is about 20 percent above the level of the medium type. On the basis of these data some estimation may be made of the extent that increase in socio-economic status, with other factors held constant, may lead to increase in traffic generation.

ESTIMATING INFLUENCE OF INCREASE IN SOCIO-ECONOMIC STATUS ON VEHICULAR TRAFFIC GENERATION

Table 11 provides an index of the range in socio-economic status of present zones. The aim of the report is to estimate how much traffic generation would increase if the number of households in the community remained constant but the socio-economic status of the community were raised. The assumption here, of course, is that changes or rises in national and regional prosperity will be reflected in improvement of the community occupational level and a rise in the level of home ownership represented in the pattern of local residential land use. Occupation and residential land use are the primary dimensions of the scale reported in Table 11.

Any estimate of how national and regional economic trends affect any particular local community must be hypothetical unless some specific relationship has already been established between these two variables. An estimate of the increase in traffic generation in Champaign-Urbana for the decade 1960-1970, for example, would be based on the following assumptions:

1. That the long-run trend of most communities follows the long-run national economic growth represented by the change in the gross national product;
2. That the increase in the gross national product (in constant dollars) of approximately 20 percent for Champaign-Urbana from 1950 to 1960 (8) was paralleled by an equivalent increase in the economic status of the community for this period, and that this increase will be replicated for the decade 1960-1970;
3. That the number of households will remain constant over the 10 years;
4. That the present relation between trips by household to the socio-economic level of the household will remain the same;
5. That since the socio-economic differences between each of the three types is roughly 20 percent, and it is also expected that the economic level of the community will increase 20 percent over the period of 1960 to 1970, each of the two lower zone types will move up during these years to the level of the next higher type;
6. That the high type of zone, with respect to traffic-generating potential as indicated in Table 3, will go to the highest socio-economic level of any zone included in this type; and
7. That the proportion of the community households in each type will remain the same. (The ground for this assumption is that there will obviously be a range in socio-economic levels of the community in 1970, and, since there is no basis for a better estimate, the distribution of the proportions of households at each level will be similar to what it was in 1960 shortly after the household survey.)

Given these assumptions, the steps in the estimation of traffic generation are as follows.

1. Estimate for each type the new number of (a) single-vehicle households and (b) multiple-vehicle households.
2. Estimate the new rate of vehicular trip generation (a) for single-vehicle households and (b) multiple-vehicle households.
3. Total the results for the three types of Steps 2 a and b.
4. Compare the estimated results of Step 3 to results obtained from the original survey in respect to the estimated increase in number of vehicular trips.

The completion of these steps gives the results indicated in Table 12. These estimates are derived by applying the trip-generation rates of 1960 for the households in the next higher type to all households in each zone. In the case of the high type, the rates for the highest zone in this classification were used. The results of Table 12 may be summarized in the form given in Table 13.

TABLE 12

ESTIMATED INCREASE IN VEHICULAR OWNERSHIP TRIP GENERATION, CHAMPAIGN-URBANA, 1960-1970[a]

Type of Zone	No. of Households: No Vehicles 1960	No Vehicles 1970	1 Vehicle 1960	1 Vehicle 1970	2 Vehicles 1960	2 Vehicles 1970	Trips: 1-Veh Household 1960	1-Veh Household 1970	2-Veh Household 1960	2-Veh Household 1970
Low	89	41	180	208	28	44	759	1,144	212	317
Medium	92	26	357	369	78	132	2,077	2,325	565	1,162
High	17	0	239	223	87	120	1,522	1,673	777	1,152
Total	198	67	776	800	193	296	4,358	5,142	1,554	2,634

[a]Based on assumption of no increase in number of households and that increase in vehicular ownership and trip generation can be attributed to general increase in community economic level.

TABLE 13

SUMMARY OF ESTIMATED INCREASE IN NUMBER OF VEHICLES AND VEHICULAR TRIP GENERATION, CHAMPAIGN-URBANA, 1960-1970[a]

Trait	1960	1970	Increase (%)
No. of vehicles	1,162	1,396	8.3
No. of trips	5,912	7,773	24.0

[a]Assuming no increase in number of households.

CONCLUSIONS

The figures in Table 13 provide the conclusions which this report attempts to establish. Since vehicle ownership and trip generation are apparently related to the socio-economic levels of households in the community, if the pattern of vehicle ownership and trip generation of this community at the time of the 1958 O-D survey continues to hold and if the socio-economic levels continue to rise at the existing national rate, there will be an increase of slightly less than 10 percent in the number of vehicles owned by the households at the time of the survey. This increase would result from the acquisition of vehicles by households not possessing them and from households owning one vehicle moving to two-vehicle ownership. At the same time, however, the rate of trip generation would increase as households moved to a higher socio-economic level as a consequence of general economic growth of the society. Consequently, the rate of increase of trip generation would be considerably greater than that of the rate of increase in vehicle ownership by households.

These conclusions appear consistent with the evidence provided by the various phases of this study. The method of demonstration was to select samples representing types of zones whose traffic-generating patterns are clearly delineated in terms of the proportions of potential trip makers actually making trips as reported in the household survey. This procedure was followed because of its analytical precision in revealing social and economic factors associated with trip generation. The survey zones involved in the sample accounted for only about 50 percent of the zones reported in the original survey, but insofar as the sample zones represented the whole range of traffic-generating patterns of the community, it would seem that conclusions based on their characteristics would be adequate descriptions of dimensions of traffic generation for the whole community.

It should be kept in mind that the community in question is specifically a middle-sized city with an atypical economic base. Obviously projection of these findings to traffic generation in general requires further testing on communities of both similar and dissimilar population size. A tentative comparison of these findings with some of the conclusions of the major surveys reported for Detroit and Chicago suggests confirmation of some of the results and differences with others. Continued systematic comparisons of such O-D studies will be necessary to develop the understanding of traffic generation necessary for effective planning for traffic engineering and control.

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Review of Existing Land-Use Forecasting Techniques

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THE BOSTON Regional Planning Project (BRPP) has retained the Traffic Research Corporation (TRC) to develop and apply for preliminary forecasts a mathematical model for estimating future distributions of population, land use and economic activities in the Boston region. BRPP plans to use this model as a device for testing and evaluating the probable future effects of transportation facilities, zoning policies, and possibly other factors under planning control on the distribution and density of development patterns throughout the region.

Most urban transportation planning studies during the past decade have produced or are producing estimates of future land use in all subregions of the areas which have been or are under study, mainly to provide a basis for estimating future traffic demand. (In this context, land use includes population and economic activities as well as structures and land areas.) Methods employed for these land-use estimates have ranged from largely intuitive or judgmental projections to systematic techniques based on a chain of quantitative reasoning which could be reproduced by another group.

The purpose of the present review is primarily to insure that existing techniques are fully utilized, where pertinent, in the development of a land-use forecasting model for the Boston region.

STUDY METHOD

This report is based on a review of the included references and on discussions with researchers concerning various aspects of their predictive techniques. An effort has been made to concentrate on techniques based mainly on explicit formal relationships rather than those which rely mostly on judgment applied subjectively to each subregion. Stress has also been placed on techniques which have been or may be calibrated and/or tested empirically.

The various land-use forecasting techniques described may be grouped into a number of categories according to types of variables, types of restraints and controls, manner of application, degree of operationality, and basic concept employed. Based on the latter criterion only, techniques may be classed as ad hoc, potential, economic, regression, behavioral, etc. Little attempt has been made to group the reviewed techniques along these lines, mainly because most of the techniques are found to fall into several categories simultaneously. The basic characteristics of each technique and some group characteristics are described.

For presentation purposes, however, it is useful to divide the techniques into three groups according to their present development stage. Group 1 comprises techniques which are operational for forecasting purposes or are now being developed to operationality. Group 2 consists of research-oriented studies, aimed primarily at gaining insight into urban processes by empirical testing of certain hypotheses. Group 3 is made up of conceptual studies primarily of interest because of the ideas involved rather than because of any empirically tested relationships which may have resulted. Again, there is some doubt concerning the group to which certain techniques belong; the distinctions are not entirely clear cut, and the choice of group has been fairly arbitrary in some cases.

An attempt has been made to describe the following aspects of each technique: input and output variables, forecasting methods and relationships, methods of calibrating

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and/or testing, data requirements and controls, and computational equipment required. Techniques falling into Group 1 have been covered in most detail, although even here some of the techniques have not been developed or described sufficiently to enable coverage of all these points. For techniques falling into Group 2, emphasis has been placed perforce on data and relationships. It has been necessary to describe techniques falling into Group 3 mostly in terms of the concepts and formulations involved.

It is, of course, recognized that the list of 14 land-use forecasting techniques reviewed in this report is not exhaustive. Some techniques, notably those employed in some of the earlier urban transportation studies, have been eliminated because it was felt that their ad hoc nature would contribute little to the present model development project. Others were not included because of their similarity to techniques which have been reviewed; for example, the Pittsburgh Area Transportation Study was developed with reference to the Chicago Area Transportation Study. Still other studies, such as those at Hartford, Conn., Washington, D. C., have been included under the name of the individuals involved. Finally, current land-use forecasting work by a number of groups (the Upper New York State Transportation Studies, Los Angeles Regional Transportation Study, Puget Sound Regional Transportation Study, Twin Cities Area Transportation Study, Southeast Wisconsin Regional Planning Study, Tri-State Transportation Commission, and Ohio-Kentucky-Indiana Transportation Study) has been omitted because of the lack of descriptive detail on their work or plans available at the present time. The land-use models previously developed or currently under development by the Traffic Research Corporation are described in a project description and progress reports which have been submitted previously to the Boston Regional Planning Project and are, therefore, not summarized in the present report.

In summarizing forecasting methods and relationships used in the various techniques, an attempt has been made to present the concepts involved as briefly as possible without oversimplification. In some cases it has been possible to quote directly the relevant mathematical equations. In other cases, however, where presentation of the mathematical formulations in symbolic form and definition of symbols would require a number of pages of quite complex mathematical notation, the mathematical formulations have been presented in words for the sake of brevity. Symbolic presentations of these equations and relationships can be found in the source documents listed in the references.

NOMENCLATURE

A number of technical terms used in describing the various techniques are briefly defined as they are used in this report.

Model—a systematic method, based on logical or mathematical relationships, for describing, simulating and forecasting real-life processes, in this case the distribution of land-use categories throughout an urban region. The term is used synonymously with technique.

Land-Use Categories—include structures, economic activities, employment, floor areas, population, land areas, and generally any items that can be used to describe urban subregions and regions in quantitative terms.

Input Variables—data categories required to operate a land-use model.

Output Variables—data categories whose subregional values are estimated or forecast by a land-use model.

Relationship—a quantitative statement showing how one variable depends on one or more other variables. It may be in the form of a mathematical function, inequality or equation, or possibly in tabular form.

Parameter—a number which is part of a mathematical relationship and is either constant in value or takes one of a number of specified values; also known variously as a coefficient or a constant.

Calibration—determination of the best values of parameters in the various relationships comprising the model so that the model describes as closely as possible historic situations and events of the type it is intended to simulate.

Independent Variable—a data category which is felt to be the cause rather than the effect of a particular process, and is, therefore, considered as an input variable rather than an output variable with reference to a relationship describing the process. Conversely, a dependent variable is a data category which is considered to be an effect of a particular process, and is, therefore, considered to be an output variable of the relationship in question.

Reliability Check—a quantitative evaluation of the probable forecasting accuracy of a model. This can be based on a statistical appraisal of the model's relationships and/or on application of the model to simulate a historical situation which was not used in its calibration, followed by a statistical comparison of calculated and observed results.

Regression Analysis—the process of describing by an equation the relationship between a dependent variable (output variable) and one or more independent variables (input variables) so that the equation so derived describes the relationship, as represented by a number of observations, with a minimum of error. A common method of regression analysis is the method of least squares.

Coefficient of Correlation, R—a statistical measure of the degree to which changes in the dependent variable are explained by changes in the independent variable(s). Definitions of this and other commonly used statistical terms may be found in standard statistical texts. Values of R quoted with reference to some of the models described herein should be treated with caution as a means of comparing models; R is influenced by factors such as number of observations, the slope of a relationship, and zone size, so that quoted values of R should not be used to compare one technique with another unless care has been taken to render other things equal. The square of this expression, R^2, is known as the coefficient of determination and is used conventionally as the measure of predictive ability of a relationship or model.

Recursive—consisting of a series of sequential forecasts where output from one forecast is used as input for the next in the series. Recursive in time consists of a series of sequential forecasts, each of a different point in time and each using about the same functional relationships between input and output, where output from the forecast of one point in time is used as input for the forecast of the next point in time.

Monte Carlo Simulation—simulation of the action of a large number of entities by simulating in detail the actions of a sampled subset of the total number of entities. The name derives from the use of random numbers in estimating probabilities required to simulate various decisions made by the sampled entities. The simulation of the activities of one randomly selected group or bundle of the entities is known as a game.

GROUP 1—OPERATIONAL OR QUASI-OPERATIONAL TECHNIQUES

Penn-Jersey Transportation Study

The Penn-Jersey regional growth model represents the largest research effort during the past few years devoted to the development of a land-use forecasting technique. Since Herbert and Stevens presented the basic theoretical structure in 1960 (2, 3), the model has been further elaborated and modified in various papers (4-8, 10, 13). At present, the model is not yet operational but is being intensively developed.

The model operates recursively in time by making a 5-year prediction, using the results of the first prediction as a basis for the next 5-year prediction.

The core of the model is the simulation of residential location based on the economic theory that individual households tend to maximize their locational advantage and that land is allocated to that group of households which can bid the highest price for it. The inputs to the activity distribution phase of the model for one iteration are as follows.

1. Inputs describing the state of the system, i.e., population location and characteristics; activity location by industry or other activity category; existing stock of buildings by area and type; vacant land by characteristics by area; accessibility to opportunities by area (from transportation model); projected income levels; in-migration to be accommodated by type of in-migrant; and growth of economic activity to be accommodated.

2. Data reflecting assumptions and policies, i.e., public open space reserved; public redevelopment; and land development controls and public services.

3. Subsidiary models, parameters and relationships such as calculation of land availability, relationships expressing rate of release of land for new uses, and rent levels from preceding iteration; household and population changes over time, applicable rates, demographic and other; probabilities of households of different types moving from initial location before end of iteration, by household type and area type; division of housing market between renters and owners, and applicable rates; relationships summarizing desirability of areas that determine household budgets to be devoted to location; formula for computing cost of transportation and costs of housing of different types, for households of different types in different areas; formulas for determining locational patterns of consumer-serving industries, including local government, on the basis of the location of population and accessibility measures (transportation conditions); growth and aging characteristics of all other industries; and locational preferences of all other industry based on area characteristics and accessibility (transportation) measures.

First, the model makes all calculations related to land availability. Only certain amounts of land are released in each zone for possible development in each use. This is contingent on zoning and redevelopment policy and on speculative holding. The latter is taken into account by withholding land in zones where rent has risen rapidly during the previous projection period. The model then proceeds to locate households by aging the households in each zone. Each household member ages 5 years or dies. Some households break up, others have children, others are newly formed, others emigrate from the region. The households remaining in the region, plus the projected in-migration, form the population in the future year. Each household will have changed character by this aging and changing of its income level and will have a certain probability of changing residence during the projection period. This information and information concerning newly formed and in-migrant households are used in calculating a pool of locators of each household type.

Each locating household type is assigned a locational budget for each zone equal to the annual amount of money it is prepared to spend therefor transportation and housing. This depends on the income of the household and its preference for different types of zones and possible housing types in the zone. The real annual cost of housing (not including land rent) and the transportation cost in each zone are then deducted from the locational budget of each household type for each zone. The transportation cost is related inversely to the accessibility of the household to destinations of the collection of trips it is likely to make during the year. The residual of these deductions from budgets is called rent-paying ability. Each household type has a unit rent-paying ability for each zone equal to the amount per square foot of land it is willing to pay to locate in its preferred housing type in that zone. It is assumed that each household type seeks to maximize its rent-paying ability and the landowners seek to maximize the returns on their property. The end result of the model is that households locate in such a way as to maximize aggregate rent-paying ability. The model simulates this process through a linear program (2, 3, 10) which maximizes aggregate rent-paying ability subject to two types of constraints: that all households must be located and that the total land used in each zone must not exceed the land made available.

The following notation is used in the formulation of the linear program.

U = areas forming an exhaustive subdivision of the region, indicated by superscripts $K = 1, 2, \ldots, U$.

n = socio-economic groups indicated by subscripts $i = 1, 2, \ldots, n$. For each group in each area, the subscript i also refers to a specific locational bundle, chosen from the set of available bundles, which affords the highest unit rent-paying ability for that group in that area.

b_i^K = annual location that a household of group i will use if it locates in area K $(i = 1, 2, \ldots, n)$.

c_i^K = annual cost to a household of group i of locational bundle it purchases in area K $(i = 1, 2, \ldots, n)$, $(K = 1, 2, \ldots, U)$.

s_i^K = number of units of land in locational bundle purchased by household of type i in area K (i = 1, 2, ..., n), (K = 1, 2, ..., U).

L^K = number of units of land made available in an iterative period for residential development in area K (K = 1, 2, ..., U).

N_i = projected number of households of socio-economic group i to be located in region during same iterative period (i = 1, 2, ..., n).

X_i^K = number of households of socio-economic group i located (by model) in area K in that iterative period (i = 1, 2, ..., n), (K = 1, 2, ..., U).

Allocation model.—The linear programming model for allocating households to land has the following form:

$$\text{Maximize } Z = \sum_{i=1}^{n} \sum_{K=1}^{U} X_i^K \left(b_i^K - c_i^K \right) \qquad (1)$$

Subject to

$$\sum_{i=1}^{n} s_i^K \; X_i^K \leq L^K \qquad (K = 1, \ldots U),$$

$$\sum_{K=1}^{U} - \; X_i^K = -N_i \qquad (i = 1, \ldots n), \text{ and}$$

$$\text{all } X_i^K \geq 0 \qquad (K = 1, \ldots U), \; (i = 1, \ldots n)$$

The model proceeds to locate consumer-oriented and government activities mostly in relation to population of each zone and nearby zones. Some attempts will be made to develop a hierarchy of such activities with respect to the size of market in order to determine the degree of orientation to residential areas.

A procedure somewhat similar to the residential model is proposed for locating industry, wholesaling, warehousing, etc., using an aging process for firms, their locational budgets, transportation costs, structure cost, and consequent rent-paying ability. Land cost in each zone will also be included, determined by the residential model. Certain types of heavy industry and specialized activities will be located by hand. Alternatively, industries may be distributed according to probabilities to all land areas where the balance between cost and desirability is suitable. Penn-Jersey staff are also considering the adaptation of Karl Dieter's polimetric model, currently under development by TRC on behalf of the BRPP, for possible use as a submodel for locating industries in the Penn-Jersey region.

The output of the model will be a spatial distribution of different types of industrial and commercial activity with the corresponding amount of land used and a spatial distribution of household types, housing types, and land rents. A transportation model for distributing and assigning trips, etc., is part of the regional growth model and uses input from and supplies output to the activity distribution phase. A flow chart of one iteration of the regional growth and transportation model is reproduced in Figure 1, (5).

The model disaggregates the independent variables to a greater extent than most other land-use models. Such disaggregation (for example, into different size households of different income levels) is designed to identify the basis of changing behavioral characteristics of aggregate groups so that these changes can be predicted more reliably when the changed composition of the groups is known. A technique called latent class analysis will be used to stratify households into a small number of homogeneous groups of different locational characteristics in order to avoid stratification on the multitudinous independent variables available from the survey data. No results have yet been reported on calibration or testing of the model. Considerable data are avail-

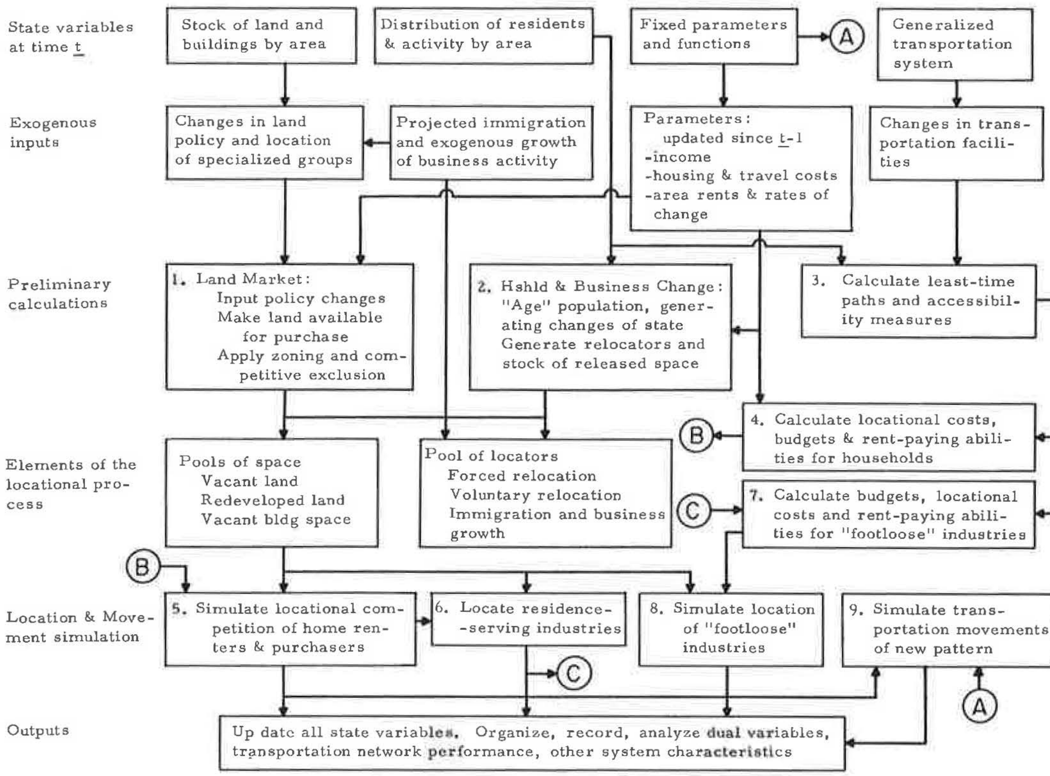

Figure 1. Flow chart: one iteration of regional growth and transportation model.

able for this purpose, including a 1960 survey of 65,000 households with information on household and trip making characteristics. The Penn-Jersey study has available an IBM 1401 data processing system and 7090 or 7094 computers. The computers will be required for application of the regional growth model.

An alternate system, the simplified distribution model (14), is also being developed to distribute land uses to Penn-Jersey districts (comprising about four zones each). This will first distribute industrial development (using the same models as the regional growth model), then households, and then household-oriented activity. Households will be distributed by specifying incremental population by household types for each county, predicting the socio-economic characteristics of each district and assigning the households accordingly. The changes in each district will be established by the initial state (socio-economic class) of the district and the probabilities of transition to other states.

Chicago Area Transportation Study

The Chicago method (29-32) cannot properly be called a mathematical model since much of the procedure involves elements of judgment rather than explicit mathematical relationships. Thus, the results of the forecast are probably not reproducible unless done by the same study team.

The region is divided into zones according to a grid system. These zones are grouped by sector and by ring. A district is a group of zones common to a particular sector and a particular ring. The object of the method is to predict the future year (1980) population and manufacturing employment by zone and the number of acres of each zone to be devoted to major land-use classes—residential, commercial, public open space, manufacturing, transportation (such as airports), streets and alleys, and others.

The procedure followed may be described as land-use accounting where predictions are made on a large area basis and the area figures are used as controls for the totals of the component subareas. The hierarchy is typically region, ring, district, zone. Numerous checks and balances are involved in the procedure and specific account is taken of discontinuities such as large regional shopping centers. Considerable emphasis is placed on internal consistency and the stability and reasonableness of results.

The procedure depends on the following data, which can be considered as input:

1. Base year land occupancy patterns—population, employment, and land use;
2. Existing zoning ordinances and community plans affecting the use of vacant land;
3. Plans for redeveloping the central built-up area; and
4. A forecast of future year total population for the city, the study area, and the metropolitan area and a forecast of total employment by industry type for the study area and the metropolitan area.

In the Chicago study, unlike in Boston, the study area lies within the metropolitan area.

As a first step, the stability of already built-up land over time was examined. It was found that the land already built-up in 1940 was used in much the same way in 1956. On this basis it was decided to use the same population density and proportional use of land in 1980 for all zones built-up in 1956, with the exception of the central area of the city, where the present conditions were substituted by a redevelopment plan of the Chicago Department of City Planning.

Second, all vacant land was classified into the various land-use classes. Public open space was designated according to present conditions and expected open space standards for the future population. Manufacturing land was designated as all land presently zoned for industry, plus tracts listed by the Commonwealth Edison Co., as favorable for industrial sites, plus other sites considered suitable. Area for streets was designated as present street area plus a percentage of usable vacant land. Railroad land, airport land, and trucking warehouse and other nonmanufacturing-industrial land was designated mainly on the basis of trends in the demand for such uses. The remaining usable land was designated as residential and commercial. Local commercial land was designated according to a per capita rate and based on a preliminary estimate of population density. Non-local commercial land was mainly regional shopping centers located according to present plans and estimates of regional requirements.

Population was distributed to the residential land by calculating holding capacity of each zone. This was done by specifying the net residential density for each zone and multiplying by residential acres. A stable pattern of density as a function of distance from the central business district (CBD) was observed between 1940 and 1956 and projected to 1980. Considerable study was made of percent capacity as a function of distance from the CBD at different points in time and in different sectors. A downward sloping curve was observed for all cases and a curve was conjectured for 1980 which would contain the expected population within the study area. Adjustments were made according to characteristics peculiar to each zone.

Manufacturing workers were distributed by a similar procedure of calculating capacities according to available land and densities, and relating percent capacity to distance from the CBD. An attempt was also made to relate workers in each ring to the population in each ring and this was adjusted according to a downward sloping percent capacity relationship with distance from the CBD.

The Chicago method was not tested for accuracy by predicting known values of a present activity using only data on past activity. One of the weak points is the percent capacity curve which, though measurable in 1956, appears to be largely arbitrary in 1980. The parameters were quantified typically by plotting survey data and in some cases data for more than one time period and observing the stability of the relationships over time; a minimal amount of statistical technique such as regression analysis was utilized and much of the adjustment was based on judgment. It appears that most of the computation could be done utilizing accounting-type data processing equipment except possibly for a few curve-fitting procedures where a computer might be of some help.

The accuracy of the procedure depends a great deal on the judgment of the study team. Considerable emphasis has been given to internal checks and alternate ways of making particular predictions as well as to maintaining control totals in aggregate areas.

The procedure of land-use accounting could be used in conjunction with more explicit mathematical prediction techniques in apportioning the land-use distribution to traffic zones from the larger subregions which might reasonably be the basic areas of the mathematical model.

Study by Voorhees, Barnes, and Hansen

This section summarizes the techniques (33-39) used to predict land-use variables in connection with transportation studies carried out in Washington, D. C., and Hartford, Conn.

Traffic prediction models require as input the values of various land-use variables for each zone. In the Hartford Area Transportation Study (35, 36, 38), the following variables had to be predicted: (a) manufacturing employment, (b) service employment, (c) retail trade employment, (d) population, and, as a by-product, (e) number of cars registered.

The percentage of total growth in manufacturing employment occurring in each zone was related to different variables by multiple correlation analysis (linear multiple regression). Ultimately nine were used: (a) highway accessibility to the labor force in the base year, (b) vacant industrial land, (c) tax rate, (d) sewer facilities index (related to system capacity), (e) rail service (subjective rating), (f) water facilities index, (g) travel time to airport, (h) promotion (activity of town in promoting industrial activity) and (i) industrial land close to expressway. It was found that (b) and (d) were of prime importance and (a), (e), and (g) were second in order of importance, though all nine variables were used in the final equation:

$$\text{Growth index} = 12X_1 + 37X_2 + 5X_3 + 34X_4 + 12X_5 + 2X_6 + 19X_7 + X_8 + 5X_9 + 120 \quad (2)$$

$$\text{Zonal growth} = \text{total growth} \times \frac{\text{zonal growth index}}{\sum \text{(zonal growth indices in all zones)}}$$

The coefficient and significance levels of the three best equations are shown in Figure 2 (36); R^2 is not stated. Note that the equation of analysis 3 was used even though four of the variables had no significance.

Distribution of growth of service employment was predicted using an arbitrary factor equal to the product of base year highway accessibility and retail employment. Distribution of retail employment growth was made proportional to distribution of population growth. Population growth was distributed according to future year employment accessibility and holding capacity for new development. (The actual form of the relationship is not stated, but is evidently similar to the linear dependence in the manufacturing land relationship.) Adjustments were made on the basis of other factors such as prestige locations and building codes from results of a questionnaire sent to building contractors. Number of cars was made proportional to population times the car ownership. The latter was predicted to vary with income for different residential density groups according to data from studies in other areas of the country.

The growth in the various land-use categories was distributed in a predetermined order using the results of the previous distribution as input to the next one. The order was established on the grounds that certain activities were more alert to changes and should be settled first. The order was industrial employment, population, retail employment (service employment was not mentioned but presumably was predicted after retail). To make a prediction for 1990, two intermediate predictions were made for 1965 and 1975. This accounted for feedback effects, where the results of the future year projection over the first time period are used to describe the base year of the next time period. The zones for which the predictions were made were the 41 cities and

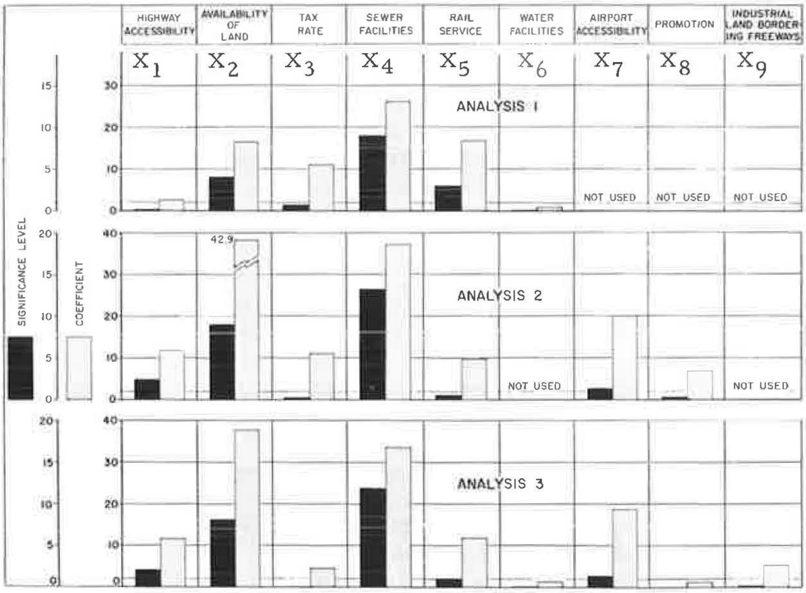

Figure 2. Bar chart of coefficients and levels of significance used in industrial land equations, Hartford area traffic study multiple correlation analysis.

towns in the Hartford area. Most of the calculations involved in applying the model were apparently carried out manually, although it is understood that U. S. Bureau of Public Roads least time path programs were used in determining accessibilities. A number of computer types, including the IBM 1401 and 7090, could be used for this purpose.

The relationships were based largely on the data describing the Hartford area in 1950 and 1958. In the predictions, considerable adjustments were made in the relationships developed, since the mathematical equations did not adequately describe the distribution of growth between 1950 and 1958. For example, it was found that much industrial development not predicted by the model occurred in a certain traffic corridor. Population change was not adequately described by the model; in particular it tended to underestimate the suburbs' share of growth. Retail employment growth did not correspond to the pro rata assignment to population growth because of the development of large shopping centers. Comparisons of estimated vs observed values of population growth distribution and retail employment distribution were presented using known values of future year (1958) industrial employment distribution and population distribution, respectively, as a basis for calculating predicted values. The comparisons were made in the form of maps showing for each year the observed value and predicted value side by side by means of bar charts. No values for R are stated, though they could presumably be calculated from the maps (Figs. 3 and 4, 36). The comparisons would probably show even poorer correspondence if predicted values of industrial employment distribution and population distribution were used respectively in the estimates.

Hansen (34) describes a relationship for predicting the distribution of metropolitan population growth as follows:

$$\frac{P_i}{P_t} = \frac{A_i^{2.7}\, O_i}{\sum\limits_{j=1,\, n} (A_j^{2.7}\, O_j)} \tag{3}$$

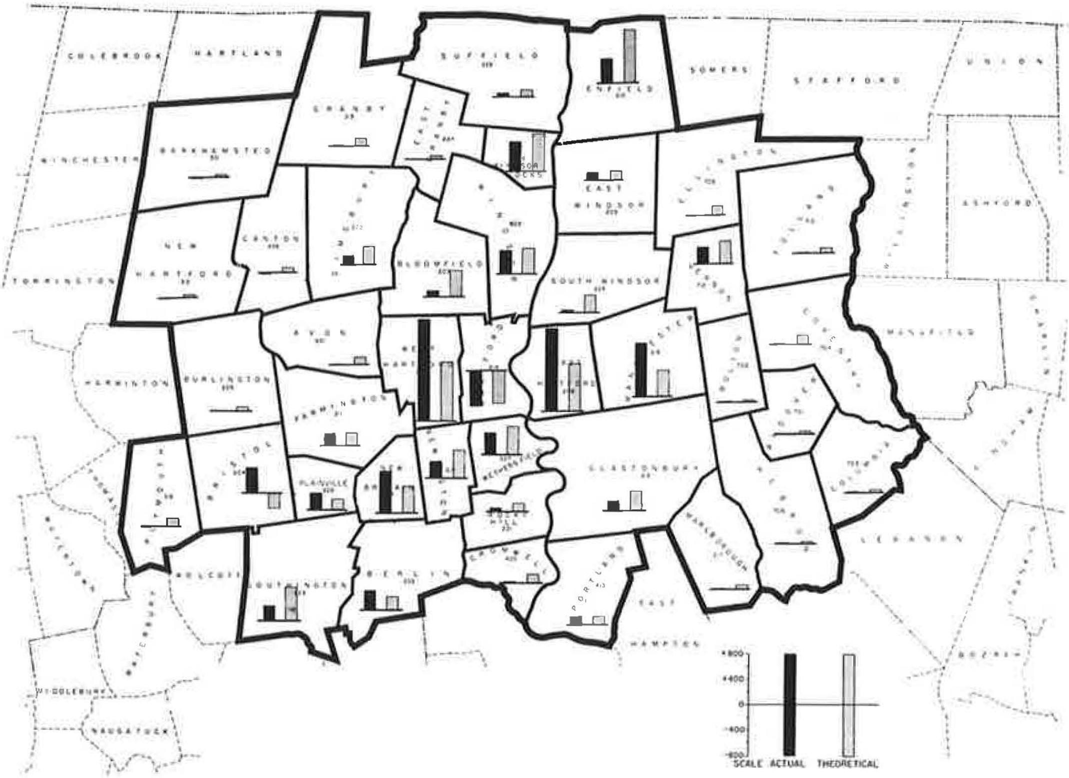

Figure 3. Retail employment change, 1947-1955, by towns, Hartford area traffic study.

where

P_i = increase in residential population zone i;
P_t = total increase in metropolitan population;
O_i = developable land in zone i; and
A_i = accessibility to (future year) employment.

The exponent 2.7 was derived from changes between 1948 and 1955 in the Washington metropolitan area. It is reported that comparison of actual and calculated subregional changes in residential population between 1948 and 1955 revealed that 40 percent of the zones showed calculated values of the changes to be within ± 30 percent of observed changes and 70 percent of the zones showed calculated changes which were within ± 60 percent of observed changes.

A similar procedure was used on behalf of the National Capital Transportation Agency to make predictions of 1980 population throughout the Washington, D. C., metropolitan region (39). The relationship used was the following:

$$P_i = P_t \frac{A_i H_i Q_i}{\sum_{j=1,n} (A_j H_j Q_j)} \tag{4}$$

where

H_j = holding capacity of a zone, based on developable land times probable future net population density; and
Q_j = a special factor taking into account features peculiar to each zone which are felt to encourage or retard growth.

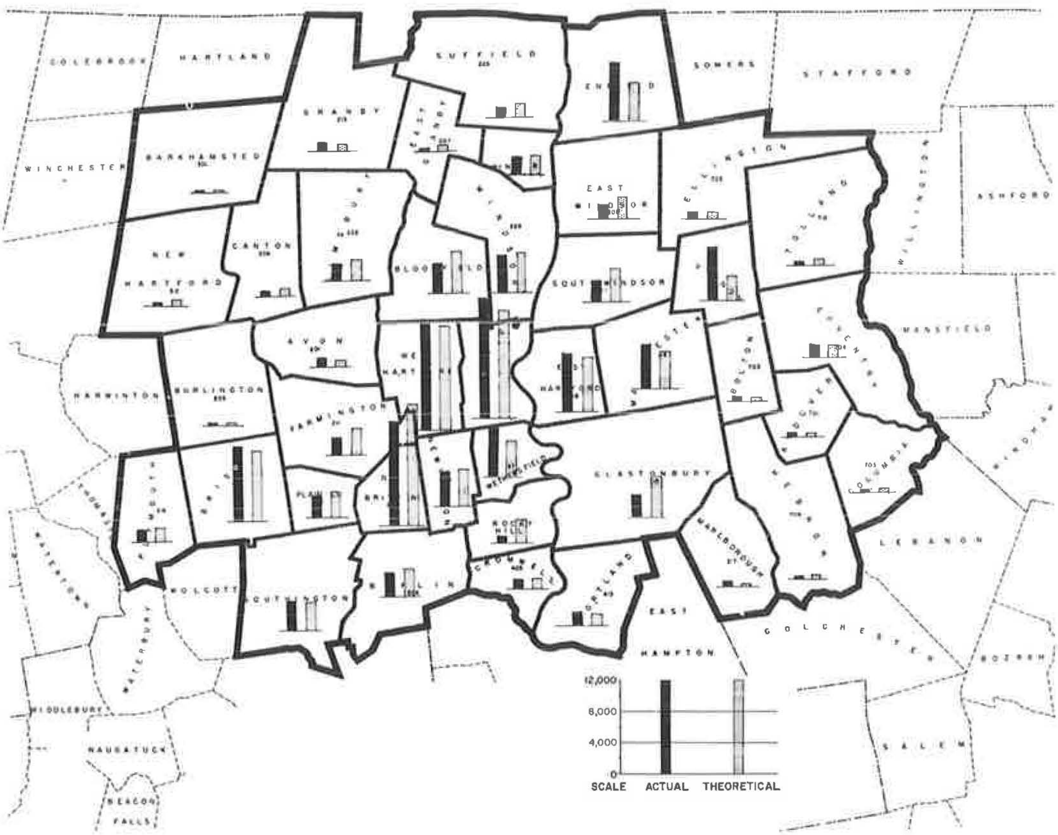

Figure 4. Population change by weighted comparison, 1950-1958, by towns, Hartford area traffic study.

As far as is known, no special calibration or testing steps were carried out as part of this procedure.

Study by Chapin and Weiss

The Chapin-Weiss model for predicting land use has only been formulated (in published form) in nonmathematical terms (40). Tests have been done on different relationships which by linear multiple regression relate two dependent residential land-use variables in zones to various independent variables characteristic of the zonal environment at the same time period and/or at a previous time period.

The linear regression models describe the following two dependent variables: (a) Y_1 = total land in urban use in each zone (in 1960); and (b) Y_2 = dwelling density (or simply "dwellings" since zones are of constant size) in each zone (in 1960). Various combinations of independent variables for two different time periods were tested. The final equations utilizing eight variables were capable of explaining 60.5 percent of the variance in Y_1 but only 44.8 percent of the variance in Y_2. These variables, listed in order of significance, are

1st rank: X_1, marginal land (bad land) not in urban use (1948 and 1960)
X_2, accessibility to work areas (1960)
X_3, assessed value of land (1948)

2nd rank: X_4, travel distance to nearest major street (1960)
X_5, distance to nearest available elementary school (1960)

X_6, residential amenity (1960)
X_7, availability of sewerage (1948)
X_8, zoning protection (not significant 1948)

The mathematical relationships are of the form

$$Y_1 = B_{11} X_1 + B_{12} X_2 \ldots + B_{18} X_8$$
$$Y_2 = B_{21} X_1 + B_{22} X_2 \ldots + B_{28} X_8 \qquad (5)$$

The variables X were chosen by running about 1,400 regressions with different mixtures of 37 variables of two time periods (1948 and 1960) on Y_1 and Y_2 for 1960 in Greensboro, N. C., a city of 200,000 population. The area was divided into 3,980 equal square zones, each 1,000 by 1,000 ft, and values of the variables were specified for each square as numbers from 1 to 9 according to a one-digit coding system. Accessibility to work areas was measured both in terms of travel time and travel distance. Comparative analyses showed no significant difference between time and distance as the basis for determining accessibilities. The criteria used in determining the independent variables were the percentage variance explained by the set of variables (i.e., R^2), and the ratio (t) of the regression coefficient to its standard deviation for each variable. Results are summarized in Table 1 (40). Apparently considerable hand coding had to be done on such a fine grid; a computer was used to calculate accessibilities and the regressions.

Tests were run on another urban area of comparable size and on two smaller towns, with similar results. Apparently no tests were made to determine the degree of fit attained when the parameters (B-values) for one city are used on the other city, or for one time period on the other time period. (X-values for two different years are used in the final equations.) Thus, no indication is given of the stability of the parameters over time. Some questions may also be raised concerning the predictability of X_2, X_5 and X_6 in the future year. According to illustrations presented (40), there appears to be some tendency to underestimate Y_1 and Y_2 in the central areas and to overestimate them in outer areas. The use of this model in prediction may, therefore, be question-

TABLE 1

RELATIVE INFLUENCE OF MIXES OF 14 AND 8 VARIABLES IN EXPLAINING TOTAL LAND IN URBAN USE AND DWELLING DENSITY, GREENSBORO, 1960[a]

Independent Variable[b]	Total Land in Urban Use				Dwelling Density			
	t-Value for Mix		Rank for Mix		t-Value for Mix		Rank for Mix	
	14 Var.	8 Var.	14 Var.	8 Var.	14 Var.	8 Var.	14 Var.	8 Var.
Marginal land not in urban use ('48 and '60)	-15.30	-16.66	2	1	-6.35	-7.39	5	3
Travel distance to nearest major street ('60)	-10.06	-11.61	4	4	-2.08	-5.15	11	6
Availability of sewerage ('48)	5.09	8.65	9	7	2.81	7.24	8	5
Distance to nearest available elementary school ('60)	-8.40	-10.44	6	6	-5.73	-7.29	6	4
Zoning protection ('48)	7.02	3.08	8	8	1.07	-0.12	NS	NS
Assess value ('48)	9.47	13.54	5	3	14.44	18.37	2	1
Accessibility to work areas ('60)	1.56[c]	15.50	NS[c]	2	-0.39[c]	9.49	NS[c]	2
Proximity to nonwhite areas ('48)	2.06	–	12	–	9.58	–	3	–
Proximity to blighted areas ('48)	0.30	–	NS	–	7.44	–	4	–
Total travel distance to high value corner ('60)	2.84	–	11	–	-2.81	–	8	–
Proximity to mixed uses ('60)	23.49	–	1	–	16.08	–	1	–
Distance to nearest playground or recreation area ('48)	-7.07	–	7	–	2.34	–	10	–
Distance to nearest convenience shopping area ('48)	4.40	–	10	–	-5.00	–	7	–
Residential amenity ('60)	11.67	10.93	3	5	-1.94	-4.97	NS	7
Multiple regression coefficient (R)	0.817	0.778			0.727	0.669		
Multiple determination coefficient (R^2)	0.667	0.605			0.529	0.448		

[a] NS = not significant (t-value less than 2).
[b] In order of input.
[c] Significance blocked by strong correlation with several independent variables, particularly those deleted in 8-variable test.

able; the authors point out that it is useful mainly in showing the significant independent variables for their proposed model.

The model (40) is to be a procedure, recursive in time, which distributes an increment of residential development during the first time period to zones of an urban area according to their attractiveness and capacity, reevaluates the attractiveness at the end of the first time period according to the new distribution and the exogenously specified changes, distributes the second increment for the second time period, reevaluates...etc.

The attractiveness of a zone is to be determined by certain priming factors, which are, according to indications of the regression analysis described (excluding those felt not to be predictable), the following: (a) accessibility to work areas; (b) travel distance to nearest major street; (c) distance to nearest available elementary schools; and (d) availability of sewerage. The effect of these priming factors also depends on a certain time lag element.

The development is to be distributed by a Monte Carlo process and conditioned on capacities determined by existing development and by zoning and density restrictions The output is the expected pattern of the distribution and intensity of development in the study area.

The method by which the priming factors are to be translated into attractiveness and thence to probabilities useful in the Monte Carlo simulation is not described in the report, but would appear to involve a technique more elaborate than linear multiple regression. Since the model has not been formulated there are no indications yet of its predictive accuracy or its computational feasibility. The accuracy is, of course, conditioned by the possiblity of predicting future work areas exogenously since these are parts of the priming factors.

GROUP 2—RESEARCH-ORIENTED TECHNIQUES

Rand Corporation

The Rand model (19-28) is not intended as a forecasting tool for predicting land use in particular zones of a metropolitan area or for direct solutions to policy problems, but rather as a framework for research into the relationships between transportation and land use (Fig. 5). As described in general terms (19), the model is recursive in time. It makes a prediction of land use and transportation variables for one time period (as short as 6 months) and uses the results of this prediction (endogenous variables), along with externally specified (exogenous variables), to predict the values for the next time period. The solid lines in the flow chart trace the sequence of steps for one time period and the dashed line represents the changes made in the status variables to be used for the next time period. The prediction starts with an exogenous industry configuration comprising employment levels, distributes this employment over the metropolitan area, and determines land rents over the area. It then calculates worker characteristics in each employment area and, using the rent surface and other variables, finds the residential locations of workers in each work place. Adjustments are then made in the status variables, including the transportation system, before the next prediction.

The actual mathematical functions used for the various calculations are not stated; rather the relationships are stated as $Y = f(x_1, x_2, \ldots, \text{etc.})$, where y and x are dependent and independent variables, respectively. In some cases alternate formulations of the relationships are presented for use where certain classes of one type of variable or the type of data available for deriving parameters lend themselves to an alternate approach. For example, percentage of an industry's workers employed in a zone is predicted for industries of high employee density but percentage of land used for that purpose is predicted for low employment density. Once the input variable (Fig. 5) and the initial values of the status variables have been specified, the model uses the following relationships (in this order) in each zone.

1. Percent of workers employed in a given industry depends on industrial land value, distance from CBD, presence of transportation facilities (for both people and goods

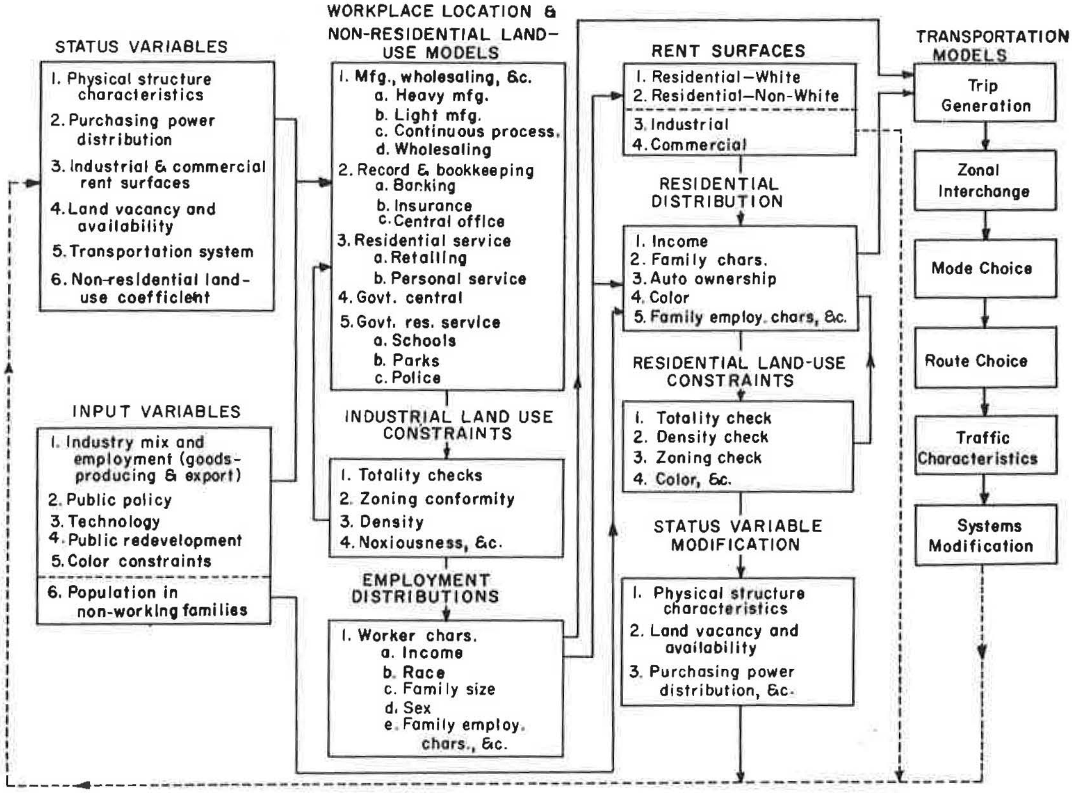

Figure 5. Model for study of urban transportation.

movement), travel time to the urban boundary, vacant industrial land, zoned industrial and commercial land, and workers' supply potential.

2. Number of workers employed (or floor space) in a given commercial or other residentially related activity depends on accessibility to purchasing power, competing commercial floor space in adjacent zones, commercial land value, and zoned industrial and commercial land. A special function which takes into account city population growth is used for CBD retailing.

3. Percent of workers in central office or related functions depends on city female employment, city commercial and manufacturing employment, travel times to city boundary, to major airport, and to best residential district in the city.

4. Government employment functional dependence is not specified but would probably employ similar models.

5. The commercial and industrial distributions are checked for overflows in the constraints and these are assigned to nearest zones with available space.

6. Worker characteristics relevant to location and trip-making decisions are calculated for each employment class and summed over all classes.

7. Commercial, residential and industrial land values are estimated separately and depend in general on the distribution of employment, purchasing power (commercial only), the transportation system and physical characteristics of structures.

8. The residential distribution of workers employed in each zone depends on rents, travel times, zoning restraints and racial prejudice, and the previously calculated worker characteristics. Nonworking households are distributed separately.

9. The residential land-use constraints work much the same way as the industrial land-use constraints.

Total population for each time period is not specified explicitly in the model as an exogenous variable but is implicit in the specification of total employment and of household characteristics of workers (i.e., family size).

Most of the parameters of the model are to be derived by cross-sectional data, that is, data at one point in time for the same metropolitan area. Other relationships will be derived from data in more than one city. The model was intended more as a research tool than as a predictor of land-use variables in particular zones of an area at a particular point in time. As formulated it has a certain drawback for use in prediction: there will probably be a discontinuity between the initial and the first predicted distributions even though the changes during a short time period (6 months) are really slight. This would result because the model predicts the absolute value of the land-use parameters instead of increments of change; in the former case the error is some percentage of the initial value, whereas in the latter the error is a percentage (though perhaps somewhat larger) of only a small increment.

As indicated, the general model (19) does not yet comprise specific forecasting equations. No calibration or testing has, therefore, been possible, nor can it be specified at this time what computational equipment would be required to apply the model. Data requirements may be inferred from the list of general relationships on the previous pages.

Augmenting this general approach, more specific studies (20-28) have been reported by Rand personnel, based on transportation and urban development data from a number of cities. One such report (20) deals with the locational choice of a household and how it varies with location of employment, income, and family size, and how the amount of its residential space consumption is determined. Empirical evidence based on data from 40,000 Detroit households is presented and logically explained on the basis of a simple theoretical model.

A locational rent function, best interpreted as a price per square foot of residential space of a stated quality and amenity, is postulated as decreasing with distance from the center and leveling off in outer zones. The negative of the slope of the locational rent function times the household's residential space can be interpreted as the marginal savings in rent per square foot as residential distance from the center and from the workplace increases. Higher space consumption will give higher marginal rent curves ($q_3 > q_2 > q_1$ in Fig. 6). A marginal transportation cost function can also be drawn (t(d)). A household will locate away from its workplace and from the center so that its marginal rent savings for a given space consumption will be equal to marginal transport costs and its total budget allocated for transportation plus rent is exhausted. The higher the budget, the greater the space consumed, and the farther away from the center a person employed in an inner zone will reside.

The Detroit area was divided into six concentric zones by distance from the center. Data on work trips and worker and household characteristics were available by origin-destination pair. Consistent patterns were found, in general harmony with the theory. For example, residential distributions tended to be farther out as income increased. When the data were examined by zone of employment it was found that this relationship no longer was as strong for outer employment rings. The relationship was determined by ranking the data for each employment zone by income class (occupation), listing for each residence zone the percentage of workers in that class residing in that zone, and examining the correlation between income and percentage by the Spearman coefficient of rank correlation. An example is shown in Table 2 (20). When the coefficient goes from largely negative to largely positive with increasing distance of the residence ring (as for employment ring 2), it indicates that higher income workers locate further out. The relation-

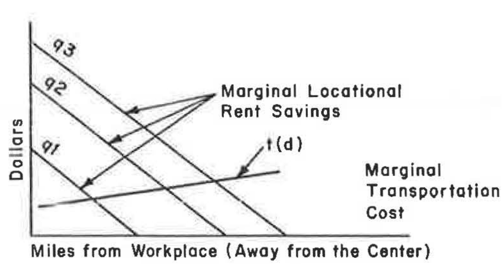

Figure 6.

TABLE 2

RANK ORDER COEFFICIENTS BETWEEN OCCUPATIONS RANKED BY INCOME AND BY RATE OF RESIDENTIAL SELECTION FOR ALL EMPLOYMENT AND RESIDENCE RINGS[a]

Employment Ring	Residence Ring					
	1	2	3	4	5	6
		(a) All Workers				
CBD		-0.86[b]	-0.74[b]	0.69	0.83[b]	0.98[b]
2		(-0.81)[b]	-0.67	0.83[b]	0.89[b]	0.71[b]
3		-0.50	(-0.64)	0.76[b]	0.88[b]	0.76[b]
4		-0.57	-0.71[b]	(-0.48)	0.88[b]	0.89[b]
5		-0.47	0.04	0.29	(-0.33)	0.19
6		-0.33	0.21	0.42	0.90[b]	(-0.61)
		(b) Male Workers Only				
CBD	(-0.69)	-0.81[b]	-0.74	0.57	0.95[b]	0.95[b]
2		(-0.50)	-0.55	0.88[b]	0.88[b]	0.90[b]
3		-0.76[b]	(-0.95)[b]	0.95[b]	0.86[b]	0.83[b]
4		-0.88[b]	-0.57	(-0.17)	0.48	0.19
5		-0.43	0.29	0.29	(-0.38)	0.38
6		-0.40	0.36	0.36	0.81	(-0.40)

[a]Figures are in parenthesis where residence and employment rings are the same.
[b]Differs significantly from zero at the 0.05 level.

ship levels down with outer employment rings since the rent curve is no longer as steep and provides less reason for different location.

Similar empirical evidence and logical explanations too lengthy to explain in this review are offered for locational phenomena associated with family size, space consumption, sex, and race. The model is not formulated in terms of statistically estimated parameters but is used rather as an explanation of the major relationships in the data. Thus, the results are not directly applicable to a land-use forecasting model except as an insight into the behavioral process of choosing a residence, given a workplace.

In two other papers (21, 25), Kain describes the derivation of regression equations to express endogenous variables, relating to workers' choice of residence, travel mode, and travel time, in terms of certain exogenous variables describing the worker characteristics in each employment zone. The exogenous variables are mean income, a proxy variable for locational rent, percentage of males, number of workers in a single family, level of transit service, and family size. Endogenous variables are percentage of workers residing in different types of housing, car ownerships, mean travel time, and percentage driving, using transit, and other modes to get to work. The equations are recursive; i.e., certain endogenous variables are used exogenously in estimating other endogenous variables. The recursive order is type of residence, car ownership, modal split, travel time. Finally, the equations are aggregated and all endogenous variables are expressed as linear functions of the original exogenous variables.

In a further paper (27), Kain reports on the testing of a model similar to one discussed previously (20). The test is carried out by determining whether certain statistics can be explained as the logical outcome of the model. The model explicitly considers several kinds of cost trade-offs available to urban households in maximizing their real income. The first kind is between housing costs and transportation costs; the second is between time and money costs in the journey to work. The model also deals explicitly with the effect of racial discrimination on the operation of the housing market. Thus, further insight is provided into behavioral characteristics in residential location.

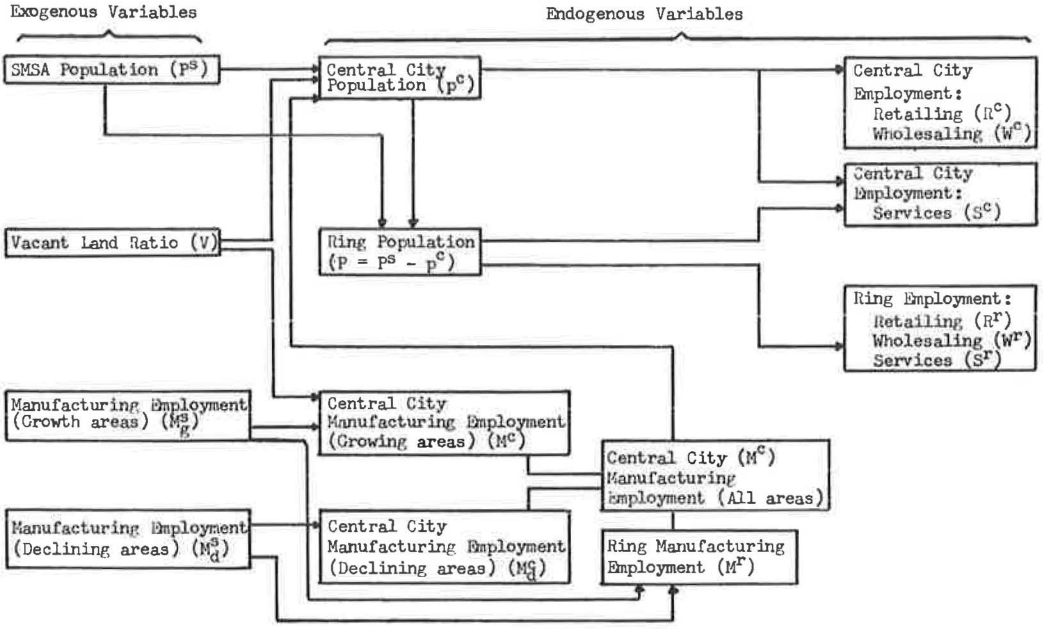

Figure 7. Model of population and employment changes.

In a comparative urban development study (26), Niedercorn and Kain analyze the 39 largest metropolitan areas in the United States with regard to changes in population and types of employment in central cities and ring areas. A recursive model is employed, whereby certain exogenous variables are used to predict some endogenous variables which, in turn, predict other endogenous variables.

The prediction sequence is illustrated in the flow chart in Figure 7 (26). Growing areas are distinguished from declining areas, and the parameters are estimated separately for each equation by regression. The equations specify annual changes both as input and as output variables, so that predictions are performed by predicting the exogenous variables for each year (i.e., changes in manufacturing employment and population for the metropolitan area and ratios of central city vacant land to total central city land area) and integrating the equations over time. Unfortunately, the subdivision is only into two zones, central city and ring, but the model might be used as an order of magnitude check for a prediction model.

Niedercorn and Kain (23) have also used data from 37 of the largest metropolitan areas in the United States to derive a simple model explaining changes in employment in central cities and concentric ring zones of general merchandizing stores (department stores with large numbers of employees per establishment) and food stores (small numbers of employees per establishment). The equations were of the form:

$$E_{kj} = \alpha_{kj} P_j Q_{kj} + \alpha_{ki} P_i Q_{kj} + \alpha_{k_4} \cdot T \qquad (6)$$

where i and j are only two zones, the center city and the ring, and

E_{kj} = employment in industry k in zone j,
P_j, P_i = population in i and j,
Q_{kj} = ratio of employment to retail sales in industry k in zone j,
α_{kj}, α_{ki}, α_{k_4} = parameters, and
T = time trend variable.

The parameters were estimated by least squares fit of the data on change in the variables during two different time periods, 1948 to 1954 and 1954 to 1958, to the first difference of the equations stated previously:

$$E_{kj} = \alpha_{kj} P_j \Delta Q_{kj} + \alpha_{kj} Q_{kj} \Delta P_j + \alpha_{ki} P_i \Delta Q_{kj} + \alpha_{ki} Q_{kj} \Delta P_i + \alpha 4 \qquad (7)$$

where $\alpha 4$ represents the effect of a unit time change. On the whole, the results appear to conform to a priori expectations on employment locations.

Study by Lowry, Rand Corporation

Lowry, in work carried out on behalf of the Pittsburgh Regional Planning Association, proposes a model (46) which is intended for predictions at 5- or 10-year intervals with a maximum (horizon) of 25 years. The proposed model is not recursive and involves nine types of simultaneous equations solved by iteration. Certain activities and the amount of land they use will be distributed exogenously by hand. Those activities treated endogenously must have the following characteristics: (a) demand for their output mostly within the region, (b) high orientation to the regional market for location, (c) market composed of a large number of independent units, (d) historical statistics separable from those of related exogenously located industries. Based on these criteria, exogenously located industries were taken to include all manufacturing, wholesaling, public utilities, research facilities, central administrative offices, government, hospitals, most outdoor recreation, agriculture, and extractive enterprises. This is well over half of the employment of the Pittsburgh region. The model predicts employment in 14 retail and service categories and residential population, and distributes these activities to zones of 1 sq mi. The output for each zone is summarized as follows:

1. Employment in m lines of retail and service trade;
2. Quantity of land in use in m lines of retail and service trade;
3. Number of resident households; and
4. Quantity of land in use by resident households.

The following notation is used in describing the model:

A = area of land (1,000 sq ft);
E = employment (number of persons);
N = population (number of households);
T = index of trip distribution;
Z = constraints;
U = unusable (land);
B = exogenous sector;
R = retail and service sector;
H = household sector;
k = category of establishments within a sector;
m = number of such categories;
i, j = individual tracts of land, defined by the grid system;
n = number of such tracts; and
a, b, c, d, e, f, g = unspecified functions or parameters.

The equations comprising the model are:

$$A_j = A_j^U + A_j^B + A_j^R + A_j^H \qquad (8)$$

$$E^{Rk} = a^k(N^H) \qquad (9)$$

$$E_j^{Rk} = b^k \sum_{i=1}^{n} \left[\frac{c^k N_i^H + d^k E_i}{T_{ij}} \right] \qquad (10)$$

$$E^{Rk} = \sum_{j=1}^{n} b^k \sum_{i=1}^{n} \left[\frac{c^k N_i^H + d^k E_i}{T_{ij}} \right] \tag{11}$$

$$E_j = E_j^B + \sum_{k=1}^{m} E_j^{Rk} \tag{12}$$

$$A_j^R = \sum_{k=1}^{m} e^k E_j^{Rk} \tag{13}$$

$$N^H = f\left(\sum_{j=1}^{n} E_j \right) \tag{14}$$

$$N_j^H = A_j^H . g . \sum_{i=1}^{n} \left(\frac{E_i}{T_{ij}} \right) \tag{15}$$

$$N^H = \sum_{j=1}^{n} N_j^H \tag{16}$$

Subject to the following constraints:

$$\begin{matrix} b^k = 0 \\ b^k > 0 \end{matrix} \text{ for } \sum_{i=1}^{n} \left[\frac{c^k N_i^H + d^k E_i}{T_{ij}} \right] \begin{matrix} < Z^k \\ \geq Z^k \end{matrix} \text{ and}$$

$$g = \frac{Z_j^H}{\sum_{i=1}^{n} \frac{E_i}{T_{ij}}}$$

These nine equations express the following relationships and identities:

1. Total available land in each zone equals the sum of land in each use (Eq. 8);
2. Total regional retail and service employment by category is a function of the number of households in the region (Eq. 9);
3. Zonal retail and service employment by category is proportional to an accessibility measure weighting households and employment access (Eq. 10);
4. Total retail and service regional employment by category equals the sum of zonal employment in the category (Eq. 11);
5. Total employment in each zone equals the sum of exogenously located employment plus employment in the endogenous categories (Eq. 12);
6. Land used by each employment category is proportional to the employment in that category, and the sum of land in each use in each category in a zone equals the total land in use in that zone (Eq. 13);
7. Regional household population is a function of total employment (Eq. 14);
8. Number of households in each zone equals the total area available for residential use times accessiblity to employment times a scale factor g (Eq. 15); and
9. Number of households in the region equals the sum of the number of households in each zone (Eq. 16).

There are also two constraints: (a) a minimum size of establishment in each category such that if calculated employment in a zone does not exceed this minimum, the employment is assigned to other zones; and (b) a maximum residential density for each zone. There are altogether 4n + mn + 2m + 2 unknowns and the same number of equations, where n = number of zones and m = number of employment categories.

Lowry proposes an iterative technique for solution of the equations but does not present a theoretical or empirical analysis of the conditions of convergence. He expresses some doubts about possible instabilities caused by the constraints. There is no constraint on maximum density of retail establishments, and, theoretically, retail employment can be assigned to a zone without available land. Lowry interprets this as possibly meaning mixed use of multistory buildings.

Considerable attention is given to the discussion of parameters required by the model. These will not be determined simultaneously but by statistical analysis of the individual equations taken separately. All necessary data are obtainable through the census and through surveys carried out by the Pittsburgh Area Transportation Study. These parameters include minimum size of establishment, maximum residential density (from zoning), retail employment as a function of population (from national data), relative weight of residential accessibility and employment accessibility for retail employment (regression analysis), employees per acre for different activities, and ratio of total employment to total number of households. The accessibility measures will use the same parameters as those derived for interaction models describing distribution of the appropriate type of trips for the given activity.

There is probably no unique solution to the land-use pattern as formulated. This depends on the actual sequence of the iterative steps. Since this is not a recursive model which distributes increments of change, there appears to be the usual danger of inconsistency of the initial period prediction with the existing pattern of development. However, Lowry asserts that this type of model is superior for long-run predictions. There is also the common danger that if the constraints are operative during predictive phases, the statistically fitted parameters may begin to lose their meaning by distortion.

Although no testing of the model has been described in the literature, the author has indicated that the model has been calibrated based on 1958 Pittsburgh data. It was then applied using 1958 regionwide control totals as input, and the calculated values of subregional land use were compared with observed 1958 values. No formal statistical evaluation of the deviations has yet been made, but the results of the test are generally encouraging. A description of this test was to be published in the fall of 1963. There are presently no definite plans for applying the model operationally, but the possibility exists that it will be utilized as a planning tool for the Pittsburgh region.

Study by Hansen for the Boston Regional Planning Project

Metropolitan residential extension is defined (51) as "the new occupancy of intrametropolitan open sites by urban housing during specified time periods." Equations are tested to examine independent variables, using data obtained from the U. S. Census and local agencies for the Philadelphia metropolitan region during the periods 1940 to 1950 and 1950 to 1956.

Four independent variables were used to describe conditions in each analysis subregion:

1. Residential settlement (B)—population at the beginning of the period divided by total area;
2. Centrality (C)—distance from the intrametropolitan center;
3. Residence accessibility (M); and
4. Employment accessibility (E).

Three different measures were used to describe the dependent variable, residential extension:

1. Dwelling construction volume (Q)—total number of new units on open land;
2. Dwelling capacity utilization ratio (V)—Q divided by the product of open site area and economical dwelling unit density; and

3. Incremental population density (Z)—population change divided by total area.

Three types of functions were tested:

1. Linear

$$Y = A_0 + A_1 X_1 + A_2 X_2 \ldots + A_m X_m \tag{17}$$

2. Exponential

$$Y = A_0 A_1^{X_1} A_2^{X_2} \ldots A_m^{X_m} \tag{18}$$

3. Power

$$Y = A_0 X_1^{A_1} X_2^{A_2} \ldots X_m^{A_m} \tag{19}$$

where A_i (i = 0, ..., m) are parameters.

The efficiency of the relationships was investigated according to four criteria:

1. Explanatory precision—ratio of corrected residual error to the mean of the dependent variable distribution for the linear functions, and the corrected residual error for the other functions;
2. Explanatory completeness—corrected coefficients of bivariate (r^2) and multivariate ($\bar{R}^2$) determination;
3. Parametric reliability (C)—ratio of the regression coefficient to its standard error, and
4. Parametric plausibility—conformance of regression coefficient signs to accepted theory.

Several hundred bivariate and multivariate regression equations were tested and their parameters were estimated by least squares. The efficiency of the equations varied greatly. The explanatory precision for equations employing Q tended to be somewhat higher than that of equations employing V or Z; however, Q tended to be poorer than V or Z in explanatory completeness. The use of multivariate regression equations instead of bivariate equations produced varying effects on efficiency but, generally speaking, moderate gains were realized in the explanatory indices at the expense of substantial reduction in parametric plausibility and reliability. The efficiency of the power equations tended to be moderately to substantially higher than that of the linear and exponential forms, which were similar to each other in overall performance. Exponential equations tended to be better than linear ones for all of the independent variables except residential settlement. Some of the results are shown in Table 3.

The subregions tested were in the Philadelphia Standard Metropolitan Statistical Area. The number of subregions in the basic set was 44 with an average size of 78.1 sq mi. A more disaggregated set of 71 subregions was tested and it was found that the explanatory precision and the explanatory completeness decreased moderately and the parametric reliability increased slightly. The question of the best exponents to use in the indices of accessibility was investigated. Accessibility (to employment, for example) was expressed as

$$E_i = \sum_{j=1}^{n} T_j (2.5 + D_{ij})^{\theta} \tag{20}$$

where

T_j = the number of jobs in region j;

2.5 = terminal time constant; and

D_{ij} = airline distance to region j from i.

TABLE 3

LEVELS OF r^2 AND R^2 FROM REGRESSION EQUATIONS YIELDING DEVELOPMENT RATE V AS ALTERNATIVE FUNCTIONS OF FOUR DEVELOPMENT FACTORS, 1950-56[a]

Factors	Linear	Exponential	Power
(b) Level of R^2			
Residential settlement (B)	0.7042	0.3401	0.8003
Centrality (C)	0.3728	0.6715	0.6415
Residence access (M)	0.7229	0.7929	0.8183
Employment access (E)	0.6090	0.8183	0.7845
(b) Level of $\bar{R}^2$			
B, C, M, E	0.8023	0.7909	0.8752

[a]N = 44 zones.

It was found that $\theta < 0$ gave superior explanatory efficiency to $\theta < 0$ and that the best values were from 1.5 to 2.0 for the linear and power functions, but from 0.5 to 1.0 for exponential functions.

Residential extension accounted for 88.7 percent of additions to the stock of dwelling units in the Philadelphia metropolitan region between 1939 and 1957. The character of residential extension is homogeneous relative to other measures of population settlement so that regression equations on this variable are likely to be fairly efficient, particularly since the study excluded all portions of the area predominantly in urban use at the beginning of the period and those including mass housing projects. Thus, the author has developed meaningful relationships accounting for a large percentage of residential land-use change but with some loss in generality from not accounting for the rest of the change. For use in prediction, it would be desirable to adapt the equations to conform to a control total for the area and possibly to capacity limitations in each subregion.

A predictive technique is also proposed (51), based directly on the derived regression equations. This technique, for which the use of electronic computing equipment would be desirable, is not operational, as it has not been subjected to historical testing. However, the technique is operable in that it could be applied to the Philadelphia region based on the derived relationships.

Study by Bogue, University of Michigan

Bogue (53) explores some aspects of the hypothesis that great cities or metropolises dominate the social and economic organization of technologically advanced societies. No mathematical models are presented for the prediction or description of metropolitan land use, but there is considerable discussion of geographical distribution of population and economic activity and its relationship to interdependence between metropolitan areas and their hinterlands.

Sixty-seven cities in the United States were selected which had populations over 100,000 in 1940 and were not parts of larger metropolitan areas. The entire United States was then subdivided in such a way that each area was assigned as the hinterland of one of the cities. The areas were subdivided according to distance from the central city and according to 30° sectors. Each sector was put into one of three classes:

1. Intermetropolitan if an intermetropolitan thoroughfare went through it to the central city;
2. Subdominant if not intermetropolitan but if it contained a major hinterland city; and
3. Local if neither of the above.

Patterns of dominance were studied by seeking consistent nonrandom differences in dependent variables for the following four-fold classification of independent variables: distance; sector type; size of metropolitan community; and size of hinterland city. The dependent variables were population density and the following indicators of specialization: per capita retail sales, per capita receipts from services, per capita wholesale sales, and per capita value added in manufacturing, as well as other measures of economic activity. Census data from 1939 and 1940 were used as a basis for the statistical analyses.

One of the major conclusions reached was that central cities tend to control the economic conditions of life in communities surrounding them by a higher degree of specialization in such functions as services and wholesaling and by their ability to foster industrial development in their immediate vicinity by providing favorable combinations of factors or production.

Population density is concentrated above the national average up to points 65 mi from the center in all areas, and up to 165 mi for areas of central city population over 500,000. It was found that central cities specialized in retail, services, and wholesale trade and that larger central cities specialize less in manufacturing than the inner zones of the hinterland and vice-versa for smaller cities. Locations outside the central city but within distances of 35 mi had a low retail sales index, though at longer distances sales kept up with population requirements. With large central cities specialization in services declined steadily with distance; with smaller central cities this decline was more abrupt but rose at a distance of 45 mi. Wholesale trade specialization was extremely concentrated in the central city. Manufacturing specialization is not characteristic of only the central city but extends through the metropolis and inner zones of the hinterland to within 45 mi of the center. In short, every zone in the hinterland was dependent on the metropolis for wholesale trade and services and the outer zones were dependent on the metropolis and inner zones for manufacturing. The central city was more specialized in services and wholesale trade than the principal hinterland cities but not in retailing and manufacturing. With increasing distance from the center, specialization of the principal hinterland cities in retail, services, and wholesaling as well as the hinterland city's trade area tends to increase.

This study suggests some measures which might operationally define the importance of different parts of a region and their relationship to the metropolitan center. In addition, it raises questions about the reasons for the concentration of certain types of activities in certain areas of a region and the implications of changing technology with regard to the continuance of this pattern. It must be kept in mind that the study was done on data of about 23 years ago. The author gave little statistical attention to time trends or to data on interzonal communication and trade, which, though harder to obtain, are the real measures of metropolitan dependence.

Study by Pendleton, University of Pittsburgh

The purpose of this study (56) was to estimate the value that residents of the Washington, D. C., metropolitan area place on highway accessibility to the CBD. The approach was to analyze through multiple regression a cross-section of sales prices of sampled residential properties sold during the first nine months of 1961 with financial assistance from the Federal Housing Administration.

Pendleton presents some information on accessibility which may be useful in land-use forecasting. From data of the Washington metropolitan area it was found that three variables—a job accessibility index (similar to that developed by Voorhees), the 1955 driving time, and the 1959 driving time—were correlated to miles from the CBD or log miles from the CBD, plus a constant term, with a coefficient of determination (R^2) between 0.84 and 0.94. From this it was concluded that accessibility may be measured in minutes, index points, or miles, and that the house value estimates should be roughly similar whatever measure is chosen.

It was found that subdividing the region by sectors and introducing dummy sector variables did not add significant explanatory power to the equations. It was also found that CBD job orientation (percentage residents working in the CBD) was significantly related to distance when the data were examined by sector. The subdivision was made to eliminate the effect of one sector's being more strongly CBD-oriented than another.

Finally it was found, by multiple regression equations relating house price to accessibility and certain house-quality variables, that accessibility, time, and distance from CBD can make a significant difference in selling price, i.e., about $444 more for a house 3 mi out than a house 4 mi out, and $206 more for a house 7 mi out than a house 8 mi out. These relationships exhibited coefficients of determination (R^2) of 0.86 for all three accessibility measures.

Pendleton draws some approximate conclusions based on these relationships concerning the value of job accessibility ($2.33 per hundred index points) and the monetary value of driving time ($0.0126/min). He points out that the latter estimate is considerably lower than generally accepted values and finds it difficult to account for this discrepancy.

The accessibility relationships derived show the importance of the CBD as a focal point for urban development. However, reported sector differences indicate the danger of assuming circular symmetry as a basis for urban models.

GROUP 3—CONCEPTUAL TECHNIQUES

Study by Garrison, Northwestern University

Garrison does not present a regional land-use model in the usual sense but limits himself to a general description of urban simulation (43) and a theoretical discussion of development at a freeway interchange or at several freeway interchanges in a region (44). Much of the latter paper (actually a set of three papers) is devoted to possible types of approaches to the problem and their advantages and disadvantages. The two heuristic models which he discusses in some detail are summarized in the following paragraphs.

The first model deals with industrial and residential land development around a single newly constructed interchange between a freeway and an arterial. The first type of industry (or residential subdivision) is selected by a Monte Carlo process; its lot size is similarly selected. Part of it is then located on vacant land in such a way as to minimize airline distance to the interchange; the rest of the lot area is located contiguously by a systematic process. The Monte Carlo game is repeated until all the land within a square surrounding the interchange is used. Different runs (using different random numbers) are tried and the resulting patterns of development are examined for common characteristics. Garrison has tried this out with a desk calculator using artificial data for the probability distributions used in the Monte Carlo games, but has not presented the results because of the arbitrary nature of the probability distribution.

The second model is an economic one, in which firms are located near different highway interchanges and workers for these firms are drawn from various residential areas according to a linear program which minimizes production cost plus workers' transportation cost subject to four types of constraints: (a) that enough workers are employed in each industry to meet the total demand for its products; (b) that the number of workers from each residential area does not exceed its labor force; (c) that the capacity of the connecting roads between each residence and work area is not exceeded; and (d) that the total amount of land used at each interchange does not exceed what is available there. Certain extensions and generalizations of the program are also discussed.

The notation for use in the linear program is as follows:

a_k = land used per employee in industry k;
i, j = residential and workplace locations (i.e., expressway interchange), respectively;
s_i = total land available at j;
x_{ijk} = number of workers from the i^{th} residential area to the j^{th} working place, in industry k;
k_{ij} = capacity of the route between i and j for the use of the ij movement only;
y_{jk} = output of the k^{th} industry at j;
d_k = demand for the output of the k^{th} industry;
b_k = number of employees required per unit of k output;
e_i = number of persons in the labor force in the i^{th} residential area;
c_k = unit cost of production in the k^{th} industry; and
t_{ij} = the cost per worker of transportation from i to j.

Thus the total cost of production and transport per worker going from i to j employed in industry k is

$$f_{ijk} = t_{ij} - \frac{c_k}{b_k} \tag{21}$$

We can also set

$$Y_{jk} = \frac{1}{b_k} \sum_i x_{ijk} \tag{22}$$

The linear program then becomes

$$\text{Minimize } \sum_i \sum_j \sum_k f_{ijk} x_{ijk} \tag{23}$$

subject to

$$\sum_i \sum_j x_{ijk} \geq b_k d_k;$$

$$-\sum_j \sum_k x_{ijk} \geq -e_i;$$

$$-\sum_k x_{ijk} \geq -k_{ij};$$

$$-\sum_k \sum_i a_k x_{ijk} \geq -s_j; \text{ and}$$

$$\text{All } x_{ijk} \geq 0$$

The model is a static one, designed to predict a settlement pattern at a point in time. The projection of the composition of a city over a long period of time would be broken down into a series of short projections. The model would be used for each short projection to allocate developments required by demands during that period.

Garrison proceeds to interpret the dual of the linear program as a maximization of the value of labor minus certain costs associated with its usc, and cxplains that such a pattern would not emerge in practice because of imperfections in the market. These are mainly minimum wage controls and also the inability to charge tolls on highways. Apparently a more serious objection to such a solution is that it implies that each residential area is connected to each work area by a road of given capacity, thus not accounting for the joint use of facilities by different trips. Also, product distribution costs and transportation costs of raw materials are not considered in the program even though firms are likely to be sensitive to these as well.

Study by Wingo, Resources for the Future, Inc.

Wingo (47, 48) attempts to organize related subjects such as demand for urban space, population distribution, land values, and transportation costs into a theoretical framework which can simulate various phenomena associated with urban growth and spatial characteristics.

Wingo's model (47) consists of the following equations which can be used to calculate the spatial pattern of population and rents if certain simplifying assumptions are made.

1. A space demand curve relating the amount of space per household to the rent of land per square foot:

$$q - (\frac{r}{\lambda})^{\frac{1}{\eta}} \tag{24}$$

where

q = quantity of land per household ($1/q$ = density);
r = rent per square foot; and
λ, η = parameters.

2. A relationship which gives cost per trip to the center of the region as a function of distance to the center and total population. This is combined with an identity stating that rent per household at point i equals the difference between annual trip cost at the farthest point of settlement in the region and cost at point i, yielding the equation:

$$R = \varphi\,(S,\ N) \tag{25}$$

where

R = rent per household,
S = distance from center, and
N = total population.

3. An integral giving total population enclosed by an area as a function of population densities and the position of its boundaries m:

$$N = \int_0^m \frac{\sigma'}{q} ds \tag{26}$$

where σ' is a parameter depending on the shape of the region.

4. The definition

$$q = \frac{R}{r} \tag{27}$$

which when combined with Eq. 24 yields

$$\frac{1}{q} = \left(\frac{R}{\lambda}\right)^{\frac{1}{\eta - 1}} \tag{28}$$

Thus, the relationships can be summarized as

$$N = \int_0^m \sigma' \left[\frac{\varphi\,(S,\ N)}{\lambda}\right]^{\frac{1}{\eta - 1}} ds \tag{29}$$

The assumptions are that all households work at the center, have the same space demand curve, and try to minimize their own transportation cost.

The author elaborates on the transportation cost function and introduces the concept of ingression loss to describe delays incurred when many people converge on one point at the same time in a system of limited capacity. He discusses the economics of the journey to work, the value of time, and the determinants of the space demand function. There is further discussion of the model and some applications when some of the simplifying assumptions are relaxed, but it is evident that gains in generality are offset by losses in descriptive simplicity. Consequently, it would appear that the model cannot now be applied to land-use forecasting except in a fairly gross sense.

Study by Alonso, Harvard University

Alonso (49, 50) describes a simple static model of the market for urban land developed along the lines of the traditional rent theory of von Thuenen which states that in a simple agricultural market where all of his product is sold at one point, the profit realized by a farmer per acre of crop equals the selling price for one acre's crop minus the production cost, minus the transport cost to the market. This profit can be capitalized by the landowner in the form of rent. The farther from the market, the more costly the transport, thus the less the profit, or rent. The curve for rent as a function of distance from the market, therefore, has a negative slope and a maximum value at zero distance from the market. When two or more crops must be grown, each has its own bid rent curve. Those crops with the steepest bid rent curves (largest transport cost per unit distance per acre of crop) tend to occupy the more central locations.

This analysis is extended by Alonso (50) to the location of business firms where not only the transport costs and other operating costs but also the volume of business changes with distance from the center. Residential households behave in a somewhat similar manner as they maximize their satisfaction in different locations.

If a curve of actual land prices, the equilibrium land rents, is given, an individual chooses his location as follows. He has a set of his own bid rent curves which differ by constants in the Y direction (parallel curves). Each curve represents a different level of accomplishment, profit for the businessman and satisfaction for the household. The lower curve is a higher level since he has to pay less for rent. The point of location and the level of accomplishment are determined by the point where this family of curves is tangent to the land value curves (Fig. 8). The point of intersection will depend roughly on the steepness of the bid rent curves. Wealthy people have less steep bid rent curves than poor people since they can afford more land and, therefore, the transportation cost per mile per acre of land (which determines steepness) is less. Thus, the wealthier people will tend to locate farther out.

Here the author's argument appears to be only one possible explanation. Others consider the dynamics of the market. For example, the poor will live close to the center since they occupy the deteriorated structures where redevelopment is too expensive; open land farther out is the only place where it is economical to build houses for the newly wealthy or moderately wealthy.

Alonso's model is purely theoretical and is developed for the simple case of a one center city with transportation in all directions. He hopes it will be useful in providing a logical structure for econometric models used for prediction.

Study by deCani, University of Pennsylvania

Three stochastic models are presented (54): a pure migration model; a birth, death and migration model; and a predator-prey model. All are formulated using differential equations and associated techniques for their solution.

In the first model an area whose total population is constant consists of two zones, A and B. Population migrates from one zone to the other at different rates proportional to the population of the other zone. Expressions are derived for the mean and variance of each zone's population and it is shown how both the mean and variance approach finite limits as time goes on.

In the second model, each zonal population not only migrates to the other in a fashion similar to the first model but also reproduces and dies off at different rates proportional to population in the same zone. In this case, populations grow exponentially and the initial population distribution has less and less of a percentage influence on the mean value as time goes on.

In the third model, a region has two populations, each of which has different birth and death rates as in the second model, but one of which tends to drive the other population from the scene. It is shown how the mean value of the second population tends to zero in a finite time while the first population continues to grow.

The author indicates how such models can be solved explicitly. However, it is evident that the explicit solutions become

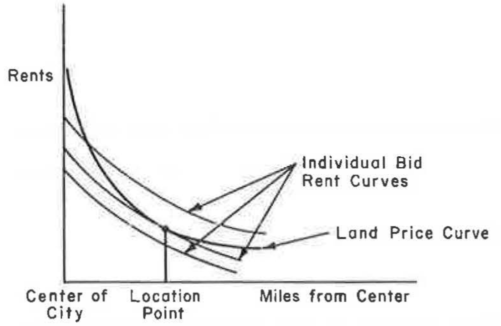

Figure 8.

increasingly difficult as complications are introduced into the assumptions about the way in which the populations interact.

Study by Horwood, University of Washington

Horwood's work (55) represents an application of a highly idealized analytic formulation to describe a smoothly varying population density surface for urban areas. An equation is presented which describes population density as a function of radius and sector with respect to the city center. Population density is assumed to vary as the inverse square of distance from the center and as a periodic function of an angle measured with the center as vertex and a major arterial as the axis. The differential equation is of the form:

$$\frac{dP}{dA} = \rho = \text{population density} \tag{30}$$

and

$$\rho = \frac{K}{r^2} = \frac{1}{2}\left[\frac{K'}{r^2} + \frac{K}{r^2}\right] + \left[\frac{K'}{r^2} + \frac{K}{r^2}\right] \cos 4\theta \tag{31}$$

where

r = distance from the center of the city;

$\frac{K}{r^2}$ = characteristic of the maximum density in a circumferential direction; and

$\frac{K'}{r^2}$ = characteristic of the minimum density in a circumferential direction.

There are four circumferential peaks each at a major arterial. An integral is stated (but not evaluated) giving the total population between two angles θ_1 and θ_2 and two arcs of radii R_1 and R_2. The total population within the ring bounded by $r = R_1$ and $r = R_2$ is given by:

$$P = \pi\left[\frac{1}{R_1} - \frac{1}{R_2}\right]\left[K' - K\right] \tag{32}$$

No empirical or theoretical basis is presented for the equation, which appears to serve only as an abstract description of urban space.

COMMENTS AND CONCLUSIONS

The various land-use models reviewed may be classified according to the following functional characteristics:

1. Whether the output variables characterize the state of the system in each zone (e.g., population, employment, and total land in each use) or changes in the state of the system over a certain period of time (by addition the state of the system can then be obtained);
2. The presence or lack of control totals (such as total regional population in future years) which are predicted exogenously;
3. The presence or lack of zonal capacities, determined exogenously, which must not be exceeded;
4. The dependence of one set of predictions on another previously determined set for the same time period (e.g., the prediction of population change which is then used to predict change in retail employment);
5. Time recursiveness, as opposed to a system which produces a direct forecast for a target year 20 or 30 years in the future with no intervening stepwise forecasts;
6. The degree to which the model is made to conform to economic rent theory in the determination of a locational pattern;

7. The degree of stratification or disaggregation which is employed in the solution (e.g., the prediction of the location of different types of households on the grounds that they either have different trip characteristics or different locational characteristics);

8. The extent to which parameters of the model are determined simultaneously in one statistical fit, as compared to their individual determination by a number of individual statistical analyses; and

9. The extent to which accessibility measures play a part in the model.

Some general observations may be made on the merits and disadvantages of these characteristics of the reviewed models.

1. The difficulty with predicting the state of the system as opposed to increments of change is that short-term projections could be in great error. For example, if we wanted to forecast the system a year from now we would do well to utilize information on the present state of the system and make small changes; a model which works from first principles would tend to introduce its statistical errors into the projections and probably produce results considerably different from those of today. However, as longer term projections are made, the present state of the system is less of an indication of the future state, and such projection may have some merit, particularly in a very gross sense for large areas.

2. Most of the models rely on an exogenous prediction of total manufacturing employment in the region. Some models also use this as a predictor of total population, which then serves as another control total. Retail employment usually does not have a control total and depends on population of individual zones. There is usually no mechanical problem with control totals since it is only a question of adjusting in one step the individual zonal figures by a factor to make their total equal the exogenous control total.

3. Most of the models make some adjustments for zonal capacities of population and employment. This is usually in the form of past observed values for population per residential acre times the number of residential acres, and similar figures for employment. The population density figures and residential acres are often set by existing zoning and subdivision control regulations. The problem here is that zoning laws are subject to change, especially under demand pressures, and to set an absolute inviolate capacity limitation requires some assurance of its applying in the future. Application of zonal capacity restraints usually involves some type of iterative procedure unless the predictive technique makes use of a mathematical function which asymptotically approaches a maximum value. A function of this nature, such as the hyperbolic tangent function proposed by Donald Hill of TRC for this purpose, may be used to simulate development of one or more land-use categories subject to zonal capacities, without the requirement of an iterative procedure. Zonal capacities are essential to the forecasting process, but they have to be recognized as assumptions about governmental regulations which may change in the future.

4. There is a tendency in the various models to predict manufacturing employment and land use first and to use this information as input to the population distribution phase which, in turn, is used as input to the retail employment distribution phase. There appears to be a definite logic in distributing retail employment after population; indeed, some empirical evidence is available on the lag of retailing establishment decentralization after the decentralization of population in the RAND study of food and general merchandizing employment (23). The arguments for predicting manufacturing before population are not so convincing. It is argued that there are only a limited number of locations suitable for certain types of industries and that these are relatively independent of population. This is held to follow from the fact that travel is becoming faster and that industry will not have much trouble recruiting workers wherever it locates, as long as it can pay a good wage. However, Penn-Jersey proposes first to predict residential land use and then to use the residential rent surface as an input into industrial land-use distribution.

5. It seems to be generally recognized that direct data flow from the end of one forecasting period to the beginning of the next is necessary, if not within the model, then at least by some type of manual updating. It is necessary because the inertia of

an urban system is such that any forecast which disregards the immediately previous state of the system may predict sudden and perhaps oscillatory changes in land use which are not reflected in real life.

6. The equation systems involved in economic rent theory become rather complex if they are not idealized to the point of having only one or two centers of employment and one or two homogeneous population groups. Even the Penn-Jersey linear program version of rent theory utilizes a set of simplifying assumptions (e.g., amenity of different land parcels for different household types) whose statistical foundations could be rather dubious; in addition, the Penn-Jersey linear program approach has been adapted to predict increments of growth instead of the total settlement pattern, as the formal rent theory model would have it do. The linear programming approach is, in general, questionable as a simulating technique because of its property of maximizing or minimizing some aggregate function (such as total rent-paying ability of all residential locators). Economic theory holds that each individual is trying to maximize his economic position, so that a linear program cannot be said to simulate locational behavior unless it can be shown that the sum of all actions to maximize individual economic position is synonymous with a maximization of the aggregate economic position. Such a relationship does not seem to be readily demonstrable for residential or industrial locators; it is difficult to evaluate the possible effects of this on the predictive realism of a linear programming model. Land-use models based on linear programs may also be questioned because of their reliance on economic motivations and their consequent exclusion of all input variables which cannot be meaningfully translated into economic terms. This limitation may exclude some variables (for example, aesthetic considerations) which have a significant effect on urban development.

7. The desirable degree of stratification of input variables depends to some extent on the type of model being used. Generally, the more behavioral the model (i.e., the more it attempts to simulate actual locational decision-making processes), the more stratification is required, since different classes of a certain variable (e.g., residential population) exhibit quite different locational tendencies. A limit on useful stratification is, of course, reached when stratified groups become so small as to be statistically unstable. A possible means of overcoming this problem is to regroup the stratified classes, by techniques such as latent class analysis or factor analysis, into fewer classes which behave alike functionally. Data availability may also be a limit on the degree of stratification possible. Similar considerations affect the degree of output variable stratification, although the overriding consideration here is the use for which model output is required.

8. None of the 14 models described in this paper comprises a fully integrated formulation which allows the simultaneous forecasting of all urban variables pertinent to regional planning studies. That is, each of the models is either one submodel, dealing with one set of variables such as residential, industrial, or commercial activities, or a number of such submodels applied serially to obtain the desired output values. An attempt to apply any set of submodels for comprehensive urban forecasts suffers from two weaknesses: (a) assumptions must be made about which submodels should be run first, i.e., which variables are primary and which are secondary in locational characteristics; and (b) relationships and parameters must be determined separately for each submodel, leading to questions (which are difficult to answer) concerning their reliability when applied in concert. Therefore, there appears to be some advantage in a model which handles all variables simultaneously and thus allows the derivation of a self-consistent set of parameters. Such a model may, however, suffer other difficulties such as parametric instability and difficulty of interpretation. Although it is a laudable goal, the fully integrated model may prove, therefore, to be difficult to achieve as an operational technique.

9. All of the models reviewed show some dependence on accessibilities, whether explicitly in terms of travel times to various types of activities in other zones, or implicitly in terms of distance to the center of the urban region. The use of distance as a measure of accessibility precludes model sensitivity to changes or proposed changes in transportation systems, which generally have little effect on travel distances but may have profound effects on travel times, costs and convenience levels. A general

disadvantage of concentric ring approaches is that they usually require ad hoc adjustments to account for manifest circular asymmetries in most urban regions.

A number of relationships derived with respect to the reviewed techniques show strong evidence of general applicability. These include the dependence of rents and transportation costs on residential locational decisions, the tendency of retail growth to follow fairly closely behind residential growth, and in general, the effects on various land-use categories of accessibilities to other land-use categories.

Based on the foregoing considerations, it is felt that a number of the concepts noted in the reviewed techniques should be studied for possible inclusion in the model developed for BRPP planning analyses of the Boston region. These include a model which forecasts changes rather than absolute values; the use, wherever possible, of exogenously determined regionwide control totals; the inclusion of a mechanism for simulating the effect of zonal holding capacities; a model which can deal with all variables simultaneously, based on relationships which have been calibrated simultaneously rather than separately; a time-recursive model using fairly short (of the order of 2 to 10 years) forecasting periods; a model containing as many behavioral relationships as may feasibly be used without an inordinate amount of mathematical complexity and/or data stratification; a fairly high degree of data stratification in initial analyses followed, wherever possible, by regrouping of data classes into fewer functionally similar groups; and a model which is sensitive to accessibilities as measured by travel times by all major travel modes, and possibly by travel costs.

Although none of the reviewed techniques provides a comprehensive model framework having all the desired properties mentioned, they represent a fund of experience and insight to draw on during the current Boston land-use model development project.

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