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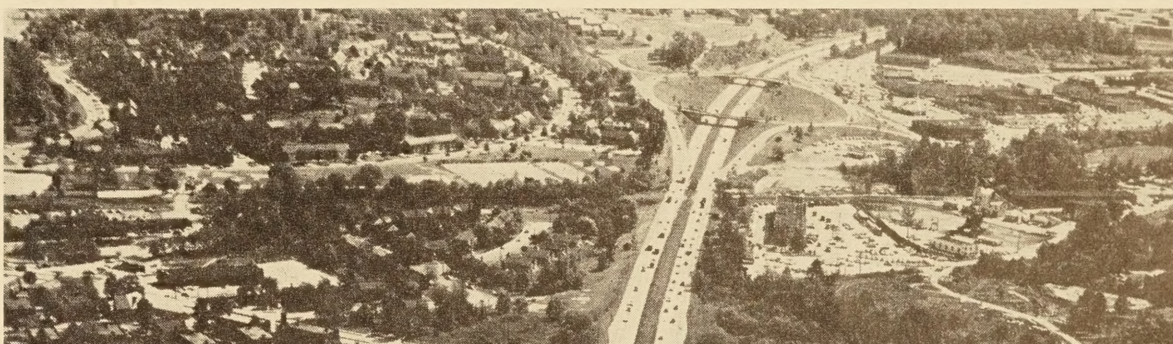

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In this issue: Two studies of trip patterns in the Washington, D. C., area. (Shirley Memorial Highway and Glebe Road interchange, Arlington County, Va.)

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IN THIS ISSUE

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Evaluating Trip Forecasting Methods With an Electronic Computer

BY THE DIVISION OF HIGHWAY PLANNING
BUREAU OF PUBLIC ROADS

Reported [1] by GLENN E. BROKKE and WILLIAM L. MERTZ, Highway Research Engineers

In forecasting trip distribution from the existing pattern, the average factor method, the Detroit method, and the Fratar method are equally accurate if each method is carried through a sufficient number of successive iterations. In all cases tested, maximum accuracy was reached in the second approximation of the Fratar method while four or more approximations were usually required with either of the other two methods.

The results of the test emphasized that the majority of the trips within a metropolitan area consist of a very large number of small-volume zone-to-zone movements, where the zones are of normal size. With sampling rates used ,these individual small-volume movements are not accurately determined. The accumulation of the small-volume movements into volumes associated with ramps, streets, and expressways should result in acceptable accuracy as calculated by statistical formulas, but this will have to be definitely established by additional research.

The advantage of using an electronic computer on research projects of this type can hardly be overestimated, even though preparing the program is difficult and time consuming. In this series of tests, the speed and accuracy of the computer permitted the attainment of results in hours instead of years after the program had been completed, without a single error attributable to the computer.

STUDIES of trip origins and destinations of residents in the Washington, D. C., area were made in 1948 and 1955. In the earlier study a 5-percent sample was obtained by interviewing the residents of one of every 20 dwelling units. In the 1955 study, the sample rate was 1 in 30 in the District of Columbia and 1 in 10 elsewhere within the area.

These two surveys offered, for the first time, an opportunity to study the changes occurring in the pattern of trips over a period of several years in a metropolitan area, i. e., the differences in the numbers of trips between the same origins and destinations. They also provided data that could be used to evaluate methods of forecasting trip volumes.

Trip Forecasting Elements

Two basic elements are involved in the forecasting of trips. One is the increase in the number of trip origins and destinations in a particular part of the city such as a zone. For brevity the number of trip origins and destinations combined have been labeled trip-ends. For example, 2 trips originating in a zone and 3 trips destined to it would be counted as 5 trip-ends. Manifestly, if only the trips made wholly within an area are considered, the total number of trip-ends in the area is exactly twice the number of trips.

The ratio of future trip-ends expected in a particular zone to present trip-ends is called the growth factor for that zone. Much work has been and is being done in this field to determine the best method of arriving at the proper growth factor. Up to now, forecasts, as far as total trip-ends are concerned, are dependent to some extent on personal judgment. In order to eliminate this variable and isolate the elements being studied, the growth factors were calculated for each zone by taking the ratio of the reported trip-ends in each zone in 1955 to the reported trip-ends in each zone in 1948. Thus any variability in predicting growth factors will not affect this study of forecasting methods.

The other basic element involved in forecasting zone-to-zone movements is the application of the growth factors of the two terminal zones in predicting the number of future trips between them. Various mathematical formulas have been developed with that end in view. It is the purpose of this study to evaluate the accuracy of these methods and the formulas used therein. Certain other methods of trip forecasting, based on population distribution, trip-attraction distribution, and distance or travel time, directly predict the number of zone-to-zone trips; but as these methods are still in the process of development they will not be discussed here.

Characteristics of the Area

One problem that had to be resolved in beginning the test was that the area covered in the 1948 Washington survey was somewhat smaller than that of the 1955 survey, and the extent and identifying numbers of many of the zones had been changed. The first step was to reconcile these differences by rezoning the metropolitan area into 254 zones and to determine both the 1948 and 1955 volumes of trips into and out of these zones.

The 254 zones covered an area which contained 96 percent of the population that lived within the 1948 cordon and 93 percent of that living within the 1955 cordon. Most of the external cordon stations in 1955 were placed at different locations from those in 1948; and therefore the trips crossing the cordon, called "external" trips, are omitted from the study, the two surveys not being comparable for this class of trip.

Within the 254 zones the population increased 38 percent during the 7-year interval, while the number of trips by persons [2] increased 42 percent. This represents a small increase in trips per person from 1.95 to 2.00. During the same interval the number of passenger cars owned by residents almost doubled, increasing 96 percent, while the number of trips made by these passenger cars went up 89 percent. This represents a small decrease in the number of trips per passenger car from 3.15 to 3.05. These comparisons seem to indicate that the number of automobile trips increases roughly in proportion to the increase in the number of automobiles, and total trips by persons increase about as population does in the Washington area.

The number of trips by various vehicle types and modes of transportation, together with population and passenger-car ownership, are shown in figure 1. The growth factors resulting from the changes between 1948 and 1955 are shown graphically in figure 2.

The increase of 89 percent in the number of passenger-car trips during the 7-year interval is rather high. It represents an average increase of almost 13 percent annually on a straight-line basis or about 9.5 percent if compounded annually.

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[1] This article was presented at the 37th Annual Meeting of the Highway Research Board, Washington, D. C., January 1958.

[2] In this article "trips by persons" include trips by drivers of automobiles, taxis, and trucks and by passengers in automobiles, taxis, and mass-transit vehicles. Pedestrian trips and the small number of trips by passengers in trucks are not included.

This high rate of increase in the Washington area, however, has the advantage of providing growth factors that are somewhat similar to the growth factors that have been forecast for about 25 years in some of the larger cities. For example, the growth factors for total vehicle trips as measured in Washington and those predicted for Detroit and Cleveland are shown in table 1.

Thus while the test of the forecasting methods is confined to the growth of Washington from 1948 to 1955, the actual growth factors are not entirely dissimilar to forecasts for Detroit and Cleveland although the latter two are for longer periods of time.

In this study, passenger-car and taxi trips were combined into one category of passenger-vehicle trips. The overall growth factor for these trips was 1.67. As for individual zones, about 6 percent had fewer trip-ends in 1955 than in 1948, and 50 percent had a growth factor smaller than 1.55. A more detailed distribution of the individual zone growth factors for passenger-vehicle trips is given in table 1.

Methods of Forecasting Trips

The 1948 zone-to-zone trips were expanded to 1955 by various formulas and the predicted values were compared with those obtained in the 1955 sample. The actual methods are subsequently described as the uniform factor method, the average factor method, the Detroit method, and the Fratar method. Symbols used in mathematical formulas are as follows:

- T_{ij} = Observed 1955 trips between zone i and zone j.
- T_{ij}' = Calculated 1955 trips between zone i and zone j.
- T_{i-j}' = Calculated 1955 trips from zone i to zone j.
- T_{j-i}' = Calculated 1955 trips from zone j to zone i.
- t_{ij} = Observed 1948 trips between zone i and zone j.
- T_i = Summation of observed 1955 trip-ends in zone i.
- t_i = Summation of observed 1948 trip-ends in zone i.
- F_i = Growth factor for zone $i = T_i/t_i$.
- T = Summation of 1955 trip-ends in entire area.
- t = Summation of 1948 trip-ends in entire area.
- F = Growth factor for entire area $= T/t$.
- t_{ix} = 1948 trips between zone i and each of all other zones designated as zone x.
- F_x = Growth factor for zone x.

Uniform Factor Method

The most simple method of expanding trips is to compute a single factor for the entire area and use it to multiply all zone-to-zone trips. This particular method is seldom used now, but because of its wide use in the past it was evaluated. Mathematically the expansion formula is $T_{ij}'=t_{ij}\times F$. There is no possibility of successive approximations with this method, such as those used in the methods subsequently described.

Average Factor Method

In the average factor method each of the 1948 zone-to-zone movements is multiplied by the average of the growth factors for the two zones involved, $T_{ij}'=t_{ij}(F_i+F_j)/2$.

After the trips from one zone, i, to all other zones have been computed by this method, the sum of all trip-ends in that zone, as determined from this calculation, T_i', will probably not equal the actual 1955 trip-ends in that zone, T_i. This discrepancy can be eliminated by a series of iterations producing successively closer approximations, as follows:

Let F_i' equal the factor needed to bring the calculated number of trip-ends T_i' to actual number T_i or $F_i'=T_i/T_i'$, and similarly $F_j'=T_j/T_j'$. Then for the second approximation, $T_{ij}''=T_{ij}'(F_i'+F_j')/2$, and similarly for a third approximation, $T_{ij}'''=T_{ij}''(F_i''+F_j'')/2$. The process can be repeated until the F factors for a new iteration equal the limiting value of 1.00.

One of the inherent disadvantages of the average factor method is that the calculated trips into zones with higher-than-average growth factors generally total less than the predicted number of trips. Conversely the calculated trips into zones with lower-than-average growth factors total more than the predicted number of trips. This systematic bias of the predicted values could result in an inordinate number of approximations and might affect the accuracy of the method.

Detroit Method

A method to alleviate this difficulty was developed by Dr. Carroll's staff for the Detroit study.[3] In this method they assumed that the trips from zone i will increase as predicted by F_i and will be attracted to zone j in the proportion F_j/F. The predicted trips from zone i to zone j can then be calculated from the equation $T_{i-j}'=t_{i-j}(F_i\times F_j)/F$. Similarly the trips from zone j can be considered as increasing as predicted by F_j and will be attracted to zone i in the proportion F_i/F.

The predicted trips from zone j to zone i can then be calculated from the expression $T_{j-i}'=t_{j-i}(F_j\times F_i)/F$. Therefore the number of trips between zone i and zone j is equal to the sum of the trips from i to j and from j to i or $T_{ij}'=T_{i-j}'+T_{j-i}'$.

Hence:

$$T_{ij}'=t_{i-j}\,\frac{(F_i\times F_j)}{F}+t_{j-i}\,\frac{(F_j\times F_i)}{F}$$

$$=(t_{i-j}+t_{j-i})\,\frac{(F_i\times F_j)}{F}$$

$$=t_{ij}\,\frac{(F_i\times F_j)}{F}$$

As in the case of the average factor method the calculated trip-ends in a particular zone will probably not equal the predicted trip-ends in that zone. Therefore new F factors can be determined as follows: $F_i'=T_i/T_i'$ and $F_j'=T_j/T_j'$. A second approximation can be calculated from the expression

$$T_{ij}''=T_{ij}'(F_i'\times F_j')/F'.$$

This same procedure can be used to calculate a third and subsequent approximations until the new F factors equal the limiting value of 1.00.

Fratar Method

The first method in which the iterative process was used in predicting trips was developed by Thomas J. Fratar in connection with the forecast for Cleveland, Ohio. Fratar considers that the distribution of the trips from any zone i is proportional to the present movements out of zone i modified by the growth factor of the zone to which these trips are attracted. The volume of the trips, however, is determined by the expansion factor of zone i.

If the trips between zones i and j, as calculated by considering all trips from zone i, are represented by the symbol $T_{ij(i)}'$ and those as calculated by considering all of the trips from zone j by the symbol $T_{ij(j)}'$, then

$$T_{ij(i)}'=t_{ij}\times F_j\times\frac{\Sigma t_{ix}\times F_i}{\Sigma t_{ix}\times F_x}\quad\text{(1)}$$

Noting that $\Sigma t_{ix}\times F_i$ can also be written as $F_i\times\Sigma t_{ix}$, then equation 1 can be written as

$$T_{ij(i)}'=t_{ij}\times F_j\times F_i\times\frac{\Sigma t_{ix}}{\Sigma t_{ix}\times F_x}\quad\text{(2)}$$

The last term in equation 2 represents basically the reciprocal of the average attracting pull of all other zones on i. It is labeled the "location" or L factor since it is somewhat dependent on the location of the zone with respect to all other zones. Since by definition $\Sigma t_{ix}/\Sigma(t_{ix}\times F_x)=L_i$, equation 2 can be rewritten as

$$T_{ij(i)}'=t_{ij}\times F_j\times F_i\times L_i\quad\text{(3)}$$

Then for all trips from zone j, it can similarly be shown that

$$T_{ij(j)}'=t_{ij}\times F_i\times F_j\times L_j\quad\text{(4)}$$

Thus the trips between zone i and zone j have been computed twice—once for all trips out of zone i and once for all trips out of zone j. The most probable value is an average of the two computations or

$$T_{ij}'=\frac{T_{ij(i)}'+T_{ij(j)}'}{2}\quad\text{(5)}$$

Substituting the identities from equations 3 and 4 in equation 5 and factoring out the common terms, the final equation is developed as follows:

$$T_{ij}'=t_{ij}\times F_i\times F_j\times\frac{L_i+L_j}{2}\quad\text{(6)}$$

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[3] *Report on the Detroit Metropolitan Area Traffic Study, Part II—Future Traffic and a Long Range Expressway Plan, March 1956.* J. D. Carroll, Jr., Study Director.

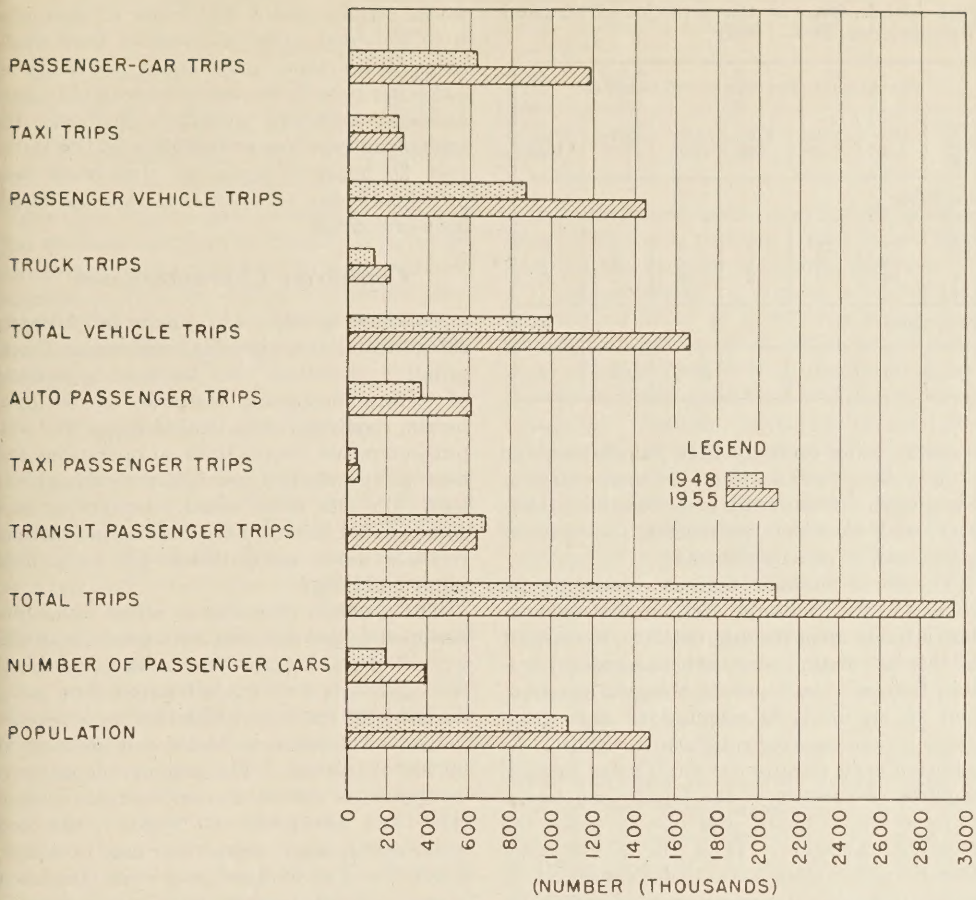

Figure 1.—Number of trips within the Washington, D. C., area by various modes of transportation, together with passenger-car ownership and population data, 1948 and 1955.

After all the zone-to-zone trips have been computed by this formula, the calculated trip-ends in a particular zone will probably not agree with the predicted trip-ends in that zone. Therefore new factors can be calculated as follows: $F_i'=T_i/T_i'$, $F_j'=T_j/T_j'$, $L_i'=\Sigma T_{ix}'/\Sigma(T_{ix}'\times F_x')$, and $L_j'=\Sigma T_{jx}'/\Sigma(T_{jx}'\times F_x')$. A second approximation can then be calculated as $T_{ij}''=T_{ij}'\times F_i'\times F_j'\times(L_i'+L_j')/2$. The same procedure can be used for subsequent approximations until the new F factors equal the limiting value of 1.00.

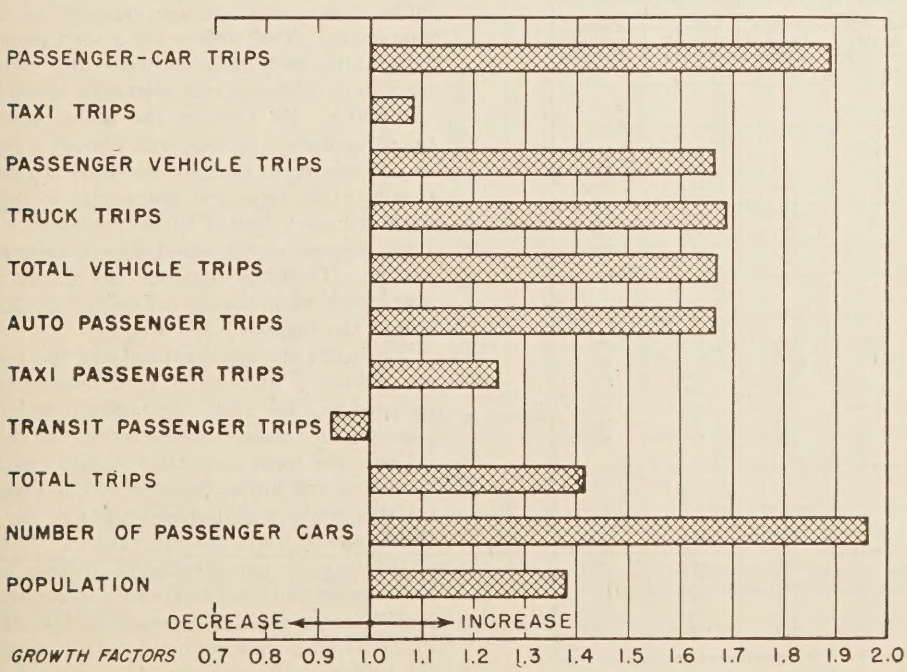

Figure 2.—Changes in the growth factors of trips by various modes of transportation, passenger-car ownership, and population, 1948–55.

Problem of Evaluation

With the Washington area divided into 254 zones, the number of possible zone-to-zone movements[4] is $[N(N+1)]/2=32{,}385$. It was expected that some of the zone-to-zone movements would be zero in 1948 and 1955 and would not need to be computed. However, it was estimated conservatively that perhaps 30,000 of the 1948 zone-to-zone movements would require expansion to 1955.

To determine whether the accuracy of the prediction was influenced by vehicle type or mode of transportation, the trips were separated by mode of travel into six categories: Passenger-vehicle trips, truck trips, total vehicle trips, mass-transit passenger trips, automobile passenger trips, and total trips by persons. Each group was expanded separately.

Expanding each of the 30,000 zone-to-zone trips made in 1948 would be almost meaningless unless some method of summarizing the comparison to the 1955 survey movements had been determined. The most obvious answer to this problem was to subtract the computed number of trips from the reported number of 1955 trips, square the differences, and accumulate the results. The sum of the differences squared could then be used to calculate the root-mean-square error of the number of trips as expanded from the 1948 data.

This summary, however, had a serious disadvantage in that the actual volume of zone-to-zone trips varies from zero to several thousand. A root-mean-square error could be inordinately affected by the relatively few large movements. Similarly, if the differences were converted to a percentage of the 1955 actual movement and the root-mean-square of the percentage computed, the result could be as greatly affected by the small movements that probably lack sufficient stability to provide meaningful information. It was therefore decided to stratify the 1948 movements by volume classes: by volumes of tens to 100, by volumes of hundreds to 1,000, and all volumes over 1,000. The numerical root-mean-square error was then computed for each volume class, and the percentage error for the class was obtained from the ratio of the numerical root-mean-square to the average 1955 volume. The proportion of all 1955 volumes in each volume class was then determined and each of the percentage errors was weighted by the proper proportion to obtain the overall percentage error.

The overall percentage error was regarded as the proper measure to evaluate the various predictive formulas. In addition, the accuracy of larger movements could be measured by an extrapolative process in which the number of average zone-to-zone movements required to make up a larger volume was determined and the basic error was divided by the square root of the number of movements required. In addition to this computation, it was desirable to know the root-mean-square error for each of the zones so that the error could be related

[4] Zone-to-zone movements as used in this article also include intrazone movements.

Table 1.—Comparison of growth factors for total vehicle trips in three major cities, and passenger-vehicle trips for Washington, D. C., only

City	Period of study or forecast	Overall growth in trip volumes	Percentage of zones with growth factors of—						
			Less than 1.00	1.00–1.49	1.50–1.99	2.00–2.99	3.00–4.99	5.00–9.99	Over 10.00
TOTAL VEHICLE TRIPS									
Washington, D. C.	1948–55	1.66	5	38	25	18	9	3	2
Detroit, Mich	1953–80	1.67	2	64	9	9	8	6	2
Cleveland, Ohio	1952–75	1.79	1	54	17	8	15	5	0
PASSENGER-VEHICLE TRIPS									
Washington, D. C.	1948–55	1.67	6	40	23	19	7	2	3

to the growth factor of the individual zones. Therefore, the difference between the expanded 1948 and 1955 movements squared was accumulated for each of the zones. It was considered likely that from this computation any inordinate error found in a particular zone could be recognized.

As has been previously explained, it is possible to carry the average factor method, the Detroit method, and the Fratar method through a number of iterations to produce successively closer approximations. To be reasonably certain that this process was continued a sufficient number of times, it was decided to calculate 10 successive approximations by each method.

Need for an Electronic Computer

It has been estimated that roughly 25 million computations would be required for this test. On the very optimistic basis that one computation can be completed in 10 seconds, using ordinary desk calculators, the project would require some 30 man-years for completion. Clearly this is not feasible. However, with electronic computers, the time required can be greatly reduced.

The three methods that use iterations are similar in that the input for the first calculation is made up of the original data, the output of this calculation and each successive iteration becomes the input of the next iteration, and so on until 10 calculations have been made if necessary for satisfactory closure. In addition each iteration of the Fratar method requires two passes of the input—one to determine the *L* factor and one to make the required expansion. Thus, the 30,000 zone-to-zone movements have to be processed 42 times, including the one pass of the data required to obtain the original growth factors.

In deciding upon the particular type of computer to be used, the first problem was to decide whether to use one with card input and output, or one with tape. The card type would require about 200 hours of computer time provided sufficient memory were available. With tape, only about 10 hours of computer time or less would be required, again assuming sufficient memory; obviously the tape-using type was preferable. In the actual test, 30 hours of computer time were used principally due to additional tests on larger zone groupings.

Table 2.—Root-mean-square error in the number of zone-to-zone trips forecast for 1955 from 1948 data, compared with 1955 survey results

Approximation number	Numerical RMS error [1]				Percentage RMS error [2]			
	Uniform factor method	Average factor method	Detroit method	Fratar method	Uniform factor method	Average factor method	Detroit method	Fratar method
PASSENGER CARS								
1	165	133	234	140	151	136	192	140
2	-------	132	129	131	-------	136	133	134
3	-------	133	148	132	-------	136	143	134
4	-------	134	129	132	-------	137	133	135
5	-------	134	136	132	-------	137	137	135
6	-------	135	131	132	-------	138	134	135
7	-------	135	133	132	-------	138	135	135
TRUCKS								
1	78	57	59	55	163	160	172	162
2	-------	55	58	55	-------	160	161	161
3	-------	55	55	55	-------	161	163	161
4	-------	55	56	55	-------	162	161	161
5	-------	55	55	55	-------	162	162	161
6	-------	55	55	55	-------	162	161	161
7	-------	56	55	55	-------	162	162	161
TOTAL VEHICLES								
1	174	137	229	138	141	124	175	125
2	-------	133	131	130	-------	122	120	120
3	-------	133	144	131	-------	121	128	121
4	-------	133	129	131	-------	122	119	121
5	-------	133	134	131	-------	122	122	121
6	-------	133	130	131	-------	122	120	121
7	-------	133	132	131	-------	122	121	121

[1] Calculated on the basis of number of zone-to-zone movements that had more than zero trips in either 1948 or 1955. Average zone-to-zone volumes were as follows: passenger cars, 84; trucks, 28; and total vehicles, 90.

[2] Calculated by determining the error in the various volume groups and weighting the error in each group in proportion to the percentage of all trips in that group.

Computer Characteristics

Computer problems in general fall into two categories: data-processing problems and computation problems. For instance, a problem of testing forecasting methods, as discussed herein, requires a great deal of input and output but rather simple internal operations and is properly classified as a data-processing problem. On the other hand, computing such things as log tables or trigonometric functions requires much computation but very little input and output.

The problem then was to select a machine designed to process data with good "read and write" characteristics and a large memory. Arrangements were made for part-time use of an IBM 705 machine which met these requirements. The machine had a core memory of 40,000 characters. The memory capacity of computers is sometimes reported in "characters" and sometimes in "words." In computer terminology, a character may be a digit, a letter or a symbol, while a word consists of a group of characters. In some computers the word is of a constant length, and in other computers the word length may be varied at the option of the programer. The computer used was a variable-word-length machine and the core-memory capacity is therefore given in characters rather than words.

The machine was equipped with two tape-record coordinators, more commonly referred to as buffers. The purpose of the buffers is to shorten the reading and writing time. Each buffer has a core storage capacity of 1,024 characters. The buffers are loaded from the tape units, and when the computer requires more data it obtains it at electronic speed from the buffer. As soon as the buffer is called upon for data, the tape unit feeding it begins to accelerate, so that by the time the buffer is empty the tape unit has begun to refill it with the next record to be processed. The same process works essentially in reverse for output. Thus the machine can go on with other work while records are being fed into and out of the buffers.

The 1,024-character capacity of the buffers also allows a number of card records to be grouped so that when the buffer calls on the tape units for data, one tape record can receive information from a number of cards without exceeding the buffer capacity. The program for this study was designed to have the machine read or write the equivalent of 24 cards of information per reading or writing cycle. As it turned out in production, the computer took a longer time to process the data on the 24 cards than was required to fill or empty the buffers so that the machine never had to wait for data, and all reading or writing time was essentially "free."

Table 3.—Variation in number of trips and reduction in percentage error with increasing zone size

Number of areas	Minimum number of trip-ends per area	Average number of trip-ends per area	Number of area-to-area possibilities	Average number of area-to-area trips	Minimum percentage of RMS error
254 zones	193	6,900	32,385	27	133
122-zone groups	10,000	14,400	7,503	116	70
66-zone groups	20,000	26,600	2,211	394	41
49-zone groups	30,000	35,800	1,225	711	34
7-zone groups	214,305	250,000	28	31,092	14
2-zone groups	731,000	870,000	3	290,192	11

The IBM 705 is a decimal machine, meaning that the entire content of memory is in condition always to be printed out as alpha-numeric information directly without conversion from binary to decimal. The machine performs internal operations at an average rate of 8,300 per second.

Preparation of Program

Since this was the first large-scale electronic computer project undertaken by the Bureau of Public Roads, the services of the National Bureau of Standards Computer Laboratory were retained to aid in the selection of the machine and in the preparation of the program. Their wide experience in this field has proved invaluable in the completion of this work.

In programing the problem the first difficulty was one of memory space, in spite of the large amount available. It was necessary to overlap the program and resort to external tape storage. Even so it was necessary to split the problem into two parts. All of the vehicle types—passenger cars, trucks, and total vehicles—were handled in the first run. The second run processed the trips by persons: automobile passengers, mass-transit passengers, and total persons. The same basic program was used for both runs, however.

It was necessary to prepare a preliminary program in order to group the single card records into groups of 24, which is the maximum number of cards within buffer capacity, and to separate them into vehicle or person categories. Included in this preliminary program were an editing routine, a volume-classification routine, and a check-sum routine. The editing routine rejected any cards with alphabetic information, i. e., over-punches, inconsistent zone numbers, etc. The volume-classification routine classified the 1948 volumes of trips into 20 volume classes. The check-sum routine summed all the volumes by modes and zones and compared the totals with a 254-card summary deck prepared independently. The preliminary program also permitted the preparation of the main program while the input data were being compiled. Any changes in the arrangement of the data taken from the cards could be taken care of in the first program without affecting the main program.

Table 4.—Root-mean-square error of the 1955 passenger-car trips forecast for the 254 zones and for different zone groupings

Approximation number	254 zones, error in trips		122-zone groups, error in trips		66-zone groups, error in trips		49-zone groups, error in trips		7-zone groups, error in trips	
	Number	Percent [1]	Number	Percent [1]	Number	Percent [1]	Number	Percent [1]	Number	Percent [1]
					UNIFORM FACTOR METHOD					
-----	165	151	415	98	499	57	747	49	19,641	38
					AVERAGE FACTOR METHOD					
1	133	136	244	77	458	49	655	42	10,180	20
2	132	136	204	72	364	44	542	37	8,300	16
3	133	136	196	71	344	43	517	36	7,810	15
4	134	137	194	71	338	42	509	35	7,690	15
5	134	137	193	71	337	42	507	35	7,540	15
6	135	138	193	71	336	42	506	35	([2])	------
7	135	138	193	71	336	42	506	35	--------	------
					DETROIT METHOD					
1	234	192	388	89	720	64	871	51	10,300	20
2	129	133	228	74	396	46	543	37	8,960	17
3	148	143	299	74	344	42	504	35	7,700	15
4	129	133	194	70	337	42	484	34	7,510	15
5	136	137	196	70	320	41	478	34	7,500	15
6	131	134	189	70	326	41	480	34	7,570	15
7	133	135	190	70	319	41	476	34	7,480	14
					FRATAR METHOD					
1	140	140	205	71	339	42	498	35	7,360	14
2	131	134	188	70	322	41	480	34	7,460	14
3	132	134	188	70	322	41	478	34	([2])	------
4	132	135	188	70	321	41	479	34	--------	------
5	132	135	188	70	322	41	478	34	--------	------

[1] A weighted percentage error was obtained by determining the percentage error in each volume class and weighting this error by the proportion of trips in that volume class. Not applicable for the 7-zone group because all volumes were in the largest volume class.

[2] No further iterations required because new F factor for all zones was 1.00.

The program was designed to have all the final output written on tape for subsequent printing. It was found that the machine would be slowed down a great deal if a printer were connected "on line." As originally designed, there was one line of printed information for each of 20 volume classes times 6 modes of travel, one line for each of 254 zones times 6 modes, and one line for each overall citywide volume for each of the 6 modes. For all of the methods tested, with their iterations, this amounted to 52,800 printed lines, or almost 1,760 pages—a real data-processing problem.

Test Results

The initial run of the computer was made for vehicle trips by passenger cars, trucks, and total vehicles. The 1948 zone-to-zone movements were projected to 1955 by a uniform factor, by the average factor method, by the Detroit method, and by the Fratar method. These projected or forecasted results were compared with the measured 1955 volumes and the differences were squared, accumulated, and used to compute a root-mean-square error for the average movement, for the various volume classes, and for the individual zones.

These results are shown in table 2 for the three types of vehicle trips. Insofar as number of trips is concerned, the errors are not large, considering that the sample was as small as 1 in 30 for an important part of the data, and in no case larger than 1 in 10. On a percentage basis, however, the errors are very large.

When the results of the first computer run became available, the question immediately arose whether the errors were primarily attributable to the forecasting methods being tested or to the preponderance of low-volume zone-to-zone movements, which are known to lack accuracy or stability at the sample rates used.

This problem was attacked by two methods: One was by a systematic enlargement of the zones to increase the volume of the zone-to-zone movements and then testing these larger volumes through the computer program; the other method was to determine the percentage distribution of the zone-to-zone trip volumes within the city, and by statistical techniques determine the accuracy that might be expected in the original trip expansion. If the 1948 zone-to-zone trip volumes as expanded from the sample were unreliable, the error would be carried on into the forecast data, and if the 1955 expanded volumes were also unreliable, the result could compound the effect of the errors due to sample variability in comparing the forecasts with the 1955 data.

Enlarging Zones

Inasmuch as zone boundaries are chosen from land-use and geographic features, the number of trip-ends in each zone is not uniform. In this study the variability was intensified by the fact that the area had to

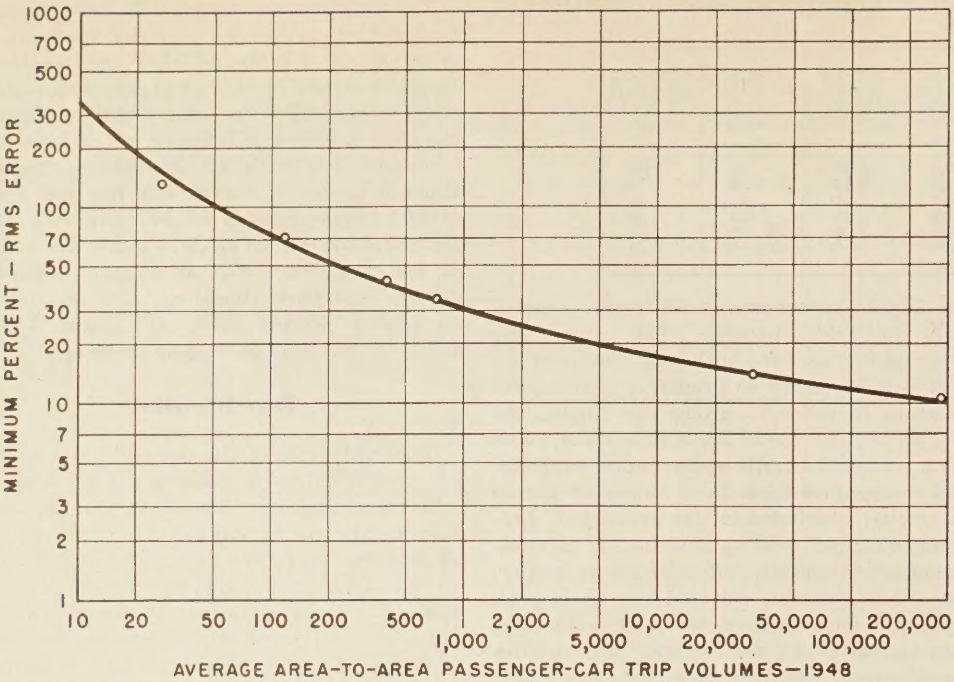

Figure 3.—Relation of average 1948 area-to-area passenger-car trip volumes and minimum percentage root-mean-square error.

be rezoned so that it would be identical in both years, and the trip-ends in the individual zones vary over wide limits. For example, the number of 1948 passenger-vehicle trip-ends averaged 6,900 per zone but varied from as few as 193 to as many as 59,870. As the initial step, therefore, adjacent zones were combined until each zone group had a minimum of 10,000 passenger-vehicle trip-ends in 1948. To minimize the effect of sample variability on the errors, this procedure was repeated to accumulate a minimum of 20,000 trip-ends per zone group, and again to accumulate a minimum of 30,000 trip-ends per group, then to divide the entire area into 7 groups, and finally into 2 groups.

The number of zones in these successive groupings, the number of 1948 passenger-car trip-ends in the average zone, and the average number of area-to-area trips are given in table 3.

Test Results of Enlarged Zones

The results of tests of each forecasting procedure for the various zone groupings are shown in table 4. As can be seen from this table, the average factor method, the Detroit method, and the Fratar method each reach essentially the same minimum error although the Fratar method reaches this minimum in the second approximation, whereas more iterations are generally required for the other methods.

The minimum percentage error, by any of the methods tested after any number of iterations for the various zone groups, and the average number of area-to-area passenger-car trips are shown in table 3.

In the case of the 2-zone group division, a second test was made by dividing the area with a line roughly at right angles to the first. The minimum percentage error for this second grouping was the same as that for the first, to the nearest percent (11 percent).

The relation between average area-to-area trip volume and the minimum percentage error is shown in figure 3. Since the minimum error for the three iterative methods is about the same, the chart can be considered as applicable to any one of them. Figure 3 is difficult to interpret because part of the error is due to sample variability and part is due to the projection method being tested. Differences in sampling rates introduce a further complication. In the 1948 survey the sampling ratio was 1:20 throughout the area, while in the 1955 survey it was 1:30 for the District of Columbia and 1:10 for the Maryland and Virginia suburbs. However, the curve should give some indication of the error to be expected in using any of the three iterative methods where the sampling rate is about the same as the average for the two Washington surveys; that is, about 5 percent.

The shape of the curve suggests that it will level off at about 10 percent. In other words an error of about 10 percent seems to be inherent in the methods tested, regardless of size of sample or areas.

Rate of closure

A measure of the efficiency of the various forecasting methods is the rapidity with which the individual zone growth factors converge toward the limiting F factor of 1.00 in successive iterations. The difference between the computed F factor at the end of an iteration and 1.00 is the factor residual error that remains in the individual zones.

The factor residual error for the 254 zones is shown in table 5 for the various iterations of the three methods. The first column indicates the approximation number; the second column shows the percentage of the zones that have no residual error (new F factor = 1.00) at the end of the approximation shown in the first column; the third column indicates the percentage of zones with a residual error less than 0.01 (new F factor between 0.99 and 1.01); the next four columns similarly show the percentage of zones with residual errors less than 0.02, 0.03, 0.05, and 0.10; and the last column shows the percentage of zones with residual errors greater than 0.10 (new F factor less than 0.90 or more than 1.10).

It can be seen from this table that the Fratar method is extremely efficient in its rate of closure. Since the F factor must be obtained for each new iteration and since

Table 5.—Factor residual error for various iterations of the average factor, the Detroit, and the Fratar methods

Approximation number	Percentage of zones with a factor residual error of—						
	0.00	Less than 0.01	Less than 0.02	Less than 0.03	Less than 0.05	Less than 0.10	0.10 and over
			AVERAGE FACTOR METHOD				
1	1	8	11	17	26	47	53
2	6	15	24	35	50	75	25
3	10	30	44	55	77	93	7
4	19	47	71	84	98	99	1
5	33	70	88	93	98	99	1
6	49	84	92	94	98	100	0
7	64	92	97	99	100	100	0
			DETROIT METHOD				
1	2	4	9	14	23	44	56
2	1	3	11	15	22	57	43
3	4	13	25	37	63	95	5
4	5	18	38	58	95	98	2
5	10	36	68	93	98	99	1
6	16	62	95	97	98	100	0
7	28	85	98	99	100	100	0
8	37	96	99	100	100	100	0
			FRATAR METHOD				
1	6	20	33	54	68	79	21
2	60	97	100	100	100	100	0
3	98	100	100	100	100	100	0
4	99	100	100	100	100	100	0

Table 6.—Average residual error related to root-mean-square error for the average factor, Detroit, and Fratar methods

Approximation number	Average factor method		Detroit method		Fratar method	
	Average residual error	RMS error	Average residual error	RMS error	Average residual error	RMS error
		Pct.		Pct.		Pct.
1	0.084	42	0.123	51	0.035	35
2	.034	37	.070	37	.003	34
3	.014	36	.032	35	.001	34
4	.007	35	.022	34	(1)	34
5	.003	35	.014	34	(1)	34

[1] Less than 0.001.

these new F factors may be easily summarized, it is suggested that they be used to indicate the desirability for additional iterations.

Number of iterations required

From the tests that have been run, the minimum root-mean-square error has always been reached in the second approximation by the Fratar method. By the other methods, however, this minimum error may not be reached until the fourth or fifth approximation. There is also a possibility that an unusual set of growth factors will develop that will not close as rapidly as those occurring in the test data.

Considering the division of the Washington, D. C., area into 49-zone groups with a minimum of 30,000 passenger-car trip-ends per group, the factor residual error was accumulated for all groups at the end of each iteration. The accumulated residual error was then divided by the number of groups to obtain the average residual error per group. This average residual error was then related to the RMS error already computed for each approximation. Table 6 indicates the results.

To be reasonably certain that greater accuracy cannot be obtained with additional iterations, it is suggested that iterations be continued until the average residual error per zone is less than 0.01.

The computer time required for each method, however, is not uniform but is approximately related to the complexity of the method. During the test, the computer time as recorded for each iteration of each method and adjusted proportionately to a common base of 10,000 zone-to-zone movements was as follows:

	Minutes
Average factor method	6
Detroit method	9½
Fratar method	12

The tabulation shows that the computer time required for the average factor method is half that required for the Fratar method. Included is the computer time needed to develop and store the various statistical measures. In an ordinary forecasting procedure these measures would not be required and the time periods would be reduced by a constant but indeterminate amount. The average factor method should therefore require something less than half the time per iteration required by the Fratar method.

Since the RMS error for the average factor method at the end of four approximations is about equal to the RMS error for the Fratar method at the end of two approximations, the overall computer time required for equal RMS accuracy is about the same. However, the rate of closure of the Fratar method is more than twice as rapid as the average factor method, and it would therefore appear to be the preferred method.

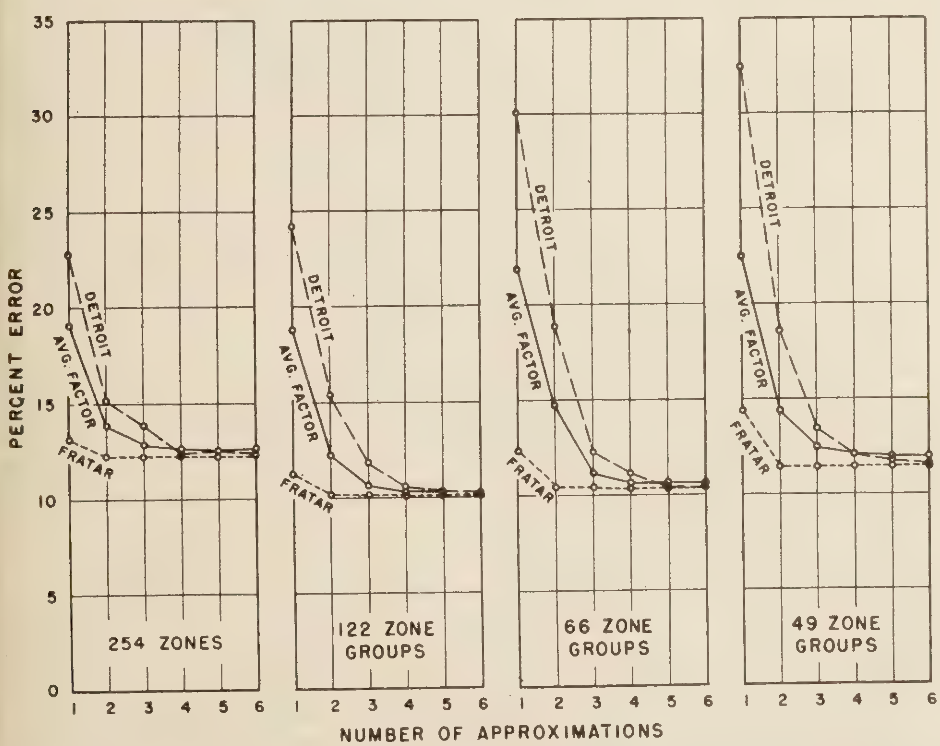

Figure 4.—Percentage error to be expected for zones grouped to provide volumes of 10,000 or more trips, based on the Detroit, average factor, and Fratar methods.

Percentage RMS Error For Accumulated Volumes

The data presented thus far have to do only with the error for the area-to-area volumes. As has been shown, the average volume between zones of the size ordinarily used is relatively small and the percentage root-mean-square error is, roughly speaking, correspondingly large.

In actual practice, the individual zone-to-zone volumes are assigned to the highway network and, therefore, each portion of the highway network represents an accumulation of zone-to-zone volumes. The volumes assigned to the highway network are our primary concern. The errors to be expected in such accumulated volumes can only be determined from actual tests and these have not yet been made. However, some indication of the magnitude of the errors to be expected can be obtained from purely theoretical considerations.

From a statistical standpoint, if the percentage error of an average zone-to-zone volume is X, the percentage error of a group of average zone-to-zone volumes is $X/\sqrt{N}$, where N is the number of individual zone-to-zone movements in the group. By dividing, 10,000 by the average zone-to-zone volume for each of the zone groupings, the number of zone-to-zone movements, N, required to accumulate to a volume of 10,000 can be determined, and the percentage RMS error of the group can therefore be calculated. The relation holds true only if the mean error of the group is zero. If the movements, however, are heavily weighted by trips from an individual zone, as they would be in the case of ramp volumes, the factor residual error, as previously explained, may be appreciable in the early iterations.

For example, if the trips on a ramp are essentially from two zones and these two zones have an average F factor for the next iteration of 1.30, the summation of trips into and out of the zones at the end of the present iteration is too low. The total number of trips for a group of zone-to-zone movements from these zones, therefore, will have a tendency to approach a volume which should be increased by 30 percent. To take this error into account, the root-mean-square of the residual errors was determined for each iteration of each method. The number of zones required to provide a volume of 10,000 was determined, and the root-mean-square residual error was added to the RMS error for individual zone-to-zone movements by taking

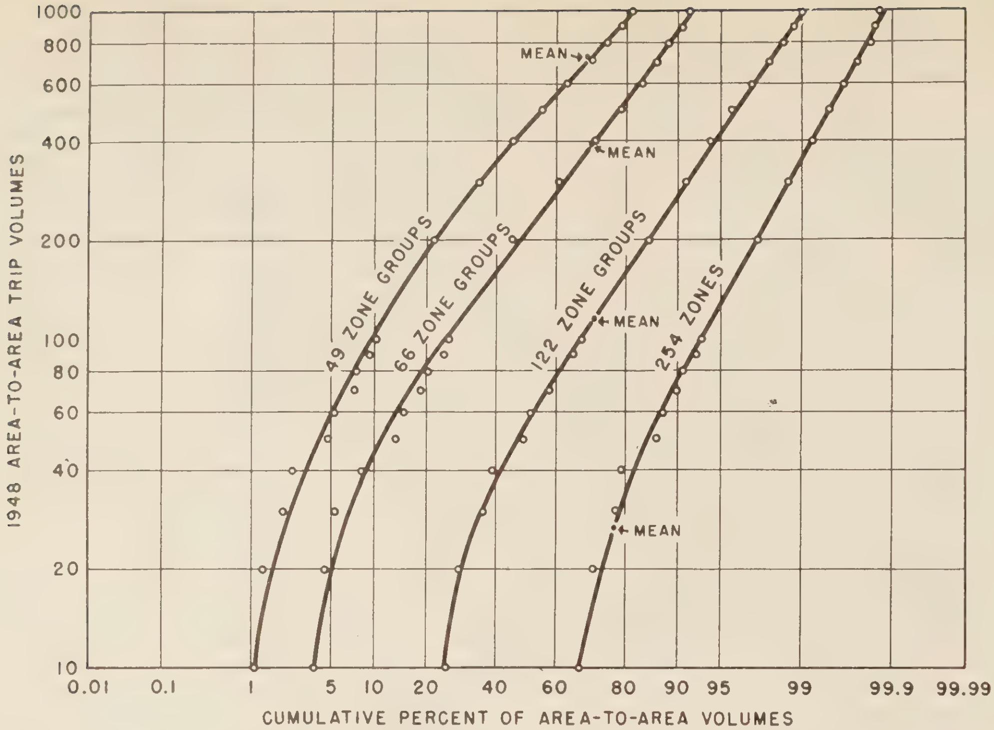

Figure 5.—Frequencies of 1948 area-to-area trip volumes of passenger cars for various zone groupings.

the square root of the sum of the squares of the two errors to determine the total error. The results of this test are shown in figure 4.

Assuming that this chart has some validity with reference to the problem, it indicates that the error for a volume of 10,000 trips is within acceptable limits and that it does not make too much difference what size zone group is used, although a minimum error was obtained for the zone grouping which had 10,000 trip-ends per group. This conclusion is dependent, to a substantial degree, on statistical inference and should be subjected to an actual test before it can be fully accepted.

Distribution of Zone-to-Zone Volumes

Even though the accumulated volumes of 10,000 or more apparently will have errors of rather modest proportions, it is desirable to inquire into the reasons for the inaccuracies of the movements between zones as they were originally planned and subsequently enlarged.

The test program was set up to count the number of zone-to-zone movements in each of several 1948 volume classes as previously described. This procedure was followed for the original 254 zones and for the subsequent groupings of 122, 66, and 49 zones.

The results of this test are shown in figure 5 for passenger cars (including taxis). Note that about 93 percent of the movements between the 254 zones have a volume of less than 100. When the number of zones was reduced to 122, about two-thirds of the area-to-area movements were less than 100; with 66 zones about one-fourth of the movements were less than 100; and with 49 zones about 10 percent were less than 100. Also note that the number of area-to-area movements which are less than the mean exceeds the number that are greater than the mean, which shows that the distribution is skewed. This is true for each of the zone groups although slightly less pronounced as the number of zones is successively decreased.

The test program also permitted the determination of the percentage of 1955 trips that were accumulated in each of the 1948 volume classes. The results of this test are shown in figure 6. Note that 50 percent of the 1955 passenger-car trips were made between zone pairs that in 1948 had a volume of less than 100 passenger-vehicle trips per day. Values for other zone groups and other 1948 volumes can be read from the chart.

In summation then, the preponderance of zone-to-zone movements within a metropolitan area is exceedingly small but because of the large number of such movements, they do account in the aggregate for a substantial portion of present or predicted trips.

Prediction Error Related to Zone-to-Zone Volumes

There is, of course, no *apriori* reason why small zone-to-zone volumes cannot be forecast with accuracy equal to large zone-to-zone volumes. The converse that the forecast error should be independent of the volume would likely seem true.

However, there is *apriori* probability that the error in the expanded number of trips from a sample survey is inversely proportional to the number of sample trips interviewed as subsequently shown.

Of all trips into and out of zone i there is a certain proportion p that will be from or to zone j. Therefore, p is the proportion of trip-ends in zone i with the other end of the trip in zone j, and $1-p$ (equals q) is the proportion of trip-ends in zone i that do not have the other end of the trip in zone j.

If s trips with an end in zone i are reported by interview, the probable number $\bar{x}$ with the other end in zone j is $s \times p$. Mathematically $\bar{x}=sp$.

From any standard statistical text it can also be shown that the standard deviation σ of the number of trips reported between zone i and zone j from sample interviews made

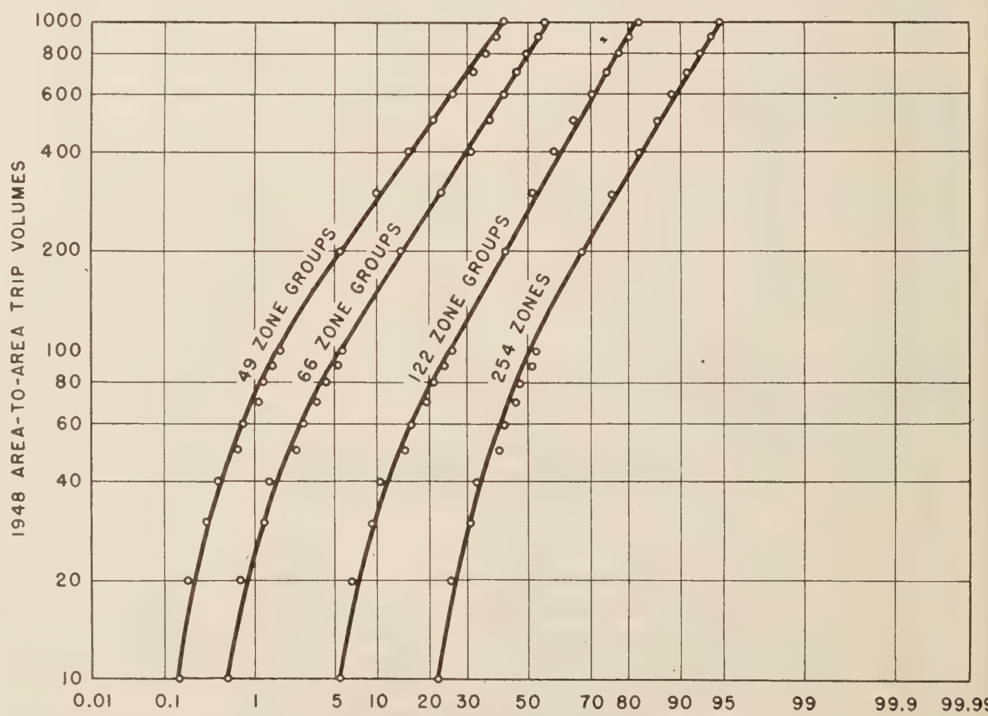

Figure 6.—Percentage of 1955 passenger-car trips that were accumulated in each of the 1948 area-to-area trip volume classes.

Table 7.—Percentage root-mean-square error by volume class of zone-to-zone movements of passenger vehicles

1948 volume class	254 zones	122-zone groups	66-zone groups	49-zone groups
20–29 [1]	195.0	121.0	95.6	106.1
30–39	222.1	101.4	86.7	83.4
40–49	279.7	118.1	81.5	73.4
50–59	141.0	96.3	82.3	89.4
60–69	139.9	107.5	92.6	89.7
70–79	108.4	74.2	78.2	76.2
80–89	154.3	95.2	94.9	54.4
90–99	128.2	83.0	54.8	73.2
100–199	133.4	93.3	64.8	64.8
200–299	80.5	69.7	58.6	52.1
300–399	60.7	64.0	56.0	43.8
400–499	54.9	56.6	50.9	38.4
500–599	42.6	42.3	45.9	44.1
600–699	51.2	40.6	46.7	48.6
700–799	88.8	41.1	31.1	26.5
800–899	38.9	26.5	57.2	31.6
900–999	18.4	21.4	33.1	38.4
1,000 and over	28.6	27.5	21.2	25.3

[1] Because of home interview sampling ratio of 1:20 in 1948, errors for volume classes below 20 cannot be accurately appraised.

of trips with one end in zone i is $\sqrt{spq}$. Mathematically $\sigma=\sqrt{spq}$.

The standard deviation σ as a proportion of the expected number $\bar{x}$ is $\sigma/\bar{x}=\sqrt{spq}/sp=\sqrt{q/sp}$.

Since p and q are constants for any pair of zones, the percentage error varies inversely with the square root of the number of trips between zone i and zone j obtained by interview. For 254 zones p will have an average value of 1/254 and q, 253/254. Thus,

$$\frac{\sigma}{\bar{x}}=\sqrt{\frac{\frac{253}{254}}{\frac{s}{254}}}=\sqrt{\frac{253}{s}}$$

Again the average zone had 6,900 trip-ends in 1948, of which about 345 were obtained by interview, so on the average $s=345$. Thus, $\sigma/\bar{x}=\sqrt{253/345}=0.86$. For an average movement in 1948, a standard deviation error of 86 percent could be expected.

Since the test of forecasting procedures uses the reported 1948 trips as the base data for calculating the 1955 trips and then compares the result with the reported 1955 trips, it would be expected that the error would be increasingly large for the smaller trip volumes, not because of errors in the forecasting procedure but due to sample variability.

The RMS error in the various 1948 volume classes for passenger vehicles in the seventh approximation by the Fratar method behaves in this manner as is shown in table 7 for each of the zone groups.

Recommended Procedures

The primary purpose of forecasting zone-to-zone volumes is for the selection and assignment of trips to a transportation network. To do this with reasonable accuracy, particularly at each ramp on an expressway network, it is imperative that the zones be of a size consistent with the distance between ramps. Thus, while increasing the size of the zone increases the accuracy of predictions of the zone-to-zone movements, this procedure adversely affects the primary purpose of forecasting. Pending further studies as outlined at the end of this article, it is recommended that zones be established in accordance with present practice and that the zone-to-zone movements be forecast by the Fratar method.

A flow chart for accomplishing this forcast on an electronic computer is shown in figure 7. This diagram is made up for an input of zone-to-zone volumes as file A and a combination input of present trip-ends, future trip-ends, and growth factors by zones as alternate inputs for file B. The program includes appropriate editing routines for checking the present trip-ends and the growth factors, if these are available independently from the zone-to-zone volumes in file A. The switches shown on the flow chart are programed transfer points resulting from decisions made at a remote point in the program. They are not switches on the console of the computer.

A program written from this flow chart includes the computation of the frequency of the new F factors, to be used as a guide for determining the need for continuing additional iterations.

Future Research

The work to date indicates that the three iterative methods are equally accurate in computing future trips, but the Fratar method arrives at the minimum error in fewer approximations. It is also more efficient in its rate of closure.

In addition it has been found that the preponderant small volume movements are individually affected by an inherent sample variability. The summation of these movements accounts for a substantial portion of the total trips. It is also known that the small-volume zone-to-zone movements are, on the average, the longer trips within the city that account for proportionately more vehicle-miles of travel and are also the trips most likely assignable to high-type highway facilities.

Accumulating trips across a grid

However, it is not necessary that the individual zone-to-zone movements be accurate if a summation of these volumes crossing the city is reasonably representative of the actual travel. To determine this relation it is proposed that each zone-to-zone movement be traced from the X and Y coordinates of one zone to the X and Y coordinates of the other. Each time this trace intersects a predetermined section of a grid line, the number of 1955 trips for this zone-to-zone movement as projected from the 1948 data and the number as determined from the 1955 survey are "remembered." When all zone-to-zone movements have been similarly traced, the number of remembered trips over an appropriate interval of each grid line is totaled. The comparison of the total number of trips projected from the 1948 data with the total number determined from the 1955 survey will give a measure of the accuracy of the projection.

The use of the trace principle automatically weights the longer trips properly in that longer trips will cross many grid lines, whereas the short trips may cross none or only a few. Further, by choosing an appropriate length along each grid line, the summation of trips to various volumes can be accomplished.

While the trace method appears to be a difficult manual task, it is comparatively simple to program for an electronic computer and would require about the same computer time as a single iteration of the Fratar method if the number of grid lines is held to a reasonable minimum.

Stabilizing the small-volume movements

Another research project which should be undertaken is the testing of methods for stabilizing the small-volume zone-to-zone movements. One of the more difficult problems in forecasting traffic is that of predicting the future number of trips for the zone-to-zone movements that are zero at the present time, since all methods tested require the multiplication of existing trips by various factors. The magnitude of this problem can be most easily visualized by remembering that about 67 percent of all possible 1948 zone-to-zone movements in the Washington survey were zero and these same zone-to-zone movements accounted for 22 percent of all 1955 trips.

In addition to the zero volumes, other low volumes are also inherently inaccurate. For an understanding of this problem it is necessary to again resort to statistical formulas. The proportional error that may be expected in random sampling of all trips from one zone to another is given by the previously defined expression $\sigma/\bar{x}=\sqrt{q/sp}$.

For example, suppose that zone i has a total of 6,000 trip-ends. Of these 6,000 assume that 666 have their other ends distributed as follows: 600 in zone j, 60 in zone k, and 6 in zone l. With a 1 in 20 sample the 6,000 trip-ends in zone i will represent 300 trip-ends obtained by interview; therefore s equals 300. Considering all of the trip-ends in zone i, the probability of any trip-end having the other

Table 8.—Theoretical error in random sampling of small trip volumes

Zone-to-zone movements	Number of trips between zones	Number of trip-ends determined by interview s	Probability of trips from zone i ending in— Specified zone p	Other than specified zones q	Proportional error	Percentage error
i to j	600	300	0.1	0.9	0.17	17
i to k	60	300	.01	.99	.57	57
i to l	6	300	.001	.999	1.83	183

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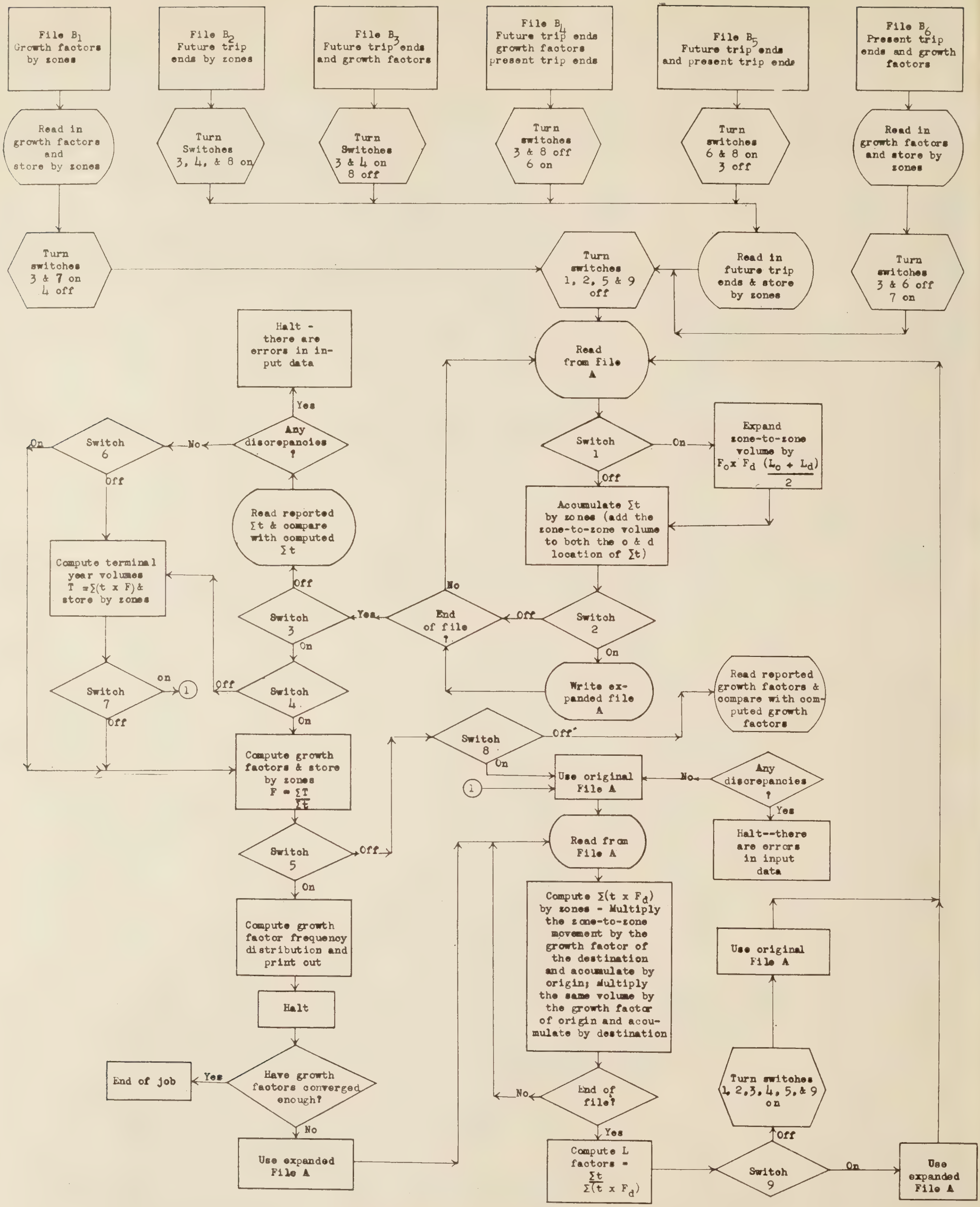

Figure 7.—Electronic computer flow chart for forecasting zone-to-zone trips by the Fratar method.

Table 9.—Theoretical distribution and probable accuracy of reported trips between zones

Reported number of trips	Probability of reported number of trips from—	
	Zone i to zone k	Zone i to zone l
0	0.05	0.74
20	.15	.22
40	.22	.03
60	.23	.01
80	.17	--------
100	.10	--------
120	.05	--------
140	.02	--------
160	.01	--------

end in zone j is 600 out of 6,000 or 0.1. Therefore $p=0.1$ and $q=1-p=0.9$. Thus for the trips from zone i to zone j, the proportional error $=\sqrt{q/sp}=\sqrt{0.9/300\times 0.1}=0.17$. Thus with a one-twentieth sample, a standard deviation accuracy of 17 percent for the trips between zone i and zone j could be expected. Similar values for zones k and l are shown in table 8.

If the sample rate is 1 in 20, it is manifestly impossible that the 6 trips between zone i and zone l will ever be reported as 6 trips. However, from the expansion of the binomial $(p+q)^s$, the frequency distr bution of the reported trips between zone i and zone k and between zone i and zone l is estimated as shown in table 9.

Thus the 6 trips between zone i and zone l are never correctly reported; 74 percent of the time they are reported as zero; and the remaining 26 percent of the time they are reported as 20 or more trips. Similarly the 60 trips between zone i and zone k are reported as 60 only 23 percent of the time, while the remaining 77 percent of the time the reported trips are in error by more than 33 percent.

Adjacent to zone i there will be other zones i_2 and i_3. To illustrate, it can be assumed that zone i_2 has 8,000 trip-ends and zone i_3 has 6,000 trip-ends; therefore since zone i has 6,000 trip-ends, in zones i, i_2, and i_3 there would be a total of 20,000 trip-ends which would represent 1,000 interviews.

Now since zones i_2 and i_3 are adjacent to zone i, it is probably true that their movements to zone l are similar in volume to the movements from zone i to l. This assumption is justified by the high correlation of distance and trip volume as established by Dr. Carroll and others. If this be true, it can be assumed that 1/1,000 of all trip-ends in zone i_2 and i_3 are to or from zone l as was the case with zone i; the 20 trips between zone l and the three i zones are divided 30 percent to zone i, 40 percent to zone i_2, and 30 percent to zone i_3. If the expansion process $(p+q)^s$ is again used to obtain the probability of the zone-to-zone movements, the results are as shown in table 10.

From a comparison of tables 9 and 10, it appears that grouping of zones will improve the accuracy of the low-volume movements. This process can be continued for other groupings. However, instead of using this rather time-consuming computation we can obtain the proportional error by the simpler equation, $\sigma/\bar{x}=\sqrt{q/sp}$, which does not indicate the frequency of the various movements but does, in one operation, compute the resulting error.

The trips between zones i, i_2, and i_3 combined and zone l will have a proportional error of $\sigma/\bar{x}=\sqrt{0.999/1{,}000\times 0.001}=\sqrt{0.999}=1.00$ or 100 percent. Thus by grouping three zone-to-zone movements the standard-deviation error has been reduced from 186 to 100 percent, assuming that the distribution of trips between zone l and zones i, i_2, and i_3 is proportional to the distribution of trip-ends in the three i zones. It is true, of course, that this assumption will not be exactly correct, but it seems likely that the error of this assumption will be less than the error added by the individual zone sample variability.

The problem of how large a grouping is desirable can be approximated from the equation $\sigma/\bar{x}=\sqrt{q/sp}$. Note that the limiting value of q is 1.00. It can never be as large as 1.00, and in almost all applications it is not smaller than 0.9. At the same time sp is equal to the number of trips, obtained by interview, between a pair of zones with perfect sampling. The value of sp can range from zero up to the value of s. The relation between the error of a zone-to-zone movement and the number of trips, determined by interview, making this zone-to-zone movement can be approximated as follows:

Number of trips	*Percentage error*
0	∞
1	100
2	71
5	45
10	32
15	26
20	22
30	18

Considering the undesirability of combining too many zones, from this tabulation it appears that zone-to-zone movements might well be grouped until the accumulated movement represents about 10 interviews.

A method to accomplish this purpose has been worked out but not tested, except by hand computation from a small sample. The sample computation indicated that the error is reduced by approximately one-third. The method requires the use of the binary system in coding a group of zones. For illustrative purposes a group of 4 zones can be considered, although in actual practice probably 16 would be required.

To illustrate, suppose that in region A the area is divided with 2 zones in each half. One-half of the zones would be designated *A0* and the other half *A1*. These pairs of zones would again be divided in half or into single zones designated *A00*, *A01*, *A10*, and *A11*. A separate region B would be similarly separated into *B00*, *B01*, *B10*, and *B11*.

Table 10.—Theoretical improvement in the accuracy of low-volume trip movements by zone grouping

Reported number of trips to zone l from—				Probability
Zone i	Zone i_2	Zone i_3	Total	
0	0	0	0	0.37
6	8	6	20	.37
12	16	12	40	.18
18	24	18	60	.06
24	32	24	80	.02

Now if only trip volumes that represent 10 interviews (or 200 trips with a 1/20 sample) are considered sufficiently stable so as not to warrant readjustment, a method of combining zones that is amenable to computer operation is required. A suitable method is as follows:

The number of trips from *A00* to *B00* is examined. If it is less than 200 (10 interviewed trips), combine zones *B00* and *B01* and find the number of trips between *A00* and *B00*+*B01*. If it is still less than 200, combine zones *A00* and *A01* and find the number of trips between *A00*+*A01* and *B00*+*B01*. If the number of trips is still less than 200, again double the B area to include 4 zones, and if necessary, double the A area to include 4 zones, and so on until the figure 200 is reached.

The advantage of the binary coding is that it provides the desired grouping through a simple arithmetic operation. The arithmetic operation simply combines the binary portion of the region code by alternate digits. For example, if *A00* is written as AA_1A_2, and *B00* is written as BB_1B_2 the combination is written $A_1B_1A_2B_2$. Starting with 0000, the digit 1 is added successively until the sum 1111 is obtained. The subtotals are then decoded by the $A_1B_1A_2B_2$ pattern and the zone-to-zone movements are then in the proper order for combining.

From the original zone-to-zone volumes and the combination totals, the preselected volume can be determined. The combination volume is then reassigned to individual zone-to-zone movements. Suppose that in the previous example all 4 of the A zones were combined and all 4 of the B zones were combined to provide a preselected volume. The total trip-ends in the individual zones in the A group are added and the proportion of the total in each A zone is determined (P_{A1}, P_{A2}, etc.). Similarly each zone of the B group is a certain proportion of the B total trip-ends (P_{B1}, P_{B2}, etc.). Then the total volume V between the groups is reassigned to individual zone-to-zone volumes, V_{A1-B1}, by the equation $V_{A1-B1}=V\times P_{A1}\times P_{B1}$, $V_{A1-B2}=V\times P_{A1}\times P_{B2}$, etc.

From sample tests made to date, this reassignment procedure appears to improve the accuracy of predicting the future zone-to-zone trip movements. Whether it improves the accuracy of predicting accumulated volumes such as would occur on road sections or ramps should be tested by the process of accumulating the trips across a grid, as previously described.

Factors Affecting Trip Generation of Residential Land-Use Areas

BY THE DIVISION OF HIGHWAY PLANNING
BUREAU OF PUBLIC ROADS

Reported [1] by GORDON B. SHARPE, Head, Urban Highway Section,
WALTER G. HANSEN, Highway Research Engineer, and
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The present and potential trip-generating power of urban residential areas can be estimated with a reasonable degree of accuracy, dependent upon the availability and reliability of certain related information. The major factors affecting trips by residents of an area are population and automobile ownership. With data normally developed from a home-interview-type origin and destination survey it is possible either to up-date residents trip information or, with slightly less reliability, to forecast the trips for some future date.

It was found that the total number of trip-ends in a residential area is approximately equal to the number of trips made by residents of that area between all origins and destinations. Therefore, any method for estimating residents trips is equally applicable to estimates of total trip-ends on residential land. As a corollary, the number of trip-ends to nonresidential land in an urban area can be estimated if the number of trips made by residents of the entire urban area are known.

Generally, about 80 percent of all trips made by residents of a residential area begin or end at home. Also approximately 80 percent of the total trip-ends on residential land, by residents and nonresidents, are home-oriented. These proportions are greater in areas where automobile ownership and economic status are low, and where population density is high. They do not vary appreciably with distance from the central business district.

These findings are based upon analyses of data from the two home-interview-type origin and destination traffic surveys made in the Washington, D. C., metropolitan area in 1948 and 1955. All results pertain to the Washington, D. C., area during the time interval studied, but it may reasonably be assumed that certain aspects of the findings and methodology will be applicable elsewhere.

SINCE 1944, comprehensive home-interview origin and destination studies have been made in well over 100 metropolitan areas. The existing pattern of travel by different means of transportation in these areas has been developed with considerable accuracy. This information has been invaluable in determining the present need for highways and transit facilities but, in itself, does not give the answer to future needs, which must be the basis for intelligent planning.

One of the basic keys to forecasting transportation needs is the establishment of the relations between travel and the type, intensity, and interrelation of land uses. When these relations have been established and trends observed, it will be possible to determine more accurately the transportation needs that will exist when anticipated urban development has taken place.

Data from a number of surveys have been analyzed to develop factors for estimating the number of trips attracted to and generated by land-use developments of different kinds, size, and intensity. These relate to specific places and times. Information on trends is comparatively meager, repeat studies having been completed in only a very few metropolitan areas. It has not, therefore, been possible to establish relations which will permit the accurate predetermination of the number of trip-ends to be expected in different areas under conditions anticipated for some time in the future, these being dependent upon the stability of a number of factors.

In the Washington, D. C., area, a home-interview type of origin and destination survey was made in 1948. A repeat study was made in 1955. In the earlier survey a 5-percent sample was obtained by interviewing the residents of 1 of every 20 dwelling units. In the latter survey, the sample rate was 1 in 30 in the District of Columbia and 1 in 10 in the Maryland and Virginia suburban areas. These two surveys provide a basis for studying factors and trends relating to urban travel habits, and several research projects have been carried out with this objective.

Scope of Study

This article is concerned with the evaluation of methods for estimating the potential generation and production of trips in urban residential developments. Another article entitled "Evaluating Trip Forecasting Methods with an Electronic Computer", which appears on pages 77–87 of this issue, is concerned with the evaluation of methods of estimating the distribution of zone-to-zone trip movements resulting from zone growth.

There are many factors, other than size, that could be expected to affect the potential generation and production of trips in urban residential developments. This article presents the results of an analysis of the effect that differences in population, automobile ownership, income per household, distance from the central business district, and population per net residential acre had on the number of trips attracted to and generated by residential land. These factors were selected because it has been possible to establish measures that are free from personal bias, and it seems that they constitute a logical premise on which to begin an analysis of total trips generated by residential land-use areas.

Because the summarization of the 1955 data has not progressed far enough to permit a study by mode of travel, the current analysis is confined to total trips to and from residential land by all modes of travel, except trips by taxi and truck operators in the course of their daily work and pedestrian trips.

Sources of Information

The trip data obtained from the Washington transportation surveys of 1948 and 1955, upon which this study is based, reflect total trips by persons for an average weekday of the respective survey periods. Data on population, automobile ownership, and distance from the central business district were also obtained from these surveys.

The 1955 family income information was obtained from the National Capital Regional Planning Council. Residential acreage figures were developed jointly by the staffs of the Washington Metropolitan Area Transportation Study, which made the 1955 survey, and the National Capital Regional Planning Council. The data developed were net residential acres; streets and all nonresidential land uses were excluded.

This article combines the results of a number of studies based upon travel data obtained from the two Washington transportation surveys. The basic data were summarized by groupings best suited for the objectives under

[1] This article was presented at the 37th Annual Meeting of the Highway Research Board, Washington, D. C., January 1958.

Table 1.—Characteristics of 10 selected residential areas included in the 1948 Washington, D. C., metropolitan area survey

Area number	Name of area	Predominant residence type	Economic class [1]	Central business district to residence: Travel distance	Central business district to residence: Average peak-hour driving time, 1950	Number of dwelling units	Number of passenger cars owned	Population	Persons per dwelling unit	Passenger cars per dwelling unit	Automobile driver trips per passenger car
				Miles	*Minutes*						
1	Massachusetts Avenue Park, D. C.	Single family detached	Very high	3.29	12	158	180	518	3.28	1.14	2.55
2	Wesley Heights and Spring Valley, D. C.	do	Very high and upper high.	5.29	16	712	1,201	2,896	4.07	1.69	3.83
3	American University Park, D. C.	Single family detached [2]	High	5.71	18	2,375	2,039	7,975	3.36	.86	4.20
4	Beverly Hills, Braddock Heights, and Del Ray, Va.	do [2]	Above average	7.43	17	1,426	1,447	5,176	3.63	1.01	4.84
5	Fairlington and Parkfairfax, Va.	Garden-type apartments	do	6.86	15	4,826	3,833	15,658	3.24	.79	4.63
6	Brightwood area, D. C.	2-family semidetached and apartments.	do	5.29	18	2,497	2,209	9,354	3.75	.88	3.77
7	U. S. Soldiers Home area, D. C.	Multifamily apartments and row houses.	Below average	2.71	12	2,101	1,404	6,913	3.29	.67	2.67
8	Shirley Homes, Va.	Government low-rent row houses.[2]	do	5.71	13	1,352	686	4,805	3.55	.51	4.21
9	Central city area, D. C.	Row houses	do	1.14	6	3,270	582	10,977	3.36	.18	1.95
10	Southwest area, D. C.	Single family detached and row houses.	Low and very low	1.14	7	6,596	1,975	28,657	4.34	.30	1.98
Total or average, 10 areas						25,313	15,556	92,929	3.67	.61	3.75
Total or average, metropolitan area						336,181	203,464	1,109,860	3.30	.61	3.10

[1] Source: *District of Columbia residential areas*, Economic Development Department, Board of Trade, Washington, D. C.; *Virginia residential areas*, estimated on the basis of comparable rentals, housing values, and income reported in the 1950 Censuses of Population and Housing. Economic classes are based on 1949 estimated income as follows: very high, $10,200 and over; upper high, $8,500–$10,199; high, $6,800–$8,499; above average, $5,100–$6,799; below average, $3,825–$5,099; low, $2,550–$3,824; and very low, under $2,550.
[2] Includes small number of apartment units.

Table 2.—Residents average weekday trips, by purpose and mode of travel, recorded in the 1948 Washington, D. C., metropolitan area survey

Area number	Resident trips per dwelling unit by purpose											Resident trips per dwelling unit by mode of travel			
	Work	Business	Medical and dental	School	Social and recreational	Change travel mode	Eating	Shopping	Serving passengers	Home	All purposes	Automobile driver	Automobile and taxi passengers	All automobile trips	Mass-transit passengers
1	1.02	0.87	----	0.15	0.58	0.58	0.15	0.58	0.30	2.17	6.40	2.90	1.75	4.65	1.75
2	2.42	.51	0.07	.36	1.98	.20	.48	.82	.58	4.60	12.02	6.45	3.36	9.81	2.21
3	1.32	.55	.06	.25	1.48	.08	.13	.75	.48	3.23	8.33	3.60	2.89	6.49	1.84
4	1.49	.33	.03	.34	.99	.11	.13	.93	.96	3.31	8.62	4.91	2.25	7.16	1.46
5	1.36	.12	.10	.33	1.00	.09	.15	.90	.52	2.97	7.54	3.68	2.22	5.90	1.64
6	1.95	.30	.06	.24	.91	.15	.18	.80	.29	2.75	7.63	3.34	1.57	4.91	2.72
7	1.62	.14	.09	.12	.53	.01	.10	.28	.11	2.45	5.45	1.78	1.11	2.89	2.56
8	1.06	.08	.03	.09	.74	.06	.11	.63	.31	2.12	5.23	2.14	1.52	3.66	1.57
9	1.23	.16	.04	.03	.17	.01	.01	.08	.01	1.54	3.28	.35	.47	.82	2.46
10	1.21	.14	.03	.08	.22	.003	.02	.11	.02	1.59	3.43	.59	.40	.99	2.44
Average, 10 areas	1.40	.22	.06	.17	.70	.06	.10	.50	.28	2.40	5.89	2.31	1.42	3.73	2.16
Average, metropolitan area	1.32	20	.05	.12	.62	.07	.09	.33	.19	2.13	5.12	1.88	1.22	3.10	2.02

consideration. For example, one very limited study utilized data for only 10 residential areas. A subsequent study was confined to the District of Columbia for which data on family income and population density were available by census tracts. Another study was based, in part, on the analysis of 118 subzones throughout the survey area that could be classed as purely residential; and, in part, on 77 of the 118 subzones grouped into 48 residential areas, each of which had 1,000 or more trip origins. Then again, tests were made using 56 of the 118 subzones grouped into 35 residential areas, each of which had 2,000 or more trip origins. Finally, an analysis was made of trips by residents of 200 zones selected so that data from the surveys would be comparable. These zones contained 96 percent of the population residing within the 1948 traffic study cordon and 93 percent of the population living within the 1955 cordon.

Table 3.—Basic data for 118 selected residential subzones in the 1955 Washington, D. C., survey area, grouped according to distance from the central business district

Rings [1]	Number of—							
	Subzones	Interviews	Residents	Dwelling units	Automobiles	Net residential acres	Residents trips [2]	Automobiles per 100 residents
2	2	46	4,689	1,820	1,182	9.5	7,574	25.2
3	3	42	4,603	1,602	881	141.8	6,853	19.1
4	16	282	17,987	6,412	5,251	487.4	32,988	29.2
5	30	379	27,014	8,817	9,305	956.3	56,973	34.4
6	25	348	18,584	5,742	6,480	782.5	39,636	34.9
7	16	454	17,735	5,190	6,242	1,041.2	39,481	35.2
8	12	279	10,727	3,007	3,657	536.8	23,386	34.1
9	12	229	9,407	2,527	3,278	1,259.2	20,793	34.8
10	2	68	3,086	798	962	215.9	6,185	31.2
Total	118	2,127	113,832	35,915	37,238	5,430.6	233,869	32.7

[1] Distance (miles) of residence from the central business district. None of the selected subzones were in rings 1, 11, 12, or 13. [2] On an average weekday in 1955.

Conclusions

The results of the analysis indicate a means of estimating residents trips and trip-ends on residential land with a reasonable degree of accuracy. It would appear desirable to ascertain and develop additional factors by which the accuracy of the technique could be greatly improved in each specific zone. It would also be desirable to continue these studies, where possible, over a longer period of time to determine whether factors such as trips per person remain constant beyond a 7-year interval. In addition, similar studies are needed in other urban areas of different sizes and with different travel characteristics; for instance, in an area where mass-transit facilities are much less prevalent or negligible.

The use of population data as estimating

(Continued on page 92)

STATE LEGAL MAXIMUM LIMITS OF MOTOR VEHI

Prepared by the

Line	State	Width inches[1]	Height ft.-in.	Length—feet[2]: Single unit: Truck	Length—feet[2]: Single unit: Bus	Length—feet[2]: Truck tractor semi-trailer	Length—feet[2]: Other combination	Number of towed units[3]: Semi-trailer	Number of towed units[3]: Full trailer	Number of towed units[3]: Semi-trailer and full trailer	Axle load—pounds: Single: Statutory limit	Axle load—pounds: Single: Including statutory enforcement tolerance	Axle load—pounds: Tandem: Statutory limit	Axle load—pounds: Tandem: Including statutory enforcement tolerance
1	Alabama	96	[6]12-6	35	40	50	NP	1	NP	NP	18,000	19,800	36,000	39,600
2	Arizona	96	13-6	40	40	65	65	1	1	2	18,000		32,000	
3	Arkansas	96	13-6	35	40	50	50	1	1	NP	18,000	[7]18,500	32,000	32,500
4	California	96	13-6	35	[9]35	[10]60	60	NR	NR	NR	18,000		32,000	
5	Colorado	[11]96	[12]13-6	35	40	60	60	1	2	2	18,000		36,000	
6	Connecticut	102	12-6	45	45	45	NP	1	NP	NP	22,400	22,848	36,000	36,720
7	Delaware	96	[6]12-6	35	42	50	60	1	1	2	20,000		36,000	
8	District of Columbia	96	12-6	35	35	50	80	1	1	NP	22,000		38,000	
9	Florida	96	[6]12-6	[14]35	40	50	50	1	1	NP	20,000	22,000	40,000	44,000
10	Georgia	96	13-6	[15]+39	[15]+45	48	48	1	1	NP	18,000	20,340	36,000	40,680
11	Hawaii	108	13-0	40	40	55	65	1	1	2	24,000		32,000	
12	Idaho	[1C]96	14-0	35	[19]40	60	65	1	1	2	[20]18,000		[20]32,000	
13	Illinois	96	13-6	42	42	50	50	1	1	2	18,000		32,000	
14	Indiana	96	13-6	36	40	50	50	1	1	2	[23]18,000	[23]19,000	[23]32,000	[23]33,000
15	Iowa	96	[6]12-6	35	[19]40	50	NP	1	NP	NP	18,000	18,540	32,000	32,960
16	Kansas	96	12-6	35	[19]40	50	50	1	1	NP	18,000		32,000	
17	Kentucky	96	[25]13-6	[26]35	[26]35	[27]50	NP	1	NP	NP	18,000	[28]18,900	32,000	[28]33,600
18	Louisiana	96	[6]12-6	35	[19]40	50	60	1	1	NP	18,000		32,000	
19	Maine	96	[30]12-6	50	50	50	50	1	1	NP	22,000		32,000	
20	Maryland	96	[6]12-6	55	55	55	55	NR	NR	NR	22,400		[31]40,000	
21	Massachusetts	96	NR	35	[19]40	45	NP	1	NP	NP	22,400		36,000	
22	Michigan	96	13-6	35	40	55	55	1	1	2	[33]18,000		[34]32,000	
23	Minnesota	96	[6]12-6	40	40	50	50	1	1	NP	18,000		32,000	
24	Mississippi	96	[6]12-6	35	40	[36]50	50	1	1	NP	18,000		28,650	[35]32,000
25	Missouri	96	12-6	35	40	50	50	1	1	2	18,000		32,000	
26	Montana	[18]96	13-6	35	40	60	60	1	1	[37]2	18,000		32,000	
27	Nebraska	96	13-6	35	[19]40	50	50	1	1	NP	18,000	18,900	32,000	33,600
28	Nevada	96	NR	NR	NR	NR	NR	NR	NR	NR	18,000	18,900	32,000	33,600
29	New Hampshire	96	13-6	35	[35]40	45	45	NR	NR	NR	22,400		36,000	
30	New Jersey	96	13-6	35	[39]35	45	[40]50	1	1	NP	22,400	23,520	32,000	33,600
31	New Mexico	[41]96	13-6	40	40	65	65	1	1	2	21,600		34,320	
32	New York	96	13-0	35	[42]35	50	50	1	1	NP	22,400		36,000	
33	North Carolina	96	[6]12-6	35	[19]40	[43]50	[43]50	1	1	NP	18,000	19,000	36,000	38,000
34	North Dakota	96	13-6	[14]35	[19]40	50	50	1	1	NP	18,000		30,000	
35	Ohio	96	3-6	35	[19]40	50	60	1	NR	NR	19,000	20,000	[44]31,500	32,500
36	Oklahoma	96	13-6	35	45	50	50	1	1	NP	18,000		32,000	
37	Oregon	96	[45]12-6	35	[35]40	[46,35]55	[35]60	1	1	[35]2	[47]18,000		[47]32,000	
38	Pennsylvania	96	[6]12-6	35	[19]40	50	[40]50	1	1	NP	22,400	23,072	36,000	37,080
39	Puerto Rico	96	12-6	NS	NS	NS		NS	NS	NS	NS		NS	
40	Rhode Island	102	12-6	40	40	50	50	1	1	NP	22,400		NS	
41	South Carolina	96	[54]12-6	[14]35	[19]40	50	60	1	1	NP	20,000		32,000	
42	South Dakota	96	13-0	35	40	50	60	1	1	NP	18,000		32,000	
43	Tennessee	96	12-6	35	40	45	45	1	[24]1	NP	18,000		32,000	
44	Texas	96	13-6	35	40	50	50	1	1	NP	18,000	18,900	32,000	33,600
45	Utah	96	14-0	45	45	60	60	NR	NR	NR	18,000		33,000	
46	Vermont	96	12-6	50	50	50	50	1	1	NP	NS		NS	
47	Virginia	96	[6]12-6	35	[35]40	50	50	1	1	NP	18,000		[56]32,000	
48	Washington	96	[5]12-6	35	[19]40	60	60	1	1	[57]2	18,000	[58]18,500	32,000	[58]33,000
49	West Virginia	96	[6]12-6	35	[19]40	50	50	1	1	NP	18,000	18,900	32,000	33,600
50	Wisconsin	96	[6]12-6	35	40	50	50	1	1	NP	18,000	[60]19,500	30,000	32,000
51	Wyoming	96	13-6	40	40	60	60	1	1	2	18,000		32,000	[62]36,000
	AASHO Policy	96	12-6	35	[19]40	50	60	1	1	NP	18,000		32,000	
Number of States	Higher	3	26	16	29	15	7	6	8	21	31		29	
	Same	48	25	35	18	30	12	45	38	30	20		16	
	Lower	0	0	0	4	6	32	0	5	0	0		5	

NP—Not permitted. NR—Not restricted. NS—Not specified.

[1] Various exceptions for farm and construction equipment; public utility vehicles; house trailers; urban, suburban, and school buses; haulage of agricultural and forest products; at wheels of vehicles; for safety accessories, on designated highways, and as administratively authorized.

[2] Various exceptions for utility vehicles and loads, house trailers and mobile homes.

[3] When not specified, limited to number possible in practical combinations within permitted length limits; various exceptions for farm tractors, mobile homes, etc.

[4] Legally specified or established by administrative regulation.

[5] Computed under the following conditions to permit comparison on a uniform basis between States with different types of regulation:

A. Front axle load of 8,000 pounds.

B. Maximum practical wheelbase within applicable length limits:

(1) Minimum front overhang of 3 feet.

(2) In the case of a 4-axle truck-tractor semitrailer, rear overhang computed as necessary to distribute the maximum possible uniform load on the maximum permitted length of semitrailer to the single drive-axle of the tractor and to the tandem axles of the semitrailer, within the permitted load limits of each.

(3) In the case of a combination having 5 or more axles, minimum possible combined front and rear overhang assumed to be 5 feet, with maximum practical load on maximum permitted length of semitrailer, subject to control of loading on axle groups and on total wheelbase as applicable.

C. Including statutory enforcement tolerances as applicable.

[6] Auto transports 13 feet 6 inches.

[7] Does not apply to combinations of adjacent load-carrying single axles.

[8] 56,000 pounds on load-carrying axles, exclusive of steering-axle load.

[9] On specific routes in urban or suburban service under special permit from P.U.C. 40 feet, also 3-axle buses with turning radius less than 45 feet without restriction.

[10] Limited by 40-foot maximum length of semitrailer to 55-foot practical maximum length in combination.

[11] Buses 102 inches.

[12] On designated highways; 12 feet 6 inches on other highways.

[13] Legal limit 60,000 pounds.

[14] Three-axle vehicles 40 feet.

[15] Truck 39.55 feet; bus 45.20 feet.

[16] 63,280 pounds maximum, except on roads

[17] 700 (L+40) when L is 18' or less; 800 structures with span of 20' or over.

[18] Buses 102 inches on highways of surface

[19] Less than three axles 35 feet.

[20] Special limits for vehicles hauling tim cultural products including livestock: sing vehicle with 3 or 4 axles permitted 66,000 permitted 79,000 pounds maximum at 43-foot

[21] On designated highways: 16,000 pounds

[22] Without tandem axles 45,000 pounds.

[23] On designated highways: single axle 22, total of all excesses of weight under one

[24] Limited to 3,500 pounds.

[25] Class AA highways: 12 feet 6 inches on

[26] On designated highways: trucks 26.5 fee

[27] Class AA highways; 45 feet on other hi

[28] Class AA highways only.

[29] Maximum gross weight on Class A highwa

[30] Including load 14 feet.

[31] Spaced less than 48 inches 36,000 pound

[32] Subject to axle and tabular limits.

[33] Single axle spaced less than 9 feet fr

[34] On designated highways only and limite

[35] On designated highways only.

[36] Auto transports permitted 50 feet.

[37] Semitrailer and semitrailer converted

[38] Dual-drive axles: otherwise 40,000 pour

WEIGHTS COMPARED WITH AASHO STANDARDS

ds, July 1, 1958

eight limit			Specified maximum gross weight—pounds[4]						Practical maximum gross weight—pounds[5]						
	Applicable to:		Truck		Truck-tractor semitrailer				Truck		Truck-tractor semitrailer				
Formula or quation	Any group of axles	Total wheel base only	2-axle	3-axle	3-axle	4-axle	5-axle	Other combination	2-axle	3-axle	3-axle	4-axle	5-axle	Other combination	Line
		X							27,800	47,600	47,600	60,010	64,650	NP	1
	Under 18'	Over 18'							26,000	40,000	44,000	58,000	72,000	76,800	2
									26,500	40,500	45,000	59,000	65,000	65,000	3
	Under 18'	Over 18'							26,000	40,000	44,000	58,000	72,000	76,000	4
800 (L+40)		X	30,000	46,000					26,000	44,000	44,000	62,000	75,000	76,000	5
			32,000	50,000	50,000	60,000	60,000	NP	30,848	44,720	51,000	61,200	61,200	NP	6
	X		30,000	46,000	48,000	60,000	60,000	60,000	28,000	48,000	48,000	56,350	60,000	60,000	7
	X								30,000	46,000	52,000	58,450	61,490	64,650	8
		X							30,000	52,000	52,000	65,200	71,115	71,115	9
								63,280	28,340	48,680	48,680	63,280	63,280	63,280	10
& 800 (L+40)	Under 18'	Over 18'							32,000	38,800	56,000	62,800	69,600	78,000	11
	X								26,000	40,000	44,000	58,000	72,000	76,800	12
			36,000	[22]41,000	45,000	59,000	68,000	72,000	26,000	40,000	44,000	58,000	68,000	72,000	13
								72,000	27,000	41,000	45,000	59,000	73,000	73,000	14
	X								26,540	40,960	45,080	59,500	70,716	NP	15
	X								26,000	40,000	44,000	55,470	63,890	63,890	16
			36,000	50,000	54,000	59,640	59,640	NP	26,900	41,600	45,800	59,640	59,640	NP	17
									26,000	40,000	44,000	58,000	72,000	76,000	18
	X		32,000	50,000	50,000	60,000	60,000	60,000	30,000	40,000	52,000	60,000	60,000	60,000	19
850 (L+40)		X					65,000	65,000	30,400	48,000	52,800	65,000	65,000	65,000	20
1,000 (L+25)		X	[32]46,000	[32]60,000	[32]60,000	[32]60,000	[32]60,000	NP	30,400	44,000	52,800	60,000	60,000	NP	21
									26,000	[35]40,000	44,000	[35]58,000	[35]66,000	[35]102,000	22
	X								26,000	40,000	44,000	58,000	68,000	72,500	23
	X								26,000	36,650	44,000	54,650	[35]58,000	[35]58,000	24
	X								26,000	40,000	44,000	55,470	64,650	64,650	25
	Under 18'	Over 18'							26,000	40,000	44,000	58,000	72,000	76,000	26
	Under 22'	Over 22'							26,780	41,200	45,320	57,134	66,590	66,590	27
	Under 18'	Over 18'							26,900	41,600	45,800	60,000	74,000	76,800	28
		X	33,400	[38]47,500	52,800	66,400			30,400	44,000	52,800	66,400	66,400	66,400	29
			30,000	40,000	60,000	60,000	60,000	60,000	31,500	41,600	55,040	63,000	63,000	63,000	30
	Under 18'	Over 18'							29,600	42,320	51,200	63,920	76,640	86,400	31
34,000+850L		X					65,000	65,000	30,400	44,000	52,800	65,000	65,000	65,000	32
			31,500	46,200	46,200	58,800	58,800	58,800	27,000	46,000	46,000	58,800	58,800	58,800	33
& 750 (L+40)	Under 18'	Over 18'							26,000	38,000	44,000	56,000	63,750	63,750	34
800 (L+47.5)		X							28,000	40,500	48,000	60,500	73,000	78,000	35
	X								26,000	40,000	44,000	58,000	66,000	66,000	36
	Under 18'	Over 18'					74,000	76,000	26,000	40,000	44,000	58,000	72,000	76,000	37
			33,000	47,000	50,000	60,000	60,000	62,000	31,072	45,080	51,500	61,800	61,800	63,860	38
															39
			[50]36,000	[51]44,000	[52]50,000	[53]60,000	60,000	88,000	30,400	44,000	50,000	60,000	60,000	88,000	40
	X								28,000	40,000	48,000	60,000	66,839	71,115	41
	X								26,000	40,000	44,000	58,000	72,000	73,280	42
		X							26,000	40,000	44,000	55,980	55,980	43,500	43
	X								26,900	41,600	45,800	57,844	61,340	61,340	44
	X								26,000	41,000	44,000	59,000	74,000	79,900	45
			30,000	40,000	50,000	[55]60,000	[55]60,000	[55]60,000	30,000	40,000	50,000	60,000	60,000	60,000	46
	X						[35]56,800	[35]56,800	26,000	40,000	44,000	56,800	56,800	56,800	47
	Under 18'	Over 18'	28,000	36,000	46,000	60,000	68,000	72,000	26,000	36,000	44,000	60,000	68,000	72,000	48
	X								26,900	41,600	45,800	57,844	63,840	63,840	49
1,000 (L+26)	X								27,500	40,000	47,000	59,500	68,000	68,000	50
	X								26,000	44,000	44,000	62,000	73,000	73,000	51
(L+24)-3L[2]	X								26,000	40,000	44,000	55,470	61,490	71,900	
	18	19							29 21 0	27 19 4	29 21 0	46 3 1	36 2 12	20 0 30	

56,000 pounds maximum.
n 18': 900 (L+40) on highways having no

otherwise as administratively authorized.

es, concentrates, aggregates, and agri-
m axle 37,800 pounds, gross weight table:
le spacing, vehicle with 5 or more axles

000 pounds: tolerance of 1,000 pounds on
load and gross weight.

r highways.

highways 30,000 pounds.

3,000 pounds.
ination: otherwise 26,000 pounds.

a dolly.

39 Or as prescribed by P.U.C.
40 Exception for poles, pilings, structural units, etc., permitted 70 feet.
41 On designated highways 102 inches.
42 Trackless trolleys and buses 7 passengers or more, P.S.C. certificate 40 feet.
43 Including front and rear bumpers.
44 Spaced less than 4 feet 24,000 pounds.
45 Certain types of vehicles and commodities under special permit on designated highways up to 13 feet 6 inches.
46 60 feet allowed truck tractor semitrailer on 4 major Interstate routes.
47 Logging vehicles permitted 3-foot wheelbase tolerance, 19,000-pound single axle, 34,000-pound tandem axle.
48 Governs gross weight permitted on highways designated by resolution of State highway commission.
49 Single unit truck with 4 axles permitted 60,000 pounds.
50 Axles spaced less than 6 feet 32,000 pounds; less than 12 feet 36,000 pounds; 12 feet or more gross weight governed by axle limit.
51 Single vehicle with 3 or more axles spaced less than 16 feet 40,000 pounds; less than 20 feet 44,000 pounds; 20 feet or more governed by axle limit.
52 Tractor semitrailer with 3 or more axles spaced less than 22 feet 46,000 pounds; not less than 27 feet 50,000 pounds.
53 Axles spaced 27 feet or more.
54 Auto transports and vehicles transporting materials for Department of Defense on highways with adequate clearance 13' -6".
55 Tandem axles on trailer equipped with adequate brakes.
56 Vehicles registered before July 1, 1956, permitted limits in effect January 1, 1956, for life of vehicle.
57 Under State highway commission rules.
58 Within discretion of enforcement officer.
59 Vehicles hauling logs permitted wheelbase and gross weight tolerances. Discretionary enforcement tolerances not included in computation of practical maximum gross weights.
60 Axle load 21,000 pounds on 2-axle trucks hauling unmanufactured forest products.
61 On Class A highways.
62 Based on ruling of Attorney General.

Table 4.—Effect of distance from the central business district on the "from" purpose distribution of trips originating on residential land in the Washington, D. C., survey area on an average weekday in 1955 [1]

Rings [2]	Percentage distribution of trips [3] from—							All "from" trips	
	Work	Personal business	Serving passengers	Changing mode of travel	Social and recreational	Medical, dental, and eating	Home	Number	Percent
2	2.2	1.0	2.6	0.7	5.4	-----	88.1	3,672	100.0
3	4.5	4.2	2.1	-----	1.5	-----	87.7	3,610	100.0
4	8.2	2.0	4.4	.5	4.8	0.6	79.5	16,598	100.0
5	4.5	2.0	5.0	.3	7.5	.7	80.0	28,076	100.0
6	5.8	1.3	4.7	1.5	4.6	1.3	80.8	19,684	100.0
7	4.8	2.7	4.7	.7	5.4	.8	80.9	18,854	100.0
8	3.8	2.0	5.3	1.0	4.8	.3	82.8	11,263	100.0
9	5.6	2.4	4.4	.4	5.3	.3	81.6	9,812	100.0
10	2.8	3.9	6.1	-----	.5	.9	85.8	2,550	100.0
Average or total	5.2	2.1	4.7	.7	5.4	.7	81.2	114,119	100.0

[1] Based on study of 118 selected residential subzones.
[2] Distance (miles) of residence from the central business district. None of the selected subzones were in rings 1, 11, 12, or 13.
[3] Trips from shopping and school were not included, because they were probably the result of small amounts of nonresidential land use.

(Continued from page 89)

factors will provide reasonable estimates of total trip-ends on residential land by all modes of travel combined. However, in order to implement the design of transport facilities, separate estimates must be made of automobile-driver trips, mass-transit trips, and trips by all other modes of travel. It would seem necessary, therefore, to determine the extent of automobile ownership as a means of making these separate estimates for particular modes of travel.

Recognizing that a variable such as automobile ownership may only be a transient predictor of trips, it still presents, when known, a rather impressive possibility for improving traffic estimates. In this regard, it is strongly urged that automobile ownership or registration records be established within urban and metropolitan areas on a basis of statistical areas, such as census tracts, police precincts, postal zones, school districts, or origin and destination zonal areas. Such a system would also enable the use of license tags in traffic analyses, and in many other studies such as those connected with civil defense and market research.

Home Trips As a Measure of Total Trip-Ends

Any study of residential land-use trip generation must take into account the number of trips origins and trip destinations (trip-ends) in a particular residential area, and the number of trips made by the residents of that area (trip production).

The present study of residential land-use trip generation and residents trip production was started several years ago with an analysis of residents trips and other factors in 10 areas of varying types and income levels, as shown in tables 1 and 2. It was initially apparent from the data that residents trip production generally increased with income, except for the highest income areas. It was equally apparent that the number of residents trips varied directly with the number of passenger cars owned per dwelling unit.

To establish the degree of reliability of these findings and to evaluate the contributing influence of these and other variables on residents trip production, a series of statistical analyses was undertaken, based on 95 census tracts in Washington, D. C. The results of these studies were valuable in that they established statistically the possibility of estimating, with a relatively high degree of reliability, residents daily trip production.[2]

One of the most important byproducts of the analysis of the 10 residential areas was the apparent value of the study as a means of estimating traffic growth for urban redevelopment projects. For example, Area 10, the southwest area of Washington, is such an urban redevelopment area. Redevelopment plans call for the construction of apartments and row houses in the residential portion of the area. If it is assumed that data developed for Area 7, an apartment and row-house area, would be representative of the redevelopment area when completed, then automobile trips per dwelling unit will increase three times while mass-transit travel will remain relatively constant. This general method of estimating trips for a given land use should be of value, particularly in planning and designing highway facilities for redevelopment projects.

[2] *A study of factors related to urban travel*, by William L. Mertz and Lamelle B. Hamner. PUBLIC ROADS, vol. 29, No. 7, April 1957.

The 10-area study provided an insight into residents total trip production, but as most of the areas studied included other than residential land uses, it was not possible to definitely determine the actual trip generation of the residential land.

To provide accurate data for such an analysis, 118 purely residential subzones [3] of the 1955 Washington transportation survey were selected. These subzones represented 7.6 percent of the total number of subzones in the survey area, and 7.2 percent of the total area population, or 113,832 residents. The basic data, including trip information, for these residential subzones are summarized in table 3 by annular areas (rings) at varying distances from the central business district.

In the home-interview surveys, trip purpose was designated as purpose "from" and purpose "to" (from home to work, from work to shopping, etc.). For trips having one end in a given area, the number from a specific purpose generally equals the number to that purpose. For example, for each trip to work at a specific location, there is a corresponding trip from work. Furthermore, there would be an equal number of trips to home and from home in the 118 residential subzones studied.

Effect of distance from the central business district

The percentage distribution by trip purpose, as affected by distance from the central business district, is shown in table 4. Trips from home constituted 81.2 percent of all trips with origins in the studied subzones, and consequently home-oriented trips constituted the same percentage of all trips beginning and ending in these residential subzones.[4] This is an average figure and does not reflect any variations which might be due to economic, geographic, and demographic factors.

The data in table 4 also show that the percentage of trips which originated from home within these residential subzones did not vary appreciably as distance from the central

[3] Unless otherwise specified, all subsequent references to residential areas refer to areas entirely residential.
[4] From a study of trips to 210 residential blocks in the Detroit, Mich., area, it was found that 73.3 percent of the incoming trips were to home. From a study of trips to 35 residential zones in the 1948 Washington, D. C , survey area, it was found that 80 percent of all incoming trips were to home.

Table 5.—Effect of family income on the purpose distribution of trips originating on residential land in the Washington, D. C., survey area on an average weekday in 1955 [1]

Income groups [2]		Percentage distribution of trips from—							All "from" trips	
Code	Amount	Work	Personal business	Serving passengers	Changing mode of travel	Social and recreational	Medical, dental, and eating	Home	Number	Percent
	Dollars									
2	2,500-4,499	2.5	-----	-----	-----	7.5	-----	90.0	2,040	100.0
3	4,500-6,999	4.6	1.7	4.5	0.5	4.5	0.6	83.6	39,560	100.0
4	7,000-9,999	4.5	2.7	4.0	.8	5.5	.6	81.9	43,671	100.0
5	10,000 and over	7.4	1.9	6.3	.8	6.1	1.1	76.4	28,848	100.0
All groups		5.2	2.1	4.7	.7	5.4	.7	81.2	114,119	100 0

[1] Based on study of 118 selected residential subzones.
[2] The assignment of an income group rating to each area was made by the National Capital Regional Planning Council. The assignment was based on an analysis of average (median) family incomes which were developed for each area with the aid of local planning commissions, using 1950 census data and income statistics reported by the Washington Evening Star Consumer Survey of 1955–56.

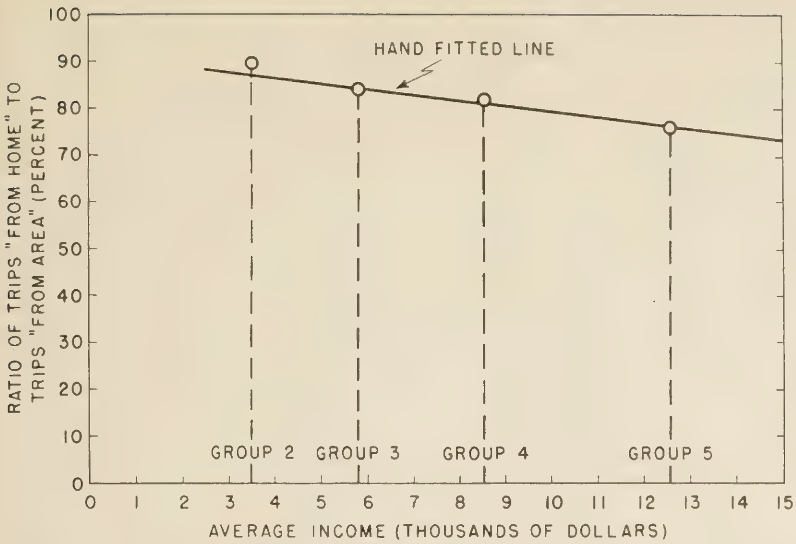

Figure 1.—Average income related to proportion of trip origins from home in 1955.

business district increased. The higher percentages of from home trips shown for rings 2, 3, and 10, compared with the other rings, may not be significant because, as shown in table 3, there were fewer interviews in these rings. This variation from the pattern is reflected in the instability of trip purpose.

Effect of variations in family income

As distance from the central business district was not an influencing factor in the proportion of residential area trips having home as a trip purpose, an analysis was made of the effect of variation in family incomes on these home-oriented trips. The results of grouping the 118 residential subzones into 5 categories of income are shown in table 5. The data indicate that the percentage of total trips originating on residential land which were from home decreased as family income increased. Although a variety of inferences could be drawn from the data, including the apparent and reasonable increase in work opportunities at homes in the highest income group areas, there are several factors left unexplained by the data. A further classification of annual income exceeding $10,000 might help to clarify the trend.

To obtain factors by which total trips originating in residential areas could be estimated, the proportion of trips from home to the total trips originating in the 118 residential subzones was plotted in relation to income, as shown in figure 1. By smoothing out the irregularities in the plotted data with a hand-fitted line, the percentages of from home trips for each income group were slightly modified, and expansion factors were developed as shown in table 6.

Table 6.—Factors developed for estimating total trips, by income groups, originating in residential areas

Income groups		Percentage of "from home" trips to total trips from area	Trip expansion factors [1]
Code	Amount (dollars)		
2	2,500–4,499	87.2	1.15
3	4,500–6,999	84.5	1.18
4	7,000–9,999	81.2	1.23
5	10,000 and over	76.4	1.31
Average, all groups		81.2	1.23

[1] 100.0 divided by percentages given in column 3.

Prior to testing the adequacy of these trip expansion factors to duplicate total trips originating in the residential areas (from all purposes), those subzones which had less than 1,000 trip origins were eliminated, or where possible combined, to provide greater stability. This resulted in a total of 48 purely residential areas composed of 77 of the original 118 subzones, either individually or in combination, being used to test the expansion factors.

The from home trips for each of the 48 areas were multiplied by (1) the applicable income-group expansion factor and (2) by the average factor of 1.23, derived from the finding that an average of 81.2 percent of trip origins in residential areas were from home. The results of these expansions compared with actual trip origins are shown in table 7.

From a detailed study of data presented in table 7, it appears that factoring by income groups improves slightly the accuracy of estimating trip origins over using an average factor. Two-thirds of the estimates were within ±8 percent of the actual values when using income factors, as compared with ±9 percent when using the average factor. The maximum error was +19 percent when factored by income, and −21 percent when using

Table 7.—Comparison of the number of trips originating in 48 residential areas in the Washington, D. C., survey area on an average weekday in 1955 with the number estimated by the application of factors to the "from home" trips

Subzones	Income group [1]	"From home" trips	Total trips originating in area	"From home" trips times income-group factor [2]	Percentage difference	"From home" trips times average factor [3]	Percentage difference
4144	2	1,161	1,334	1,335	--------	1,428	7
1712-3	3	1,238	1,787	1,461	−18	1,522	−15
3143	3	2,076	2,338	2,449	5	2,553	9
3312	3	931	1,069	1,098	3	1,145	7
4752	3	1,586	1,830	1,871	2	1,950	7
4861	3	1,238	1,427	1,461	2	1,522	7
5143	3	1,852	2,006	2,185	9	2,278	14
5314	3	1,795	2,393	2,118	−11	2,208	−8
5325	3	1,089	1,395	1,285	−8	1,339	−4
5653	3	1,389	1,581	1,639	4	1,708	8
5741	3	1,201	1,218	1,417	8	1,477	12
6353	3	1,780	2,107	2,100	--------	2,189	4
6469	3	1,790	2,097	2,112	1	2,202	5
6611-2-3	3	3,017	3,475	3,560	2	3,711	7
7825	3	1,101	1,244	1,299	4	1,354	9
7872-4	3	1,369	1,638	1,615	−1	1,683	3
8732	3	2,497	3,106	2,946	−5	3,071	−1
1331	4	1,102	1,195	1,355	13	1,355	13
1622-3	4	2,774	3,143	3,412	8	3,412	8
2245	4	1,079	1,117	1,327	19	1,327	19
2325	4	785	1,022	965	−6	965	−6
2333-4	4	1,040	1,365	1,279	−6	1,279	−6
2622-3	4	2,473	2,955	3,042	19	3,042	19
2643	4	890	1,055	1,094	4	1,094	4
2872	4	1,431	1,730	1,760	2	1,760	2
3434-6-7	4	1,547	1,832	1,902	4	1,902	4
3444	4	1,217	1,493	1,497	--------	1,497	--------
3524-6	4	1,890	2,325	2,325	--------	2,325	--------
3581-2	4	1,196	1,736	1,471	−15	1,471	−15
6476	4	1,194	1,487	1,468	−1	1,468	−1
7311-3	4	2,649	3,111	3,258	5	3,258	5
7452	4	1,265	1,403	1,556	11	1,556	11
7842-6-7	4	2,784	3,614	3,424	−5	3,424	−5
7911	4	784	1,098	964	−12	964	−12
8242-3	4	3,605	4,277	4,434	4	4,434	4
8426	4	913	1,247	1,122	−10	1,122	−10
1164	5	1,730	2,690	2,266	−16	2,127	−21
1322-3-5	5	1,737	2,146	2,275	6	2,136	1
2341-2-3	5	1,578	2,280	2,067	−9	1,941	−15
2421-5-7	5	1,822	2,551	2,387	−6	2,241	−12
2512	5	1,248	1,736	1,634	−6	1,535	−12
2521-2-3-5-6-7-8	5	3,077	3,900	4,031	3	3,785	−3
2531-5-6	5	1,997	2,465	2,616	6	2,456	--------
2613	5	1,019	1,136	1,334	17	1,253	10
2732	5	714	1,098	935	−15	878	−20
2743	5	1,597	2,128	2,092	−2	1,964	−8
2851	5	1,241	1,411	1,625	15	1,526	8
8343	5	984	1,431	1,289	−10	1,210	−15

[1] See tables 5 and 6.
[2] Factors used to expand home trips to total trips for each income group are given in table 6.
[3] An average factor of 1.23 was used to expand home trips to total trips.

Table 8.—Residential characteristics of 48 selected areas in the Washington, D. C., survey area on an average weekday in 1955

Subzones	Number of automobiles per 100 residents	Number of residents per residential acre	Trips from home divided by trips from area	Trips to and from home divided by total trips by residents	Number of trips per resident
			Percent	*Percent*	
3434-6-7	14	81	84	92	1.2
3312	17	86	87	93	1.8
4144	20	184	87	94	1.0
5143	21	144	92	95	1.3
6353	23	97	84	84	1.5
3444	26	92	82	95	1.5
2421-5-7	27	21	71	78	1.9
5314	27	73	75	80	1.6
5325	27	52	78	91	1.5
5741	27	26	91	81	1.9
2512	29	49	72	76	2.5
5653	29	24	88	86	1.5
2245	30	45	97	82	2.5
6611-2-3	30	30	87	80	1.7
7825	30	61	88	93	1.8
8242-3	30	23	84	72	2.6
3143	31	286	89	81	2.2
4752	31	32	87	83	2.3
8426	31	13	73	81	2.0
3524-6	32	77	81	79	1.6
7872-4	32	11	84	82	2.2
8732	32	5	80	79	2.3
4861	33	50	87	88	1.6
6476	33	64	80	68	2.4
7311-3	33	28	85	55	2.7
1164	34	38	64	82	2.0
1622-3	34	14	88	82	2.5
2613	34	16	90	82	2.3
2872	34	12	83	71	1.9
6469	34	57	85	69	2.5
7452	34	64	90	94	1.8
2743	35	18	75	80	2.8
1712-3	36	12	69	76	2.8
2341-2-3	36	27	69	77	2.0
1331	37	29	92	68	2.8
2333-4	37	31	76	73	2.6
2643	37	31	84	78	2.2
2851	37	5	88	74	2.5
3581-2	37	29	69	80	2.0
8343	41	21	69	80	2.4
2521-2-3-5-6-7-8	42	29	79	74	3.2
2531-5-6	42	33	81	82	2.6
7842-6-7	42	17	77	89	2.1
7911	42	8	71	76	2.2
2325	45	45	77	88	2.9
1322-3-5	46	10	81	78	2.7
2622-3	46	65	84	80	2.4
2732	49	14	65	70	2.7

an overall expansion factor. In appraising these results, it should be remembered that the comparisons were made for individual subzones, and that the basic trip data for any one subzone could have a sizeable error. Additional study shows that the error decreases as trip volumes increase, when using either income factors or the average factor to expand from home trips.

From the foregoing the conclusion may be drawn that if the number of from home trips of any residential area is known, the total trips generated by that area can be estimated with an acceptable degree of reliability. Thus, trips generated by the residential land in any zone can be assigned to that land.

Automobile ownership and population density

Now that trips can be assigned to residential land, it should be possible to relate these known values to the various characteristics of the residential area. It has been shown that the proportion of trips originating in residential areas that are from home tends to decrease as income increases. There are, however, other influencing factors which must be considered. To determine the effect that automobile ownership and population density had on the percentage of from home trips, correlations between each of the independent variables and the percentage of from home trips were made for these same residential areas. The results of these analyses are plotted in figures 2 and 3. (Residential characteristics and trip data for these areas are presented in table 8.) Regression equations were fitted to the points by the method of least squares. Although these points do not indicate a marked trend, especially those in figure 3, related studies have shown a measurable relation between trips and both automobile ownership and population density. It is believed that the sampling variability may have somewhat obscured the relations in this case, but they should not be ignored.

Since, for a given area, the trips to home are generally about equal to the trips from home, then 81.2 percent of all trips to and from the selected residential areas are home-oriented. In effect, this means that on an average 81.2 percent of all trips to and from residential areas in the Washington area are made by the residents of those areas. The percentage varies with income, automobile ownership, and population density.

In summary, the total number of trip-ends in any residential area can be determined, if the number of trips to home and from home are known, by expanding the home-trip volumes by income, automobile-ownership, or population-density factors. An attempt will now be made to develop methods for estimating trip-ends on residential land from a knowledge of total residents trips to all origins and destinations.

Residents Trips Between All Origins and Destinations

An analysis of the data developed by the Washington transportation studies of 194[illegible] and 1955 showed that 84 percent of all residents internal area trips began or ended at home in each of the 2 years studied.[5] The percentages of residents trips which were made to and from home were computed for 4[illegible] selected purely residential areas and are presented in table 8. Table 9 shows the percentages for 118 subzones grouped by income and distance from the central business district. Correlations were made between these percentages and the previously mentioned independent variables. The results of these analyses are presented in figures 4–6, and show

[5] A study of travel patterns in 50 cities showed that an average of 82 percent of the total trips by residents had either an origin or destination at home. The range was from about 70 to 92 percent.

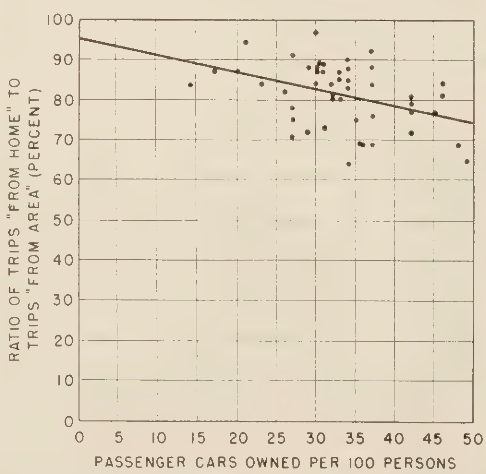

Figure 2.—Automobile ownership related to proportion of trip origins from home in 1955.

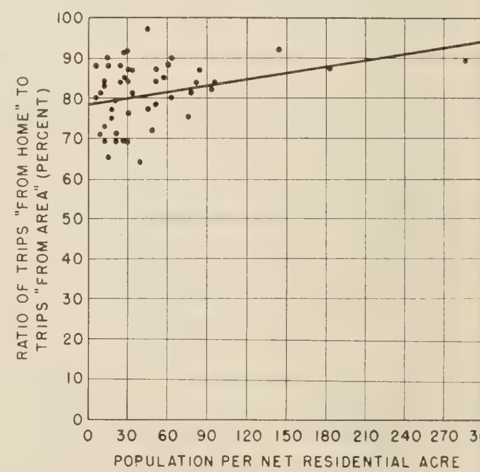

Figure 3.—Population density related to proportion of trip origins from home in 1955.

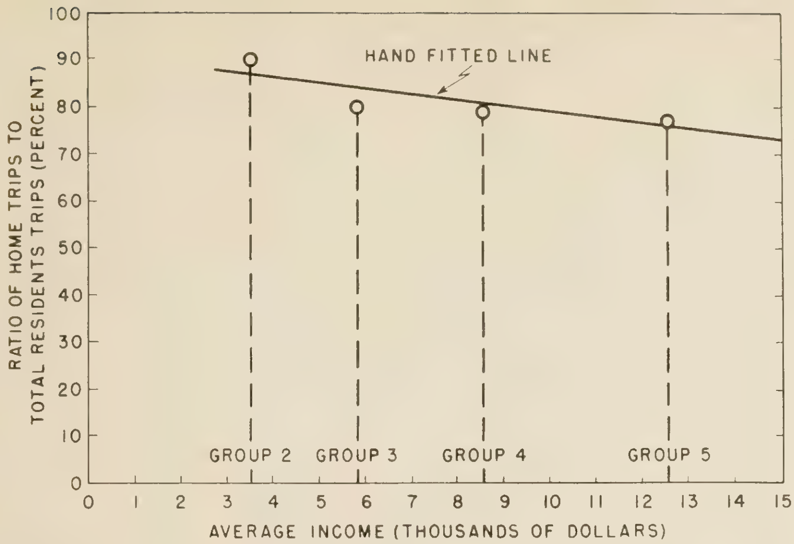

Figure 4.—Average income related to proportion of residents trips to and from home in 1955.

Table 9.—Effect of income and distance from the central business district on the percentage of residents trips to and from home on an average weekday in 1955 [1]

Variables	Number of residents trips to and from home	Total trips by residents	Percentage of to and from home trips to total trips
Income groups: [2]			
2	3,670	4,071	90.1
3	66,138	82,212	80.4
4	71,558	90,280	79.3
5	44,082	57,306	76.9
Rings: [3]			
2	6,474	7,574	85.5
3	6,334	6,853	92.4
4	26,398	32,988	80.0
5	44,898	56,973	78.8
6	31,794	39,636	80.2
7	30,492	39,481	77.2
8	18,662	23,386	79.8
9	16,022	20,793	77.1
10	4,374	6,185	70.7
Total	185,448	233,869	79.3

[1] Based on a study of 118 selected residential subzones.
[2] See tables 5 and 6.
[3] Distance (miles) of residence from the central business district. None of the selected subzones were in rings 1, 11, 12, or 13.

that the percentage of residents trips that started or ended at home tends to decrease as either income or automobile ownership increases, but appears to increase as population density increases. These patterns, it should be noted, have approximately the same relation that the percentage of from home trips to total trips originating in a residential area had to the variables.

It may be concluded, therefore, that the ratio of home trips to total residents trips is related to the ratio of home trips to total trip-ends. It follows then that the total number of trips by the residents of an area should be a useful index for estimating the total number of trip-ends attributable to the residential land use in that area, by both residents and nonresidents.

The factors to convert residents trips to residential land-use trip-ends were developed for each of the selected independent variables and are presented in table 10. As these conversion factors do not vary appreciably with any of the independent variables, a conversion factor of 1.0 was used. As previously indicated, this means that the total number of trip-ends in a residential area is equal to the total number of trips made by the residents of the area between all origins and destinations.

The number of trip-ends were then estimated from residents trips, using the factor of 1.0, and compared with the actual number of trip-ends, as determined from the transportation survey, in 35 purely residential areas which had 2,000 or more trip-ends and in which residents of 20 or more sample dwelling units were interviewed. These data are presented in table 11. This comparison shows that in 3 out of 4 cases, the estimated number of trip-ends was within 10 percent of the survey results. Part of the error that does exist is undoubtedly due to the small size of the areas studied, and to the use of only one conversion factor.

Thus, the total number of trip-ends attributable to the residential land use of an area can be estimated with an acceptable degree of accuracy from the total number of trips made by the residents of that area. The problem now is how best to determine residents trips.

Residents Trip Production

A previous analysis based on travel data obtained from the 1948 Washington, D. C., metropolitan transportation study determined the influencing effect of each of four variables, individually and combined, on the number of trips made by the residents of 95 census tracts in the District of Columbia.[6] These variables were distance from the central business district, income, automobile ownership, and population density. A technique known as "analysis or partition of the variance" was employed to estimate the significance of each of the independent variables. It was established in this study that the use of all four variables combined did not significantly increase the accuracy of predicting trips over that which was obtained using only automobile ownership and population density combined. Furthermore, automobile ownership was found to be the most reliable single predictor, with very little additional accuracy gained by combining it with population density.

[6] See footnote 2, page 92.

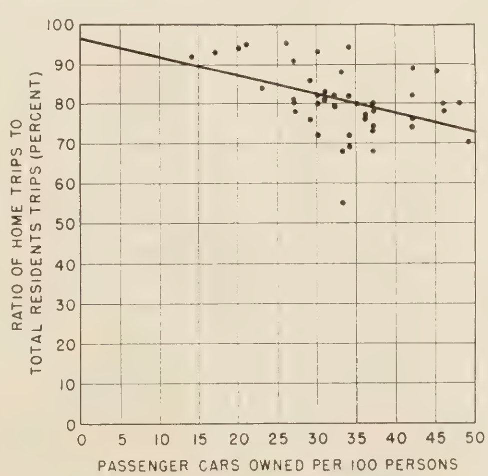

Figure 5.—Automobile ownership related to proportion of residents trips to and from home in 1955.

Assuming that automobile ownership remained the most reliable single indicator of residents trips, the 1955 data on trips per person were correlated with automobiles owned per 100 persons to determine an estimating equation for residents total trips. Total residents trip production and information concerning automobile ownership are obtainable for any area where a home-interview traffic study has been made and not just those areas which are purely residential. This correlation was based on 200 areas or zones for which the required information was available from both the 1948 and 1955 Washington surveys. The estimating regression equation is $Y=0.6+0.04X$, where Y equals trips per person, and X equals passenger cars owned per 100 persons. The correlation coefficient is $+0.71$ and the standard error of estimate is 0.39 trip per person.

Using this equation and the conversion factor of 1.0 developed previously, the residents trips and, consequently, the resi-

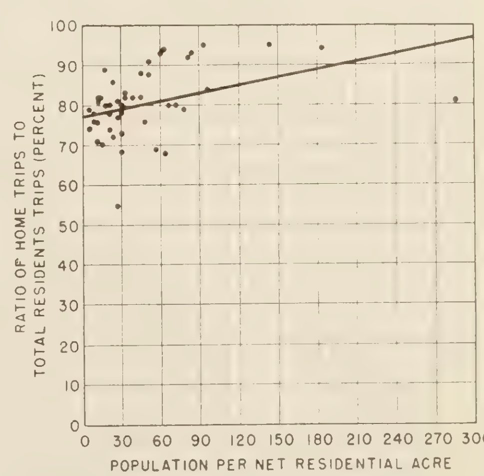

Figure 6.—Population density related to proportion of residents trips to and from home in 1955.

Table 10.—Conversion factors for estimating number of trip-ends in residential areas in the Washington, D. C., survey area on an average weekday in 1955

Independent variables	Trip-ends at home related to total trip-ends in a residential area	Residents trips to and from home related to total trips	Total residents trips related to total trip-ends in a residential area (col. 3 divided by col. 2)
Rings: [1]	*Percent*	*Percent*	
2	88.1	85.5	0.97
3	87.7	92.4	1.05
4	79.5	80.0	1.01
5	80.0	78.8	.98
6	80.8	80.2	.99
7	80.9	77.2	.95
8	82.8	79.8	.96
9	81.6	77.1	.94
10	85.8	70.7	.82
Income groups: [2]			
2	90.0	90.1	1.00
3	83.6	80.4	.96
4	81.9	79.3	.97
5	76.4	76.9	1.01
Automobile ownership: [3]			
5	92.6	93.7	1.01
10	90.6	91.4	1.01
15	88.6	89.1	1.01
20	86.5	86.7	1.00
25	84.5	84.4	1.00
30	82.5	82.1	1.00
35	80.4	79.8	.99
40	78.4	77.4	.99
45	76.4	75.1	.98
50	74.4	72.8	.98
Population density: [4]			
30	80.3	79.5	.99
60	81.8	81.4	1.00
90	83.3	83.3	1.00
120	84.7	85.2	1.01
150	86.2	87.1	1.01
180	87.7	89.0	1.01
210	89.9	90.9	1.02
240	90.6	92.8	1.02
270	92.1	94.7	1.03
300	93.6	96.5	1.03

[1] Distance (miles) of residence from the central business district. None of the selected subzones were in rings 1, 11, 12, or 13.
[2] See tables 5 and 6.
[3] Automobiles owned per 100 residents.
[4] Persons per residential acre.

dential trip-ends were estimated for each of the 35 residential areas listed in table 11. The estimated trip-ends were compared with the actual survey values to test the accuracy for prediction purposes. Twenty-five or 71 percent of the estimates were within ±15 percent of the actual survey values, and 88 percent were within ±25 percent. The average error was 14.5 percent.

An intensive study of those areas with an extremely high percentage of error might result in a reasonable explanation of the differences. Once again, it should be remembered that these comparisons refer to relatively small areas and the so-called actual number of residents trips is subject to error due to sample variability inherent in the basic survey.

Therefore, it is also possible to estimate with a fair degree of accuracy the trip-ends of the residential portion of an area if the population and automobile ownership for that area are known. It must be pointed out, however, that these estimates are based upon a particular overall citywide relationship between residents trips per person and automobile ownership.

Table 11.—Comparison of estimated and actual trip-ends in 35 residential areas in the Washington, D. C., survey area on an average weekday in 1955

Subzones	Distance from the central business district	Number of home interviews	Estimated number of trip-ends [1]	Actual number of trip-ends	Percentage difference, estimated and actual trip-ends
	Miles				
3134	2	29	5,106	4,676	9.2
5143	3	24	3,903	4,012	−2.7
1164	4	31	4,220	5,380	−21.6
2421-5-7	4	25	4,650	5,102	−8.8
3434-6-7	4	24	3,359	3,664	−8.3
5314	4	30	4,468	4,786	−6.6
7311-3	4	124	6,365	6,222	2.3
3524-6	5	26	4,779	4,650	2.8
6353	5	20	4,234	4,214	.5
6469	5	21	5,174	4,194	23.4
7825	5	55	2,367	2,488	−4.9
7842-6-7	5	96	6,248	7,228	−13.6
2512	6	20	3,297	3,472	−5.0
2521-2-3-5-6-7-8	6	25	8,300	7,800	6.4
2613	6	30	2,485	2,272	9.4
6611-2-3	6	107	7,578	6,950	9.0
7452	6	47	2,689	2,806	−4.2
8343	6	24	2,460	2,862	−14.0
1622-3	7	60	6,770	6,286	7.7
2622-3	7	104	6,177	5,910	4.5
2732	7	21	2,037	2,196	−7.2
2743	7	39	3,996	4,256	−6.1
7872-4	7	37	3,350	3,276	2.2
8242-3	7	86	10,024	8,554	17.2
8426	7	26	2,244	2,494	−10.0
1712-3	8	31	3,253	3,574	−9.0
2643	8	32	2,290	2,110	8.5
4752	8	37	3,807	3,660	4.0
4861	8	45	2,824	2,854	−1.0
5741	8	32	2,965	2,636	12.5
2851	9	33	3,355	2,822	18.9
5653	9	48	3,242	3,162	2.5
7911	9	22	2,060	2,196	−6.2
8732	9	67	6,347	6,212	2.2
2872	10	48	4,041	3,460	16.8

[1] Estimated trip-ends equals residents trips.

Residential Trips As a Measure of Nonresidential Trip-Ends

If, as has been shown, the number of residents trips provides a useful basis for estimating total trip-ends in residentia[l] areas, it is reasonable to test its applicatio[n] as a measure of nonresidential trip-ends. Obviously, the difference between total trip-ends in an urban area and trip-ends o[n] residential land could be assigned to non[-]residential land. But, it has not been practi[-]cable to isolate each parcel of residential lan[d] to determine the trips generated thereby.

However, in this study the total number o[f] home trips is known, and these must hav[e] been generated by residential land. It ca[n] be assumed then, that these home trip[s] represent the same proportion of total trip[s] to all residential land as the home trips i[n] the 118 selected (purely residential) subzone[s] are to the total trips destined to these areas. In this manner, it was found that 19 percen[t] of the trips destined to residential land wer[e]

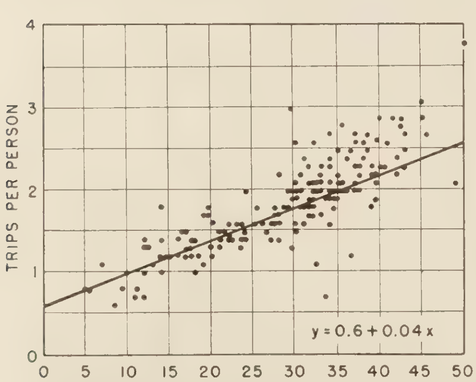

Figure 7.—Trips per person related to automobile ownership in 1955.

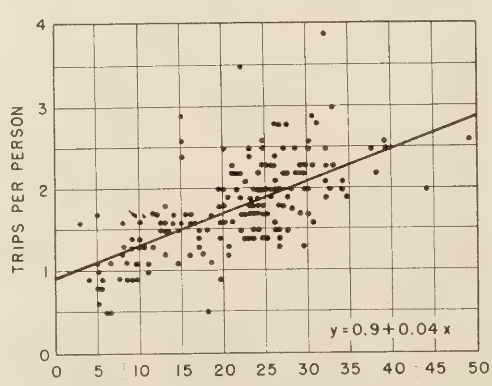

Figure 8.—Trips per person related to automobile ownership in 1948.

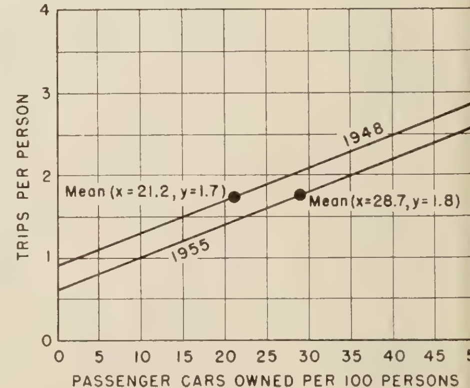

Figure 9.—Comparison of relations betwee[n] trips per person and automobile owner[-]ship in 1948 and 1955.

Table 12.—Distribution of internal trip-ends by land use

Land use	Washington, D. C., surveys		Detroit, Mich.	50 cities
	1948	1955		
Residential:	*Pct.*	*Pct.*	*Pct.*	*Pct.*
Home	42	42	39	41
Other	11	11	14	11
Nonresidential	47	47	47	48
Total	100	100	100	100

other than to home. Also, since 58 percent of all trips in the metropolitan area were for other than to home purposes, it follows that 19 percent of 58 or 11 percent of all trips are generated by residential land for a purpose other than to home. This means a total of 53 percent (42+11) of all trip-ends are on residential land and the remaining 47 percent are on nonresidential land. In table 12, these results are compared with the Washington, D. C , 1948 data and with those for 50 cities, similarly developed, and with data from Detroit, Mich.

Stability of Residents Trips Per Person and Automobile Ownership

To determine the stability of the relation between residents trips per person and automobile ownership, an additional correlation between the two variables was made for the same 200 areas using data developed from the 1948 Washington area transportation survey. The results of this analysis are presented in figure 8. A comparison of the regression line in figure 8 and the regression line based on 1955 data (fig. 7) is shown in figure 9. A study of these two lines indicates that the relation between trips and automobile ownership has not been stable, but has shifted measurably during the 7-year period. The only difference between the two lines is the value of the constant (0.9 for 1948 and 0.6 for 1955) where the regression line intersects the *Y* axis. Statistical *t* tests showed that the difference between these two constants was highly significant and could not be accounted for by sampling variability. Measures obtained from the analyses are as follows:

	1948	*1955*
Correlation coefficient	+0.67	+0.71
Standard error of estimate	.41	.39
Average trips per person, $\bar{y}$	1.7	1.8
Average automobile ownership per 100 persons, $\bar{v}$	21.2	28.7

Further analysis of the regression lines gives an insight into the reasons for the shift. The fact that the slope of the regression lines (0.04) remained the same during the interval between the study periods is of particular importance. Equally important is the fact that, although the average automobile ownership increased from 21.2 to 28.7 automobiles per 100 persons, an increase of 35 percent, the average number of trips per person remained relatively constant. The explanation, therefore, for the shift in the regression lines appears to be the increase in automobile ownership. This, in effect, means that during the 7-year interval the numerical relationship between the two variables changed due to the increase in automobile ownership in 1955, but the relative association between the two variables, as indicated by the correlation coefficients, remained almost constant.

If these relations are valid and the trend is assumed to be consistent in the future, then it should be possible to forecast residents trip production and residential land-use trip generation in the Washington area for any future year, provided that population and automobile ownership for that year are known or can be accurately forecasted. In fact, estimates could be readily obtained from the indices developed in table 13, which may be taken from a family of regression curves assuming a constant average number of trips per person and a uniform slope, similar to those in figure 9. The use of this table would require estimates of the citywide average automobile ownership for the future year plus estimates of automobile ownership for each zone or area for which potential trip data are desired.

Residents trip production for 1955 for each of the previously mentioned 200 areas was estimated by the indices in table 13. The estimated trips were correlated with the actual trips as found in the survey, and the data are presented in figure 10. It is readily apparent that the degree of association between the estimated and actual trips is very high. The square of the correlation coefficient (+0.98)

Table 13.—Indices for estimating the number of trips to and from residential subdivisions of the Washington, D. C., survey area [1]

Automobile ownership per 100 residents in each subdivision	Trips per resident, based on automobile ownership (per 100 residents) values for the entire survey area of—										
	20	21	22	23	24	25	26	27	28	29	30
5	1.20	1.16	1.12	1.08	1.04	1.00	0.96	0.92	0.88	0.84	0.80
10	1.40	1.36	1.32	1.28	1.24	1.20	1.16	1.12	1.08	1.04	1.00
15	1.60	1.56	1.52	1.48	1.44	1.40	1.36	1.32	1.28	1.24	1.20
20	1.80	1.76	1.72	1.68	1.64	1.60	1.56	1.52	1.48	1.44	1.40
25	2.00	1.96	1.92	1.88	1.84	1.80	1.76	1.72	1.68	1.64	1.60
30	2.20	2.16	2.12	2.08	2.04	2.00	1.96	1.92	1.88	1.84	1.80
35	2.40	2.36	2.32	2.28	2.24	2.20	2.16	2.12	2.08	2.04	2.00
40	2.60	2.56	2.52	2.48	2.44	2.40	2.36	2.32	2.28	2.24	2.20
45	2.80	2.76	2.72	2.68	2.64	2.60	2.56	2.52	2.48	2.44	2.40
50	3.00	2.96	2.92	2.88	2.84	2.80	2.76	2.72	2.68	2.64	2.60

[1] Determined from correlation of trips per resident and automobile ownership in the Washington, D. C., survey area, 1948 and 1955. To compute number of trips, multiply population of each subdivision by appropriate index.

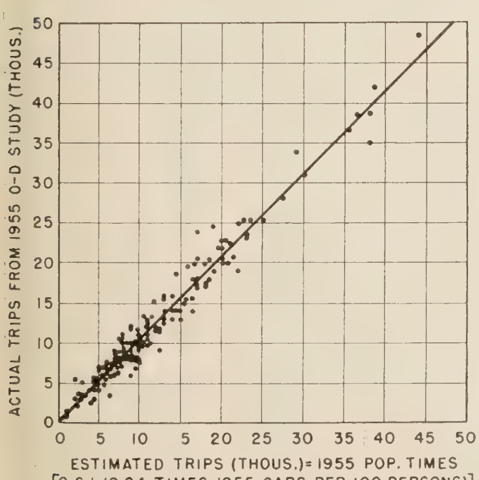

Figure 10.—Actual trips related to estimated trips. Estimates based on relation of trips per person and automobile ownership.

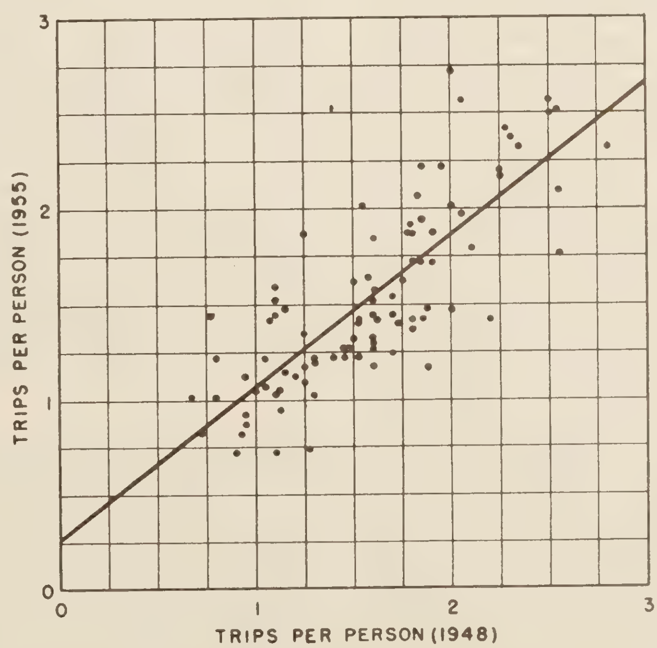

Figure 11.—Relation of trips per person in 1948 and 1955.

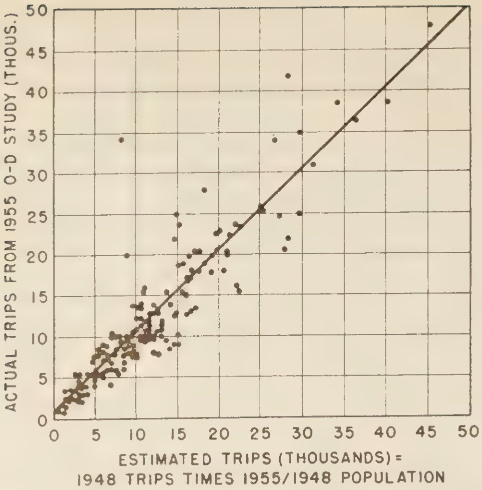

Figure 12.—Actual trips related to estimated trips. Estimates based on change in population between 1948 and 1955.

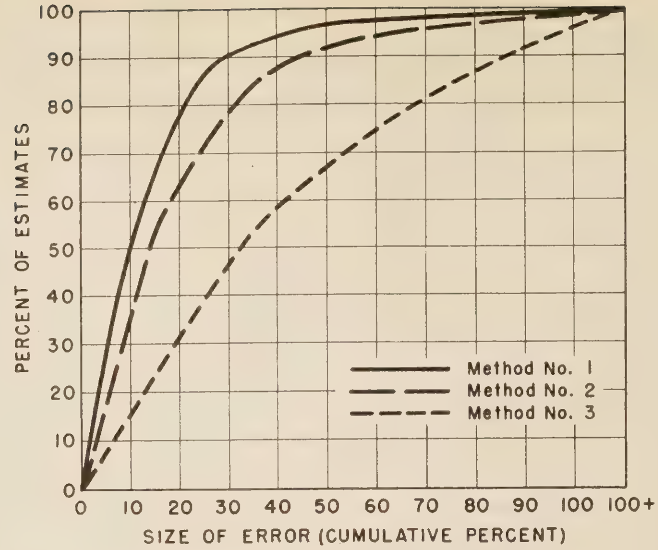

Figure 13.—Comparison of three methods for estimating residents trips.

indicates that the change in automobile ownership and change in population over the 7-year period explained 96 percent of the variation in trip production (residents trips) and residential land trip generation for 1955. Two-thirds of the estimated values were within ±15 percent of the survey results.

In the event automobile ownership data are not available or are too difficult to develop, one or more of the other previously mentioned independent variables could be substituted with, of course, a probable decrease in predictability.[7]

Stability of Residents Daily Trip Production

To forecast accurately residents trip production and residential area trip generation by the method just described would require accurate estimates of population, as well as one or more factors related to trip production and generation, such as automobile ownership, income, etc., for each zone or area for which trip forecasts are desired. Admittedly, this process could prove to be more difficult, and the results perhaps would not be as satisfactory as those obtained from estimates derived from only one independent variable.

The previous comparison between 1948 and 1955 data showed that average trips per person remained almost constant during the 7-year period. Assuming that this consistency is not just a happy balance of plus and minus values, but rather the result of a consistency in the individual figures which comprise this average, then a second and easier method for projecting trip production and residential land trip generation to future years will be available.

To test this consistency or stability of residents daily trip production, trips per person in 1948 were compared with trips per person in 1955 for 95 census tracts in the District of Columbia. The results of this comparison are shown in figure 11. The correlation coefficient is +0.80. This means that the same factors that affected trips in 1948 were still applicable in 1955. Therefore, it can tentatively be assumed that residents trip production in any desired area for which prior survey results are available can be forecasted by multiplying trips per person for the base year by population of the area for any future year.

Residents trips for 1955 for each of the previously mentioned 200 areas were estimated in this manner, using 1948 trip data as the base. A comparison between the estimated and actual survey values is shown in figure 12. The results of this analysis show that two-thirds of the estimated values were within ±25 percent of the actual values (see method 2 in table 14) and the correlation coefficient was +0.94. In other words, this means that the change in population alone was 88 percent effective in explaining the 1955 residents trip production and, consequently, residential land-use trip generation.

Growth in Automobile Ownership as an Indicator of Potential Trips

To measure the effect of automobiles owned, alone, as a predicting variable for estimating 1955 residents trip production and residential land-use trip generation, 1948 trips for the 200 areas were multiplied by the ratio of 1955 automobiles owned to 1948 automobiles owned. The analysis revealed that this method of estimating residents trips was not nearly as effective as the two previous methods described. In this case the correlation coefficient was +0.88. Data in table 14 and figure 13 compare the accuracy of three methods developed for estimating 1955 residents trips and residential trip generation for the 200 areas studied.

Estimating Future Traffic Potential of Residential Areas

Assuming that the travel patterns of the Washington, D. C., metropolitan area are not unlike the travel patterns of other cities, the following methods and procedures have been developed for estimating with a fair degree of accuracy total residents trips for any area. As the factor to convert residents trips to trip-ends on residential land was found to be approximately equal to 1.0, these methods will also give the trip generation due to any residential portion of the study area.

Method No. 1

1. Compute the residents trips per person for each zone in the area for which population and trip data are given.

2. Compute automobile ownership (per 100 persons) for each zone.

3. Let x=automobiles per 100 persons, y=trips per person, and n=number of zones. Solve the following simultaneous equations for a and b:

$$\Sigma y = an + b\Sigma x$$

$$\Sigma xy = a\Sigma x + b\Sigma x^2$$

Table 14.—Comparison of three methods for estimating 1955 residents trips for 200 areas in the Washington, D. C., survey area

Maximum error in percent (plus or minus)	Estimating method No. 1[1]	Estimating method No. 2[2]	Estimating method No. 3[3]
	Percent of estimates	*Percent of estimates*	*Percent of estimates*
5	30.9	18.5	7.8
10	51.0	39.5	15.7
15	67.2	54.5	26.2
20	79.4	63.5	33.0
25	88.7	68.5	40.3
30	91.2	78.0	47.6
35	92.2	86.0	53.9
40	94.1	88.0	57.6
45	95.6	91.0	63.9
50	96.6	93.5	68.6
55	97.1	95.0	71.2
60	97.1	95.0	75.4
65	97.1	96.5	79.1
70	98.0	97.0	82.2
75	98.0	98.5	85.9
80	98.5	98.5	87.4
85	98.5	98.5	88.0
90	98.5	98.5	89.0
95	98.5	99.0	89.5
100	98.5	99.0	92.1
Average error	±15.4	±20.9	±50.3

[1] Estimating equation: y=1955 population [0.6+(0.04× 1955 automobiles per 100 residents)]
[2] Estimating equation: y=1948 residents trips × 195 population/1948 population.
[3] Estimating equation: y=1948 residents trips × 1955 auto mobile ownership/1948 automobile ownership.

[7] See footnote 2, page 92.

4. Determine the estimating equation $y=a+bx$). This equation provides an estinate of the trips per person corresponding to utomobile ownership in a particular area for n overall citywide automobile ownership alue ($\Sigma x/n$) existing at the time of the survey. To apply this relationship to a future time, t is necessary to compute the parallel curve or an overall automobile ownership value estinated for the future data ($\Sigma x'/n$). This is one by assuming that y and b remain constant nd by solving for the new a in the following quation: $\bar{y}=a'+b\bar{x}$.

The trips per person for each area can then e calculated by substituting in the new equaion ($y=a'+bx'$) for each estimated value of utomobile ownership in the study areas. If esired, an index table similar to table 13 ould be prepared.

Although this has not been tested, instead f using automobile ownership data, it should be possible to utilize the techniques just described by substituting population density, income, distance from the central business district, or a combination of these variables.

Method No. 2

1. Compute the ratio of residents trips per person for each zone in the area.
2. Estimate the future population of each zone.
3. Multiply 1 times 2 for each respective zone.
4. In zones for which prior trip data are not available, estimates can be made by comparison with zones having similar characteristics.

Method No. 3

1. Determine the number of trips and automobiles owned for each zone in the area.
2. Estimate the future number of automobiles owned in each zone.
3. Multiply the number of trips by the ratio of future to present automobiles owned.

The application of the most desirable method of estimating the potential trip generation in residential areas is dependent upon the availability and reliability of correlative data. For instance, although the first method appears to be the best, it must be pointed out that its accuracy depends upon the reliability of the estimated population and automobile ownership data. In the examples discussed in this article, the number of persons and the number of automobiles were known from origin and destination surveys. However, to estimate residential trips for a future period, the population and automobile ownership information is not available and must be estimated. Since automobile ownership estimates are likely to be less accurate than population forecasts, method No. 2, utilizing population data alone, may well be more accurate in forecasting trips.

Current Structural Bridge Steels: A Survey of Usage and Economy

*BY THE BRIDGE DIVISIOI
BUREAU OF PUBLIC ROAD*

Reported by NATHAN W. MORGAN, Bridge Engineer

THE advent of welding for steel bridges, and a demand for higher strength steels for large structures and those requiring higher working stresses, gave rise, a couple of decades ago, to a number of continuing research studies covering the characteristics of structural steels and leading to the promulgation of new specifications and the revision of others. This article summarizes and compares the characteristics of the common bridge steels available in this country and attempts to answer the more frequent questions concerning their use.

Standard bridge steels are manufactured by the leading steel producers that roll plates, shapes, and bars. The characteristics of end products are governed by the applicable standard specifications of the American Society for Testing Materials or by proprietary specifications. During the past quarter century, welding has been increasing progressively as a means of fabrication, and since the midcentury the tempo of this program has been intensified. Therefore, welding is not ignored in this survey.

ASTM, Military, and Proprietary Specifications

The standard structural steels considered here are those covered by the following ASTM Standards:

ASTM–A6–57T.—General requirements for delivery of rolled steel plates, shapes, sheet piling, and bars for structural use (*1*).[1]

ASTM–A7–56T.—Steel for bridges and buildings (*2*).

ASTM–A8.—Structural nickel steel (*3*).

ASTM–A94.—Structural silicon steel (*3*).

ASTM–A141.—Structural rivet steel (*3*).

ASTM–A195–52T.—High-strength structural rivet steel (*3*).

ASTM–A242.—High-strength low-alloy structural steel (*3*).

ASTM–A325–55T.—Quenched and tempered steel bolts and studs with suitable nuts and plain hardened washers (*3*).

ASTM–A373–56T.—Structural steel for welding (*2*).

ASTM–A406–57T.—High-strength structural alloy rivet steel (*1*).

Also considered are the following military specifications which cover high-strength steels with characteristics somewhat similar to ASTM–A94 and A242:

MIL–S–16113B (Navy), dated December 4, 1953.—Steel plate, hull and ordnance, structural, black (uncoated), and zinc-coated (galvanized).

MIL–S–20166 (Navy), dated October 3, 1951.—Steel: bars and shapes (for hull construction) (including material for drop and miscellaneous forgings).

The following proprietary structural specifications are also considered here because they are in common use:

"Medium Manganese," "Manganese Vanadium," "Mayari R," "Man-Ten A242," "Cor-Ten," "Tri-Ten," and "T1."

These steels which are produced by two companies, can be and are produced with similar or identical characteristics by other companies, but usually on order to the purchaser's specifications.

There are structural steels other than those discussed in this article. However, it is believed that their characteristics closely coincide with comparable steels discussed here, and for that reason they are omitted.

Definitions

The term "alloy" steel refers to a steel (1) in which the maximum range specified for the content of alloying elements exceeds one or more of the following limits: manganese 1.65 percent, silicon 0.60 percent, copper 0.60 percent; or (2) in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized commercial field of alloy steels: aluminum, boron, chromium up to 3.99 percent, cobalt, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect (*4*).

The terms "low-alloy" or "high-strength" steel comprise a specific group of steels with chemical compositions specifically developed to impart higher mechanical property values and greater resistance to atmospheric corrosion than are obtainable from conventional carbon structural steels containing copper. High-strength low-alloy steel is generally produced to mechanical property requirements rather than to chemical composition limits (*5*).

In general, alloy steels and high-strength low-alloy steels are more difficult to produce than carbon steels, both in the mills and in fabricating shops. Thus, these steels are somewhat more costly. The purpose of such steels is to obtain economy in long-span o costly structures where overhead clearance i limited or where the use of higher workin stresses will reduce the tonnage of steel re quired; and in cases where corrosion resistanc is of economic importance, without increasin the thickness of metal for this purpose. Thes steels may or may not be of welding quality.

In the following sections of this article, th steels previously listed and the specification governing them are discussed individually Physical properties and prices are given i table 1; chemical analyses, in table 2. Th price data are only approximate, and are give mainly for the sake of comparison. Price vary between manufacturers and by location c mill, and are subject to frequent change; thos given are as of October 1, 1957. The price represent basic steel costs and do not includ the various manufacturing extras, such a apply to special metallurgical requirements dimensions, processing, quantity, packing marking, and other items.

Among the steels used for highway bridges the A7 steel remains the best choice for ordi nary riveted construction. When high strength steel is required for long-span c heavy structures, the likely choice would b either Medium Manganese or Man-Ten A24 steel.

When welding is involved, A373 steel shoul be used since it largely meets the metallurgica requirements for welding and forms the basi for the American Welding Society bridg specifications (*6*). When the use of high strength steel becomes economical, the usua choice would be either Manganese-Vanadiun or Tri-Ten steel. Mayari R steel may b used if welding quality is specified and th hardenable elements are thereby limited. Th differential cost between A373 and A7 steel averages about $5.00 per ton except for kille steel in plates between 1 inch and 1½ inche thick, where the differential is $18.00 per ton

For high-strength steel members, large rivet or high-strength bolts should be used. It i hoped that an ASTM standard specificatio governing a more satisfactory high-strengt steel will soon be available.

ASTM Specification Steels

Common requirements, ASTM–A6–57T

Specification ASTM–A6 covers a group c common requirements which, unless othe wise specified in the purchase order in a

[1] Italic numbers in parentheses refer to the list of references on page 104.

individual specification, apply to rolled steel plates, shapes, bars, and sheet piling under each of the other ASTM standard or tentative specifications previously listed, except A325. This general specification was gathered out of the other specifications in 1949 and has been issued separately as ASTM–A6 since that time. It covers the general clauses, such as definitions, test specimens, defect, marking, inspection, permissible variations in dimensions and weights, and the welding of surface imperfections. It is therefore necessary that specification A6 be used in conjunction with each of the other specifications.

Plates are classed as flat, hot-rolled steel over 6 inches in width and 0.23 inch or over in thickness, or over 48 inches in width and 0.18 inch or over in thickness. Bars are

Table 1.—Physical properties and prices of structural steels

Steel specification	Physical properties [1]												Price of steel per pound [2]			
	Tensile strength, minimum or range		Yield point, minimum		Elongation, minimum				Reduction in area, minimum		Bend test		Plates		Other	
					In 8 inches		In 2 inches									
	Thickness, inches	P. s. i.	Thickness, inches	P. s. i.	Thickness, inches	Percent	Thickness, inches	Percent	Thickness, inches	Percent	Thickness, inches	Ratio of bend diameter to thickness	Thickness,[1] inches	Cents	Examples [3]	Cents
ASTM–A7–56T		[4] 60,000– 75,000		33,000	5/16–¾	[5] 21	To 3½	[5] 24		---	To ¾ ¾–1 1–1½ 1½–2 Over 2	½ 1 1½ 2½ 3	To ½ ½–1 1–1½ Over 1½	5.20 5.20 5.20 5.95 ----	S L WF Pl ----	5.275 5.875 5.625 5.85 ----
ASTM–A373–56T		58,000– 75,000		32,000	5/16–¾	[5] 21	To 3½	[5] 24		---	To ¾ ¾–1 1–1½ 1½–2 Over 2	½ 1 1½ 2½ 3	To ½ ½–1 1–1½ Over 1½	5.25 5.45 6.10 6.20 ----	S L WF Pl ----	5.425 6.025 5.975 6.10 ----
ASTM–A94–54		80,000– 95,000		45,000	5/16–¾	[5] 16	To 3½	[5] 19	To ¾	[5] 30	To ¾ ¾–1 1–1¼ Over 1¼	1 1½ 2 2½	To ½ ½–1 1–1½ Over 1½	6.45 6.40 6.40 6.50	S L WF Pl	6.675 7.275 7.025 7.05
Medium Manganese, similar to Man-Ten A242 [7].	To ¾ ¾–1½ 1½–4	72,000 70,000 65,000	To ¾ ¾–1½ 1½–4	50,000 46,000 42,000	To ¾ ¾–1½ 1½–4	18 19 19	To ¾ ¾–1½ 1½–4	20 24 24		--- --- ---	To ¾ ¾–1 1–1½ 1½–2 2–4	1 1½ 2 2½ 3	To ½ ½–1 1–1½ Over 1½	6.40 6.40 6.40 6.50 ----	S L WF Pl ----	6.525 7.125 6.875 7.05 ----
ASTM–A242–55	To ¾ ¾–1½ 1½–4	70,000 67,000 63,000	To ¾ ¾–1½ 1½–4	50,000 46,000 42,000	5/16–¾ ¾–1½ 1½–3½	[5] 18 [5] 19 [5] 19	1½–4	[5] 24		--- --- ---	To ¾ ¾–1 1–1½ 1½–2 2–4	1 1½ 2 2½ 3	To ½ ½–1 1–1½ Over 1½	7.625 7.625 7.625 7.725 ----	S L WF Pl ----	7.80 8.40 8.15 8.275 ----
Manganese-Vanadium and Tri-Ten (A242 steels).	To ¾ ¾–1½ 1½–4	70,000 67,000 63,000	To ¾ ¾–1½ 1½–4	50,000 46,000 42,000	To ¾ ¾–1½ 1½–4	18 19 19	To ¾ ¾–1½ 1½–4	[8] 22 ([9]) 24		--- --- ---	To ¾ ¾–1 1–1½ 1½–2 2–4	1 1½ 2 2½ 3	To ½ ½–1 1–1½ Over 1½	7.625 7.625 7.625 7.725 ----	S L WF Pl ----	7.75 8.35 8.10 8.275 ----
Mayari R (an A242 steel).	To ¾ ¾–1½ 1½–4 Over 4	70,000 67,000 63,000 60,000	To ¾ ¾–1½ 1½–4 Over 4	50,000 46,000 42,000 40,000	5/1 –¾ ¾–1½ 1½–4	[5] 18 [5] 19 16 --	To ¾ ¾–1½ 1½–4 Over 4	22 ([9]) [5] 24 20		--- --- --- ---		---- ---- ---- ----	To ½ ½–1 1–1½ Over 1½	7.625 7.625 7.625 7.725	S L WF Pl	7.80 8.40 8.15 8.275
Cor-Ten (an A242 steel).	To ½ ½–1½ 1½–3	70,000 67,000 63,000	To ½ ½–1½ 1½–3	50,000 47,000 43,000	To ½ ½–1½ 1½–3	18 19 19	To ½ ½–1½ 1½–3	22 ([9]) 24		--- --- ---	To ½ ½–1½ 1½–3	1 2 3	To ½ ½–1 1–1½ Over 1½	7.625 7.625 7.625 7.725	S L WF Pl	7.75 8.35 8.10 8.275
AREA, high-strength steel.	To 1 1–1½ 1½–4	78,000 75,000 72,000	To 1 1–1½ 1½–4	50,000 47,000 45,000	To 1 1–1½ 1½–4	[10] 17 [10] 18 [10] 19	1½–4	21 -- --	To 1 1–1½ 1½–4	[10] 30 [12] 27.5 ([9])	To ¾ ¾–1 1–1¼ Over 1¼	1 1½ 2 2½	([11])	([11]) ---- ---- ----	S Pl ---- ----	[11] 7.375 [11] 7.90 ---- ----
ASTM–A141–55		52,000– 62,000		28,000		24		--		---	([13])	([13])		----	----	----
ASTM–A406–57T		68,000– 82,000		50,000		20		--		---		----		----	----	----
T1	¼–6	105,000–135,000	¼–6	90,000		--	¼–2 2–4 4–6	18 17 16	¼–2 2–4 4–6	55 50 45	To 1 1–2	2 3 ----	To ½ ½–1 1–1½ Over 1½	14.30 13.55 13.55 14.30	---- ---- ---- ----	---- ---- ---- ----
ASTM–A8–54		90,000–115,000		55,000		14		--		30		----		----	----	----
ASTM–A195–52T		68,000– 82,000		38,000		20		--		---		----		----	----	----
MIL–S–20166, H. T. grade.	Under ¼ ¼–½ ½–1 1–2 Over 2	90,000 87,000 84,000 84,000 82,000	Under ¼ ¼–½ ½–1 1–2 Over 2	50,000 48,000 45,000 42,000 40,000		-- -- -- -- --		-- -- -- -- --		--- --- --- --- ---		---- ---- ---- ---- ----		---- ---- ---- ---- ----	---- ---- ---- ---- ----	---- ---- ---- ---- ----
MIL–S–16113B, H. T. grade.	Under ½ ½–1½ 1½–2 Over 2	92,000 88,000 86,000 85,000	Under ½ ½–1½ 1½–2 Over 2	50,000 47,000 44,000 42,000		-- -- -- --		-- -- -- --		--- --- --- ---		---- ---- ---- ----		---- ---- ---- ----	---- ---- ---- ----	---- ---- ---- ----

[1] Thickness dimensions are exclusive of the lower limit and inclusive of the upper limit; e. g., 1 to 1½ inches means over 1 inch and including 1½ inches.

[2] Prices are base cost at the mill, and include mill welding of imperfections (ASTM–A6); they do not include fabrication or erection. Prices vary somewhat among manufacturers and between mills, and are subject to frequent change. The prices quoted are as of October , 1957, and are for quantities of 25 tons or more.

[3] S=shapes; L=4-x 4-x ½-inch angle; WF=30-x 10½-inch wide flange section; and Pl=20- x¾- x 240-inch plate.

[4] For plates to 1½ inches, 60,000–72,000; for all shapes and for plates over 1½ inches, 60,000–5,000.

[5] For variations, see ASTM specifications (in the case of Mayari R, see ASTM–A242).

[6] Price of 5.625 cents applies to beams of the following dimensions (inches): 36 x 16½, 36 x 12, 33 x 15¾, 33 x 11½, 30 x 15, 30 x 10½, 27 x 14, 24 x 14, 21 x 13, 14 x 16, 14 x 14½, 12 x 12, and 10 x 10.

[7] Physical values for the two steels differ slightly.

[8] For Tri-Ten steel only.

[9] Not specified.

[10] For variations, see AREA Specification; proceedings of AREA for 1958.

[11] Check with manufacturer as to availability and price.

[12] Reduced from 30 percent by ½ percent for each 1/16 inch of thickness over ¾ to 1½ inches.

[13] 180 degrees bent flat cold.

Table 2.—Chemical composition of structural steels (percentages by ladle analysis)

Chemical composition (percent)	Steel specifications																
	ASTM-A7-56T	ASTM-A373-56T	ASTM-A8-54	ASTM-A94-54	AREA[1]	ASTM-A141-55	ASTM-A195-52T	ASTM-A406-57T	ASTM-A325-55T	ASTM-A242-55[1]	MIL-S-20166, H. T. grade	MIL-S-16113B, H. T. grade	Medium Manganese and Man-Ten A242	Manganese-Vanadium and Tri-Ten	Mayari R[3]	Cor-Ten[3]	T1[3]
Carbon (maximum)	----	[4]0.26–.28	0.43	0.40	0.30	----	0.30	0.08	[5]0.30	0.22	0.18	0.18	[2]0.27	0.22	0.12	0.12	0.10–.20
Manganese	----	[6].50–.90	[7].80	----	[5]1.20	----	[7]1.65	.25–.50	[5].30	[7]1.25	[7]1.30	[7]1.30	1.10–1.60	[7]1.25	.50–1.00	.20–.50	.60–1.00
Phosphorus (maximum):																	
Acid	0.06	------	.04	.06	.06	0.06	.06	------	.048	----	------	------	------	----	------	------	--------
Basic	.04	.04	.04	.04	.04	.04	.04	------	.048	----	.04	.04	.04	.04	.12	.07–.15	.040
Sulfur (maximum)	.05	.05	.05	.05	.05	.05	.05	------	.058	.05	.05	.05	.05	.05	.05	.05	.050
Silicon	----	[8].15–.30	------	[5].20	[7].30	----	[7].25	.70–1.00	----	----	.15–.35	.15–.35	[7].30	[7].30	.10–.50	.25–.75	.15–.35
Copper	[5,9].20	[5,9].20	[5,9].20	[5,9].20	[5,9].20	[5,9].20	[5,9].20	.50–.75	----	----	[7].35	[7].35	.20–.35	[5].20	.20–.50	.25–.55	.15–.50
Nickel	----	------	3.00–4.00	----	----	----	----	.70–1.00	----	----	[7].25	.25	------	----	.50–1.00	[7].65	.70–1.00
Chromium	----	------	------	----	----	----	----	------	----	----	[7,10].15	[7,10].15	------	----	.40–1.00	.30–1.25	.40–.80
Vanadium	----	------	------	----	----	----	----	------	----	----	[5].02	[5].02	------	[5].02	------	------	.03–.10
Molybdenum	----	------	------	----	----	----	----	------	----	----	.05	[7].06	------	----	------	------	.40–.60
Other[11]	----	------	------	----	----	----	----	.10–.30	----	----	[5].005	[5].005	------	----	------	------	.002–.006

[1] Other elements shall be added by the manufacturer to give the prescribed mechanical properties.
[2] For Medium Manganese, 0.25; for Man-Ten A242, 0.27.
[3] Typical composition.
[4] According to thickness: to ½ inch, 0.26; ½–1, 0.25; 1–2, 0.26; 2–4, 0.27; and shapes and bars, 0.28.
[5] Minimum percentage.
[6] For plates over ½ inch, group A shapes; and bars over 1 inch. For group A shapes, se sizes given in table 1, footnote 6.
[7] Maximum percentage.
[8] For plates over 1-inch thick.
[9] If specified.
[10] Chromium shall not be added intentionally, 0.00 percent chromium desirable.
[11] Specification ASTM-A406-57T, aluminum; MIL-S-20166 and MIL-S-16113B, t tanium; and T1, boron.

classed as rounds, squares, and hexagons of all sizes, flats 13/64 inch (0.2031 inch) and over in thickness and not over 6 inches wide, and 0.230 inch or more in thickness and over 6 inches to and including 8 inches wide, special bar sections, and bar-size shapes under 3 inches in maximum cross-sectional dimension. Shapes are rolled, flanged sections having at least one dimension of the cross section 3 inches or greater.

Ladle analyses for each heat of steel record the percentages of carbon, manganese, phosphorus, sulfur, and other elements specified or restricted by the applicable specification. This analysis is made from a test ingot taken during the pouring of the heat. A check analysis may be made by the purchaser. The chemical composition thus determined must conform to the applicable specification for check analysis as to elements required or restricted.

Steel for bridges and buildings, ASTM–A7–56T

The ASTM–A7 specification had its origin in 1901, following the age of wrought iron. It has been revised frequenty in both physical and chemical characteristics before appearing in its present form. In 1949, the A7 specification for bridge steel was combined with the A9 specification for building steel, giving the present specification for steel in bridges and buildings.

This material is the common mild carbon steel so widely used for all kinds of steel structures, in the form of shapes, plates, and bars of structural quality. It is manufactured by both the open-hearth and electric-furnace processes. Acid Bessemer A7 steel is not used for bridges or other dynamically loaded structures.

Carbon steel meeting the A7 specification is essentially a steel for riveted construction, since welding was not in view when the specification was promulgated. There are no carbon or manganese limitations, nor is a deoxidation process of manufacture specified. This steel may be characterized as being possibly impact or notch sensitive and hardenable in the zone affected by the heat of welding, particularly for the thicker sections or under cold temperature service, and is thus not a trustworthy weldable steel. The present American Welding Society bridge specifications (*6*) permit the use of A7 steel not over 1 inch thick for minor parts not proportioned for calculated stresses.

Structural steel for welding, ASTM–A373–56T

Structural steel for welding, covered by specification ASTM–A373, has a base price somewhat greater than A7 steel.

A373 steel is recommended for use in all welded bridge construction except as otherwise stipulated by the American Welding Society bridge specifications (*6*). As has been noted, A7 steel, which is permissible for members not over 1 inch thick, may be used for minor parts not proportioned for calculated stress, or for strengthening and repair of existing structures, if it is economical to do so. This is interpreted to mean that A373 steel should be used for trusses, girders, beams, arches, rigid frames, floor beams, stringers, floor expansion devices, shoes, and other main members, but A7 steel may be used for lateral and longitudinal sway bracing, diaphragms, floor slab armor parts, railings, and similar minor parts.

For rolled beams with welded cover plates, A373 steel is required for both cover plates and beams except in cases where the engineer desires to use A7 steel, in which case approval may be given for the use of A7 steel for both beam and cover plates providing the cover plates are not over 1 inch thick. However, it is believed that there is now less reason for using A7 steel in these cases, since A373 steel has become more readily available.

A373 steel is recommended for floor expansion dams because experience has shown that the heavy impact from wheel loads tends t loosen rivets. A373 steel is recommended fo welded shoes because the use of thick plate and large size fillet welds is usually mor economical than steel castings. Steel H-pile to be spliced by welding may be either A37 of A7 steel.

For composite beam and girder construction the welding of shear connectors to compressio flanges or to those parts of tension flange where the tensile stress does not exceed 7 percent of the allowable stresses, A373, A7 or other steels considered weldable becaus of favorable conditions may be used satisfac torily. The welding of shear developers t tension flanges where the tensile stress exceed 75 percent of the allowable stress is no considered satisfactory.

Structural nickel steel, ASTM–A8

Structural nickel steel covered by th ASTM–A8 specification is used primarily fo the main stress-carrying members of larg structures. The specification covers the manufacture of shapes, plates, and bars up to 1½ inches thick.

A8 steel is not classed as weldable. I agreed between the manufacturer and th purchaser, welding may be used to conditio surface imperfections, using low-hydroge type electrodes E10015 or E10016, togethe with not less than 212° F. preheat. Othe specific instructions are contained in specification ASTM–A6. Specification A8 includes some tolerance tables which supersede similar provisions in ASTM–A6.

Structural silicon steel, ASTM–A94

Specification ASTM–A94 covers structural silicon steel used in special high-strength shapes, plates, and bars intended primarily for main stress-carrying members.

This steel is not classed as weldable. If agreed between the manufacturer and the purchaser, welding may be used to condition surface imperfections, using low-hydrogen type electrodes E6015 or E6016, together with not less than 212° F. preheat. Other specific instructions are contained in specification A6.

A94 steel has been used since the 1920's in many bridges, large and small. For smaller structures, such as beam or girder spans, the A94 steel is used for main load-carrying members. For large structures, it is used for specific members, such as chords, web members, towers, and sometimes for floor systems, in order to reduce the dead-load weight. While A94 steel has served well in structures, it is not an ideal high-strength steel.

Its hardness causes difficulties in fabrication, resulting in many surface defects during rolling. A94 steel has a lower yield point than other high-strength steels, up to 1½-inch thickness. Its lump-sum fabrication cost is about 10 percent higher than A7 steel. It has lost its favor largely because of its high carbon content.

AREA high-strength steel

Committee 15 of the American Railway Engineering Association has recently presented a specification (*7*) covering high-strength shapes, plates, and bars intended primarily for use in main stress-carrying members. This specification was intended to supersede ASTM–A94. It is subject to the general requirements of specification ASTM–A6.

Cost data on this steel are not available for small or medium tonnages. It is understood this steel is not commercially available from all manufacturers.

Structural rivet steel, ASTM–A141

Specification ASTM–A141 covers soft carbon-steel rivets for structural purposes, and has been used since 1932. The material has proved to be very satisfactory.

High-strength structural rivet steel, ASTM–A195–52T

Specification ASTM–A195 covers high-strength rivet steel. Bars are manufactured into rivets either by the hot-heading process without annealing or by the cold-heading process with annealing at 1,450° F., and cooled slowly in the furnace or in still air.

Some difficulty has been experienced in the driving of these high-strength carbon-manganese rivets, in certain instances. For this reason, a new high-strength rivet steel specification has been published by the American Society for Testing Materials with the designation A406–57T, high-strength structural rivet steel.

Tests indicate that the new steel is free from the difficulties experienced with A195 steel, to which it is similar in physical properties, but radically different in chemical composition.

Quenched and tempered steel bolts and studs, ASTM–A325–55T

High-strength bolts have been in use since 1951. Their use is rapidly expanding, both for the replacement of rivets and, in some instances, for field connections in lieu of welding or riveting, where high strength is required.

High-strength bolts, studs, nuts, and washers are covered by ASTM–A325. Open-hearth or electric-furnace steel is used, except that acid Bessemer-process steel may be used for nuts.

Bolts up to 3 inches in diameter are covered by the specification. The physical properties required are obtained by heat treating under uniform conditions, quenching in a liquid medium, and tempering by reheating uniformly to not less than 800° F.

The nuts may not be heat treated but washers are either quenched and tempered or carburized, quenched, and tempered. For the bolts, the specified minimum content of both carbon and manganese is 0.30 percent each. For carburized washers, the specification requires carbon, 0.25 percent maximum, and manganese, 1.00 percent maximum.

A recent study by AREA Committee 15 (*8*) draws the following conclusions:

1. The bolted joints have proved superior to riveted joints.
2. There will be some loss in the clamping action of some bolts, possibly due to a reseating of the steel members.
3. Bolts tightened into the plastic range stay tight.
4. The bolts should be tightened to considerably higher values than the minimum recommended to provide for a subsequent loss in clamping action.
5. Extremely low temperatures have not adversely affected the bolts.
6. The enclosed area of the bolt shank and threads that have been properly installed will not rust.

High-strength, low-alloy structural steel, ASTM–A242

Specification ASTM–A242 covers high-strength, low-alloy structural steel shapes, plates, and bars for riveted and welded construction, intended primarily for use where savings in weight and resistance to atmospheric corrosion are important. To the specified limits of carbon and manganese, the manufacturer is required by the specification to add such alloying elements as necessary to give the specified mechanical properties. If the steel is purchased for welding, the suitability of the chemical composition for the welding process, under the given conditions, should be based upon evidence acceptable to the purchaser.

All of the high-strength steels have less ductility than A7 steel. This lower ductility is frequently recognized by the engineer specifying a higher grade of workmanship for fabrication. For example, all rivet holes in all thickness of material are subpunched and reamed or drilled full size in order to avoid incipient cracks around the edges of the holes, since such defects might act as stress-raisers and promote fatigue failures or brittle failures. Some engineers use more edge distance for rivets in high-strength steels. Flame-cut edges are considered satisfactory if flame softening by post-heating is used.

It should be noted that the high yield point for this and other high-strength steels, except that covered by ASTM specifications A8 and A94, varies with the thickness when over about ¾ inch. The high-strength steels, being the same modulus of elasticity as A7 steel, have less resistance to deflection and buckling because of the use of higher working stresses.

Thus the rules for stiffeners, slenderness ratios, and ratios of plate width to thickness are more restricted. Compression flanges for composite construction buckle more easily and need special attention, particularly for erection. Rivets should preferably be not less than 1 inch in diameter. In cases where total thickness of parts riveted is ¾ inch or less, smaller size rivets may be desirable. Tack welds should be made with low-hydrogen electrodes. The A242 steels are more difficult to draw up tight before riveting or welding than the A7 steel. Fabrication costs are said to be about 5 percent greater.

The high-strength carbon steels cost 20 to 30 percent more per pound than A7 steel. However, it will often be found that these high-strength steels are more economical for movable bridges, the suspended spans of cantilever bridges, and other large and heavy structures, because of the lesser amount of steel required and the resultant savings in material cost and freight charges.

Military Specifications

Mention should be made of military specifications for high-strength steel, which are somewhat similar to the high-strength steels covered by the ASTM–A94 and A242 specifications. These are MIL–S–20166 for shapes and bars (*9*) and MIL–S–16113 for plates (*10*).

These military steels are of excellent weldability. Their cost is high because of the special manufacturing process involved.

Proprietary Steels

The proprietary steels discussed here are not covered by ASTM standard specifications, and hence must be ordered from the manufacturers by individual specification or on the basis of the manufacturer's specification.

The requirements should be included that the steel shall be manufactured by the open-hearth or electric-furnace processes. The general requirements of the ASTM–A6 specification apply.

Medium Manganese and Man-Ten A242 steels

Medium Manganese steel, manufactured by the Bethlehem Steel Company, and Man-Ten A242 steel, manufactured by the United States Steel Corporation, are high-strength steels that have been widely used for riveted structures, being in the strength class of A94 silicon steel. They meet the physical requirements, but not the chemical requirements, of the ASTM–A242 steel specification. Their cost is considerably less than that of ASTM–A242 steel, and even less than that of A94 steel.

These steels are not classed as weldable steels, although secondary welding, such as for surface conditioning, is more acceptable than for A94 steel. The welding of shear developers may be considered permissible for compression flanges. These steels contain copper and are very satisfactory for high-strength riveted steel bridge construction where corrosion resistance is important. Although the specifications of the two companies are not exactly alike, they are nearly so.

Manganese Vanadium and Tri-Ten steels

Manganese Vanadium steel, manufactured by the Bethlehem Steel Company, and Tri-Ten steel, manufactured by the United States Steel Corporation, both comply with the requirements for ASTM–A242 steels and cost about the same as other A242 steels. They also practically meet the specification MIL–S–12505 (CE) (*11*).

These steels are recommended for use where a high-strength steel of weldable quality is required. They contain copper and are satisfactory for welded bridge construction where high strength and corrosion resistance are desirable.

Mayari R and Cor-Ten steels

Mayari R steel, manufactured by the Bethlehem Steel Company, is said to be satisfactory for welding, providing the customer stipulates that the steel is to be welded. Cor-Ten steel, manufactured by the United States Steel Corporation, is said by the manufacturer to have satisfactory weldability for thicknesses up to ½ inch and will have tensile strengths equal to or in excess of the base metal; metal over ½ inch thick is to be used for riveted construction.

These steels are recommended for use where a high-strength steel and resistance to corrosion are desired. Both steels contain copper, nickel, and chromium and are therefore more resistant to corrosion than the high-strength steels discussed previously.

Quenched and tempered high-strength steel, T1

The very-high-strength steel designated as T1 by its manufacturers is not recommended for use unless properly heat treated. In this condition, it possesses toughness and weldability considerably above that usually expected at this high-strength level. It has excellent welding properties; low-hydrogen type electrodes are used, the strength or class depending upon the subsequent heat treatment.

This steel also has a high resistance to atmospheric corrosion, about four times that of carbon steel. It may have a maximum hardness of 410 VPN [2] in the heat-affected zone and may require special equipment for some fabrication operations. Preheating before flame cutting is also necessary.

The cost of T1 steel is high, yet it has been used to advantage for the very highly stressed members in large bridges or other structures. Its use at present is largely for welded pressure vessels and earth-moving equipment. T1 steel is furnished in the form of plates, bars, forgings, and semifinished products.

[2] Vickers diamond pyramid hardness number as specified in Federal Test Method Standard No. 151, Metals.

References

(1) 1957 Supplement to Book of ASTM Standards, Part I, Ferrous Metals.

(2) 1956 Supplement to Book of ASTM Standards, Part I, Ferrous Metals.

(3) 1955 Book of ASTM Standards, Part I, Ferrous Metals.

(4) Steel Products Manual, Alloy Steel, American Iron and Steel Institute, July 195, p. 5.

(5) Steel Products Manual, High Strength Low Alloy Steel, American Iron and Steel Institute, May 1955, p. 5.

(6) Standard Specifications for Welded Highway and Railway Bridges, 1956, American Welding Society.

(7) Proceedings of the American Railway Engineering Association, vol. 58, p. 687.

(8) *Use of High-Strength Structural Bolts in Steel Railway Bridges.* Report of Committee 15—Iron and Steel Structures. American Railway Engineering Association Bulletin, vol. 56, No. 520, Jan. 1955, p. 598.

(9) Military Specification (Navy), MIL–S–20166, Oct. 3, 1951. Steel: Bars and shapes (for hull construction) (including material for drop and miscellaneous forgings).

(10) Military Specification (Navy), MIL–S–16113B, Dec. 4, 1953. Steel plate, hull and ordnance, structural, black (uncoated), and zinc-coated (galvanized).

(11) Military Specification MIL–S–125((CE), Mar. 2, 1953. Steel: Structural, low alloy, for welded engineer equipment.

Motor-Vehicle Size and Weight Limits

A comparison of State legal limits of motor-vehicle sizes and weights with standards recommended by the American Association of State Highway Officials is given in a table on pages 90–91. The statutory limits reported in this tabulation, prepared by the Bureau of Public Roads as of July 1, 1958, have been reviewed for accuracy by the appropriate State officials.

Statutory limits are shown for width, height, and length of vehicles; number of towed units; maximum axle loads for single and tandem axles; and maximum gross weights for single-unit trucks, truck-tractor semi-trailer combinations, and other combinations.

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PUBLICATIONS

A Report of Factors for Use in Apportioning Funds for the National System of Interstate and Defense Highways, House Document No. 300 (1958). 15 cents.
Bibliography of Highway Planning Reports (1950). 30 cents.
Braking Performance of Motor Vehicles (1954). Out of print.
Consideration for Reimbursement for Certain Highways on the Interstate System, House Document No. 301 (1958). 15 cents.
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Design Capacity Charts for Signalized Street and Highway Intersections (reprint from PUBLIC ROADS, Feb. 1951). 25 cents.
Electrical Equipment on Movable Bridges, No. 265T (1931). 40 cents.
Factual Discussion of Motortruck Operation, Regulation, and Taxation (1951). 30 cents.
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Highway Bond Calculations (1936). 10 cents.
Highway Capacity Manual (1950). $1.00.
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1945 (out of print).	1949, 55 cents.	1953, $1.00.
1946 (out of print).	1950 (out of print).	1954, 75 cents.
1947 (out of print).	1951, 60 cents.	1955, $1.00.
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Legal Aspects of Controlling Highway Access (1945). 15 cents.
Local Rural Road Problem (1950). 20 cents.
Manual on Uniform Traffic Control Devices for Streets and Highways (1948) (*including 1954 revisions supplement*). $1.25.
Revisions to the Manual on Uniform Traffic Control Devices for Streets and Highways (1954). *Separate*, 15 cents.
Mathematical Theory of Vibration in Suspension Bridges (1950). $1.25.
Needs of the Highway Systems, 1955–84, House Document No. 120 (1955). 15 cents.
Opportunities in the Bureau of Public Roads for Young Engineers (1958). 20 cents.
Parking Guide for Cities (1956). 55 cents.
Principles of Highway Construction as Applied to Airports, Flight Strips, and Other Landing Areas for Aircraft (1943). $2.00.
Progress and Feasibility of Toll Roads and Their Relation to the Federal-Aid Program, House Document No. 139 (1955). 15 cents.
Public Control of Highway Access and Roadside Development (1947). 35 cents.
Public Land Acquisition for Highway Purposes (1943). 10 cents.
Public Utility Relocation Incident to Highway Improvement, House Document No. 127 (1955). 25 cents.
Results of Physical Tests of Road-Building Aggregate (1953). $1.00.
Roadside Improvement, No. 191MP (1934). 10 cents.
Selected Bibliography on Highway Finance (1951). 60 cents.
Specifications for Aerial Surveys and Mapping by Photogrammetric Methods for Highways, 1956: a reference guide outline. 55 cents.
Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP-57 (1957). $2.00.
Standard Plans for Highway Bridge Superstructures (1956). $1.75.
Taxation of Motor Vehicles in 1932. 35 cents.
Tire Wear and Tire Failures on Various Road Surfaces (1943). 10 cents.
Transition Curves for Highways (1940). $1.75.

Single copies of the following publications are available to highway engineers and administrators for official use, and may be obtained by those so qualified upon request addressed to the Bureau of Public Roads. They are not sold by the Superintendent of Documents.

Bibliography on Automobile Parking in the United States (1946).
Bibliography on Highway Lighting (1937).
Bibliography on Highway Safety (1938).
Bibliography on Land Acquisition for Public Roads (1947).
Bibliography on Roadside Control (1949).
Express Highways in the United States: a Bibliography (1945).
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