Use of Gravity Model for Describing Urban Travel

An Analysis and Critique[1]

RICHARD J. BOUCHARD and CLYDE E. PYERS
Urban Planning Division, U. S. Bureau of Public Roads

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.

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[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:

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

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

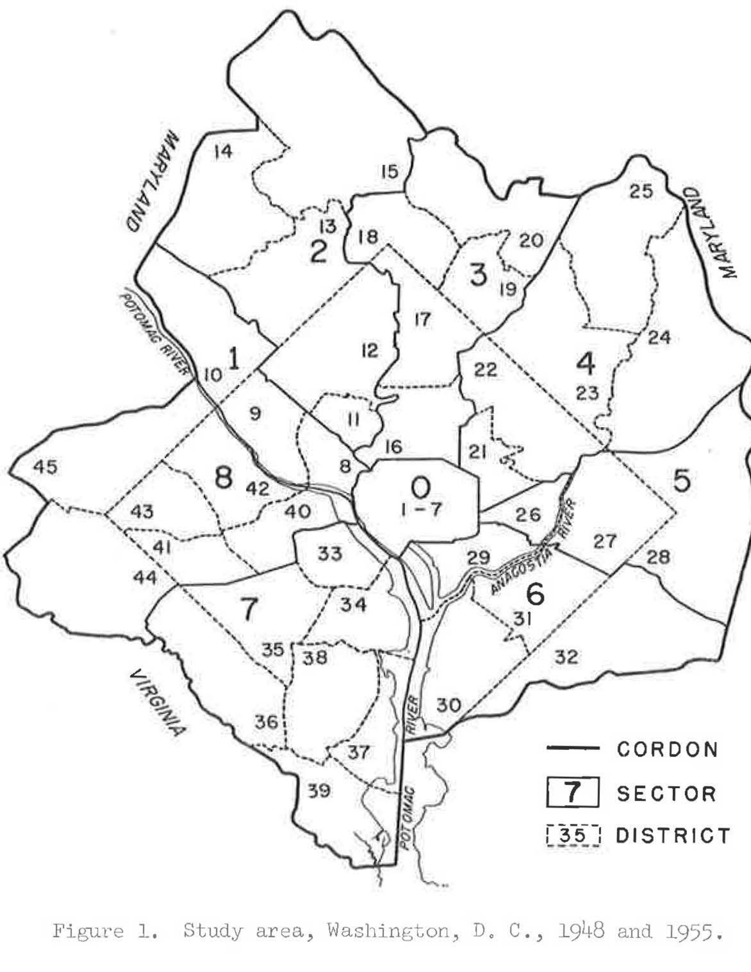

Figure 1. Study area, Washington, D. C., 1948 and 1955.

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

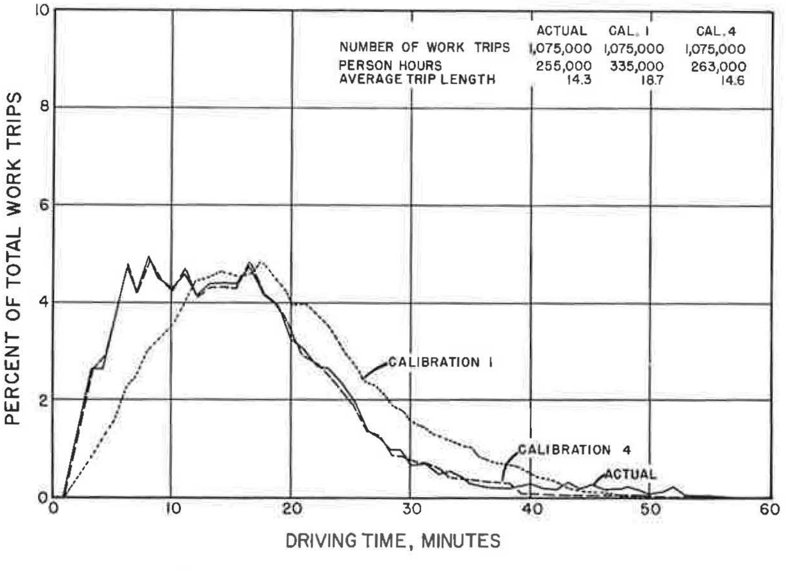

Figure 2. Trip length distribution for work trips, 1955.

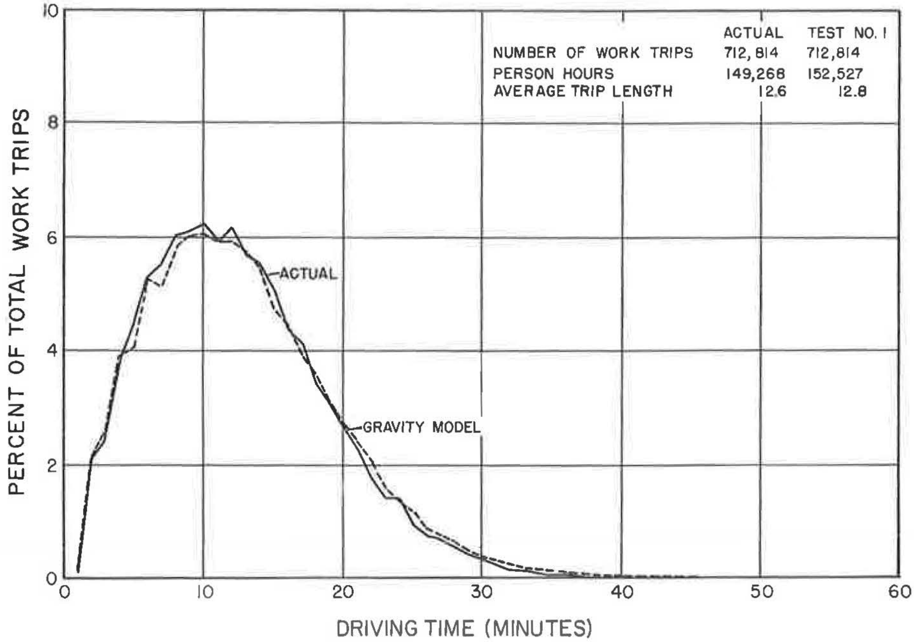

Figure 3. Trip length distribution for work trips, 1948.

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

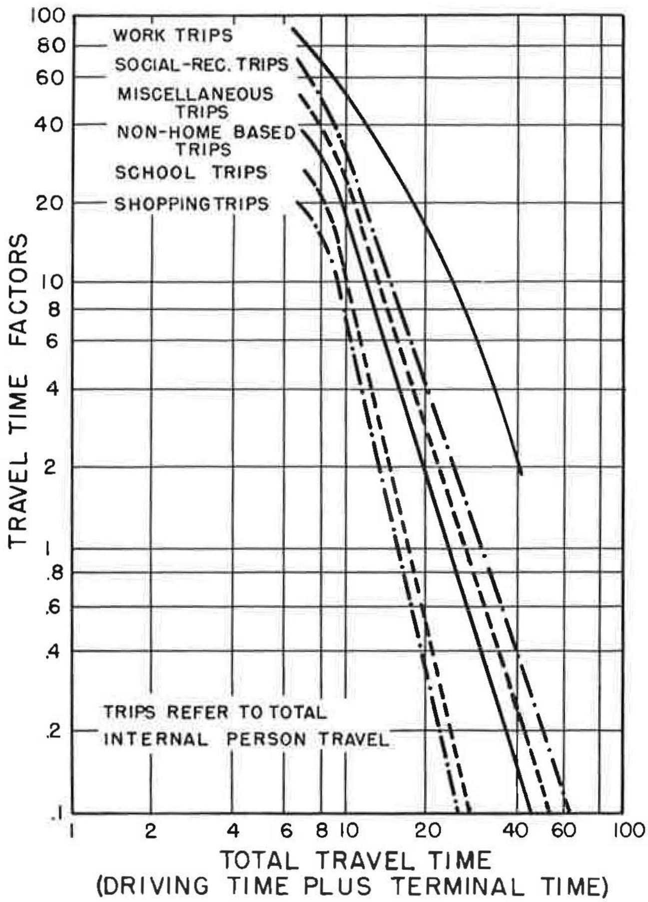

Figure 4. Final travel time factors, 1955.

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

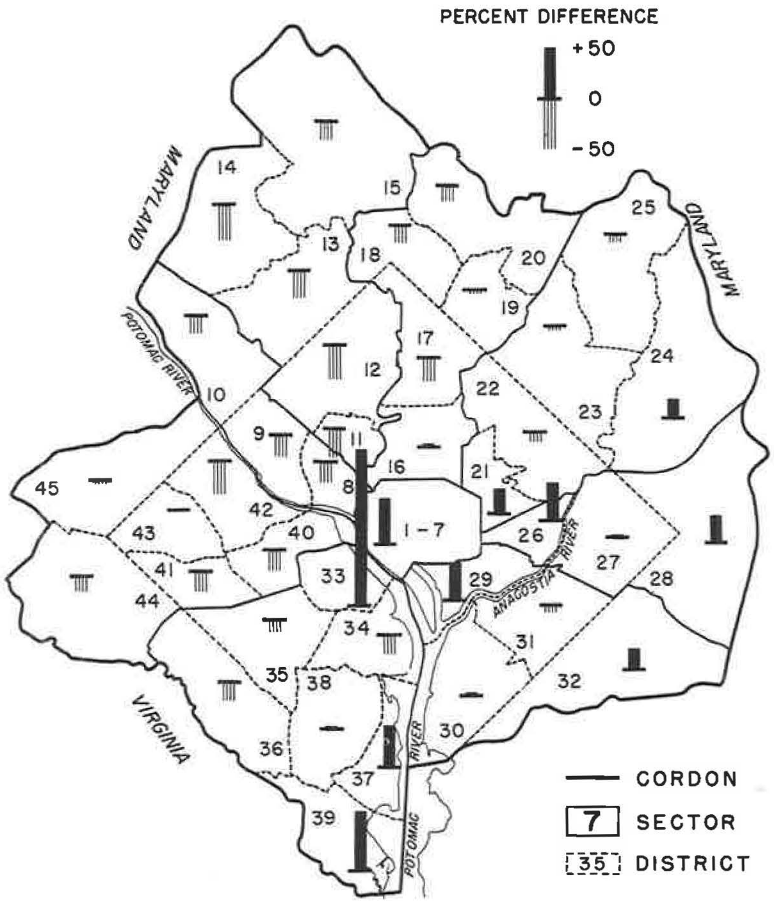

Figure 5. Differences between actual and estimated work trips to zero sector, Calibration 9.

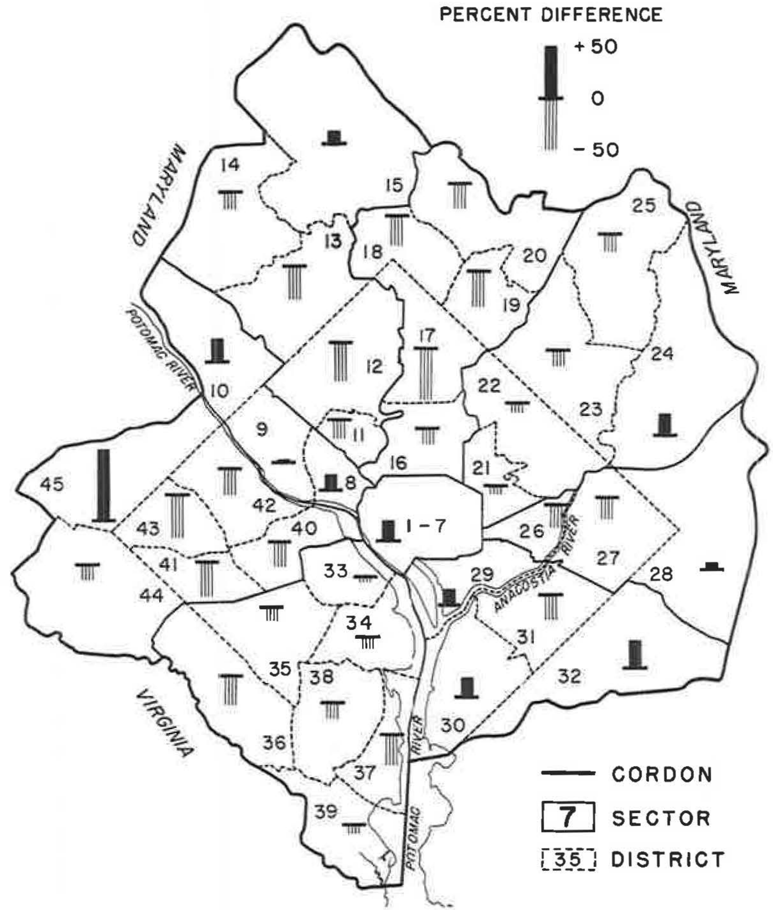

Figure 6. Differences between actual and estimated nonwork trips to zero sector, Calibration 9.

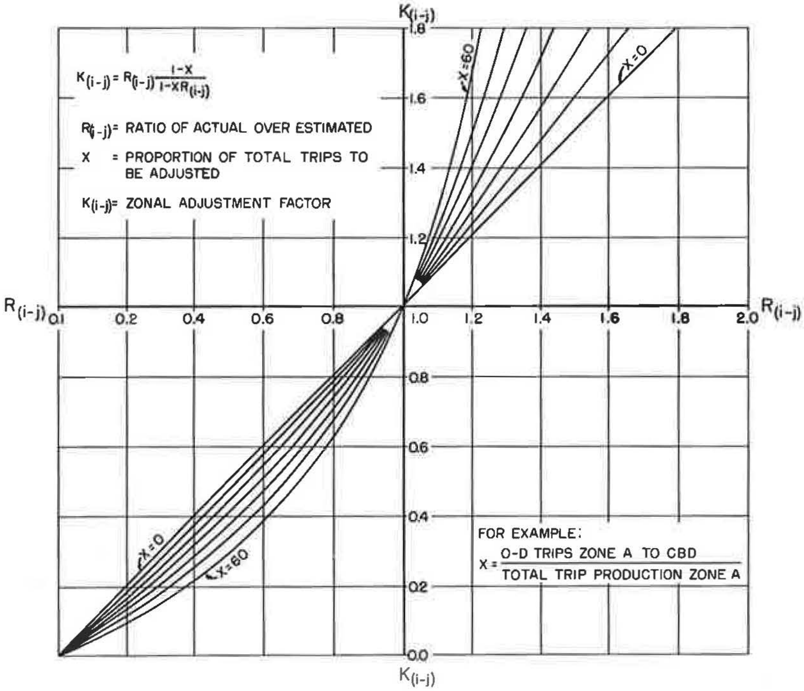

Figure 7. Adjustment factor curves for work trips to CBD, 1955.

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) Survey	Trips (thousands) Model	Diff. (%)
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,

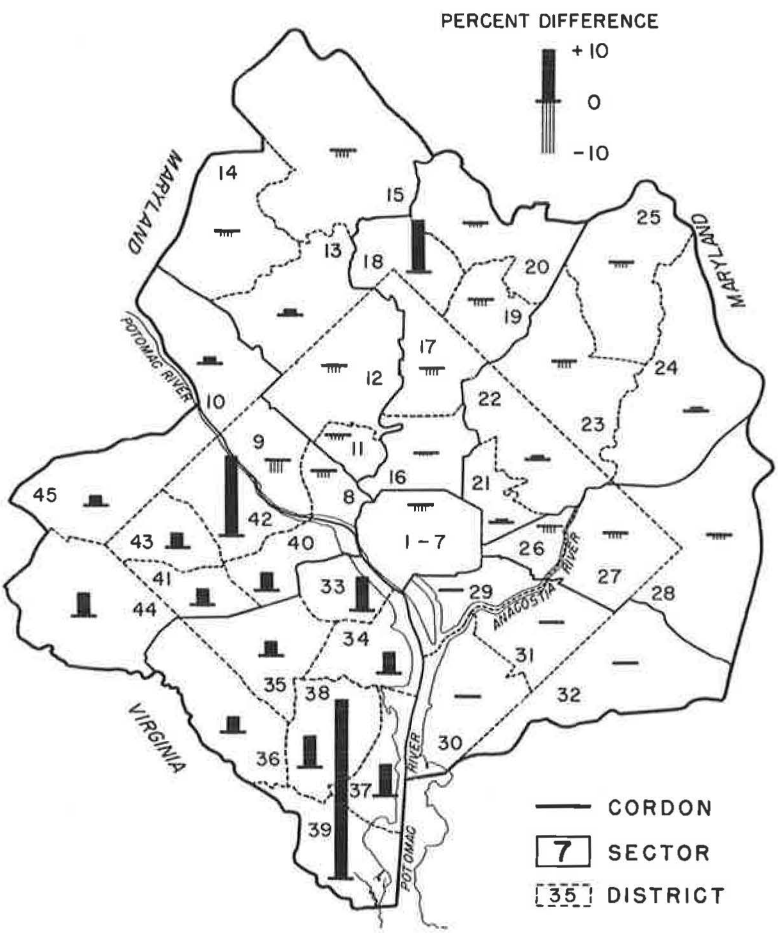

Figure 8. Differences between actual and estimated work trips to zero sector, Calibration 10.

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.

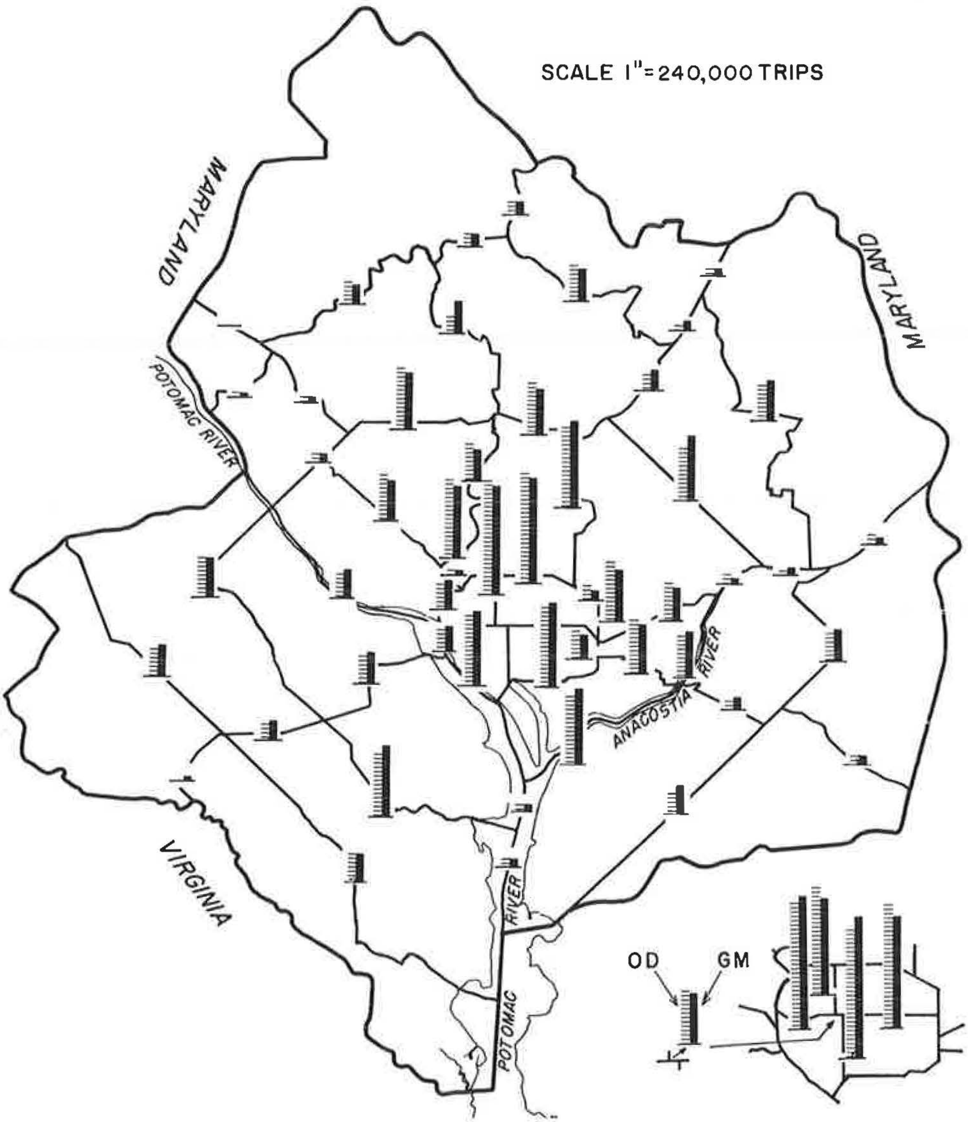

Figure 9. Comparison of screenline crossings, work trips, 1955.

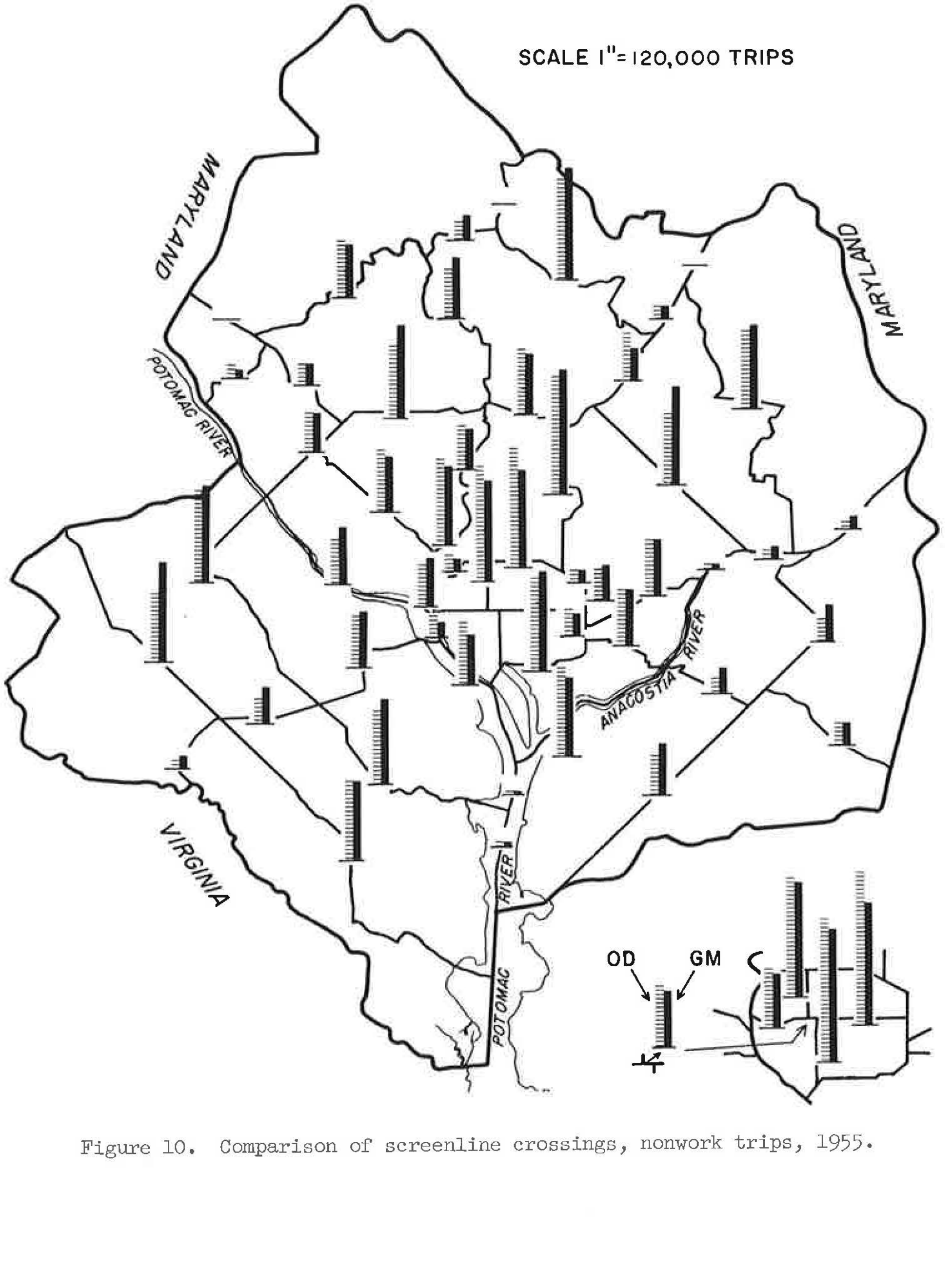

Figure 10. Comparison of screenline crossings, nonwork trips, 1955.

TABLE 11

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

Volume Group	Work Trips: No. of Interchanges	Work Trips: Mean Value	Work Trips: RMSE	Work Trips: $\frac{RMSE}{Mean} \times 100$	Nonwork Trips: No. of Interchanges	Nonwork Trips: Mean Value	Nonwork Trips: RMSE	Nonwork Trips: $\frac{RMSE}{Mean} \times 100$
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

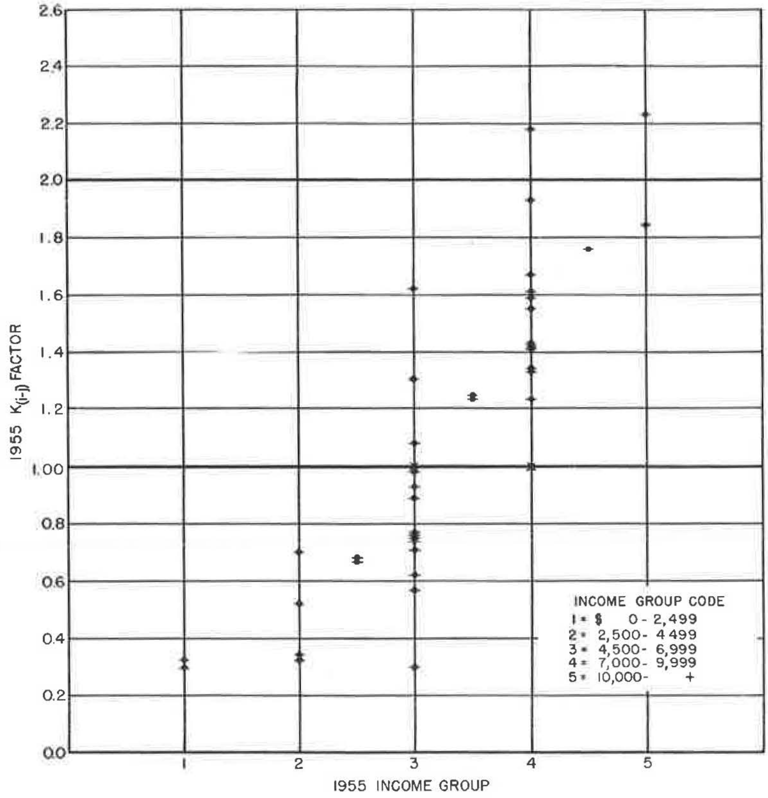

Figure 11. 1955 income group vs 1955 $K_{(i-j)}$ factors per O-D district.

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

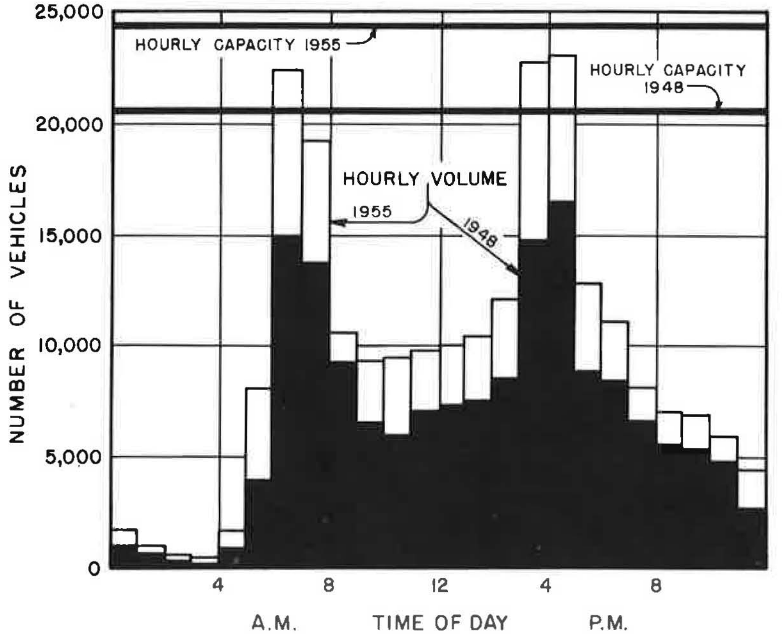

Figure 12. Potomac hourly traffic and capacity for 1948 and 1955.

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.

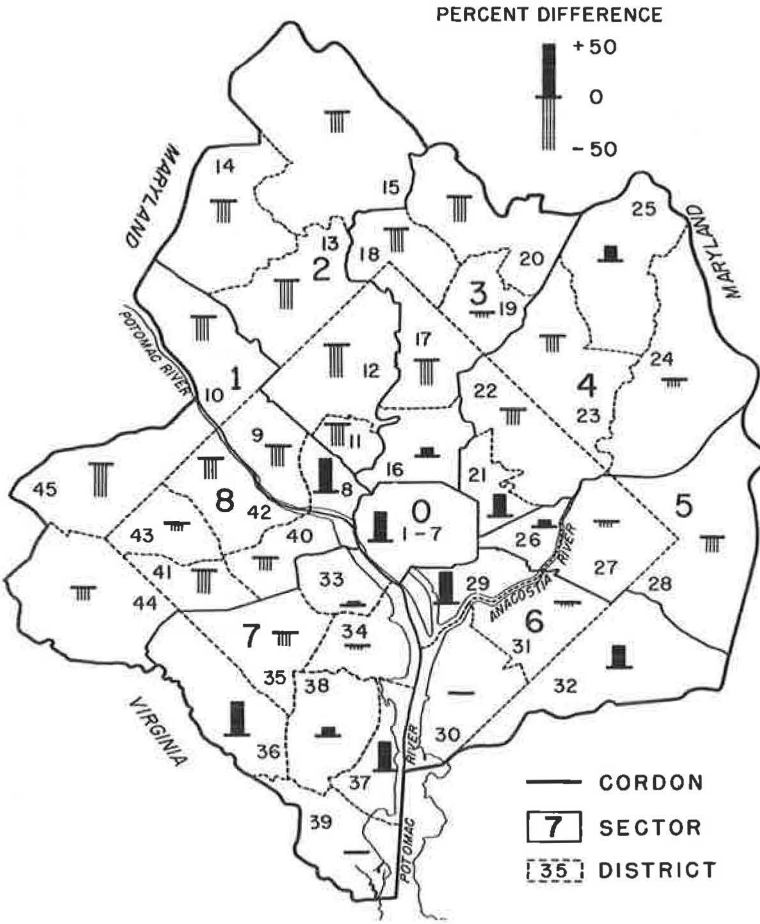

Figure 13. Comparison of work trips to zero sector, Test Run 4 vs home interview survey, 1948.

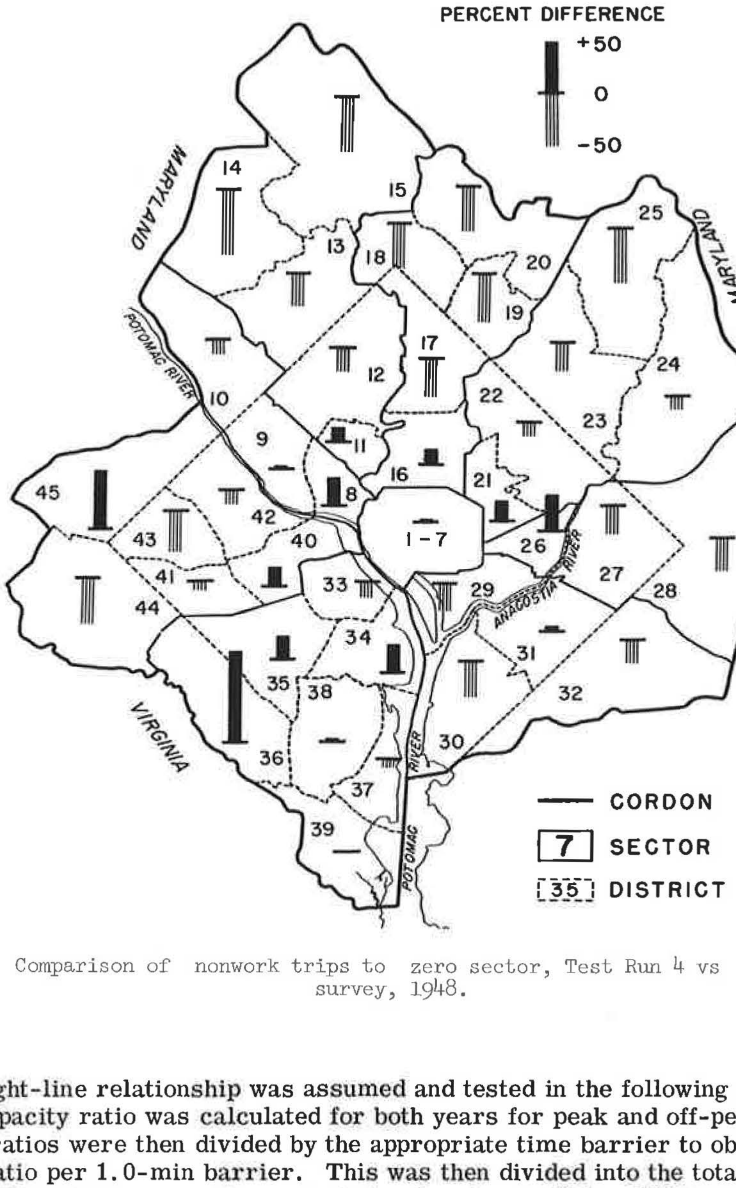

Figure 14. Comparison of nonwork trips to zero sector, Test Run 4 vs home interview survey, 1948.

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

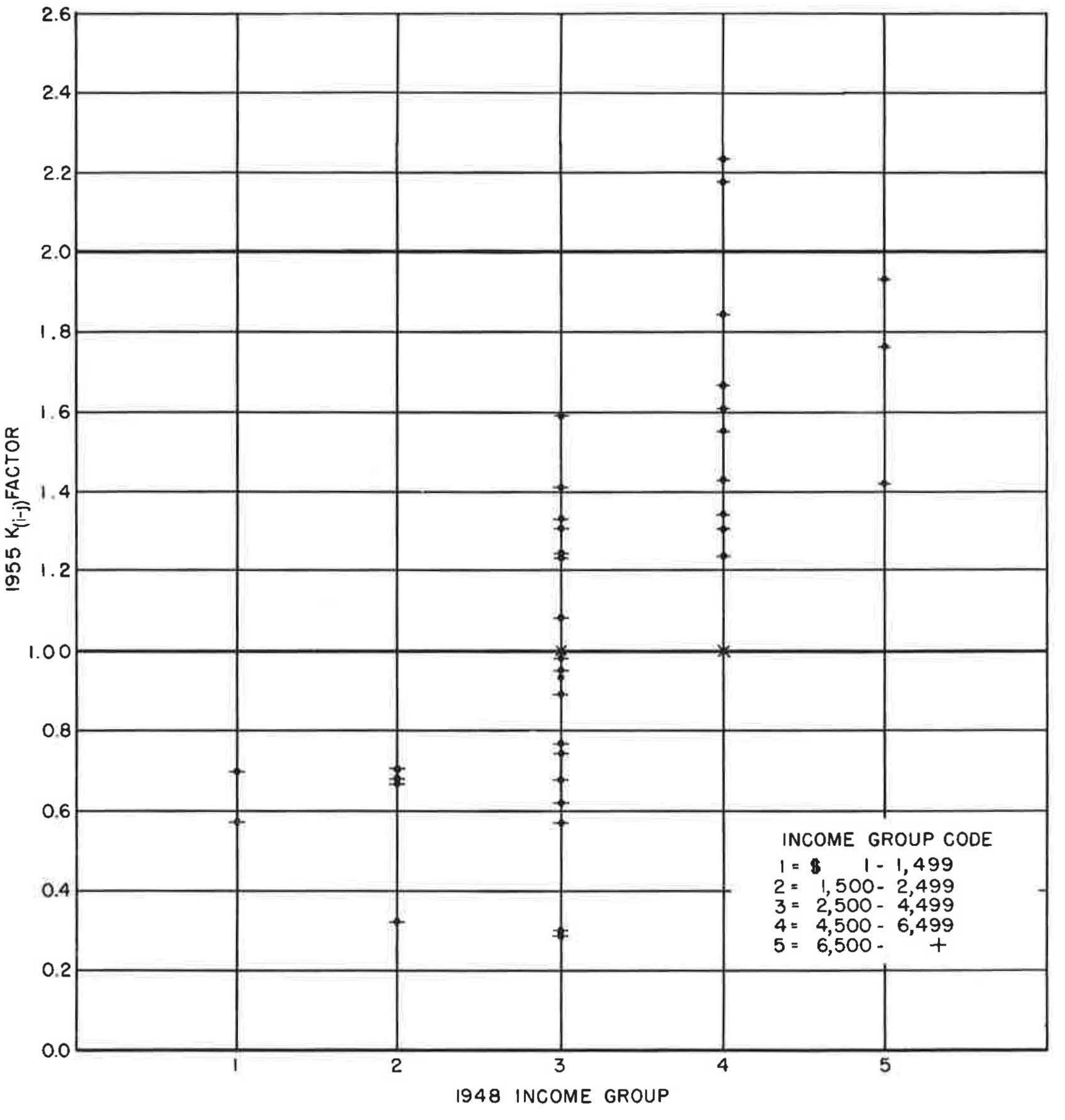

Figure 15. 1948 income group vs 1955 $K_{(i-j)}$ factors for O-D district.

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						Anacostia River					
	Trips Orig. in (thousands)						Trips Orig. (thousands)					
	Virginia			Maryland and D. C.			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.

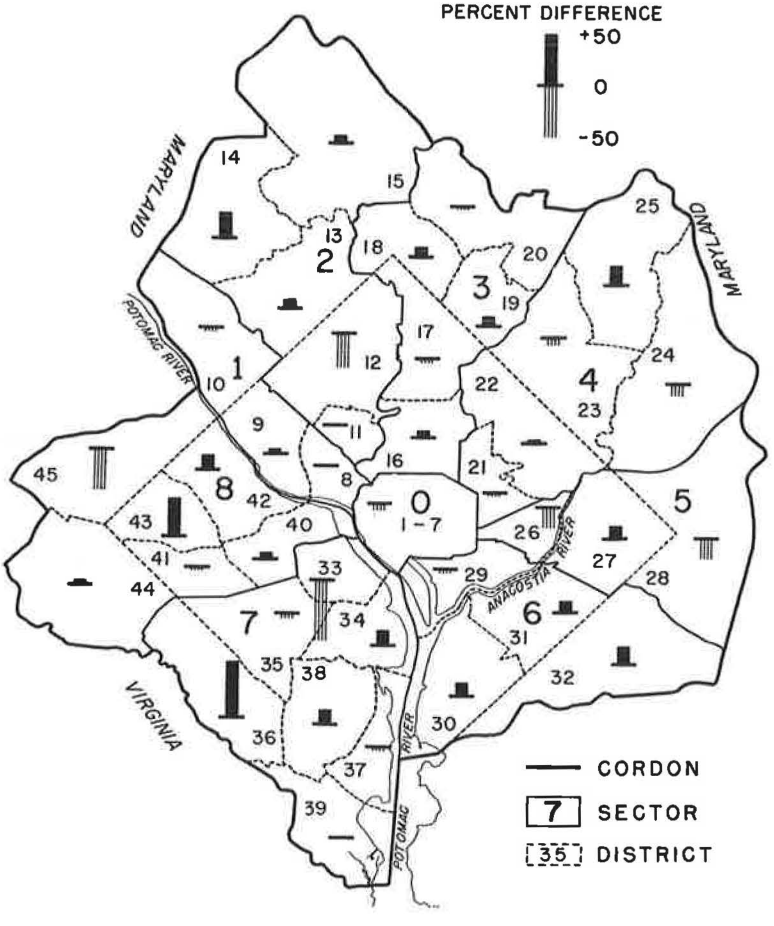

Figure 16. Comparison of work trips to zero sector, Test Run 5 vs home interview survey, 1948.

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.

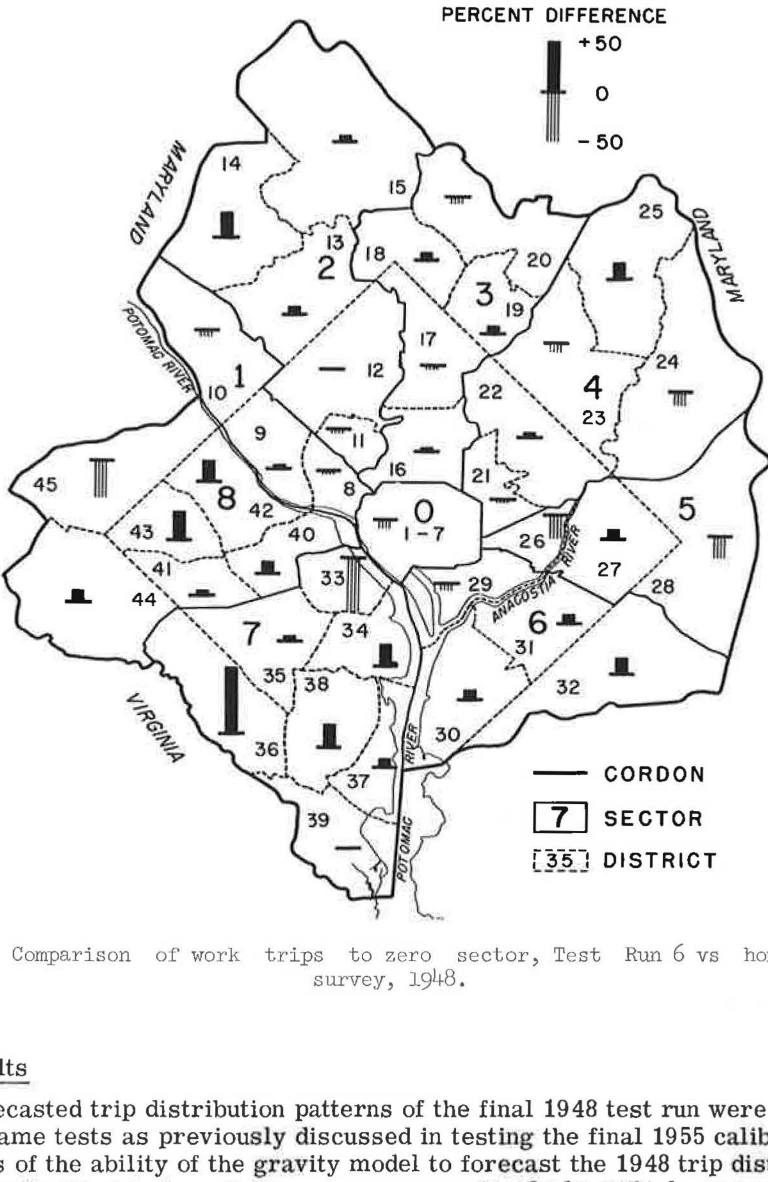

Figure 17. Comparison of work trips to zero sector, Test Run 6 vs home interview survey, 1948.

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

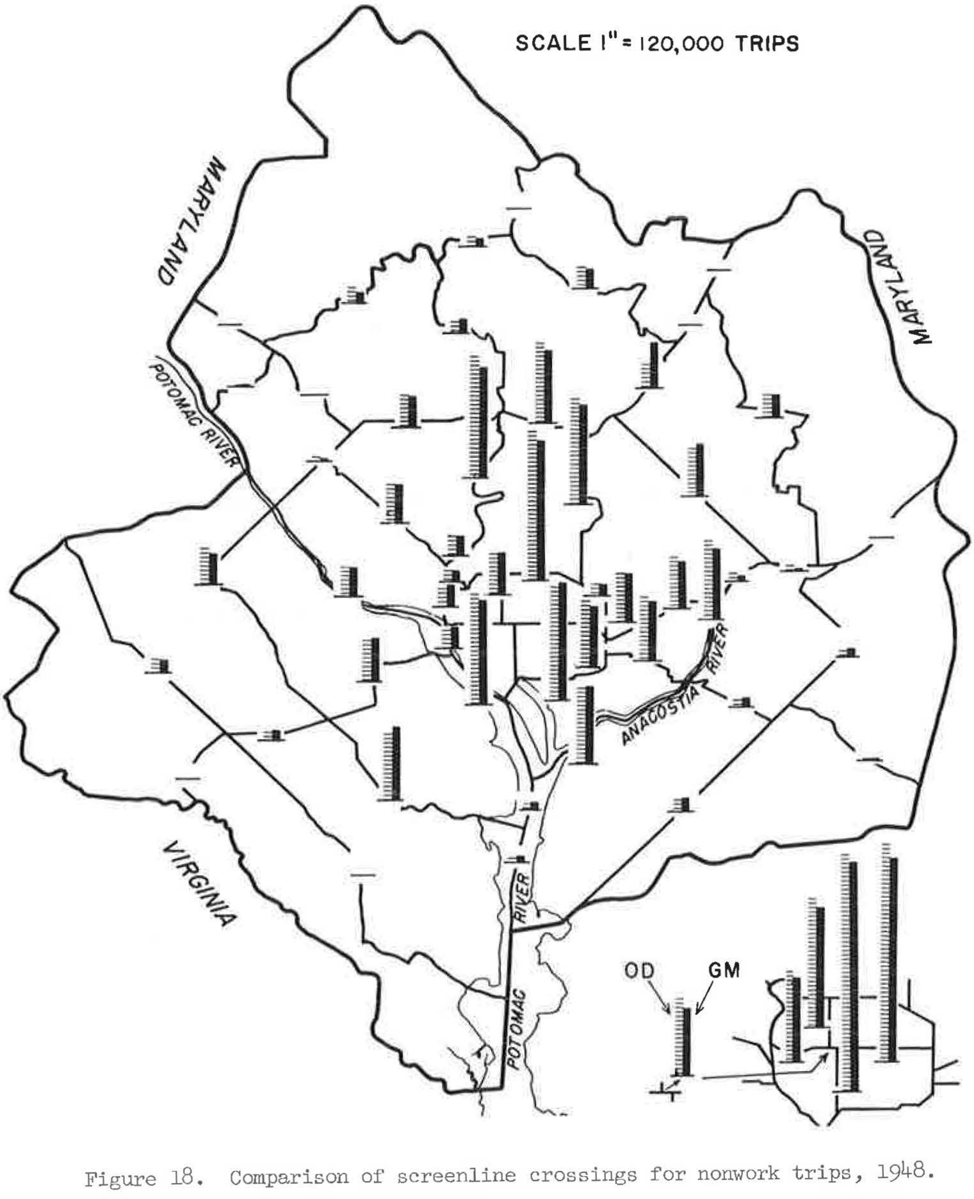

Figure 18. Comparison of screenline crossings for nonwork trips, 1948.

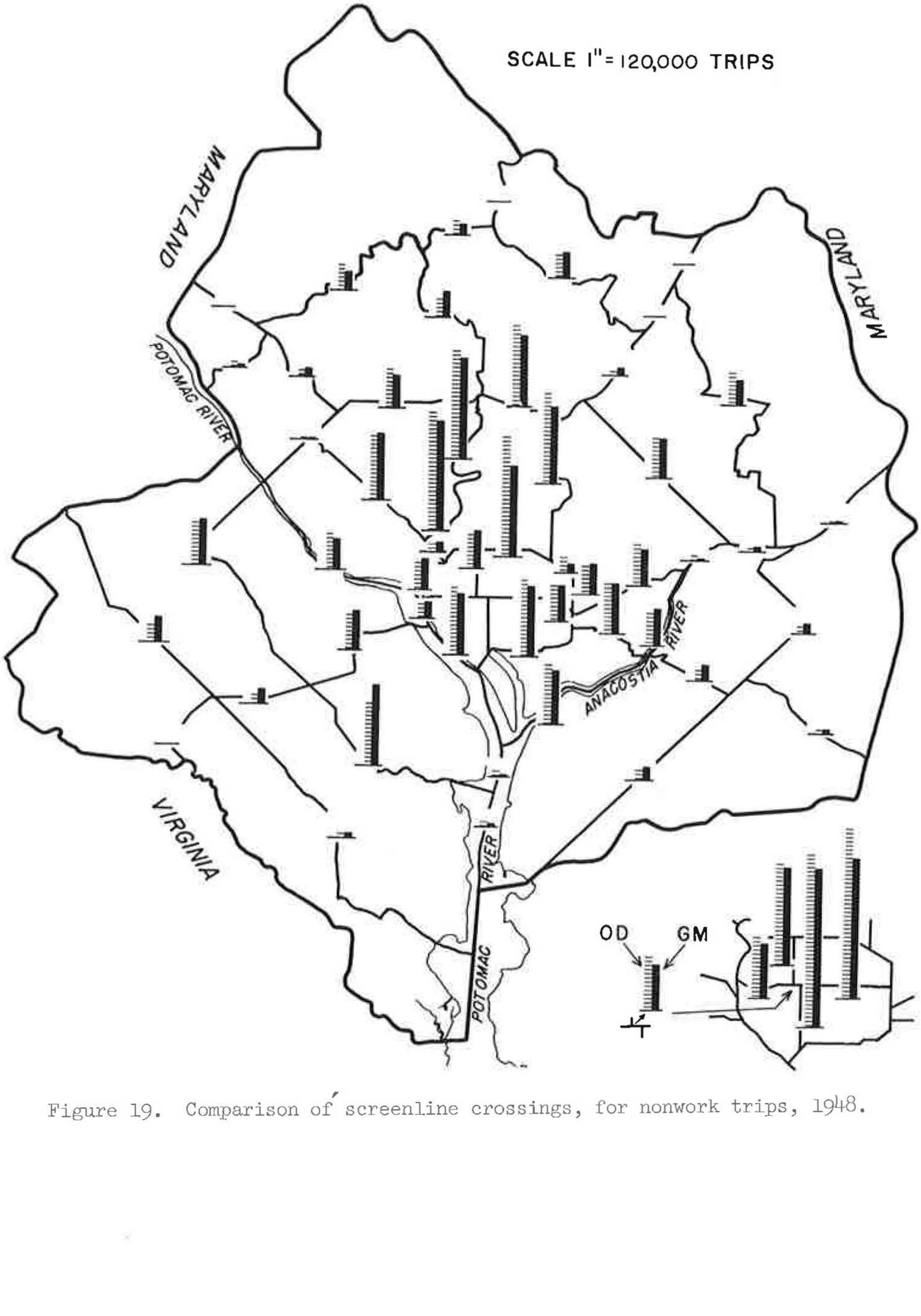

Figure 19. Comparison of screenline crossings, for nonwork trips, 1948.

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.

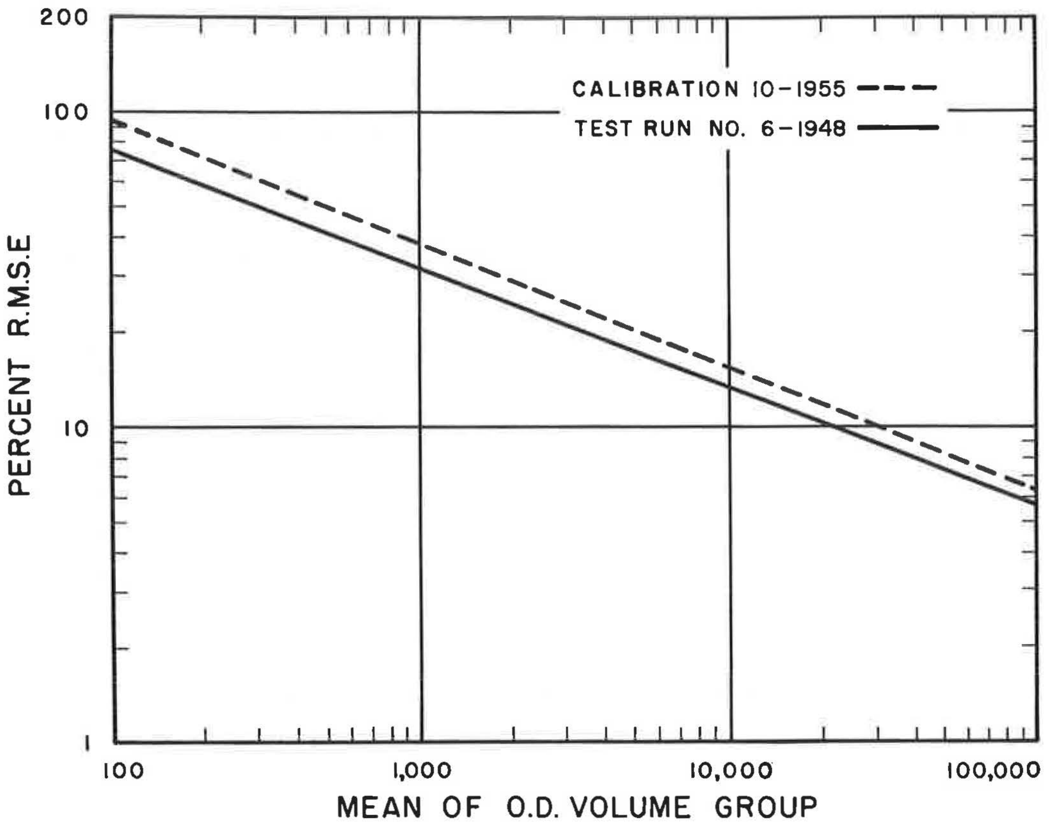

Figure 20. Comparison of root-mean-square error by volume group, district movements (O-D vs G.M.) work trips, 1948 and 1955.

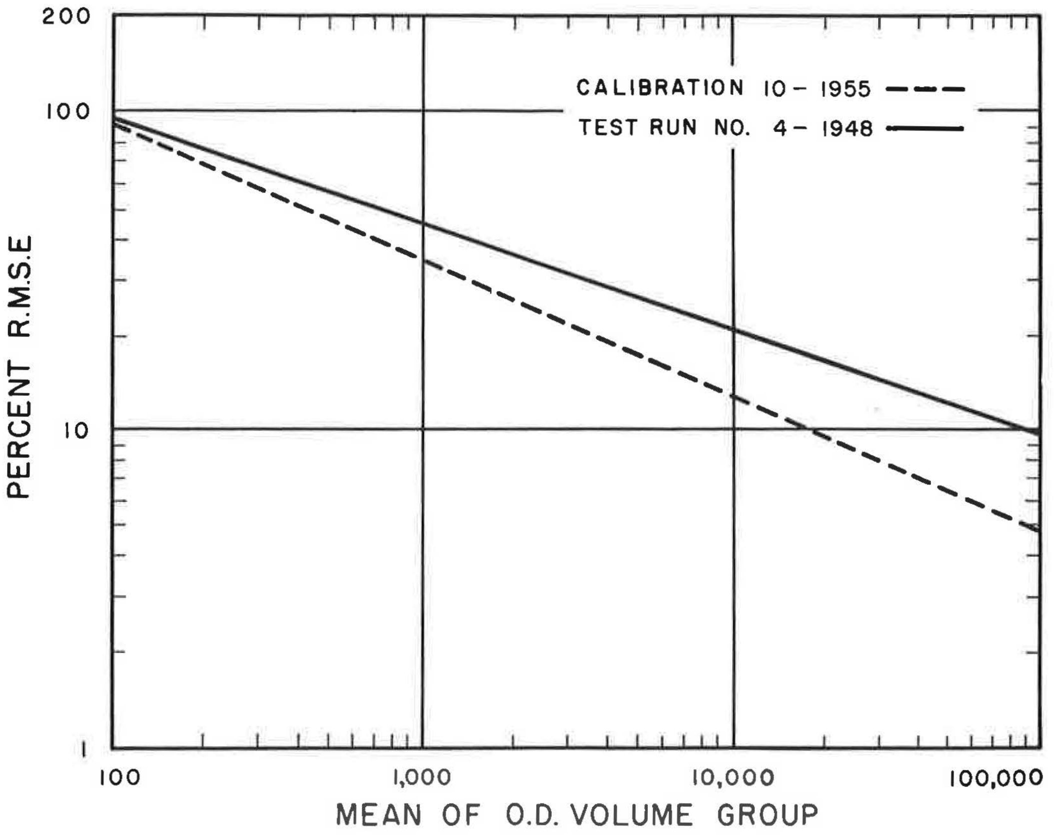

Figure 21. Comparison of root-mean-square error by volume group, district movements (O-D vs G.M.) social-rec. trips, 1948 and 1955.

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 44,170	2,373 2,978	5,702 4,236	9,319 9,469	4,586 5,340	1,547 1,496	6,005 7,292	7,577 8,499	1,335 1,573
1	19,726 19,920	2,021 1,692	1,757 2,210	1,826 1,670	452 584	248 147	976 920	2,247 1,881	329 558
2	34,604 35,781	1,773 1,886	8,112 6,852	4,420 4,830	1,538 1,378	276 257	1,237 1,284	3,054 2,280	199 665
3	100,937 102,522	4,137 4,127	9,599 11,111	29,534 27,966	6,632 9,923	1,844 1,707	8,289 6,672	11,931 8,503	1,460 1,832
4	52,082 51,485	1,936 1,704	3,219 3,726	8,134 10,920	16,360 13,894	2,457 2,749	8,633 8,072	5,430 5,355	643 989
5	36,445 34,007	1,524 1,118	2,002 1,849	5,803 5,034	7,030 6,699	4,299 4,297	8,901 11,172	3,698 5,209	556 873
6	38,567 40,634	1,474 1,327	2,286 1,762	4,758 3,859	5,046 4,114	2,093 2,552	20,791 18,492	5,049 7,076	875 1,123
7	30,227 29,552	930 1,356	997 1,606	1,347 2,377	871 1,299	478 507	2,596 3,612	28,864 15,143	2,693 3,551
8	25,259 26,374	1,328 1,242	1,017 1,357	1,698 1,521	688 743	512 274	1,746 1,907	9,774 10,864	7,487 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 89,539	5,182 6,648	7,952 6,414	23,253 20,646	7,477 7,248	4,432 3,496	7,381 8,640	5,656 5,542	3,142 3,413
1	17,034 19,891	13,832 9,298	13,030 14,236	3,621 5,314	1,437 505	306 183	1,010 677	1,855 1,212	1,379 2,188
2	23,188 20,057	7,430 11,612	62,805 56,304	15,447 23,012	2,427 1,516	323 322	1,354 705	1,482 975	1,321 1,294
3	60,264 56,017	4,536 4,299	14,592 21,122	93,237 92,775	9,416 13,703	3,314 1,557	4,784 1,843	2,226 1,385	1,497 1,166
4	28,580 28,093	1,547 694	1,788 2,009	12,937 19,314	39,632 34,657	5,373 5,715	3,618 3,725	1,193 693	732 497
5	19,581 19,510	615 352	919 502	7,765 3,741	6,521 8,055	14,784 14,384	8,437 12,088	537 687	520 360
6	27,554 29,052	1,553 717	1,172 725	6,329 2,810	3,400 4,246	5,776 8,887	33,779 32,416	2,134 1,870	476 852
7	23,485 25,338	1,946 2,025	1,861 1,333	3,001 2,542	999 804	667 604	2,841 2,921	69,500 63,572	10,972 16,136
8	12,761 12,805	3,074 3,598	1,351 1,799	2,299 1,793	796 447	204 296	555 1,231	8,653 13,828	40,480 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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