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Origin and Destination Characteristics

8 Reports

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Foreword

Origin and destination studies are useful in the planning, design and operation of transportation routes and terminals. When such studies appeared on the scene several decades ago, the procedures were relatively simple. As facility demand increased and all forms of transportation began to be considered, O-D studies necessarily became more comprehensive and increasingly complex. The advent of the high-speed computer brought additional technology to bear on the problems—the 1962 highway legislation served to further this type of work—so that O-D studies have virtually achieved scientific status although admittedly operating in an area where a great deal of "art" as compared to "science" still exists.

The papers in this RECORD present for the most part findings derived from the massive transportation studies under way in the large urban areas of the country. The roles of the various modes, the fine points of the methodology emphasized, the problems involved in handling large amounts of data—all these aspects and many more are presented here. Officials of agencies such as highway departments, transit companies, urban transportation planning groups and city planning organizations will find the material to be of interest. However, the chief beneficiaries will be those involved in the day-to-day operation of the many urban transportation studies.

The first paper examines trip generation and trip attraction as found in two small Canadian cities. Relationships existing between various factors and the relative degree of error expected with different sample sizes are reported.

The difficult task of predicting potential rapid transit trips from those trips made using surface transit has been examined for the Washington, D.C., area in the second paper. Using special computer programs, the authors evolved a sensitive diversion analysis technique, results of which indicated greater accuracy in the prediction of trips over previously utilized methods.

In the third paper, a Tri-State Transportation Commission researcher reports on the various techniques used to estimate and distribute auto ownership for forecasting person and vehicle trips. Numerous variables were investigated and it was found that the best methodology used the combined effects of household income and residential density.

Cost savings possible through simulation techniques, alternate sampling methods and refinement and elimination of present procedures in transportation studies are explored by two consultants in the fourth paper. The large sums of money spent on urban planning could be reduced if techniques shown in this paper were employed. Two discussions explore the views presented.

The problems of programming an algorithm to find minimum time paths through a large transit system are set forth in the next paper. Step-by-step descriptions and flow charts of the "tree-building" algorithm and transit "pathfinder" algorithm are presented. Use of the pathfinder program is said to significantly reduce the number and degree of problems confronting the analyst.

In the sixth paper, a Tri-State Transportation Commission analyst has explored sampling methods for collecting transit passenger data. A method of sampling existing transit services to obtain the requisite data is outlined.

Three examples are given of surveys using the sample design, and the results of the three different surveys are compared.

The next paper, by a Bay Area Transportation Study researcher, presents a novel traffic assignment procedure designed essentially to cope with the problem of evaluating large numbers of transportation system alternatives, rather than just elements of a system or only a few alternatives, as is presently the case.

Three consultants show, in the final paper, how intercity highway travel can be projected using O-D data. In Illinois and Arizona, functional classification systems of streets and highways were developed. Trip length and traffic volume data were utilized to develop the future facility needs for 1985. The paper outlines the basic procedures employed (different for each state) and the results achieved.

Contents

Trip Production and Attraction Characteristics in Small Cities

M. D. HARMELINK, Department of Highways, Ontario;
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H. M. EDWARDS, Queen's University, Kingston, Ontario

Several factors affecting the estimation of trips produced by and attracted to various areas of a small city were examined for various trip purposes. The trip production study was conducted for one city only, Kingston, Ontario, while the trip attraction study treated two cities, Kingston and Barrie, Ontario. Planning and assessment departments and home-interview O-D surveys provided all the basic data. For the most part, 24-hour person trips by vehicle were studied.

In the production study, attempts were made to relate trip production to car ownership, population, distance from CBD, residential density, proportion of single-family dwelling units, and percentage of the population less than five years of age. The most reliable predictor of trip production was found to be car ownership. Results indicated decreased accuracy of trip estimation with increased segregation of trip purpose, and showed little improvement in the trip estimates with increased sample sizes. In the attraction study, relationships were found between attracted trips and the assessed value of land and buildings and area of land in each of four land-use categories. The results of the study have expected application in both conventional O-D surveys and mathematical traffic models.

•FOR proper evaluation of the transportation problems in an urban area, a knowledge of traffic movements within the area is essential. A quantitative understanding of the factors which influence traffic movement is, therefore, of major importance.

As an outgrowth of comprehensive origin-destination studies and the relation of area traffic movements to land use and economic and population characteristics of the area, mathematical models (formulae) describing traffic movements have been developed and used for predicting future traffic movements in the area. Home-interview O-D surveys are still required for model formulation since they provide the most reliable input data necessary for the model (1). It is claimed, however, that fewer interviews are required for model formulation than for conventional O-D surveys.

This paper describes trip production and attraction characteristics in small cities. Certainly, previous attempts have been made to relate the number of trips produced by residents of an area to certain population and location characteristics. Kudlick, Fisher, and Vance (2) used car ownership and population as predictors of trips from a zone. Others have used labor force as a predictor of work trips, where such data were available (3). Mertz and Hamner (4) used car ownership, population density, income per household, and distance from the CBD as predictors of total trips, but found that car ownership was the most reliable predictor.

Attempts have also been made to relate the number of trips attracted to an area to land-use characteristics of the area. Voorhees (3, 5), Barnes (6), and Kudlick, Fisher,

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and Vance (2) all used employment and population as predictors of trips attracted to a zone. Harper and Edwards (7) found a strong relationship between the total number of daily person trips attracted to the CBD and the floor-space area in three use categories—retail, service-office, and manufacturing-warehousing.

However, few investigations of the factors affecting trip production and attraction appear to have been made for small cities (less than 75,000 population), where good land-use data are less generally available. Moreover, the effects of sample size on accuracy of trips estimates and on the optimum trip purpose groupings to be used have seldom been examined. These matters were felt to warrant investigation. A further innovation was relating trip attraction to assessment values (readily available in small cities) rather than to employment in each of several categories, estimates which may not be so readily available in small cities. Besides reflecting intensity of land use and competitiveness between different land uses, assessment will also reflect multiple usage of land or buildings. It is recognized that assessment values will probably not be equal to real market values, but they should reflect relative values within the same land-use categories. Moreover, since the assessment process is generally treated in a quasi-judicial manner (by the method governing appeal), assessed values of land and buildings have little tendency to reflect speculation in land and building values and thus supply stable, consistent measures of land-use intensity as it exists—not as the market thinks it should exist.

The city selected for the trip production study was Kingston, Ontario (study area population of 63,000). The cities selected for the attraction study were Kingston and Barrie, Ontario (study area population of 22,000). The data used in the studies were obtained from the planning and assessment departments in each city and from the home-interview origin-destination study conducted in each city in 1961 according to Bureau of Public Roads recommendations.

TRIP PRODUCTION

Research Procedure

The trip production study was concerned only with daily (24-hour) person trips by vehicle made by residents of the study area. Data from separate truck, taxi, and external roadside surveys were excluded, and there was no modal split. Fifty-five traffic zones were used in the study, of which 49 were Group A zones (predominantly single-family dwelling units) and 6 were Group B zones (predominantly multiple-family dwelling units).

Three sample sizes (based on the total number of dwelling units) were selected to cover a reasonable range of sizes and to bracket the number of 1,000 interviews suggested as adequate for gravity model formulations (8). The emphasis in this study was placed on systematic sampling rather than cluster sampling. Cluster sampling has been used in several model formulations; however, Hansen, Hurwitz, and Madow (9), Deming (10), and Lieder (11) all suggest reasons for preferring systematic sampling to cluster sampling, the primary reason being smaller variance. The samples were selected by systematically sampling the original 12½ percent dwelling unit sample identification number; the results of the sample selection are shown in Table 1. Although no definite conclusions could be drawn regarding variability among samples of the same size, the two 5 percent samples were tested to observe qualitatively the kind of differences that might arise.

To examine the effect of various trip purpose categories on accuracy of prediction, trip production studies were made for seven trip purposes, as follows:

1. Total trips,
2. Home-origin work trips,
3. Non-work home-origin trips,
4. Non-home-based trips (neither origin nor destination at home),
5. Home-origin shopping trips,
6. Home-origin social-recreational trips, and
7. Miscellaneous home-origin trips.

TABLE 1

KINGSTON SAMPLE SELECTION

Sample Designation	Sampling Rate	Sample Size: No. of D.U.'s	No. of Sample D.U.'s selected out of every 10 Home-Interview D.U.'s
S-.025-K	2.5%	508	2
S-.05-1-K	5.0%	983	4
S-.05-2-K	5.0%	984	4
S-.10-K	10.0%	1967	8

Note: "S-.025-K" designates a $2\frac{1}{2}$% sample of Kingston data

The category "total trips" for a given zone refers to all person trips by vehicle made by the residents of that zone, regardless of origin or destination of trip, and excludes all trips made to or from the zone by non-residents of the zone. The "miscellaneous" category includes trips made for the purposes of personal business, medical-dental service, school, eating a meal, changing mode of travel, and serving passengers.

If it is assumed that all home-origin trips return home, estimates of total trips may be made in three ways, using different combinations of the given trip-purpose categories, as follows:

Total Trip Estimate 1:	Trip Purpose Category 1
Total Trip Estimate 2:	Trip Purpose Categories 2, 3, 4
Total Trip Estimate 3:	Trip Purpose Categories 2, 4, 5, 6, 7

For the sample sizes tested, attempts were made by means of simple and multiple regression analysis to relate sampled trips per D.U. for various purposes to sampled values of the following land-use parameters and characteristics of the zonal population:

x_1 Cars/dwelling unit
x_2 (Cars/dwelling unit)^2 = x_1^2
x_3 Persons/dwelling unit
x_4 (Persons/dwelling unit)^2 = x_3^2
x_5 Airline distance from CBD (tenths of miles)
x_6 $\log_{10}$ (airline distance from CBD) = $\log_{10} x_5$
x_7 Residential density (dwelling units/net residential acre)
x_8 $\log_{10}$ (residential density) = $\log_{10} x_7$
x_9 Proportion of single-family dwelling units
x_{10} Percentage of population less than 5 years of age

In the regression analysis, the observations were weighted in accordance with the number of dwelling units in the zone.

The estimation equations of best fit are fully documented (12). The equations for total trips, home-origin work trips, and home-origin shopping trips are given in Table 2.

The trip estimation equations showed that in Kingston, car ownership was the most reliable single predictor of the trips produced by residents of a zone. For almost all estimates, car ownership was a variable in the estimation equations, and only for home-origin shopping or social-recreational trips was the multiple regression equation an improvement over the simple regression equation using car ownership alone as the independent variable or predictor.

An important observation was that, for a given trip purpose category, although the regression equations derived from the larger sample sizes appear to be better estimating equations by virtue of their larger coefficients of correlation and smaller standard errors, the actual regression equations for different sample sizes show a distinct similarity. This similarity was evident for all trip purpose categories except home-origin shopping and social-recreational trips, where greater equation differences occur.

TABLE 2
BEST REGRESSION EQUATIONS FOR TRIP PRODUCTION ESTIMATES (KINGSTON)

Sample	Total Trips	Home-Origin Work Trips	Home-Origin Shopping Trips
S - .025 - K	$y' = -2.327 + 8.757x_1$ $r = 0.87$ $S_e = 1.39$ Trips/D.U.	$y' = 0.149 + 1.002x_1$ $r = 0.71$ $S_e = 0.29$ Trips/D.U.	$y' = -0.017 + 0.448x_6 - 0.0085x_{10}$ $r = 0.47$ $S_e = 0.24$ Trips/D.U.
S - .05 - 1 - K	$y' = -2.484 + 8.289x_1$ $r = 0.90$ $S_e = 1.05$ Trips/D.U.	$y' = -0.025 + 1.095x_1$ $r = 0.75$ $S_e = 0.25$ Trips/D.U.	$y' = 0.902 - 1.152x_1 + 0.859x_2 - 0.328x_8$ $r = 0.85$ $S_e = 0.12$ Trips/D.U.
S - .05 - 2 - K	$y' = -2.710 + 8.751x_1$ $r = 0.91$ $S_e = 1.04$ Trips/D.U.	$y' = -0.013 + 1.145x_1$ $r = 0.79$ $S_e = 0.23$ Trips/D.U.	$y' = 0.038 + 0.399x_6 - 0.012x_{10}$ $r = 0.66$ $S_e = 0.14$ Trips/D.U.
S - .10 - K	$y' = -3.041 + 8.983x_1$ $r = 0.94$ $S_e = 0.70$ Trips/D.U.	$y' = -0.024 + 1.124x_1$ $r = 0.81$ $S_e = 0.19$ Trips/D.U.	$y' = -0.056 + 0.155x_2 + 0.209x_6$ $r = 0.81$ $S_e = 0.10$ Trips/D.U.

Note: y' = Trips/D.U.

Trip Estimates and Discussion of Errors

From the regression equations, the number of zonal trips for each trip purpose category was calculated from the actual zonal values of the basic parameters listed previously and the total number of zonal dwelling units. The actual zonal values of the basic parameters (except for distance from the CBD and residential density, which were measured directly) were obtained from an expansion of the original 12½ percent sample to 100 percent, due to lack of better data. However, where sample sizes smaller than 12½ percent were tested, it was assumed that base data comparable to those obtained from the expansion of the 12½ percent sample to 100 percent would be available from planning sources, and the comparable base data could be substituted in the estimating equations.

For a comparison of actual and estimated trips, the actual number of trips was obtained in each case from an expansion of the original 12½ percent home-interview survey data to 100 percent. Although it was recognized that these actual trip values are probably in error, they were used as the standard of comparison in this analysis because they are the generally accepted figures, because they have been used as a standard of comparison in other studies (7, 13, 14), and because there was no available substitute.

The estimated trip volumes were compared with the corresponding actual trip volumes and the errors or discrepancies were calculated. These results are documented elsewhere (12), and are shown graphically for total trips, home-origin work trips, and home-origin shopping trips in Figures 1, 2, and 3 respectively.

So that Figures 1-3 could be plotted, actual zonal volumes of trips were grouped into arbitrary ranges of trip volumes. For each range of trip volumes, the root-mean-square (RMS) error was calculated and plotted as a percent at the arithmetic mean of the trip volumes in the range:

$$\text{RMS error} = \sqrt{\frac{\sum_{i=1}^{n} \left(V_{est} - V_{act}\right)^2}{n}} \tag{1}$$

where

V_{est} = estimated volume,
V_{act} = corresponding actual volume, and
n = number of zones in range.

$$\text{Percent RMS error} = \frac{\text{RMS error}}{\overline{V}} \times 100 \tag{2}$$

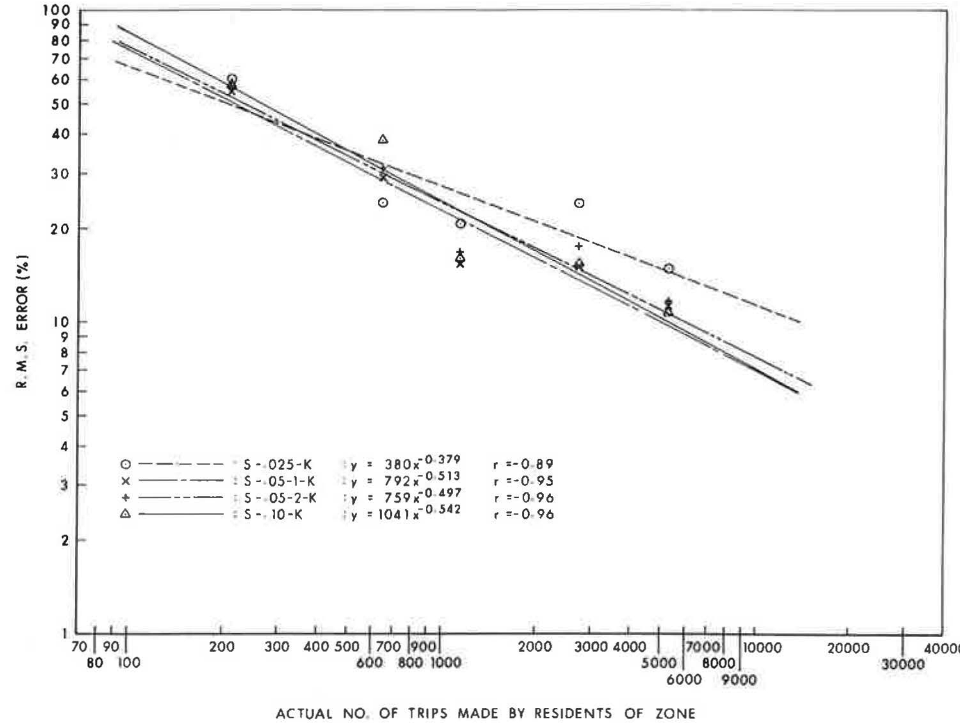

Figure 1. Errors in production estimates of total trips for various sample sizes.

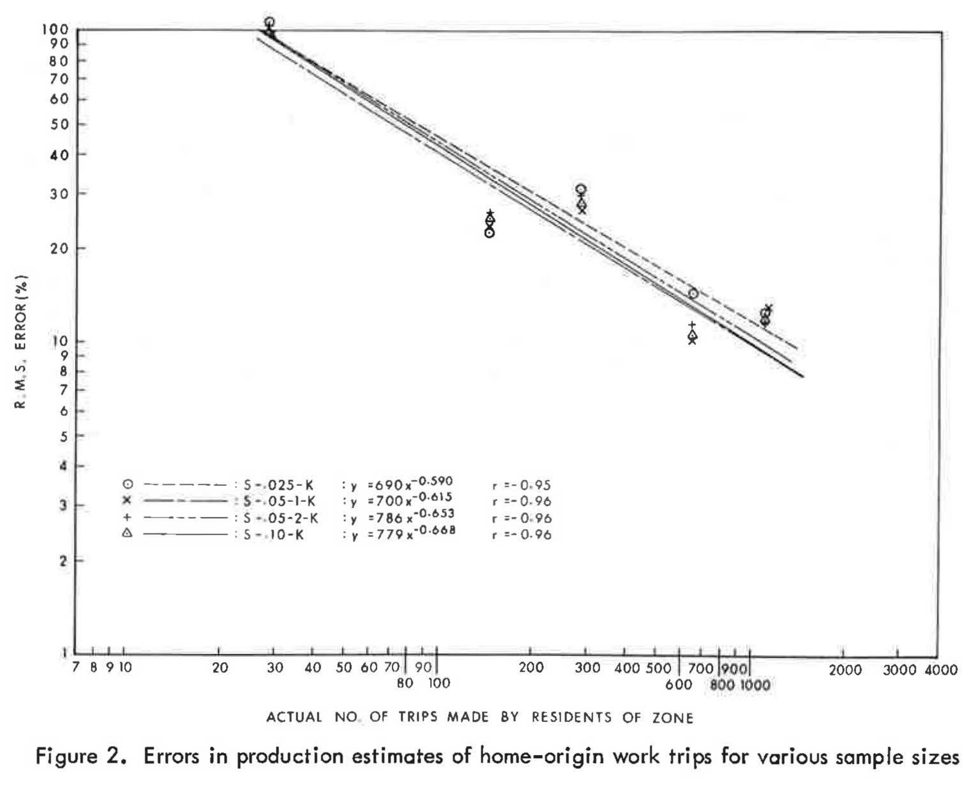

Figure 2. Errors in production estimates of home-origin work trips for various sample sizes.

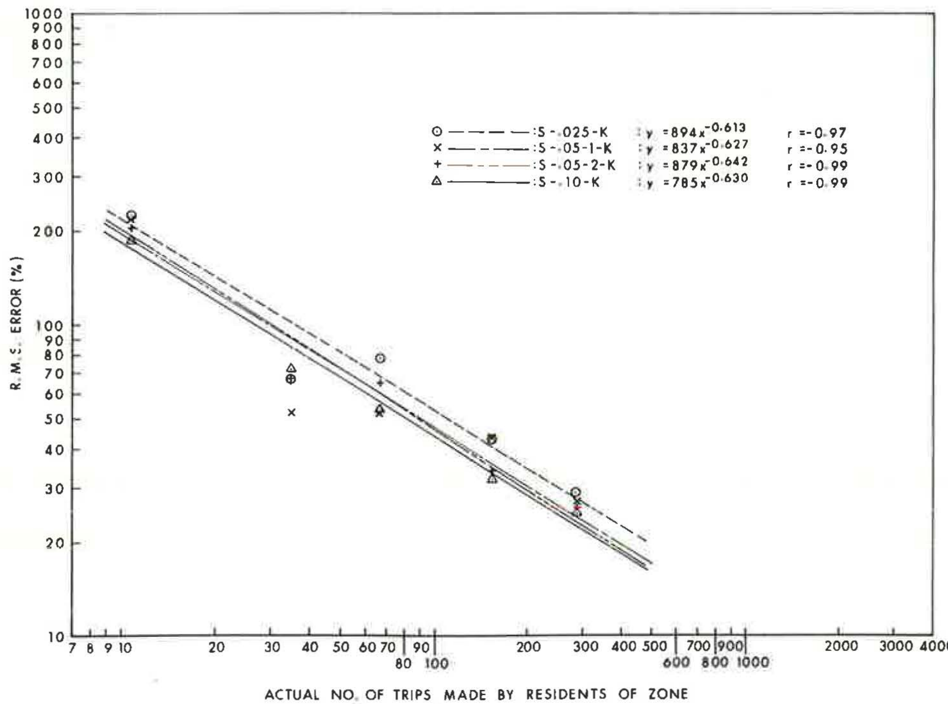

Figure 3. Errors in production estimates of home-origin shopping trips for various sample sizes.

where $\overline{V}$ = mean actual trip volume in range. The percent RMS error was plotted against $\overline{V}$.

Now, similar estimating equations, though derived from different sample sizes, would be expected to produce trip estimates of comparable accuracy. Generally this was found to be true, as shown by Figures 1-3. For total trips, home-origin work trips, non-work home-origin trips, non-home-based trips, home-origin social-recreational trips, and miscellaneous home-origin trips, the 5 percent samples appear to produce results as good as or better than the 10 percent sample, with some overlap of the curves. The $2\frac{1}{2}$ percent sample is generally slightly poorer than the 5 percent or 10 percent samples, but the differences are not great. For home-origin shopping trips, larger sample sizes appear to improve the estimates slightly, but again the differences are not great. This seems to indicate that sample size (within the range of sample sizes tested) has little effect on accuracy of trip production estimates, and that a considerable cost saving could be made by using a relatively small systematic sample. The use of a small sample is, of course, contingent upon the adequacy of a small sample

TABLE 3

COMPARISON OF RMS ERRORS AMONG TRIP PURPOSE CATEGORIES

Trip Purpose Category	Average RMS Error at Zonal Trip Volume of			
	10	100	1000	10000
Total	-	79%	24%	7%
Home-Origin Work	205%	42%	10%	-
Non-Work Home-Origin	110%	41%	15%	-
Non-Home-Based	-	69%	24%	-
Home-Origin Shopping	194%	45%	-	-
Home-Origin Soc.-Rec.	116%	40%	-	-
Miscellaneous Home-Origin	-	44%	20%	-

for trip attraction and distribution as well as for trip production. The effect of sample size on trip attraction estimates is described in a later section of this paper.

In all cases, the percent RMS errors decrease with increasing trip volume. With increased segregation of trip purposes, the trip volumes considered are smaller, and the percent RMS errors are generally larger over the range of trip volumes. However, Table 3 shows that at a given zonal trip volume, the errors are about the same size for all trip purpose categories except for total trips and non-home-based trips, whose errors are somewhat larger and approximately equal. Although the percent RMS error at 10 zonal trips shows considerable variability, the absolute difference is quite small and insignificant.

No definite conclusions can be made at present regarding the number of trip purpose categories that should be used in a small city. Table 3 indicates that for a given volume, average percent RMS errors will be approximately equal for all trip purpose categories except total trip and non-home-based trips. It would appear then that the smaller trip purpose categories may be used for production estimates, but the larger trip purpose categories should be used as a check on them. Even then, however, the check may not provide much of an improvement over the individual purpose categories used separately. For example, in a given zone assume:

		Approx. RMS Error	Approx. Absolute Error
No. of Home-Origin Work Trips	= 100	42%	42
No. of Non-Work Home-Origin Trips	= 100	41%	41
No. of Non-Home-Based Trips	= 30	120%	36

Assuming that the home-origin trips return home,

No. of Home-Oriented Work Trips	= 200	42%	84
No. of Home-Oriented Non-Work Trips	= 200	41%	82
No. of Non-Home-Based Trips	= 30	120%	36
Total No. of Zonal Trips	= 430	Total Error	= 202

Thus using the individual purpose categories, the RMS error $\approx 202/430 = 47$ percent. Using Figure 1, for total trips, at 430 trips, the RMS error is about 37 percent, an improvement of about 10 percent. Using an even further segregation of purpose categories, and assuming the 200 home-oriented non-work trips to be made up of 70 home-oriented shopping trips, 70 home-origin social-recreational trips, and 60 miscellaneous home-oriented trips, the RMS error on total trips is about 62 percent, compared with 47 percent and 37 percent as determined earlier.

Grouping zones into districts also has the general effect of reducing percentage errors. When the trip estimates for individual zones were summed to district totals, the percentage errors for the district totals were generally found to be quite small in relation to many of the percentage errors in the individual zonal estimates. As with trip purpose categories, as greater definition and segregation are sought (in this case, of land areas), the accuracy of trip production estimates is decreased.

In traffic model analysis, trip production values have generally been assumed correct, and where discrepancies arise in screenline checks or trip length distributions, adjustments have been made to either the attraction figures or the time function used in distribution. This study indicates, however, that errors in trip production estimates may be sizable. Thus, it would seem appropriate to examine the effect that higher production rates might have on trip distribution and assignment, especially in critical areas.

Theoretical Standard Error Determination About the True Zonal Production Values

In the preceding discussion of errors, the errors were determined using the actual, or expanded home-interview, numbers of trips produced by each zone as the standard of comparison. It is recognized that these actual values may themselves be in error, but they were accepted as being the best available standard of comparison.

While it is not possible to determine the errors measured about the true or correct, but unknown, zonal values (of which the actual zonal values are estimates), it is possible to determine statistically the range in which the true zonal value is expected to lie, and this expected error in the estimate of the true zonal value may be combined with the standard error of the regression line to obtain a statistical expected standard error of the zonal trip estimate.

The derivation of this expected standard error is as follows:

Sampling is carried out in a number of zones in a specified area, and Z_T is the total number of sampled zones. For each zone i, the sample provides an estimate of the mean number of trips per D. U.,

$$\hat{y}_i = \frac{\text{Sample trips, zone i}}{\text{No. of sampled D. U.'s in zone i}} = \frac{\Sigma y_{ij}}{n_i} = \text{Sample No. of trips per D. U. produced by zone i}$$

where y_{ij} = sample number of trips from D. U. j in zone i. For zone i, the variance of the number of trips per D. U. is (9):

$$S^2_{y_i} = \frac{\Sigma (y_{ij} - \hat{y}_i)^2}{n_i - 1} \left(1 - \frac{n_i}{N_i}\right)$$

where N_i = total number of D. U.'s in zone i, and

$$\left(1 - \frac{n_i}{N_i}\right) = \text{finite population correction, zone i,} = fpc_i$$

These $\hat{y}_i$ values, with their corresponding $\hat{x}_i$ values, were combined in a regression analysis. This produced the regression line $y' = a + bx$. The estimate of the number of trips produced by zone i is then:

$$Y_i' = N_i \, y_i' \qquad (3)$$

where y_i' = regression estimate of trips per D. U. for zone i. The variance of this estimate, from which the standard error of the estimated Y_i' may be determined, is:

$$\text{Var } (Y_i') = \text{Var } (N_i \, y_i') = N_i^2 \text{ Var } (y_i') \qquad (4)$$

The true variance of y_i', the regression estimate of trips per D. U., is:

$$S^2_{y_i'} = \frac{\Sigma (y_i' - \bar{y}_i)^2}{\nu_i} \qquad (5)$$

where

$\bar{y}_i$ = true, or correct, value of trips per D. U. for zone i, and
ν_i = degrees of freedom, zone i.

This true variance $S^2_{y'_i}$ is made up of two parts:

1. The variance between the regression estimates and the sample estimates of trips per D. U.—this variance is the square of the standard error of the regression line.
2. The variance between the sample estimates of trips per D. U. and the true values of trips per D. U.—this part is normally not considered, because it is usually assumed that the observed values used in regression analyses are true, not sampled, values.

Considering the sums of squares only,

$$\begin{aligned}\Sigma(y'_i - \bar{y}_i)^2 &= \Sigma\left[(y'_i - \hat{y}_i) + (\hat{y}_i - \bar{y}_i)\right]^2 \\ &= \Sigma(y'_i - \hat{y}_i)^2 + 2\Sigma(y'_i - \hat{y}_i)(\hat{y}_i - \bar{y}_i) + \Sigma(\hat{y}_i - \bar{y}_i)^2\end{aligned}$$

The two parts of the variance are independent. Therefore, the cross-product term becomes zero, and

$$\Sigma(y'_i - \bar{y}_i)^2 = \Sigma(y'_i - \hat{y}_i)^2 + \Sigma(\hat{y}_i - \bar{y}_i)^2 \tag{6}$$

or

$$S^2_{y'_i} = \frac{\Sigma(y'_i - \hat{y}_i)^2}{\nu_i} + \frac{\Sigma(\hat{y}_i - \bar{y}_i)^2}{\nu_i}$$

i. e.,

$$S^2_{y'_i} = S^2_e + \frac{\Sigma(\hat{y}_i - \bar{y}_i)^2}{\nu_i} \tag{7}$$

The true value of the zone average, $\bar{y}_i$, is unknown. However, in general terminology, the variance of sample means about the true mean may be determined from

$$S^2_{\bar{y}} = \frac{S^2_y}{n} = \frac{\Sigma(y - \hat{y})^2}{n(n-1)} \text{ (fpc)}$$

Now, in a given zone i, a sample of n_i D. U.'s provides $\hat{y}_i$ and

$$S^2_{y_i} = \frac{\Sigma(y_{ij} - \hat{y}_i)^2}{n_i - 1} \text{ (fpc}_i\text{)}$$

and the variance of $\hat{y}_i$ about $\bar{y}_i$, the true mean, will be

$$S^2_{\bar{y}_i} = \frac{S^2_{y_i}}{n_i} \tag{8}$$

and for a given zone,

$$S^2_{y'_i} = S^2_e + S^2_{\bar{y}_i} \tag{9}$$

Over all or selected zones, a pooled or weighted estimate of this variance may be determined from

$$S^2_{\bar{y}} = \frac{\nu_1 S^2_{\bar{y}_1} + \nu_2 S^2_{\bar{y}_2} + \nu_3 S^2_{\bar{y}_3} + \dots + \nu_p S^2_{\bar{y}_p}}{\nu_1 + \nu_2 + \nu_3 + \dots + \nu_p}$$

where p represents the p th and final zone to be included in the pooled variance calculation.

Now, since in each zone,

$$S^2_{\bar{y}_i} = \frac{S^2_{y_i}}{n_i} = \frac{SSD_i}{n_i\,\nu_i}\ (fpc_i)$$

where SSD = sum of squares of deviations, then,

$$\nu_i\, S^2_{\bar{y}_i} = \frac{SSD_i}{n_i}\ (fpc_i)$$

Therefore:

$$S^2_{\bar{y}} = \frac{\frac{SSD_1}{n_1}(fpc_1) + \frac{SSD_2}{n_2}(fpc_2) + \ldots + \frac{SSD_p}{n_p}(fpc_p)}{\nu_1 + \nu_2 + \ldots + \nu_p} \qquad (10)$$

Also, $\nu_i = n_i - 1$. Hence,

$$\Sigma\nu_i = \sum_{i=1}^{p} (n_i - 1) = \Sigma n_i - p$$

so that

$$S^2_{\bar{y}} = \frac{\sum_{i=1}^{p} \frac{SSD_i}{n_i}(fpc_i)}{\sum_{i=1}^{p} n_i - p}$$

Since $S^2_{y'} = S^2_e + S^2_{\bar{y}}$, therefore

$$S^2_{y'} = S^2_e + \frac{\sum_{i=1}^{p}\sum_{j=1}^{n_i} \frac{(y_{ij} - \hat{y}_i)^2}{n_i}\left(1 - \frac{n_i}{N_i}\right)}{\sum_{i=1}^{p} n_i - p} \qquad (11)$$

Two assumptions have been made in the derivation of Eq. 11:

1. Within a given zone, the frequency distribution of the number of trips per D. U. is approximately normal; and
2. Among all zones, the variances of the number of trips per D. U., $S^2_{y_i}$, are approximately equal.

Both assumptions were found to be false. The frequency distribution in the first assumption appeared to be a truncated normal distribution rather than normal, and the $S^2_{y_i}$ varied considerably from zone to zone, often because of an occasional very high value of trips per D. U. of 20 or more.

For this analysis (total trips only), the weighted average zonal variance was determined for each sample size by summing the individual sums of squares of deviations about the zonal means and dividing by the total number of sampled D. U.'s less the number of zones. Thus, for zone i,

$$S^2_{y_i} = \frac{SSD_i}{n_i - 1} (fpc_i)$$

Over all zones, and assuming fpc_i is the same for all zones, the weighted average zonal variance becomes

$$\overline{S^2_y} = \frac{\sum_i SSD_i}{\sum_i (n_i - 1)} (fpc) = \frac{\sum_i SSD_i}{\sum_i n_i - Z_T} (fpc)$$

where Z_T = total number of sampled zones. For any zone having n_i sampled D. U.'s,

$$S^2_{y'_i} = S^2_e + \frac{\overline{S^2_y}}{n_i}$$

The values of S^2_e, $\frac{\Sigma SSD_i}{\Sigma n_i - Z_T}$, and fpc for each sample size (the two 5 percent samples have been averaged) are given in Table 4. On the basis of Table 4, Figure 4 was plotted for comparison with Figure 1. In a sense Figure 4 is somewhat artificial, for the $S_{y'_i}$ values, from which the RMS errors in Figure 4 are derived, are related to the number of dwelling units rather than the number of trips. Each point plotted in Figure 1 represents a certain range of trip volumes; in order to provide a comparison with Figure 1, the same zones grouped for each range in Figure 1 were grouped for each point in Figure 4.

The RMS error and $S_{y'_i}$ are analogous measures of dispersion, whose squared values are equal to the average value of the squares of the deviations from a central value. In the case of the RMS error in Figure 1, the central value is the expanded or actual number of trips; in the case of the RMS error in Figure 4 derived from S_{y_i}, the central value is the true number of trips, and this RMS error expresses the statistical expectation of the variation from this value. The values plotted in Figure 4 were obtained by finding $\overline{x}$, the average number of zonal total trips in each range, and $\overline{N}$, the average number of total zonal dwelling units in each range. The average RMS error for each range is then, from Eq. 4,

$$\text{RMS error} = \overline{N}\, S_{y'_i}$$

Expressed as a percentage of the average zonal trip volume in the range,

$$\text{Percent RMS error} = \frac{\overline{N}\, S_{y'_i}}{\overline{X}} \times 100 \qquad (12)$$

TABLE 4

VALUES OF S^2_e, $\frac{\sum SSD_i}{\sum n_i - Z_T}$ AND fpc BY SAMPLE SIZE (TOTAL TRIPS)

Sample Size	S^2_e	$\frac{\sum SSD_i}{\sum n_i - Z_T}$	fpc	$S^2_{y'_i}$
2 ½%	1.93	28.05	0.975	$S^2_{y'_i} = 1.93 + \frac{28.05}{n_i} (0.975)$
5 %	1.09	22.40	0.950	$S^2_{y'_i} = 1.09 + \frac{22.40}{n_i} (0.950)$
10 %	0.49	22.58	0.900	$S^2_{y'_i} = 0.49 + \frac{22.58}{n_i} (0.900)$

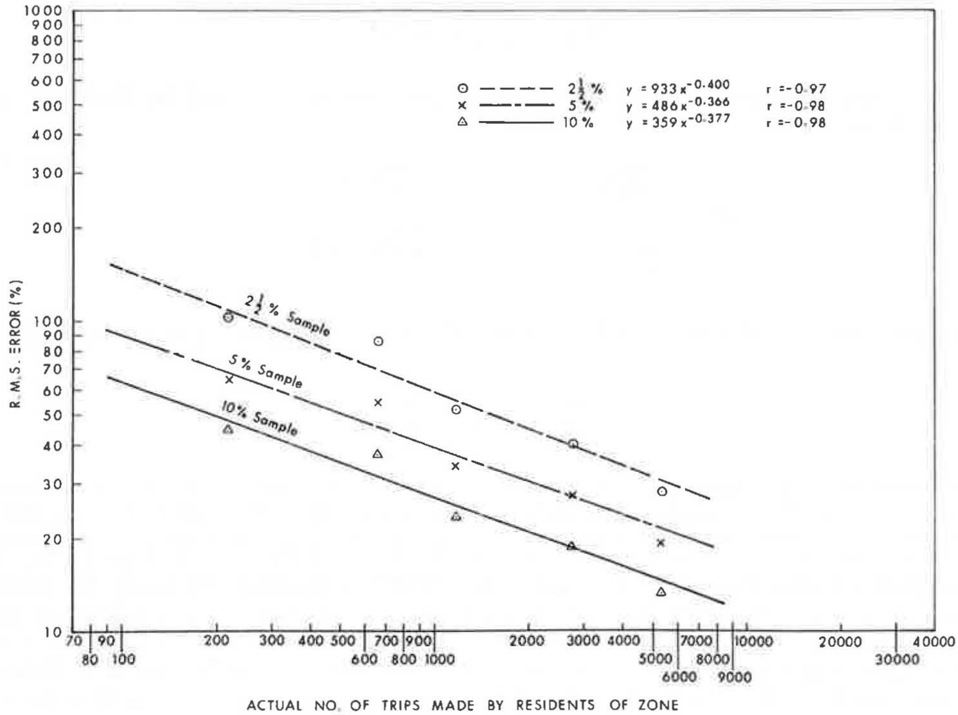

Figure 4. Relationship between RMS error based on total trips S_{y_i}' and trip volume.

Comparison of Figures 1 and 4 indicates that larger errors may be expected statistically than are apparently obtained when the actual number of trips is used as the standard of comparison. It is to be expected that some of the actual trip volumes used as standard in Figure 1 are in fact in error, so that the true errors in the trip estimates cannot be determined. On the other hand, if the trip estimation equations are very similar among sample sizes, and if they produce very similar zonal trip volume estimates, it follows that the error curves must be very similar, as they are in Figure 1. Figure 4 therefore shows not the true RMS error, but rather what we might consider the limit of the expected RMS error and the dependence of that limit on sample size.

TRIP ATTRACTION

Research Procedure

The trip attraction study was conducted for both Kingston and Barrie, and it too was concerned only with daily person trips by vehicle made by residents of the study area.

TABLE 5

BARRIE SAMPLE SELECTION

Sample Designation	Sampling Rate	Sample Size: No. of D.U.'s	No. of Sample D.U.'s Selected out of every 10 Home-Interview D.U.'s
S-.04-B	4.0%	260	2
S-.08-1-B	8.0%	504	4
S-.08-2-B	8.0%	502	4
S-.16-B	16.0%	1006	8
S-Total-B	20.0%	1254	10

Fifty zones were used in the Kingston study and 31 zones in the Barrie study. For Kingston, the same sample sizes were used as for the production study: $2\frac{1}{2}$ percent, 5 percent, 10 percent, and in addition, the full $12\frac{1}{2}$ percent sample. For Barrie, the systematic sample sizes tested were 4 percent, 8 percent, 16 percent, and the full 20 percent sample, with the 16 percent sample size approximating 1,000 interviews, as shown in Table 5.

The trip purpose categories examined in the attraction study were the same for both Kingston and Barrie, and were designated as follows:

ALL: The total of all purpose categories
1: Trips to work
2: Trips made to conduct personal business
8: Trips made to shop
0: Trips made to home

The modal breakdown was also examined to some extent in that examinations were made for

1. All modes combined (excluding walking trips), and
2. Auto driver and passenger combined.

Since the investigation was based on the assumed existence of a relationship between the trips attracted to an area and certain assessment-area variables, it seemed reasonable to assume that if a relationship did exist, it would exist not only for the total trips attracted to any area for various trip purposes but also for different sized samples of these trips. In an attempt to determine a possible relationship, multiple regression analyses were performed on trips obtained from the various samples selected and the following assessment-area variables:

x_1 Assessed value of residential land (thousands of dollars)
x_2 Assessed value of residential buildings (thousands of dollars)
x_3 Assessed value of commercial land (thousands of dollars)
x_4 Assessed value of commercial buildings (thousands of dollars)
x_5 Assessed value of industrial land (thousands of dollars)
x_6 Assessed value of industrial buildings (thousands of dollars)
x_7 Assessed value of public land (thousands of dollars)
x_8 Assessed value of public buildings (thousands of dollars)
x_9 Area of residential land (acres)
x_{10} Area of commercial land (acres)
x_{11} Area of industrial land (acres)
x_{12} Area of public land (acres)

The assessment information was obtained by examining the assessment rolls of each city and recording the assessed value of each piece of land and building under its particular land-use category (residential, commercial, industrial, and public) for the traffic zone in which it was located. The land areas in each land-use category for each traffic zone were obtained by planimetry from the land-use maps prepared by each city.

The estimation equations of best fit are documented in a separate report (12). The equations for all purposes, work trips, and shopping trips, for all modes combined are given in Tables 6 and 7 for Kingston and Barrie respectively.

Again, the equations obtained for each travel mode category and trip purpose appeared to be similar in form, for a given city, although there was little or no similarity between cities. This does not necessarily imply that a common relationship is impossible. Rather, it is believed that the differences exhibited in this study may reflect variations in assessment philosophies and methods in the two cities.

The relationships developed also appear to be realistic for each city, in that the assessment-area variables tending to have the most pronounced effect in the estimating equations are those which are most logically associated with the trip purpose under consideration; that is, shopping trips are very dependent upon the commercial assessment-area variables, work trips are dependent upon commercial, industrial, and public assessment-area variables, etc.

TABLE 6

REGRESSIONS EQUATIONS FOR TRIP ATTRACTION ESTIMATES, ALL MODES, KINGSTON

Sample	All Purposes	Work Trips	Shopping Trips
S - .025 - K	$Y' = 163 - 4.058x_1 + 1.432x_2 - 0.468x_3 + 5.430x_4 + 0.226x_8 + 23.64x_9 - 19.37x_{10} + 3.76x_{11}$ $r = 0.98$	$Y' = 100 - 0.576x_1 + 1.352x_4 + 3.746x_5 + 1.658x_7 + 0.054x_8 + 4.89x_9 - 13.41x_{10} + 2.05x_{11}$ $r = 0.97$	$Y' = 15 - 0.790x_3 + 1.687x_4 - 0.98x_9 + 27.09x_{10}$ $r = 0.95$
S - .05 - 1 - K	$Y' = 183 + 0.900x_2 - 0.915x_3 + 4.236x_4 - 1.785x_7 + 0.292x_8 + 10.57x_9 - 26.04x_{10} + 2.89x_{11}$ $r = 0.98$	$Y' = -64 - 0.471x_1 + 0.838x_4 + 1.767x_5 + 1.514x_7 + 0.074x_8 + 4.17x_9 - 12.30x_{10} + 1.99x_{11} - 0.67x_{12}$ $r = 0.96$	$Y' = 2 - 0.804x_3 + 1.619x_4 - 1.10x_9 + 25.95x_{10}$ $r = 0.93$
S - .05 - 2 - K	$Y' = 301 + 0.944x_2 + 3.244x_4 + 0.247x_8 + 2.75x_{11}$ $r = 0.96$	$Y' = -33 + 0.332x_1 + 1.275x_4 + 1.350x_5 + 0.305x_6 + 1.071x_7 + 0.099x_8 + 3.00x_9 - 19.41x_{10} + 0.73x_{11} - 1.21x_{12}$ $r = 0.98$	$Y' = 4 - 0.142x_1 - 0.604x_3 + 1.514x_4 + 18.95x_{10}$ $r = 0.96$
S - .10 - K	$Y' = 162 - 3.007x_1 + 1.115x_2 - 0.503x_3 + 4.424x_4 + 0.209x_8 + 20.47x_9 - 24.16x_{10} + 2.93x_{11}$ $r = 0.98$	$Y' = -41 - 0.425x_1 + 1.031x_4 + 1.424x_5 + 0.195x_6 + 1.250x_7 + 0.092x_8 + 3.50x_9 - 10.31x_{10} + 1.26x_{11} - 1.11x_{12}$ $r = 0.98$	$Y' = 9 - 0.679x_3 + 1.519x_4 - 1.06x_9 + 21.60x_{10}$ $r = 0.95$
S - Total - K	$Y' = 103 - 2.850x_1 + 1.298x_2 - 0.377x_3 + 4.186x_4 + 0.189x_8 + 17.23x_9 - 21.96x_{10} + 3.10x_{11}$ $r = 0.98$	$Y' = -2 + 0.811x_4 + 0.439x_6 + 0.731x_7 + 0.126x_8 + 1.19x_9 - 5.88x_{10} + 0.70x_{11} - 2.37x_{12}$ $r = 0.98$	$Y' = -1 - 0.138x_1 - 0.702x_3 + 1.540x_4 + 18.58x_{10}$ $r = 0.96$

Note: Y' = No. of trips attracted to zone

TABLE 7

REGRESSION EQUATIONS FOR TRIP ATTRACTION ESTIMATES, ALL MODES, BARRIE

Sample	All Purposes	Work Trips	Shopping Trips
S - .04 - B	$Y' = -79 + 1.476x_2 + 4.023x_4 - 11.148x_7 + 9.92x_{11} + 28.99x_{12}$ $r = 0.92$	$Y' = -16 + 0.849x_1 + 1.028x_4 + 0.216x_6 - 1.07x_9 + 4.20x_{11} + 2.14x_{12}$ $r = 0.97$	$Y' = -32 + 1.054x_4 - 0.276x_8 + 1.02x_9 + 4.90x_{11} + 2.67x_{12}$ $r = 0.92$
S - .08 - 1 - B	$Y' = -150 + 4.719x_1 + 0.617x_2 + 6.137x_3 + 1.449x_8 + 17.76x_{10} + 8.33x_{11}$ $r = 0.96$	$Y' = -23 + 1.111x_1 + 2.127x_3 + 0.628x_4 - 1.076x_5 + 0.696x_6 + 0.279x_8 - 1.61x_9 + 2.28x_{11}$ $r = 0.98$	$Y' = -57 + 2.630x_3 - 0.100x_8 + 1.34x_9 + 6.09x_{10} - 1.15x_{11}$ $r = 0.91$
S - .08 - 2 - B	$Y' = -53 + 1.342x_2 + 5.751x_3 + 1.429x_4 - 11.675x_7 + 0.735x_8 + 9.28x_{10} + 8.42x_{11} + 21.52x_{12}$ $r = 0.95$	$Y' = 16 + 3.326x_3 - 0.325x_5 + 0.471x_6 - 1.229x_7 + 0.173x_8 + 1.28x_{11} + 1.73x_{12}$ $r = 0.99$	$Y' = -10 + 2.161x_3 + 0.423x_5 - 0.047x_8 + 0.45x_9 - 0.87x_{11}$ $r = 0.98$
S - .16 - B	$Y' = -139 + 2.856x_1 + 0.925x_2 + 2.062x_4 + 0.940x_5 + 0.724x_8 + 15.30x_{10} + 7.38x_{11} + 8.83x_{12}$ $r = 0.97$	$Y' = -5 + 0.631x_1 + 2.475x_3 + 0.341x_4 - 0.654x_5 + 0.574x_6 + 0.155x_8 - 1.00x_9 + 2.41x_{11} + 1.49x_{12}$ $r = 0.99$	$Y' = -75 + 2.585x_3 + 0.335x_6 - 0.196x_8 + 1.80x_9 + 7.15x_{10} - 3.90x_{11}$ $r = 0.91$
S - Total - B	$Y' = -96 + 2.110x_1 + 1.309x_2 + 6.230x_3 + 1.164x_4 - 3.183x_7 + 0.939x_8 + 11.42x_{10} + 9.45x_{11} + 11.22x_{12}$ $r = 0.98$	$Y' = -14 + 0.951x_1 + 6.825x_3 - 0.738x_4 - 1.616x_5 + 1.063x_6 - 1.06x_9 + 1.66x_{12}$ $r = 0.99$	$Y' = -89 + 3.046x_3 + 0.370x_6 - 0.223x_8 + 2.21x_9 + 8.02x_{10} - 4.48x_{11}$ $r = 0.90$

Note: Y' = No. of trips attracted to zone

Trip Estimates and Discussion of Errors

Substitution of the zonal assessment-area data in the estimation equations provided estimates of the number of trips attracted to each zone within the city by travel mode category and trip purpose for each sample size. These trip estimates were compared with the expanded home-interview O-D trip data (actual) and the differences were calculated. The results of these comparisons (12) are shown for all purposes, work trips, and shopping trips, for all modes combined, in both Kingston and Barrie, in Figures 5 through 10. So that these figures could be plotted, actual zonal volumes of attracted trips were grouped into arbitrary ranges of trip volumes, and the percent RMS errors were calculated in the same way as for the trip production estimates.

As in the trip production study, one would expect similar estimation equations to produce trip estimates approximately comparable in accuracy. Examination of the Kingston results shows that this expectation generally holds true. For work trips, personal business trips, shopping trips, and "to home" trips, the 5 percent samples appear to produce results as good as the 10 percent sample with some overlap of the curves. The 2½ percent sample is generally somewhat poorer than the 5 percent or 10 percent samples. For trip purpose ALL, the errors appear to decrease with increase in sample size. Regression equations based on the total O-D sample do not appreciably improve the accuracy of trip estimates.

The error results for Barrie are more variable, although in all cases but shopping trips, the regression equation based on the total O-D sample does appear to improve considerably the accuracy of trip estimates. Only for shopping trips does the 4 percent sample give consistently poorer results than the 8 percent or 16 percent samples. For

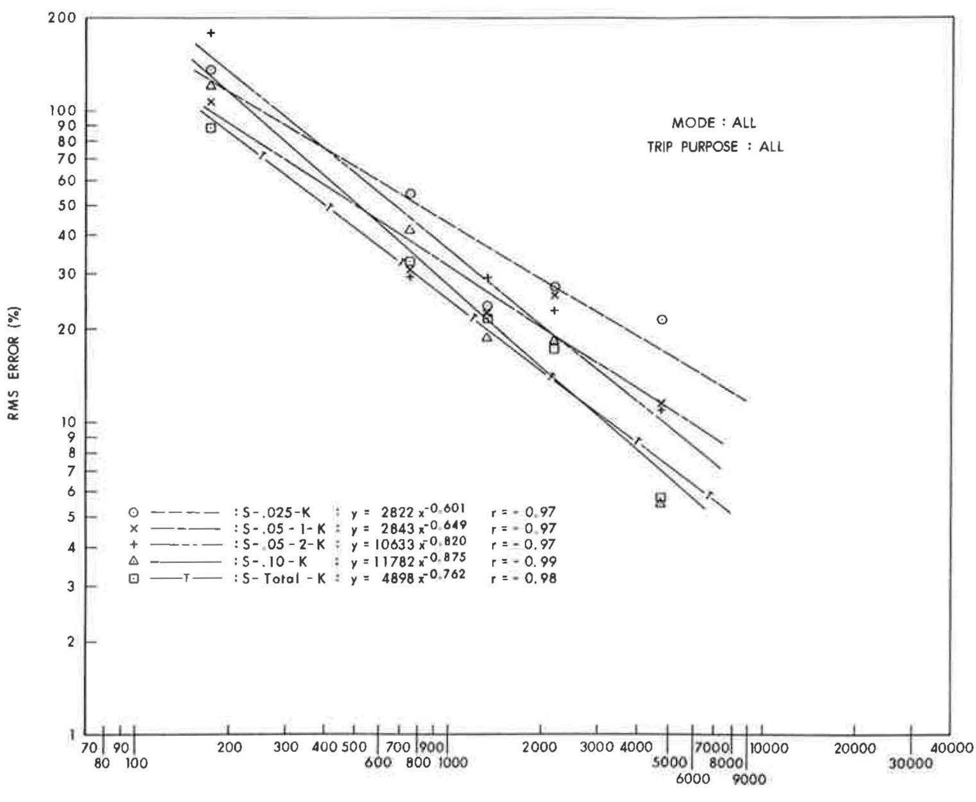

Figure 5. Errors in trip attraction estimates, Kingston.

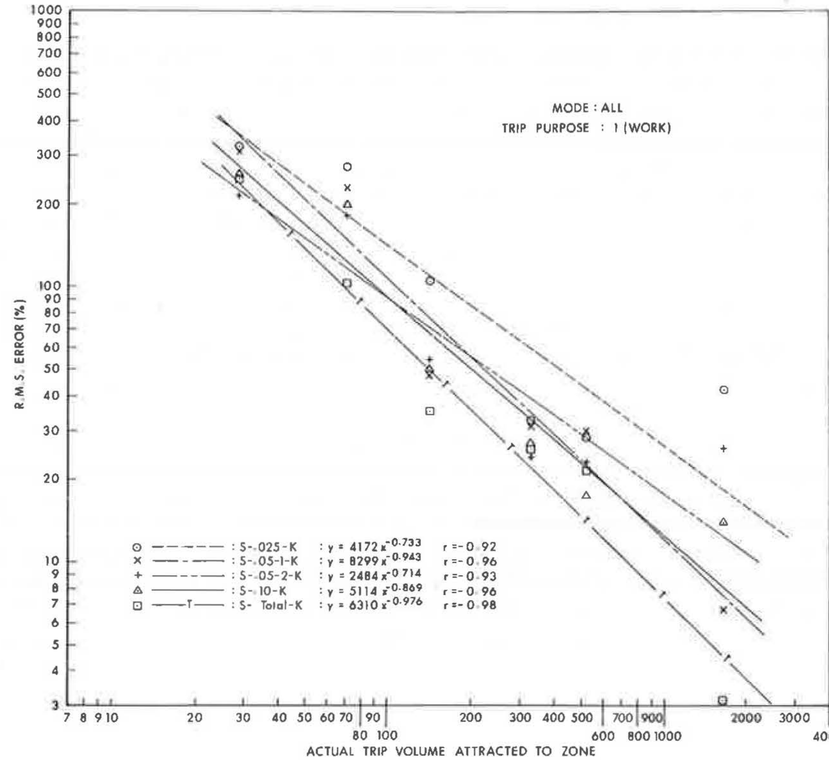

Figure 6. Errors in trip attraction estimates, Kingston.

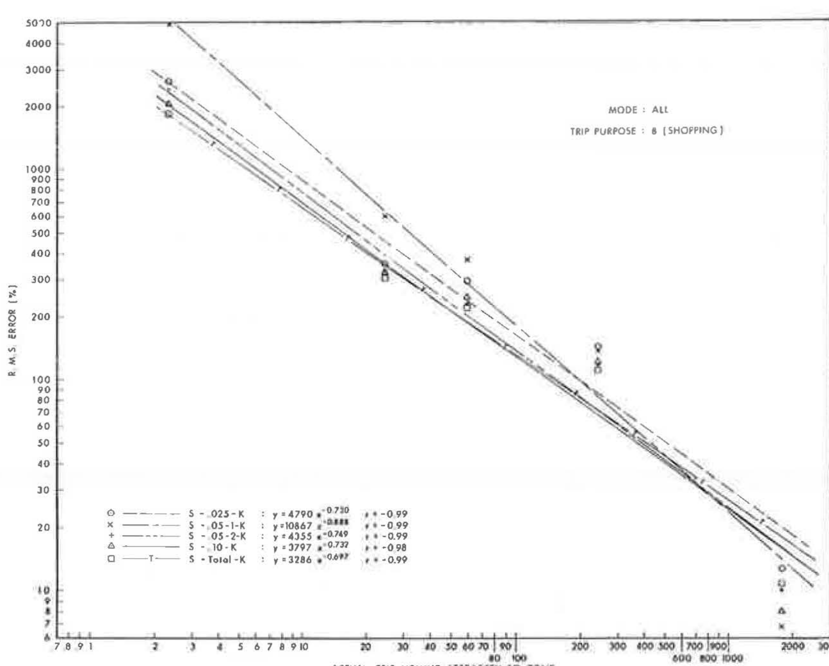

Figure 7. Errors in trip attraction estimates, Kingston.

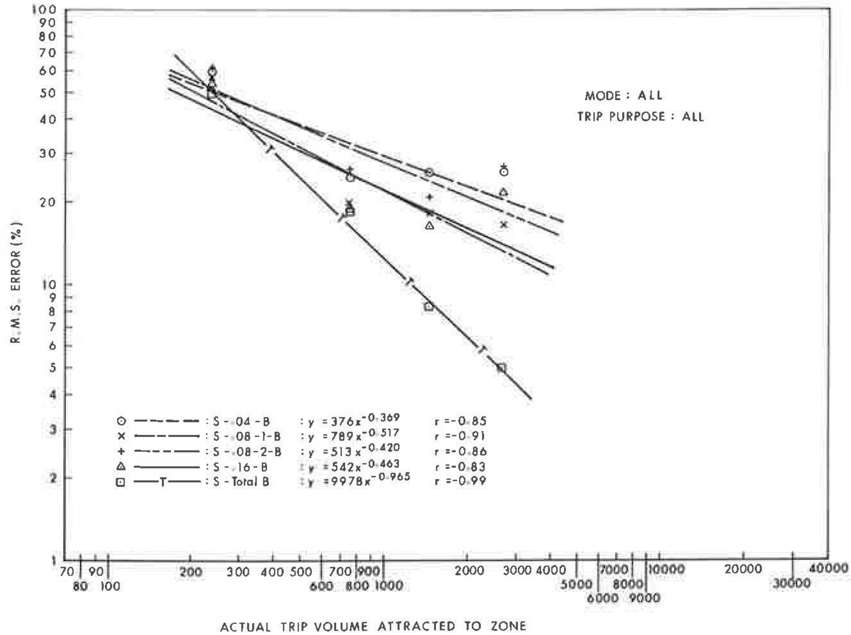

Figure 8. Errors in trip attraction estimates, Barrie.

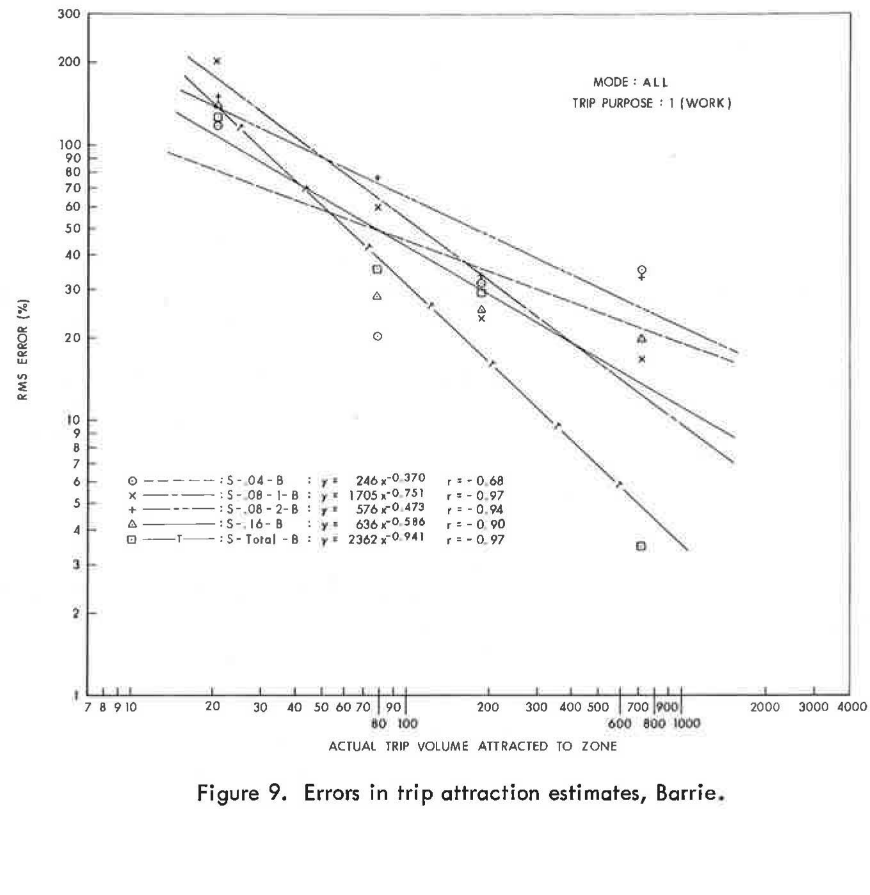

Figure 9. Errors in trip attraction estimates, Barrie.

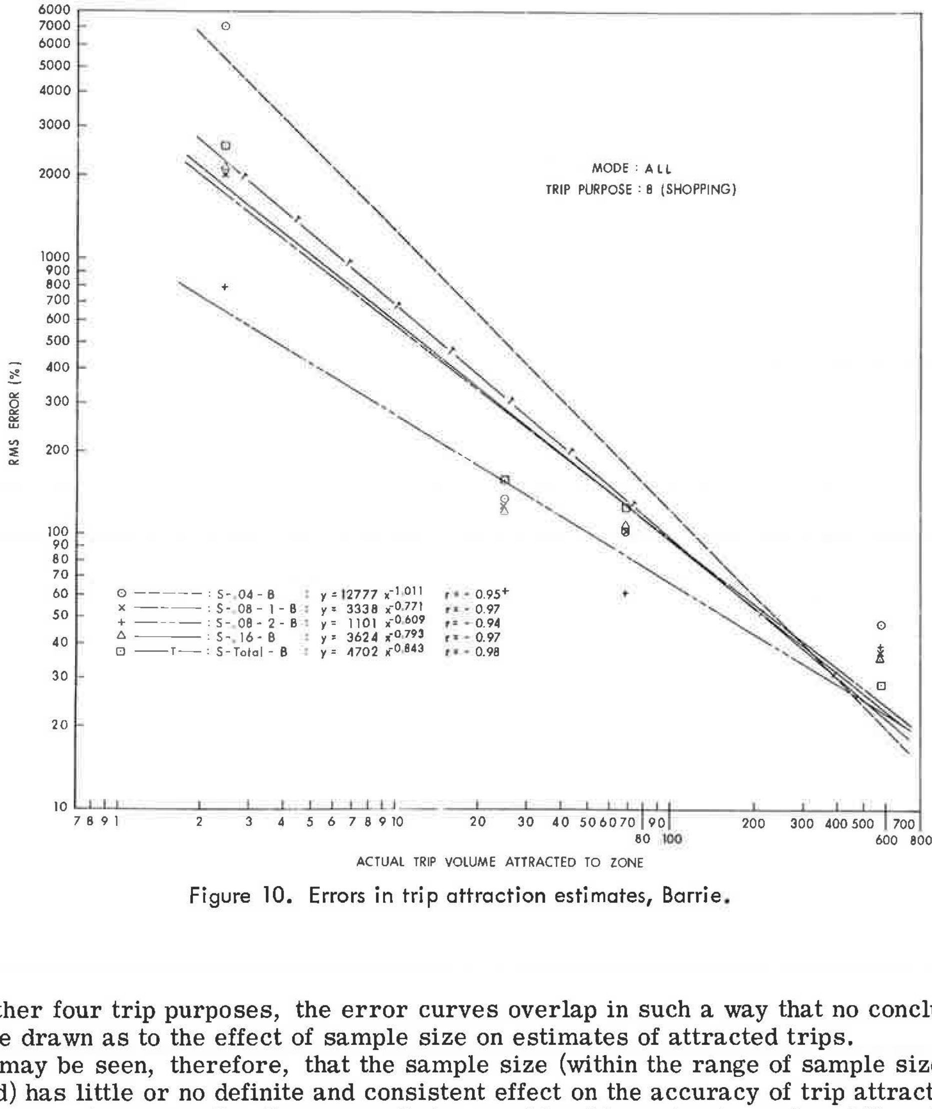

Figure 10. Errors in trip attraction estimates, Barrie.

the other four trip purposes, the error curves overlap in such a way that no conclusions can be drawn as to the effect of sample size on estimates of attracted trips.

It may be seen, therefore, that the sample size (within the range of sample sizes tested) has little or no definite and consistent effect on the accuracy of trip attraction estimates. Consequently, it appears that a considerable saving in cost could be achieved by using a relatively small O-D sample.

For the smaller attracted volumes, it may be noted that the percent RMS error is so great as to cause one to question the value of small trip volumes. This implies that perhaps zone boundary selection should be governed to some extent by the number of trips attracted to the zone.

The attraction study shows that trip attraction estimates, as well as production estimates, may exhibit sizable errors. Again, however, it is suggested that the estimates are useful, and that it would seem appropriate to examine the effects of higher production and attraction rates on trip distribution and assignment in critical areas.

Although no calculations were made, the method of determining theoretical standard errors about the true zonal values, as outlined in the production study, should also be applicable, with minor modifications, to trip attraction.

CONCLUSIONS

1. Estimation equations may be developed for small cities which relate trip production to car ownership primarily as well as to other population and land-use parameters,

and which relate trip attraction to assessment and land-use parameters. For trips having the same trip purpose and mode of travel, the equations developed for a given city show similarity and also appear to be logical in that the expected significant variables play a predominant role in the estimating equations.

2. Comparison of the estimating equations for trip attraction for the two cities indicates some dissimilarities. It is suggested that variations of this kind might be reduced if equalization of assessment between cities could be accomplished.

3. The size of the origin-destination sample used to develop the estimating equations does not appear to affect significantly the accuracy of trip estimates, although theoretically it would be expected to. (Accuracy here means agreement with expanded O-D survey results.)

4. The size of the percent RMS error in trip estimation appears to increase with more extensive breakdown or segregation of trip purpose categories and land areas. On the one hand, variation of estimating equations among trip purposes is quite evident (especially for trip attraction), indicating that separate equations would appear to be necessary for estimating these different kinds of trips. On the other hand, it would appear that attempts to stratify trips too extensively will result in rather sizable errors.

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Estimation of Sub-Modal Split Within the Transit Mode

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Because riders diverted from surface transit comprise the bulk of patrons on new central-city rapid transit lines, effective estimation of sub-modal split is of major importance to rapid transit patronage forecasting. The estimation of sub-modal split for the National Capital Transportation Agency's initial subway system is described. Data from the Skokie Mass Transportation Demonstration Projects were used to construct a logistics curve sub-modal split relationship which compared satisfactorily with previous data. Weighted excess times were introduced to represent travel convenience in curve derivation and in transit computer network coding. Overall alternate travel times with excess time weighting of 2.5 appeared to be sufficient input to adequately predict sub-modal split.

Analysis techniques used a combination of special computer programs and standard traffic assignment programs. The resultant diversion analysis was found very sensitive to the assumed rapid and surface transit routings and headways. Results indicated use of all-or-nothing assignment for diversion computation would not have provided the accuracy required for the NCTA study.

•THE transportation planning process in its recent development has moved from concern with predicting the future of a single mode of travel to use of modal split techniques for evaluating the future interaction of public transit and the private automobile. Closer examination of the public transit mode is now leading to investigation of sub-modal split. We are now being asked if the trip-maker, having chosen the transit mode, will use bus, rail, or some other available alternate.

This is not a question of mere academic interest. Experience with rapid transit facilities opened in the past two decades both here and abroad indicates that the bulk of urban riders will be those diverted from surface transit. In Cleveland, Toronto and Boston, studies of patronage on new rail lines indicate a minimum of 80 percent of the riders are not new to public transit. Even the Chicago Skokie Swift demonstration, where the new rapid transit service was an extension entirely outside the central city, reports that 50 percent of the riders made their entire former trip by transit, and 74 percent used transit for some portion of their former trip (1).

These percentages are not presented to discredit the very real importance of trips attracted to improved transit service from the private auto, trips kept from ultimate loss to auto, or trips which would not have been made at all without the new service. The point to be made is that, particularly for central city rapid transit proposals, estimation of patronage should include detailed examination of the numbers of persons who will use the new facility in preference to surface transit.

In Washington, D.C., the initial rail rapid transit system authorized by Congress is to be almost entirely within the central city. The importance of sub-modal split in estimation of patronage on this system was recognized at the outset in the design of traffic

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forecasts prepared for Washington's National Capital Transportation Agency (NCTA). In the course of the project a sub-modal split relationship suitable for application to individual interchange volumes was derived, and methodology for its application to large numbers of origin-destination zone combinations was developed and applied.

This paper reports on the sub-modal split relationship development and application, with the reporting being necessarily within the context of the studies conducted for NCTA. In these studies the sub-modal split computations were applied to a trip table of existing transit trips in the manner of a diversion analysis. The resultant trip table consisting solely of rapid transit trips was then subsequently modified to introduce the effects of estimated change in modal split (auto vs transit) and area growth and change. The relationships and methods discussed should, however, be equally pertinent to any investigation where sub-modal split must be predicted for a given body of trips.

DERIVATION OF THE SUB-MODAL SPLIT RELATIONSHIP

Two important simplifying assumptions were immediately applicable in the derivation of a sub-modal split model for the NCTA study. First, there were only two sub-modes sufficiently important to be considered: the future rail system and its complementary bus network. Second, fares were to be assumed equal via either bus or rail for any given trip.

In addition, it seemed not unreasonable to assume that passenger loadings and transport equipment conditions would in the aggregate not seriously affect sub-modal choice. The same general standards of passenger loading would presumably apply to both bus and rail. Although the rail equipment would initially be newer, this condition would cease to exist as operation continued. It was also felt that a satisfactory relationship could be found that would not require the socioeconomic characteristics of the trip-maker as an input. Certainly the principal effects of such characteristics are felt in the choice of the prime mode of travel. Once consigned to mass transit, there is no apparent reason why the captive rider should approach his sub-modal selection differently than the rider by choice.

In accordance with these assumptions and logic, a relationship was sought which would take into consideration the two remaining model split parameters of importance—relative travel time and relative convenience of travel. Several diversion curves previously

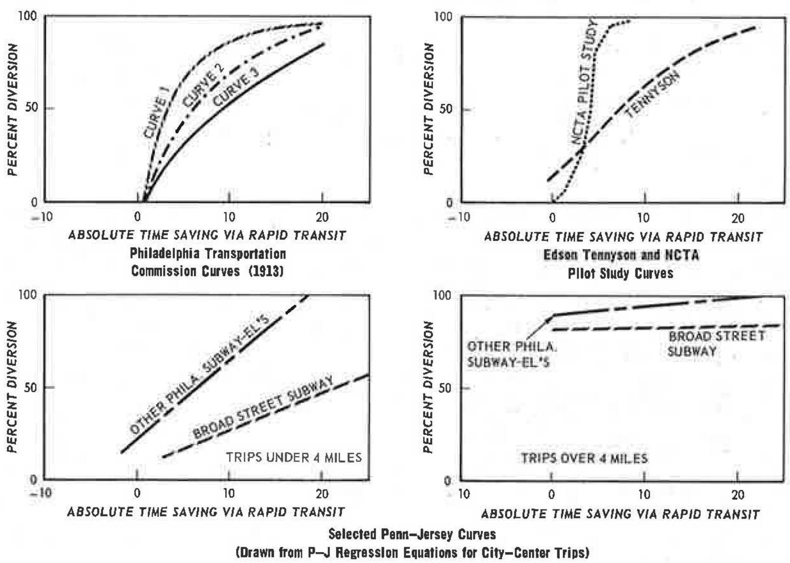

Figure 1. Previously derived rapid vs surface transit diversion curves.

prepared were examined for applicability and to serve as a check against any new derivations. These curves are presented in Figure 1. All use time saving in minutes via rapid transit to compute the percent diversion from surface transit to rapid transit.

The Philadelphia Transportation Commission curves are from early studies of Market Street Elevated patronage (2). They were reputedly used with satisfactory results in estimating Broad Street Subway passenger volumes. The three curves apply respectively to trips requiring no extra transfer via rapid transit, one extra transfer, and two extra transfers. The first two were fitted to field data and the third was assumed on the basis of the trend shown by the first two.

The Tennyson curve was based on surface-transit passenger counts of alighting passengers and passengers riding through at points of sub-mode choice in Newark, Philadelphia and Waukesha (3). In each case the alternative routes continued on to a common destination. The curve is interesting in its use of the Detroit Metropolitan Area Study freeway diversion relationship to establish the shape of the curve. It is intended for use when one extra transfer is required via rapid transit. One extra transfer was similarly involved in the data collected for the NCTA Pilot Study curve shown (4). In this investigation interviews were conducted at a bus stop north of a mode change point on Philadelphia's Broad Street Subway. Each person was asked his destination and whether or not he intended to transfer to the subway. Travel times including walking, waiting and running time were computed in detail for the alternative routes. Thirty-five interviews of persons who had a true sub-modal choice were completed and the curve shown was drawn by connecting the resultant data points.

The Penn-Jersey study linear diversion curves illustrated were the product of regression analyses of sub-modal split computed from origin-destination data and arrayed against sub-mode travel time differences derived from a coded transit network (5). The analysis was conducted using trips aggregated on a district-to-district basis. The regression was run separately for the Broad Street Subway as compared to other Philadelphia rapid transit, for trips under and over four miles in length, and for city center and non-city center trips. Only the results for city center trips are shown.

Although all of the existing diversion curves investigated were based primarily on travel time difference, a measure of the quality of service provided is implicit. The Philadelphia Transportation Commission curves were stratified by the number of extra transfers involved in the rapid transit trip as compared to surface transit. The Tennyson and NCTA Pilot Study curves were specifically intended for use when one extra transfer was involved. The variations between the various Penn-Jersey equations may well be reflections of differing quality of service offered the separate categories of trips considered.

Research done in Toronto and Washington on choice of the prime mode of travel has indicated excess time to be a useful measure of travel service (6, 7). In the trip by transit, excess time is made up of the time spent walking, waiting, and transferring. In studies where excess time has been evaluated it has been shown to be a more heavily weighted factor in mode choice than transit running time when both are expressed in identical units.

In recent work by Alan M. Voorhees and Associates the weighting of excess time has been applied directly in transit network computer coding. The network is coded not in true time but in equivalent time, with true walking, waiting and transfer link times multiplied by an appropriate equivalence factor. When a minimum path through the network is chosen it is the minimum equivalent or weighted time path. The overall travel time involved in the minimum path is expressed in equivalent time.

An excess time equivalence factor of 3 has generally been used, based on a study of Washington modal split relationships developed from the 1955 origin-destination survey and more recent government employee surveys. Recent unpublished regression analysis of origin-destination data from Calgary along with general experience with the excess time factor indicates a somewhat lower multiplier of 2.5 may be appropriate.

In approaching the question of sub-modal split it would seem likely that the excess time measure of travel convenience would have the same or a similar effect as it does in the choice of the prime mode of travel. Accordingly this line of investigation was

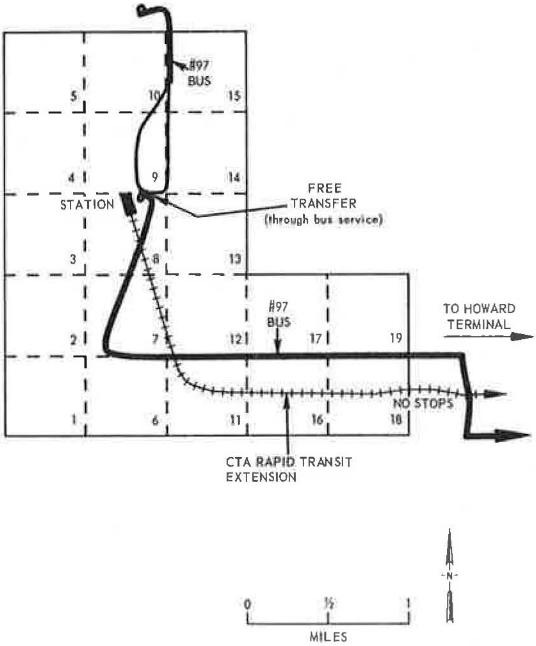

Figure 2. Portion of Skokie, Illinois, showing analysis zones and competing transit sub-modes.

pursued in the work for NCTA. The weighting of excess time links in the future transit computer network was provided for and a sub-modal split model which would be responsive to equivalent travel times was sought.

Data recently made available from the Department of Housing and Urban Development CTA-Skokie and Intra-Skokie Mass Transit Demonstration Projects in Illinois made possible the derivation of a new curve. In the Skokie area the newly instituted "Skokie Swift" rapid transit extension parallels and competes with an established bus route also operated by the Chicago Transit Authority. At the same time the bus route provides feeder service to the rapid transit extension. The two facilities are shown in Figure 2, along with the system of Chicago Area Transportation Study traffic zones to which passenger origins were coded. Transit fares on the two alternate sub-modes are the same except for local trips.

CTA-Skokie Demonstration Project postcard surveys on the Skokie Swift rapid transit extension and the parallel Chicago Transit Authority No. 97 bus were used to provide origin data from 19 zones (1, 8). The 19 origin zones selected were those where other bus services were determined to have a minimal effect on the mass transit market. All trips were assumed to pass through Howard Terminal, terminus of the two competing routes, and this was used as a common destination. Known percentages of local trips on the CTA No. 97 bus were removed using as a data source boarding and alighting counts from the Intra-Skokie Mass Transportation Demonstration Project (9).

Equivalent travel times by alternate sub-modes were computed from each selected origin zone to Howard Terminal using excess time factors of 1, 2, 2.5 and 3. Since trip-making data were for the full service day of the rail and bus facilities, weighted averages of peak and off-peak running times and waiting times were used. The computations were as follows (WF indicates the weighting factor):

Time via Bus

Total of:

(Walk time to bus) × WF
(Average bus waiting time) × WF
(Bus running time to Howard Terminal) × 1
(Howard Terminal walk time) × WF

Time via Rail

Total of:

(Walk time to bus) × WF
(Average bus waiting time) × WF
(Bus running time to rail) × 1
(Average rail waiting time) × WF
(Rail running time to Howard Terminal) × 1

or Total of:

(Walk time to rail) × WF
(Average rail waiting time) × WF
(Rail running time to Howard Terminal) × 1

The smaller of the total equivalent times computed via rail was the one used. Walk time within terminals was included only for the bus-to-rail transfer at Howard Terminal, all other transfers being across-the-platform or nearly so. None of the trains or buses considered operated through to Chicago.

Percent of travel by rail was plotted against equivalent time savings via rail (positive or negative) for each of the excess time weighting factors tried. The values calculated using the 2.5 equivalence factor were chosen for statistical analysis.

Not only was the 2.5 factor the most promising from the standpoint of previous modal split investigations, but the curve initially delineated using this factor (and as later purposefully formulated) passed exactly through the point of 50 percent diversion at zero equivalent time difference between sub-modes. The possibility that this effect was partially happenstance cannot be discounted unless further research using travel data from varied locations substantiates the positioning of the equivalent-time diversion curve. Assuming such substantiation, the prediction of 50-50 sub-modal split when alternative equivalent times are equal is most satisfying. It would imply that sub-modal choice is indeed less complex than the choice of prime mode, and that it can be adequately explained by travel time differences in conjunction with the use of weighted excess times as a measure of convenience.

The final equivalent-time diversion curve was formulated by first applying regression analysis and then hand-fitting a logistics curve to the data points. The resultant sub-modal split relationship can be expressed by

$$y = \frac{100}{e^{-0.3X} + 1}$$

where X is the equivalent time saving via rail (equivalence factor of 2.5) and y is the percent using rail. Weighting each data point by the number of observations, the R^2 of the curve is 0.886. This R^2 value is computed by comparing predicted and actual percent sub-modal split on an interchange basis.

The data points and curve are shown in Figure 3. Note that no attempt was made to fit the points for analysis zones 12, 17, and 19. The data points for these zones,

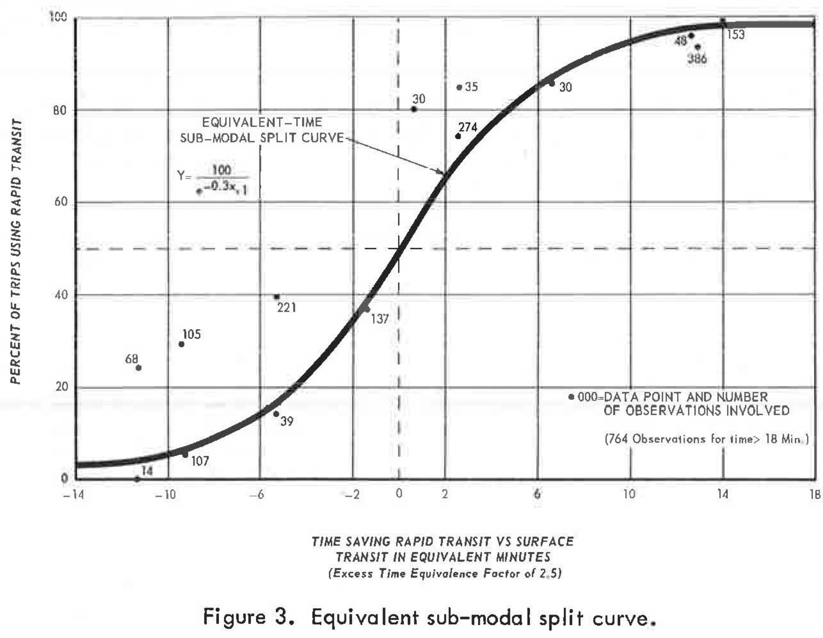

Figure 3. Equivalent sub-modal split curve.

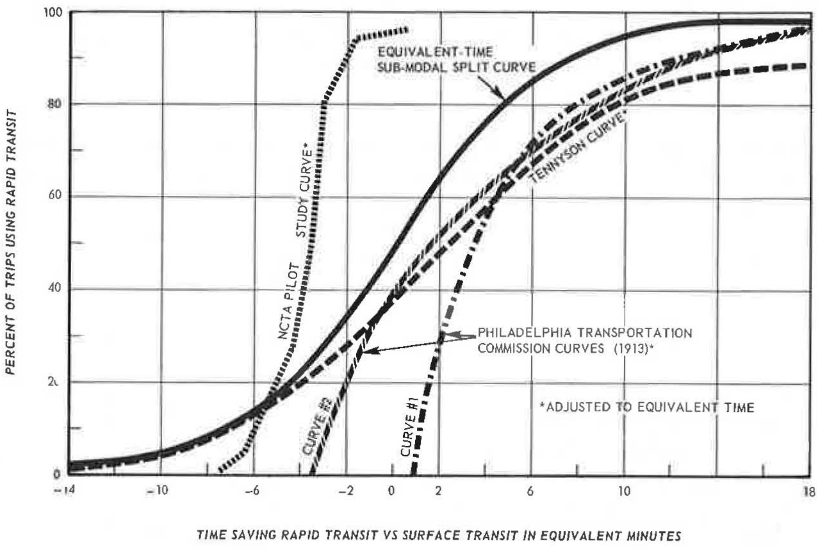

Figure 4. Equivalent-time sub-modal split curve shown in comparison with previously derived curves.

which produce 221, 105 and 68 trips respectively, are found in the left-hand portion of Figure 3. For these zones the path to the railhead is quite divergent via bus and via auto. Although auto was not explicitly considered in the analysis, some moderate percentage of the trips from the origins chosen to the rail line are park-ride or kiss-and-ride. It was felt that for these zones where the paths were divergent a bias was being introduced in favor of rail. This is seen in the placement of the data points. All points were considered, however, in computation of the 0.886 R^2 value.

There are obvious dangers in dependence on a curve derived from a single data source. It was felt necessary therefore that the new curve compare satisfactorily with previous data on the subject. To make this comparison the Philadelphia Transportation Commission, Tennyson, and NCTA pilot study curves were plotted in the same context as the new equivalent-time diversion curve. (The Penn-Jersey curves were considered inapplicable to universal predictive use because of their identification with individual subway routes.) The plotting is shown in Figure 4. For comparability the placement of the curves had to be recomputed using equivalent times. In the case of the NCTA Pilot Study curve, full information was available to do this recomputation. For the other curves excess times were approximated. The new curve appears reasonable when compared with the previous data, lying as it does mostly within the space circumscribed by the older curves.

APPLICATION OF THE SUB-MODAL SPLIT RELATIONSHIP

A perhaps obvious but very important first step in applying a mass transit sub-modal split relationship to a future system as was done for NCTA is to develop in detail the total system that is to be tested. Trip choice between surface and rapid transit is, within the central city, heavily dependent on the character of feeder service available to serve the rapid transit, and on the character of the bus lines remaining in competition with rapid transit. Furthermore, the situation is not like that encountered in a central city freeway diversion analysis, where the competitive system (the surface streets and arterials) will not be changed significantly by the introduction of the freeway. A bus system can be expected to radically change in character upon introduction of rapid transit. The surface transit emphasis will change from that of trunk line operation to that of feeder and local operation.

The results of the NCTA forecasts showed the sub-modal split to be very sensitive to the assumed bus system. Both bus routings and bus headways were important. Results of this sensitivity are illustrated later by means of a contour map of percent diversion.

The future feeder and local bus system designed for the purpose of allowing diversion computations as part of the NCTA analysis was developed with the cooperation and assistance of the local bus operators. It was desired that it represent the most logical coordination of bus and rail service which could be devised pending availability of traffic forecasts. Routing, running times and headways were prepared for each proposed line. Although the system was for study purposes only it was reviewed with the bus companies, the local regulatory body, and NCTA to insure that it was in fact a viable and practicable proposal.

Once the system to be tested was designed, the sub-modal split computation proceeded utilizing both special computer programming and standard Bureau of Public Roads traffic assignment programs (10). The NCTA study involved 580 traffic zones and a 29-station rapid transit system. The basic computational problem at hand was to compute for each combination of zones the minimum equivalent time via surface transit and the minimum equivalent time via rail rapid transit, and to use these times to compute the interzonal sub-modal split percentages and volumes. The computational design was influenced by the desire to produce station-to-station tables of rail trip volumes later in the study process.

The future bus and rail system was computer coded using the link-node system of representation including links for walking, waiting and transfer time. There were two departures from standard coding procedure. As previously discussed, the link times representing excess time were multiplied by an equivalence factor of 2.5. In addition, the nodes depicting the 29 rapid transit stations were numbered in sequence following the 580 zone centroids and included on the parameter card as centroids. This allowed minimum paths to be traced and times to be computed not only between all zones but also between all zones and rapid transit stations. The need for this will be seen shortly.

The computation of minimum time via rapid transit posed special minimum path building problems. For many zone combinations the rail route involved use of feeder bus, so use of the network links representing bus routes could not be disallowed. This meant that under normal path-building techniques it would be possible for an all-bus path to be chosen, and this would indeed happen whenever such a path was any amount faster than the minimum path via rail. But it was this latter path which was always required for comparison.

Freeway diversion analysis techniques have in the past used reduced-time freeway network links to attract minimum paths to the freeway even when they would otherwise have lain elsewhere (10, p. III-60). A similar approach could be followed with rapid transit links. However, there were two disadvantages to this approach from the point of view of the NCTA study. First of all, not all paths can be forced through a set of links by the expedient of using reduced times. Some "paths via rail" would actually not use rail links and the corresponding minimum times would be erroneous. The resultant spurious trip diversions could be weeded out only by means of a traffic assignment, as is done as an integral part of the freeway diversion procedure. Secondly, such a procedure would not provide basic data required to build simply and cheaply a rail station-to-station table of trip volumes, which the alternate procedure devised was able to do.

The technique adopted was to write a special program which utilized minimum paths computed between zones and stations, along with rail system station-to-station times, to choose a minimum combination. The program computed the total equivalent time for all reasonable combinations of origin-to-station, station-to-station, and station-to-destination minimum times for each zone pair, chose the minimum total, and recorded the two stations involved. The record of the minimum combination stations for each zone pair allowed rail trip volumes from zone-to-zone trip tables to be, at any subsequent stage of analysis, accumulated by means of a simple program into zone-to-station or station-to-station trip tables. These could be assigned to produce link volumes or formatted for direct presentation.

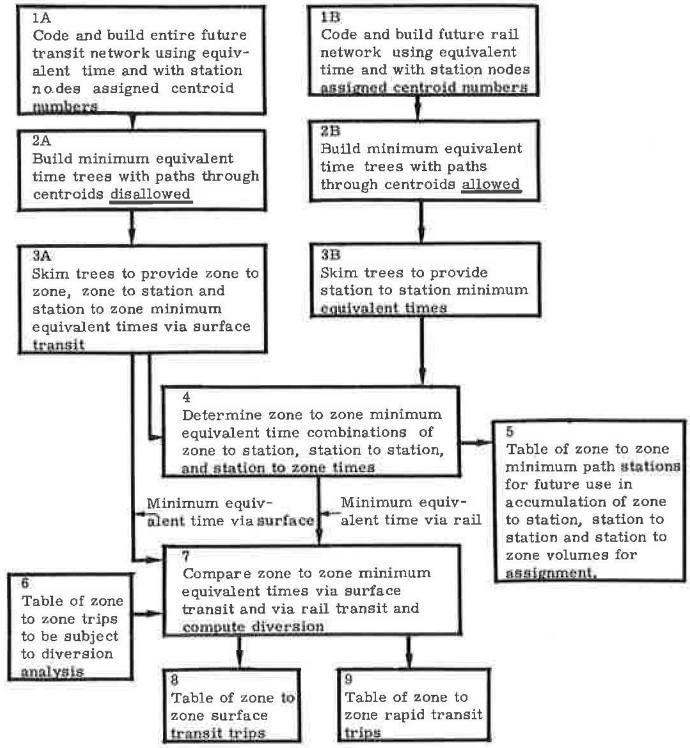

Figure 5. Computer process flow chart for application of the sub-modal split relationship.

The computation process is summarized in the flow chart in Figure 5. Steps 1, 2 and 3 use Bureau of Public Roads programs PR-6, PR-1, and PR-130 respectively. Steps 4 and 7 require special programs, as does the volume accumulation into special trip tables mentioned in item 5.

Note that as shown in step 2A the zone-to-zone, zone-to-station, and station-to-zone trees are built with minimum paths through centroids not allowed. This keeps these paths off the rail links of the network as is desired. It also means, however, that steps 1A-3A cannot be used to compute station-to-station rail times. This must be done in steps 1B-3B using a separate computer network which need consist only of the rail system links.

The use of a diversion curve, as contrasted to any all-or-nothing assignment technique, produced a very fine-grained sub-modal split analysis. The detail of the resultant analysis is shown in Figure 6 by means of a contour map. The map shows the Washington, D. C., rail system tested for NCTA and contours indicating the percent of transit trips from any geographic area using rail for at least part of the trip to the one specific destination zone indicated on the map by the letter A. Contours are drawn at intervals of 10, 25, 50, 75 and 90 percent rail sub-modal split. Note that for a complete picture of the sub-modal split using this method of graphic presentation, one map would have to be drawn for each destination zone of interest.

The destination zone used in Figure 6 is sufficiently removed from the rail system that rail trips to it must use a feeder bus for delivery. Hence the use of rail to get to this particular zone is lower overall than to zones served directly by stations.

The sensitive interaction of the bus and rail system can be seen by reference to specific points on the map. As an example, note the low rail usage from area B to A despite the presence of a nearby station. The cause is a frequent direct bus service coded into the network between the two areas. By contrast rail usage from closer-in

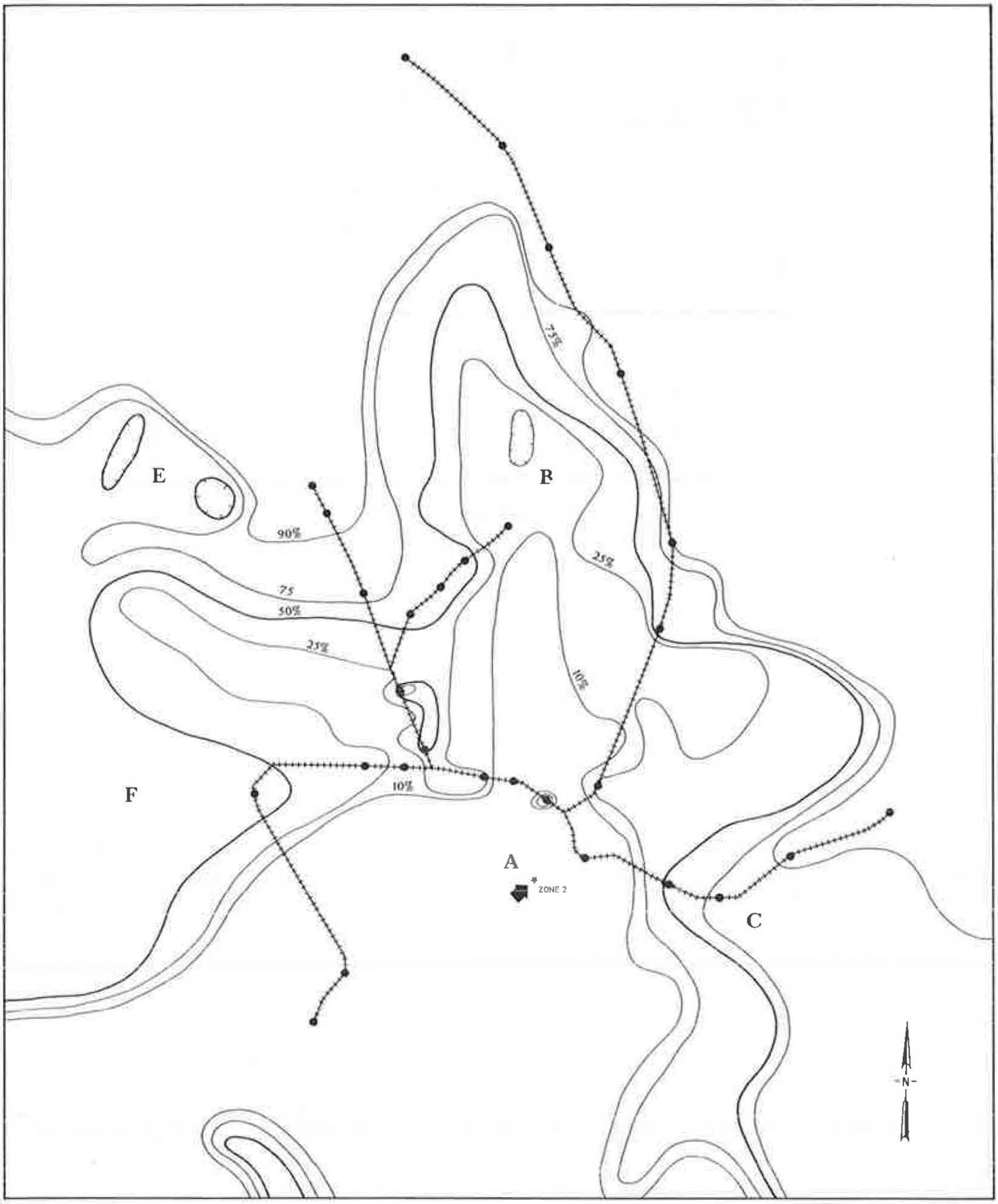

Figure 6. Percent diversion contours, transit trips to and from zone 2 (from Washington, D.C., patronage forecasts for NCTA authorized system).

area C to A is much higher. The reason is closer headways on the rail line involved combined with relatively indirect bus service.

An anomaly purely caused by bus routing can be seen at the areas identified by letters D and E. The rail usage from D is high because of good direct bus service east to a rapid transit line. At E, bus service to the same rapid transit line is poorer, and percent rail usage is predicted to be lower. Equivalent through bus service headed toward zone A passes through both areas D and E.

A final point to be made can be illustrated by reference to area F and the 50 percent contour line in Figure 6. In an all-or-nothing transit assignment using the same equivalent times as was done in this analysis, all areas beyond the 50 percent line would be assigned to rail. In essence, there would be 100 percent diversion. All trips from F to A would by all-or-nothing assignment go by rail. The curve-derived diversion is just over 70 percent.

In highway analysis the approximations caused by all-or-nothing assignment are assumed to adequately cancel out, thanks to the diversity of auto trips. Transit trips are not as diverse. In the NCTA estimates, for instance, over half of all present-day transit trips and over three-quarters of all projected 1980 rail trips are destined for the downtown area. A serious error of approximation in estimating sub-modal split to downtown will not be canceled out.

Contour plots, including the one illustrated, to different parts of downtown indicate area F in Figure 6 would be assigned 100 percent by rail to all of downtown using all-or-nothing techniques. Yet the diversion curve rail percentages for such trips ranged as low as 58 percent for the specific destination zones plotted. The station serving area F would have its patronage overestimated by all-or-nothing assignment by perhaps 15 to 25 percent. This situation is probably not unique. In any case, individual station-to-station volumes derived by all-or-nothing techniques would clearly be meaningless for close-in stations.

CONCLUSIONS

Use of diversion curve techniques as compared to all-or-nothing assignment would appear justified in transit sub-modal split analysis where close-in central city rapid transit stations and routes must be evaluated in detail. Such analysis can be feasibly accomplished for small rail networks by the methods discussed. Overall patronage estimates or estimates for stations sufficiently removed from downtown probably do not require the diversion curve approach for sub-modal split analysis, although an actual direct comparison of all-or-nothing transit assignment and diversion curve results would be helpful in reaching a more definitive conclusion.

Sub-modal split analysis using equivalent times, i.e., weighted excess times, appears to be an effective technique, particularly with the weighted times made a part of the transit network description. Although sub-modal cost differentials were not involved in the studies described here, there would appear to be no reason why they could not be investigated and treated in a similar manner.

The sub-modal split curve and corresponding excess time equivalence factor presented here should ideally be refined and verified using data from several more locations. Preferably this should include a network analysis using city-wide transit origin-destination data for alternative transit modes. Such an investigation would have to consider in detail the excess and running times involved in each interzonal interchange, or in some other manner explicitly consider travel convenience. Without such detail it is doubtful that further research would be very fruitful.

With the next generation of transit assignment computer programs now becoming available, greater flexibility is being made possible in both factoring and tabulating of particular interzonal values such as walk time, initial wait time and transfer time (11). The computational abilities of these new programs will give an assist to research into the effect of such factors on mode choice. Many of these factors could probably be investigated most easily by first reaching an understanding of their effect on sub-modal split before evaluating them in terms of the more complex choice of prime mode.

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Auto Ownership Revisited: A Review of Methods Used in Estimating And Distributing Auto Ownership

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The intent of this study is to examine some of the methods used for estimating and distributing auto ownership. The importance of auto ownership is described for the generation of person trips and for the modal split decision. The key variables in the auto ownership estimation process used by some transportation studies and analysts are reviewed for their logic and predictive power. The preliminary findings from the Tri-State Transportation Commission are used to check out the logic of the variables used in this process.

In a test of the forecasting capability of these variables, auto registrations (by county for the years 1950 and 1960) for the New York Metropolitan Area were extracted from State Vehicular Records and used as a data base along with census data describing the social and economic factors of the predictors. Equations were derived from the 1950 data, applied to the 1960 data, and checked for accuracy with the auto registration figures for 1960.

In addition, techniques for deriving total auto registrations for an area are examined as well as the methodology employed to factor up the small area predictions to this control total. Finally, recommendations are offered for the process of setting up techniques for estimating and distributing auto ownership.

•ONE of the most important factors used in the trip generation process of forecasting person and vehicle trips is auto ownership. For example, the Chicago Area Transportation Study (CATS) found an excellent correlation between autos owned per dwelling place and destinations per dwelling place. The Pittsburgh Area Transportation Study (PATS) derived similar results from this relationship (Figs. 1, 2).

Auto ownership is also a significant determinant of mode choice. The households that do not have an auto available to them are in part captive to the service that transit supplies. In addition, those households in which another member of the household has a more pressing need for the family car (e.g., the housewife in the suburbs) are also constrained as to mode choice in their journey to work. PATS data point up the relationship of auto ownership and residential density on transit trips. Figure 3 shows the descreasing rate of transit trips to the central business district (CBD) with increasing auto ownership, consistent through the range of density readings.

While it is generally agreed that auto ownership rates must be studied and considered in any predictive trip generation equations and/or models, there does not seem to be this concurrence on the methodology employed in predicting and distributing auto ownership. The techniques used by some transportation studies and analysts in the field were reviewed, and the references used by this author are given in Table 1.

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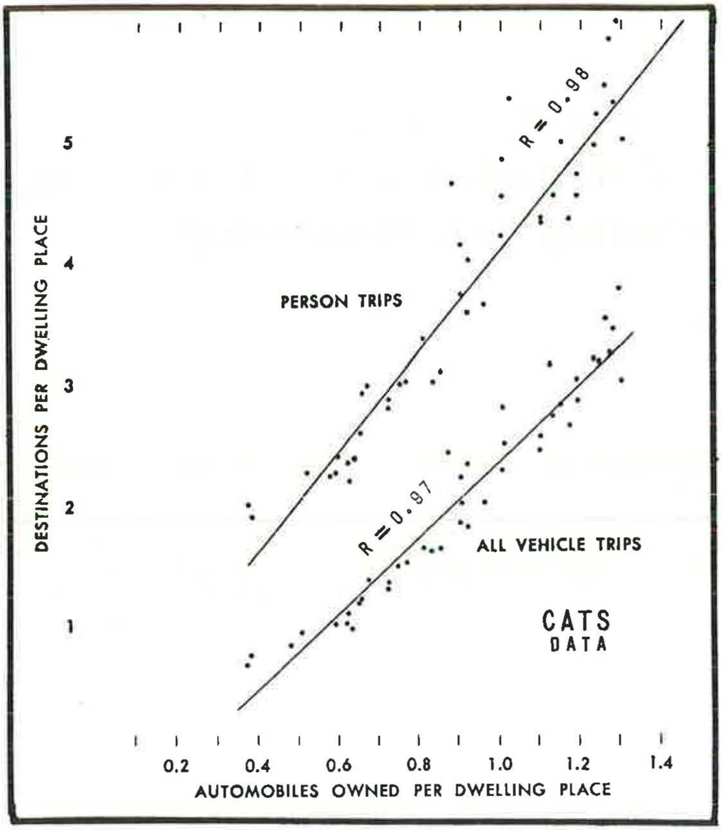

Figure 1. Person and vehicle trip destinations per dwelling place related to automobile ownership.

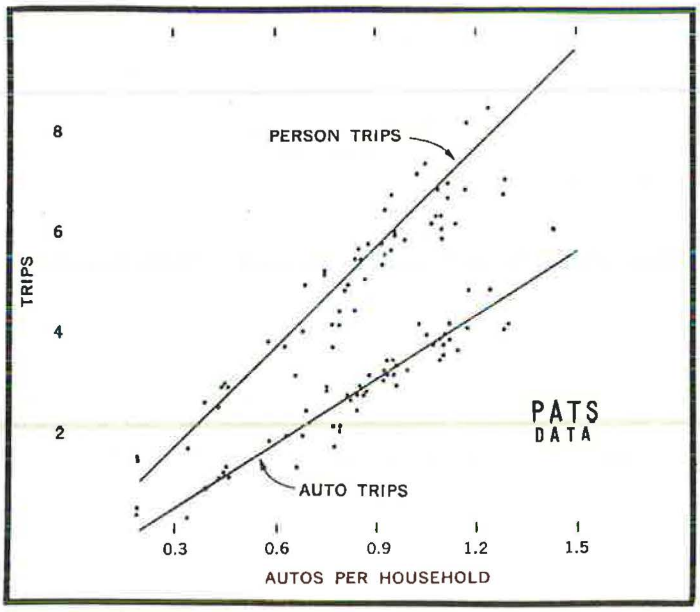

Figure 2. Person and auto trips per household related to auto ownership.

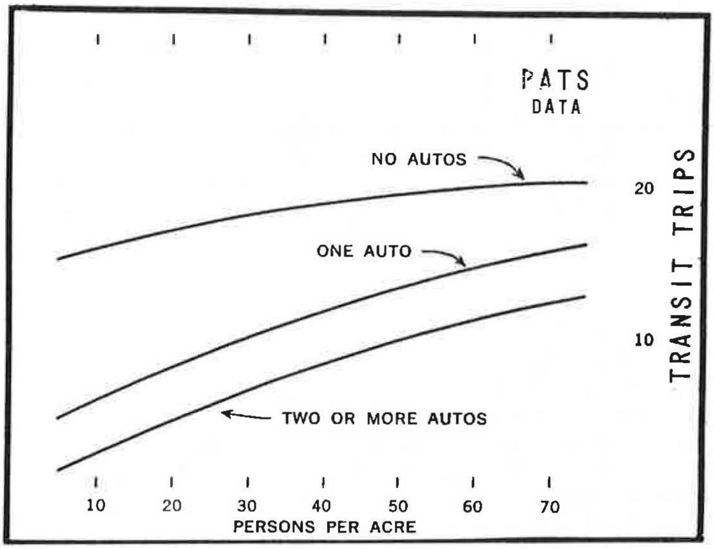

Figure 3. Golden Triangle transit trips per hundred population by auto ownership related to net residential density.

TABLE 1

SELECTED TECHNIQUES USED FOR ESTIMATING AUTO OWNERSHIP

Procedure Classification	Variable(s) Used	References
Pittsburgh Area Transportation Study	Dependent variable: persons/auto Independent variable: persons/residential acre	PATS Volume I and II Technical Paper No. 14, Distributing Future Car Ownership, Nov. 1961 Technical Paper No. 3, Vehicle Registration Forecast, June 10, 1960
Nathan Cherniack, Economist, The Port of New York Authority	Dependent variable: autos/acre Independent variable: households/acre	Critique of Home-Interview Type O-D Surveys in Urban Areas, HRB Bulletin 253, 1960
Puget Sound Regional Transportation Study	Dependent variable: autos/household Independent variable: persons/household	Staff Report No. 9, 1985 Forecasts of Trucks and Passenger Vehicles Owned at Households, April 1964 Staff Report No. 13, Forecasting Household Characteristics for Determining Trip Production-Generation Rates, June 1964
Social Statistics	Dependent variable: autos/household Independent variables: persons/household socioeconomic status	The Use of Social Statistics in Estimating Auto Ownership (Abridgment), by William Michelson, Highway Research News No. 16, Dec. 1964
Chicago Area Transportation Study (Procedure used for Auto Ownership Forecast for Fox River Valley Study)	Dependent variable: autos/household Independent variable: household income	CATS Car Ownership Forecast: A New Approach, by S. V. Ferrera, CATS Research News, June 1965
Penn-Jersey Transportation Study	Dependent variable: autos/household Independent variables: log median household income log households/residential acre	P-J Memo from E. O. Fichtner to Richard Hubbell, Acting Director, April 5, 1965

VARIABLES USED IN ESTIMATING AUTO OWNERSHIP

The variables most commonly used for estimating auto ownership are residential density, household income, and persons per household. These variables have been used individually and also in linear combinations as determinants of auto availability. (For the purposes of this report, auto availability and auto ownership are used interchangeably.)

In the following pages, each of the foregoing variables is studied to determine (a) how well these independent variables reproduce the survey data for auto availability; (b) the logic of the variable and the methodology used as a predictive device; and (c) the results of predictions that have been made using these variables vs the results derived from control totals (a trend of the dependent variable, autos per household). Finally, recommendations are made on the desirability of using each of the variables to forecast autos. In addition, recommendations for changes (or additional efforts) are made in order to render the equations or models used operational in the sense of producing reliable future estimates.

Density

The measures usually employed to represent density in predicting auto ownership are net residential density (persons per residential acre), gross density (persons per acre), and percent single unit structures. In addition, households per acre may be used in lieu of persons per acre.

The correlation results of density vs autos are usually very good for the base or study year. For example, in the Tri-State New York Metropolitan Study, using preliminary home interview results with 278 zones as data points (in expanding the home interview survey from a 1 percent sample to its representative universe, the study area was divided into 278 expansion areas or zones), and fitting the data to a best-fit straight line, the results are as follows (see also Figs. 4, 5):

Dependent Variable	Independent Variable	R^b	$S/\overline{X}^c$
Vehicles/household[a]	(Log of) Gross density (living quarters/sq mile)	0.92	23%
Vehicles/household	Percent single unit structures	0.93	22%

[a]Vehicles/household includes private autos, rented cars and trucks and taxis available to the household.
[b]R = Coefficient of correlation.
[c]S = Standard error of estimate; $\overline{X}$ = Mean of dependent variable.

The results from the Chicago Area Transportation Study also showed good correlations for the survey year using a measure of density to estimate autos. Fitting a parabolic curve to the data from 77 districts in the study area (Fig. 6), the standard error was ±15 percent for the relationship of autos per acre vs households per acre. (This relationship was derived by Nathan Cherniack—see Table 1.)

The Pittsburgh Area Transportation Study, using persons per residential acre as a measure of density, produced a good fit for the relationship of autos per population vs density. The standard error of estimate was 19 percent, using a total of 220 zones in the study area for this analysis.

The variable density has reproduced autos available very well for the survey year. However, if one thinks about using a measure of density for estimating future auto ownership, a careful look at a curve of vehicle availability vs household income, stratified by number of housing units (HU) in the structure (Fig. 7), should indicate that residential density (measured by number of units in the structure), when used as the sole criterion or function for predicting autos, will underestimate autos by a significant number. The areas that are presently at a capacity such that no new growth is expected (or, in other words, when the density will remain constant) must also maintain their constant rate of auto ownership according to the stated relationship (autos vs density). This appears false, since as income changes (rises) with a constant density, the car ownership rate will also change (increase). To illustrate, a change in income from \$6,000 to \$8,000 in ≥ 5 HU/structure will yield an increase in auto availability from 0.46 autos/household to 0.62 autos/household. A change in income of \$8,000 to \$12,000 in

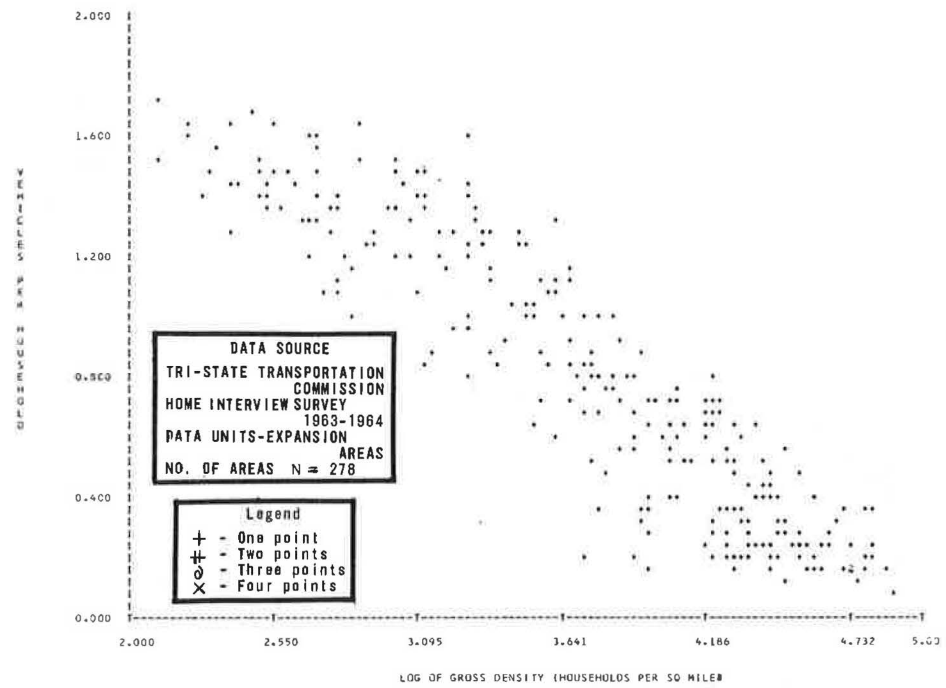

Figure 4. Vehicles per household vs log of gross density.

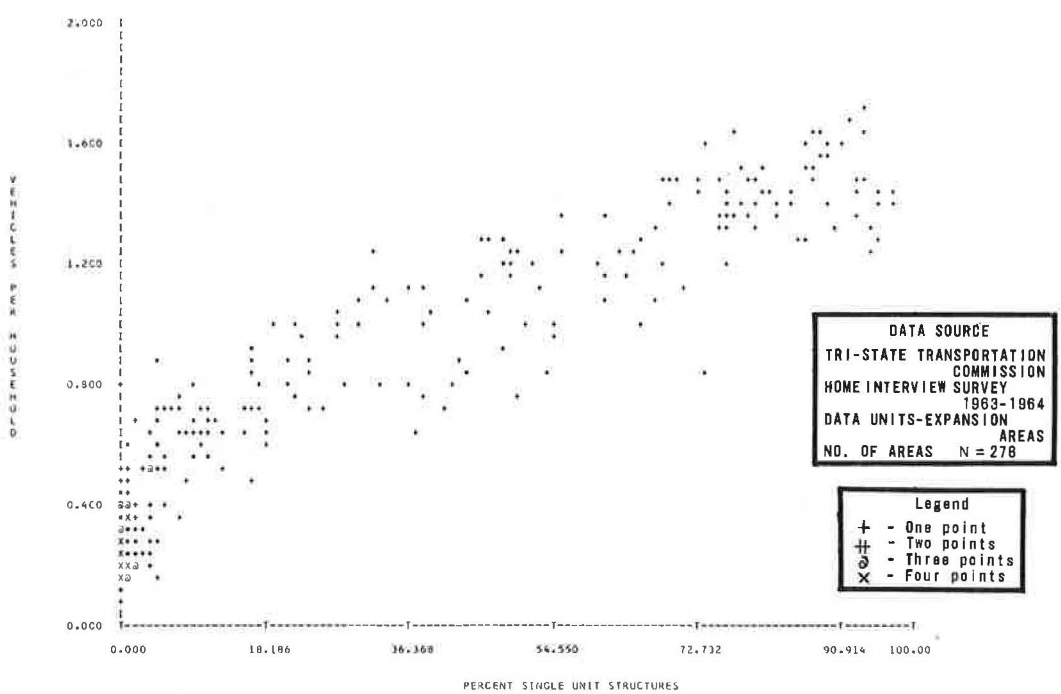

Figure 5. Vehicles per household vs percent single unit structures.

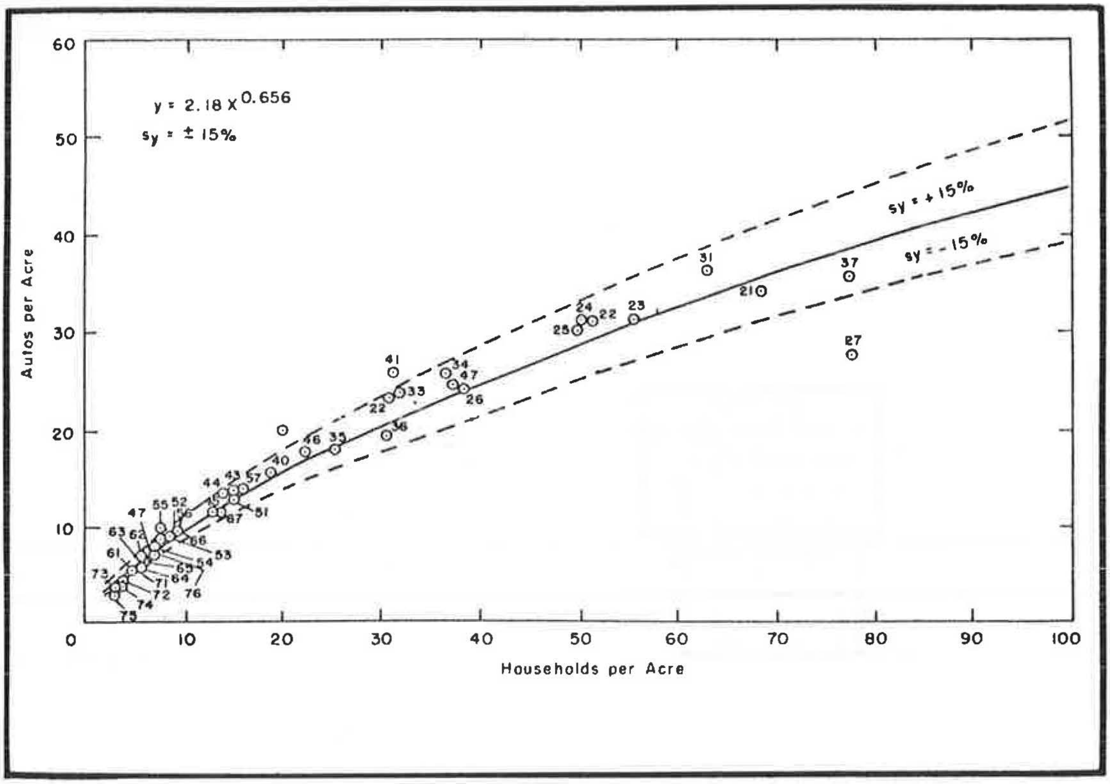

Figure 6. Relation between autos per acre and households per acre for 77 districts in Chicago, 1956–57.

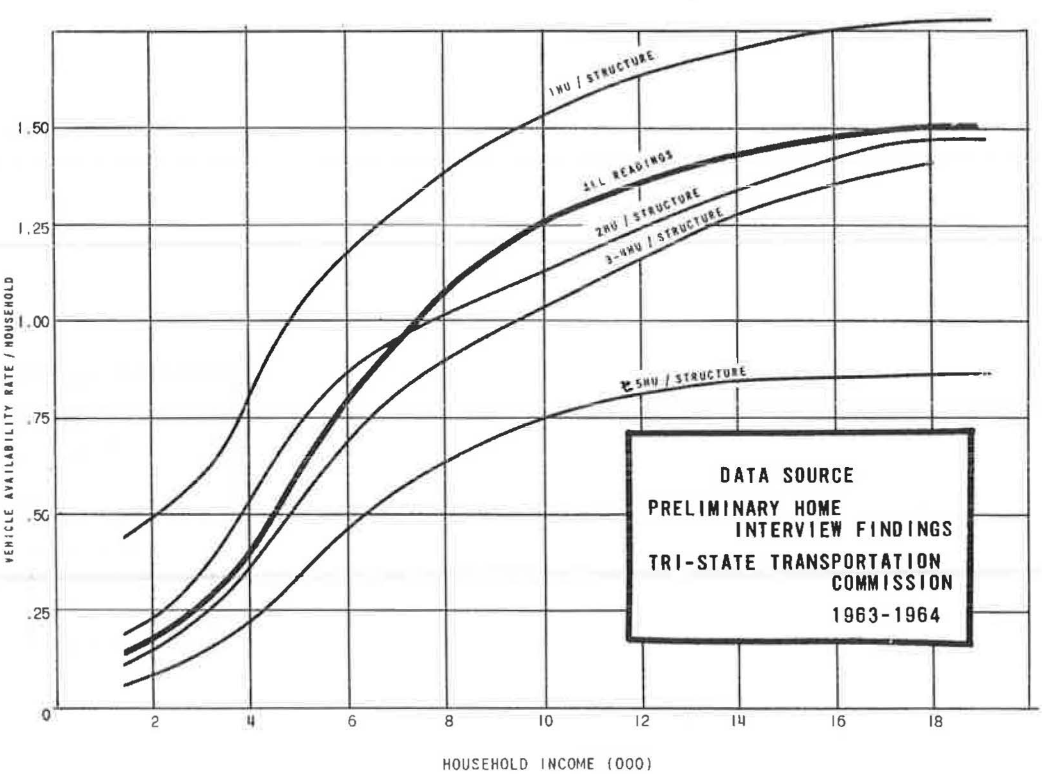

Figure 7. Vehicle availability vs household income, stratified by number of housing units in structure.

single unit structures will yield an increase in auto availability from 1.38 autos/household to 1.65 autos/household.

The studies that used density as the sole variable to forecast autos found that their prediction underestimated the expected number of autos derived from control totals. In distributing future auto ownership, PATS used the best-fit straight line of persons per residential acre vs autos per person. PATS estimated the independent variable for the forecast year and then predicted autos per person using the regression results. However, this method distributed only 55 percent of the "expected" total auto increase. The expected increase in autos was derived from a trend analysis of the dependent variable (autos per person) and a comparison of PATS data to that of the United States. PATS then had the task of distributing the remaining 45 percent of the autos. This was completed by distributing them as a direct function of the population of each zone.

In a general conclusion, the cross-sectional type analysis of density vs autos is not valid for predictive purposes. The reasoning that when any zone B reaches the density of a zone A it will have the same auto availability rate as zone A appears to be false unless the element of time is introduced to the solution. This element of time refers to the natural growth of autos per household in zone A due to the effect of increased real household income, more leisure time, etc.

Household Income

Preliminary results from the Tri-State Transportation Study have shown that the relationship between income and autos is approximately a straight line in the low- and middle-income range and then flattens out (or is parabolic) for the higher incomes (Fig. 8). Using zonal data (n = 278 zones), and fitting a straight-line relationship between median household income and vehicles per household, the correlation results were only fair with a coefficient of correlation of 0.68 and a standard error of 48 percent (Fig. 9).

Whereas household income has been used in combination with other independent variables in predicting vehicles, it has not been used by transportation studies as a sole

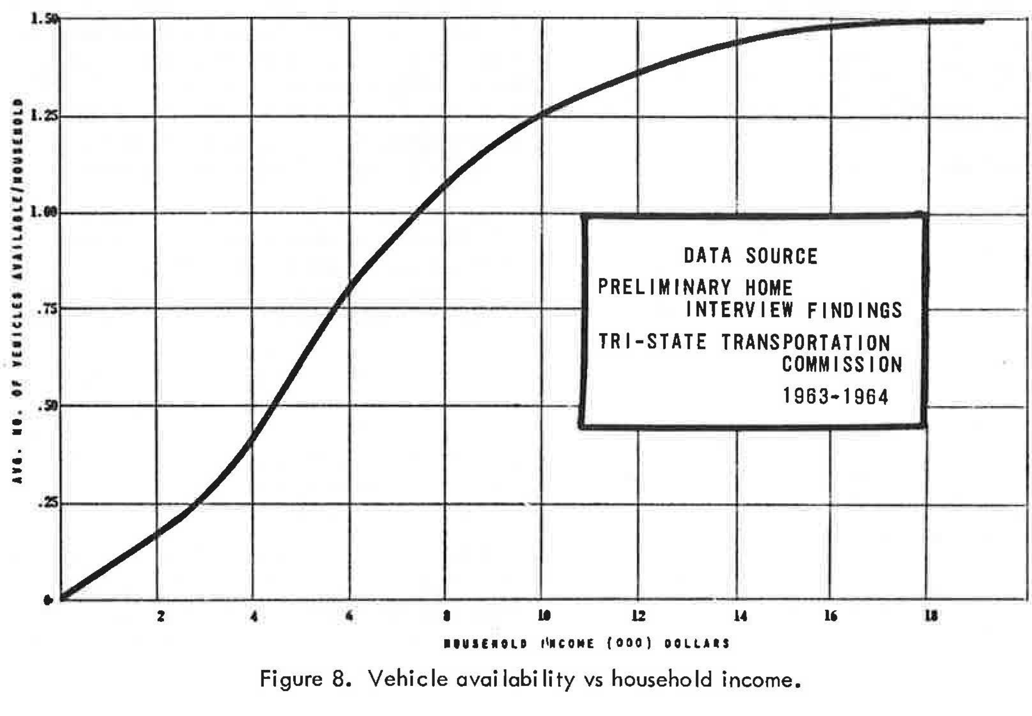

Figure 8. Vehicle availability vs household income.

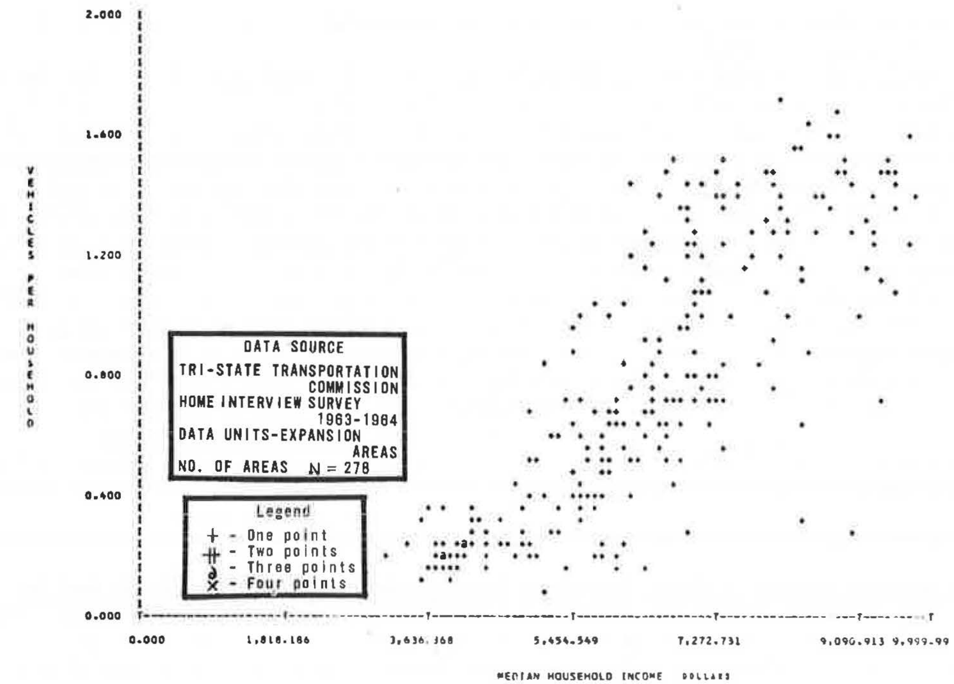

Figure 9. Vehicles per household vs median household income.

TABLE 2

CATS PROCEDURE FOR FORECASTING AUTOS PER HOUSEHOLD

Income Class ($)	Percent of Households in Survey Year	Change*	Percent of Households in Forecast Year
0-3, 000	15	0 -7.5	7.5
3, 000-5, 000	13	+7.5 -6.5	14.0
5, 000-7, 000	24	+6.5 -12.0	18.5
7, 000-10, 000	27	+12.0 -13.5	25.5
10, 000-15, 000	14	+13.5 -7.0	20.5
15, 000-25, 000	4	+7.0 -2.0	9.0
25, 000+	3	+2.0 0	5.0

*Assuming a change in real income per household of 50% for the survey year to the forecast year, the percent in each income class is changed as follows: 50% of the households in each income class are shifted to the next class. Thus, the income class $0-3,000 which initially contained 15% of all households, now has only 7.5% of the households, with 7.5% shifting to the $3,000-5,000 income class. The $3,000-5,000 income group loses 50% x 13% or 6.5% to the next income group and thus has a +7.5% - 6.5% total change or an increase of 1% of households for the forecast year.

Assuming the number of persons per household will remain constant (survey year to forecast year) the total number of autos per zone is determined by multiplying the auto ownership rates (by income class) by the number of households: $\left(\frac{\text{Estimated Pop.}}{\text{Pop./Household}}\right)$ (Auto/Household)

independent variable for a regression-type analysis. Income, however, has been used as the single independent variable in a process for estimating autos per household. This process, recently developed by CATS (see Table 1), uses the following methodology for estimating autos per household and total autos for an area:

1. Establish from survey results the percent of households owning 1, 2 and 3 or more autos per income group;
2. Predict a single figure of percent growth of real income (per household) for the survey year to the forecast year; and
3. Hold the rates from (1) constant with the percent of households in each income group changing at the same rate as the real income change (survey to forecast year). The method used in this procedure is outlined in Table 2.

Critical Appraisal of CATS Procedure—The CATS methodology is limited by its rigid and arbitrary movement from one income class to the next. It is in a sense tied in to the classification of its income classes for its results. For example, for the $10, 00 to $15, 000 income classification, a uniform income increase of 50 percent should propel all of the households in the class into the next one ($15, 000 to $25, 000) and not the 54 percent (7. 5 ÷ 14) suggested by the CATS method. The author suggests that the methodology would have real merit if a uniform or normal distribution is assumed for each income class and the households moved through time as follows:

Income Class	Percent of Households in Survey Year	Change
$0-3000	15	0 -5.0%
$3000-5000	13	+5.0% -10.8%

To explain, if everyone's income is increased 50 percent and a uniform distribution is assumed for each income class, then all the households earning $2000 or more in the survey year will be propelled to the next class. Thus, ⅓ of 15 percent or 5 percent of the households move to the $3000-$5000 class and ⅔ of 15 percent or 10 percent of the households remain in the $0-$3000 classification.

The results of the two procedures for predicting household income distributions (CATS vs uniform distribution) are given in Table 3.

Limitations—The CATS procedure, modified by the stated recommendations in the procedure of moving households through and within the income groups, has merit for forecasting autos by studying the changes in real income. One assumption inherent in this procedure is that the growth in any county or zone between the survey year and the forecast year will approximate the density configuration already intact in that area. In other words, the additional households should have approximately the same percentage distribution of single family units and apartment houses. For example, if the growth of a suburban community is expected mainly in two-story garden apartment houses, then the relationship between household income and auto availability when not stratified by density will produce rates on the high side for autos available per household for these new garden-type apartments. In a similar manner, if the growth is expected predominantly in single family units, above and beyond the distribution of single unit structures/ total units for this area for the survey year, then the rates derived from the survey data will produce results on the low side for the additional units (see Fig. 7).

TABLE 3

COMPARISON OF TWO PROCEDURES FOR FORECASTING HOUSEHOLD INCOME DISTRIBUTIONS

Income Class ($)	Percent of Households in Survey Year	Percent of Households in Forecast Year	
		CATS Method	Uniform Distribution
0-3, 000	15	7. 5	10. 0
3, 000-5, 000	13	14. 0	7. 2
5, 000-7, 000	24	18. 5	8. 5
7, 000-10, 000	27	25. 5	22. 3
10, 000-15, 000	14	20. 5	31. 0
15, 000-25, 000	4	9. 0	14. 6
25, 000+	3	5. 0	6. 4

Assuming a mean income value as the midpoint of each income group and the mean value of the open-ended class of $25,000+ as $40,000, then the mean household income for the survey year was $8,310. Under the assumption that everyone's income increases by 50%, then the mean value of a household income for the forecast year should be about $12,500. The mean income for the CATS procedure of rigidly moving 50% of the households from one group to the next produced a mean income of $10,430 while the recommended shifting of households by assuming a uniform distribution produced a mean income of $12,300.

The procedure also has other recognizable limitations in the assumptions. The average income increase is assumed to be constant for each income class. Thus, if the increase is 50 percent, the household earning $10, 000 will move to $15, 000 while the household earning $3, 000 will move to $4, 500. Data from the New York Tri-State Metropolitan Region for income distributions for the years 1950 and 1960 show that the income increase is not distributed uniformly for each class (Fig. 10). In this time period, the increase for the middle-income class in 1950 was greater than that for the lower and upper classes. In addition, there was a spreading out of the range or flattening out of the curve for these middle-income classes in this 10-year period.

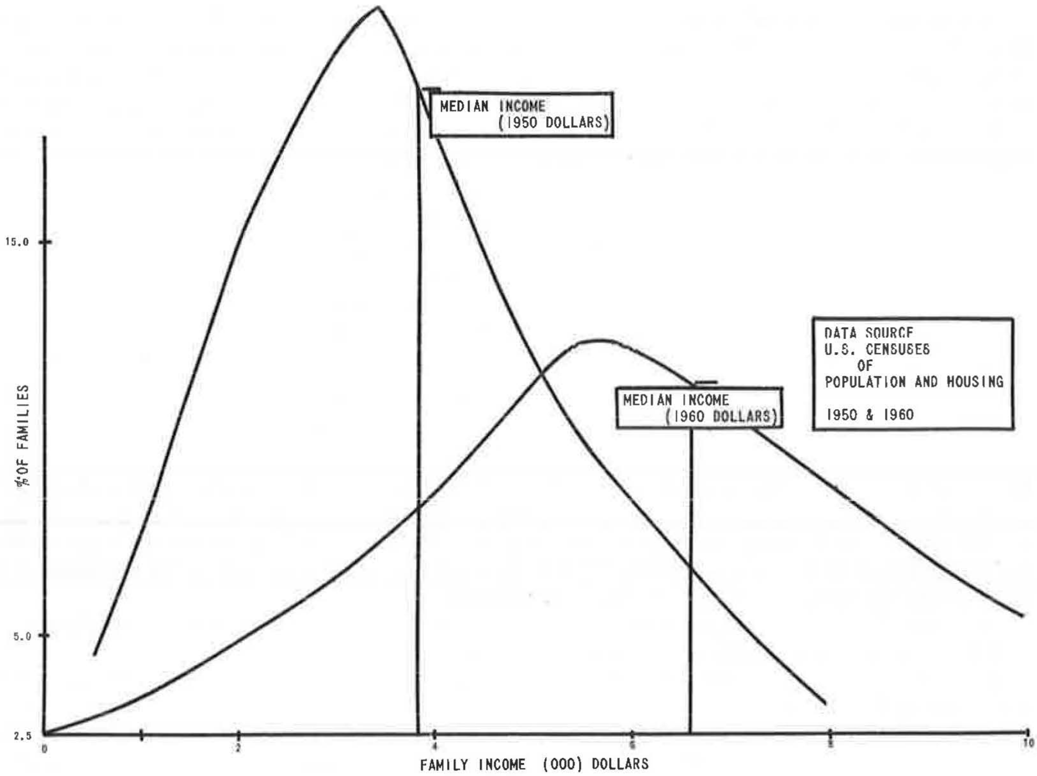

Figure 10. Family income distributions for the New York Metropolitan Area, 1950-1960.

Input to this procedure also includes an estimate of the average change in real income by area, between the survey year and the forecast year. Data are available for this input from the U. S. Department of Commerce in the Survey of Current Business publications, which report personal income per consumer unit by year, by state and also for the United States. In addition, income data are available from census surveys every 10 years (with the possibility in the future that such reporting will be made at 5-year intervals). The Census Bureau reports income data for census tracts, municipalities, and counties.

The use of household income (as specified in the modified CATS procedure) appears valid as a technique for forecasting autos. It is recommended, however, that care be exercised in using the technique in the following areas of concern:

1. Checking that the distribution of new housing units by type is approximately equal to that existing (if a large difference exists, the estimates of autos must be adjusted accordingly);

2. Checking the validity of the assumption that everyone's income increases by a uniform amount; and

3. Making a concentrated effort to insure that the estimated average change in real income from the survey year to the forecast year is reasonable and reliable.

Persons Per Household

The variable of persons per household has been used by the Puget Sound Regional Transportation Study as the sole determinant for distributing autos for a forecast year. This distribution was made on the basis of a linear regression relationship between

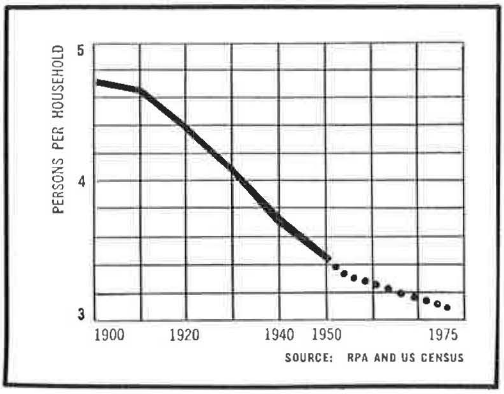

Figure 11. Persons per household vs year for the New York Metropolitan Area.

TABLE 4

REGISTERED AUTOS PER HOUSEHOLD FOR NEW JERSEY COUNTIES IN THE TRI-STATE METROPOLITAN AREA*

County	Year 1940	1950	1960
Bergen	1.01	1.03	1.26
Essex	0.84	1.00	1.02
Hudson	0.60	0.72	0.77
Mercer	0.90	1.05	1.18
Middlesex	0.94	0.91	1.23
Monmouth	1.07	1.15	1.26
Morris	1.14	1.04	1.42
Passaic	0.81	1.00	1.09
Somerset	1.08	1.12	1.02
Union	1.00	1.20	1.33

*Number of households were abstracted from census data; number of registered autos were abstracted from state registration totals.

average household size and average number of automobiles per household (autos per household increases with increasing household size). Using survey results, this relationship reproduced the survey results (by analysis zone) to within an accuracy of ±0.05 autos per household on the average.

Since autos increased faster than population (independent estimates), Puget Sound underestimated the total number of autos distributed by approximately 28 percent, or 255,666 automobiles, when checked with control totals. The trend total was derived in part by an historical trend of the dependent variable autos per household using an admittedly small number of households for the base.

For the New York Tri-State Metropolitan Area, the household size has been on the decline since 1900, with the number of households increasing about 1.4 times faster than the population (Fig. 11). Furthermore, county data for 1940, 1950 and 1960 for the New Jersey portion of the Metropolitan Area indicate that autos per household are on the increase (Table 4).

Evidence from the data for the New York Metropolitan Area has shown that autos per household increased while persons per household decreased (contrary to the Puget Sound results). It is thus recommended that persons per household should not be used as a sole determinant of autos per household.

INTRODUCING THE ELEMENT OF TIME IN ESTIMATING AUTOS FOR A FORECAST YEAR

In describing residential density as a predictor of auto availability, it was pointed out that this independent variable would underestimate the number of autos because auto ownership changes at a much more rapid rate with time than does density. Hoch, in a CATS paper (1), introduces time as a function of his analysis procedure. The methodology of this procedure is as follows: Budget data are gathered relating income to autos registered for a number of different years. A linear equation $Y = MX + B + Kt$ is derived where Y is autos per household, X is a measure of household income and $B + Kt$ is the Y axis intercept. The observed intercept $B + Kt$ is then related to the average household income (for the different years in which the data were collected). The forecast year intercept is then derived by extrapolating the curve of intercept value vs average income (Fig. 12).

Another method of introducing time in the predictive function is to relate auto availability to the combined effect of household income and residential density. If the density of an area remains the same, then the auto availability rate per household will increase if the real income per household increases. In addition, a move or shift from one density level to another will produce a real change in auto availability. Preliminary results from the Tri-State Transportation Study show excellent linear correlations between the combination of density and income in estimating autos. Using expansion areas as zones ($n = 278$ zones) for observation points, the results are as follows:

Dependent Variable	Independent Variables	R	S/$\bar{X}$
Vehicles/household	Median Household Income Percent Single Unit Structures	0.94	20%
Vehicles/household	Median Household Income Log of Gross Density (living quarters/sq mile)	0.95	19%

Probably more significant than the good correlation for one point in time between the foregoing independent variables and vehicles per household is the seemingly logical reaction of these variables (rate of change with time) with that of auto availability.

Validity and Limitations of the Procedures

The use of the combined time series and budget study procedure for forecasting autos (Hoch's methodology) is considered valid, although some inherent assumptions must be recognized before employing the procedure. Since data on income vs auto ownership are available only for the United States, one must assume that the relationship derived with national data holds for the study area under consideration. Care must also be exercised in the extrapolation of the relationship between mean income and the intercept value.

The procedure of using household income and density to forecast autos is also a valid and logical process although this technique has some of the same limitations as those discussed previously in the section on income, such as estimating the real income change as well as the distribution of income classes.

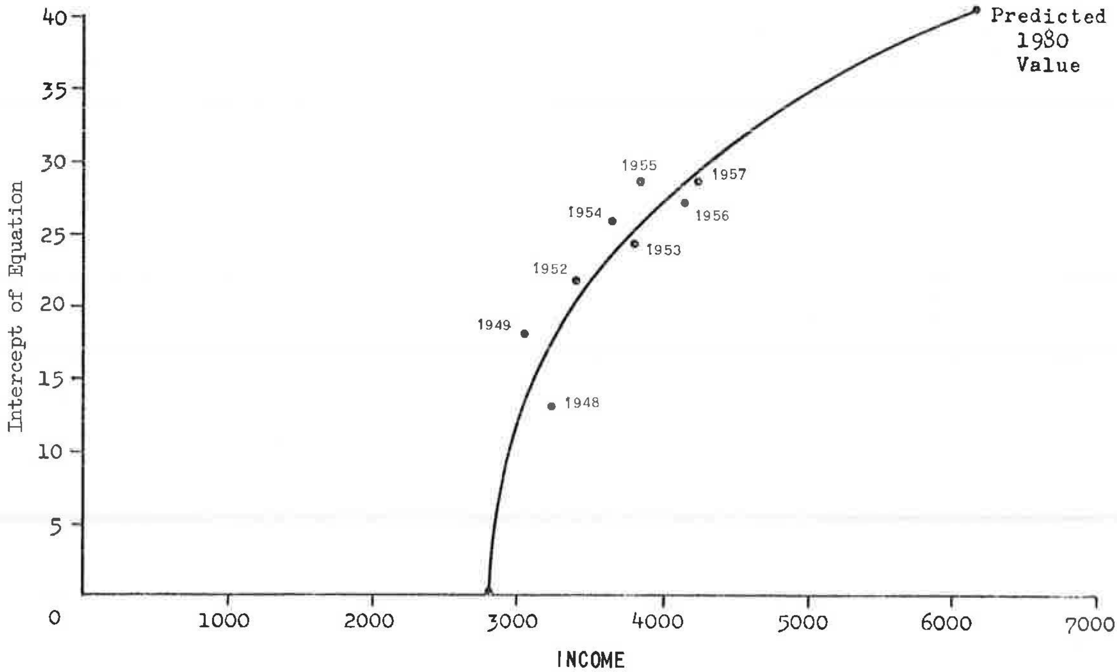

Figure 12. Relation of intercept in equation to average income (using equation to forecast autos, United States data).

DERIVING CONTROL TOTALS

In conjunction with estimating autos per household or the total number of automobiles for a study area by using independent causal variables, most studies control these estimates by applying a trend analysis to the dependent variable autos per household or autos per person. The basic data available for such control totals are the yearly tabulations from the Automobile Facts and Figures Handbook. These tabulations present the percent of households owning 1 or more cars for the United States by year starting in 1948 to the present and the percent households owning 2 or more autos by years for the years 1954 to the present. One method that transportation studies have used to establish a control total of autos for their study area is to extrapolate the percent of household in each auto ownership class, as developed from United States data. This assumes that the percentage distribution of households in the auto ownership classes (0, 1, 2 or more autos) for the study area approximates that for the United States, and more important, that this relationship (of study area to the U. S.) will hold in the future.

Automobile Facts and Figures also tabulates the number of autos registered by county, by year, for selected counties in the United States. In addition these tabulations include estimates of population and households. The State Motor Vehicle Agencies also publish yearly data by county on auto registrations. A second method of establishing control totals is to draw a trend of autos per person by county, for a number of years. A control total of autos per person could be established by studying these trends as well as data from other areas. A maximum rate of autos per person could be established by determining what portion of the population will most likely own an auto. To illustrate, assume the portion of the population either under 18 or over 65 years (for the forecast year) is 40 percent, and that no one in these two age groups is likely to own an auto;

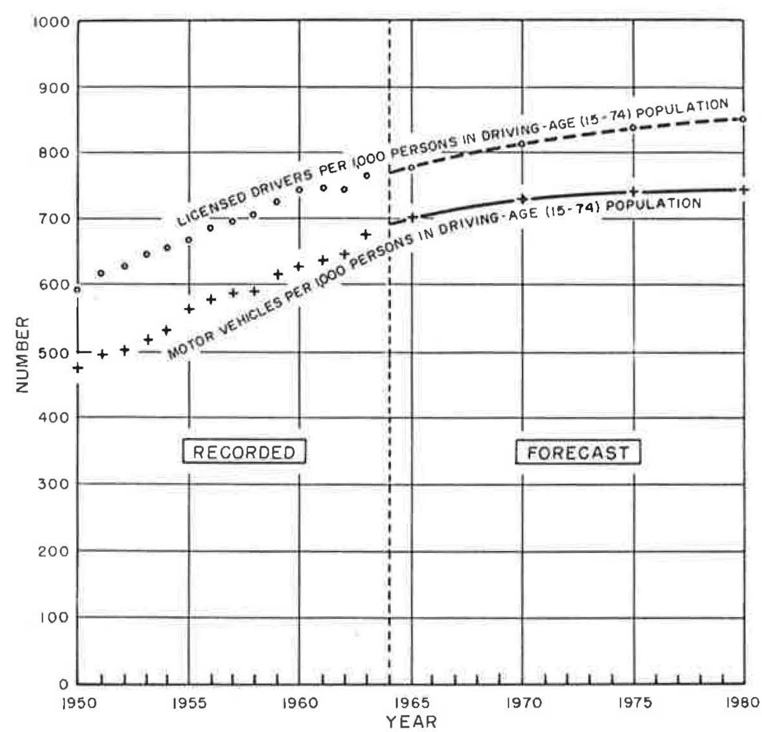

Figure 13. Relationship of the number of licensed drivers and vehicle registrations to population in the vehicle operating age groups.

then the maximum rate of autos per person for this area is 60 autos per 100 persons. This, of course, presumes an average rate of 1 auto per person in the 18-65 age group. The absolute minimum rate would be the present rate of autos per person assuming that autos will increase at the same rate as population. More reasonable control totals of autos per person may be established within these maximum and minimum rates.

A study by the Highway Statistics Division of the Bureau of Public Roads (2) has indicated that the technique of relating the number of licensed drivers to autos owned is very useful for predictive purposes. Data collected for the total population of the United States, the persons of driving age, and the number of licensed drivers produced the relationships shown in Figure 13. This graph shows a good fit of licensed drivers/1000 persons vs year as well as motor vehicles/1000 persons vs year. More important, a stable relationship is also shown between licensed drivers and motor vehicles. The curves (parabolas) are then extrapolated to yield estimates of drivers and vehicles for the future.

Either of the outlined procedures, trend of percent households vs car ownership rate by year, or trend of autos per person by year, is considered valid for establishing a trend of autos per person or of autos per household. The latter method is preferred for the following reasons:

1. Use of United States data presumes that the study area characteristics will be similar in the future to those of the United States;
2. A curve of percent households owning 1 or more autos vs time does not yield reasonable control limits, except that the total should not exceed 100 percent, and it also does not reflect individual household behavior; and
3. A trend of persons per household can be checked for reasonableness. The data for this type of analysis are also readily available at the level of the study area.

Use of Control Total vs Estimates From Independent Variables

The estimate of total autos derived from a technique or model using independent variables should be reasonably close when compared with that established by the control totals. If the two estimates differ substantially (i.e., greater than ±20 percent), then there is reason to review carefully both procedures. Too often the total derived by a trend of autos/household is held fixed even though the data source to derive these results is not as rich or reliable as that used in the model using independent variables.

The ideal case involves the establishment of reasonable maximum and minimum limits of persons/auto and the acceptance of the results produced by the independent variables or models if they fall in this range.

TESTING FOR THE PREDICTIVE POWERS OF THE VARIABLES

The process of determining the equation(s) and/or models for use in predicting autos usually consists of formulating a logical hypothesis and then testing it against the survey data. Too many times, however, the variables for the process are chosen by an analysis of the survey data. In other words, the process is often a sophisticated method of curve fitting. The measure of success of a procedure is not primarily how well the curve fits for the present (measured by the coefficient of correlation and the standard error of estimate), but how well the relationship holds up over time. In lieu of a time machine, the analyst must test his procedure by gathering up data for two periods in time. The data may not be too rich in information or source, and they may not be for the specific area under consideration, but nevertheless they can serve as an indication of the predictive power of the variables chosen. This type of analysis coupled with the logic of the variables in describing the change over time is a must for insuring an acceptable performance by the estimating process.

It was thus decided to test the predictive power of variables most often used for estimating auto ownership: (a) residential density, (b) household income, and (c) persons per household. These tests were made on the variables taken one at a time and also in combinations. The two points in time for this study were 1950 and 1960 since census data were available by county for these two years. The areas chosen for the analysis

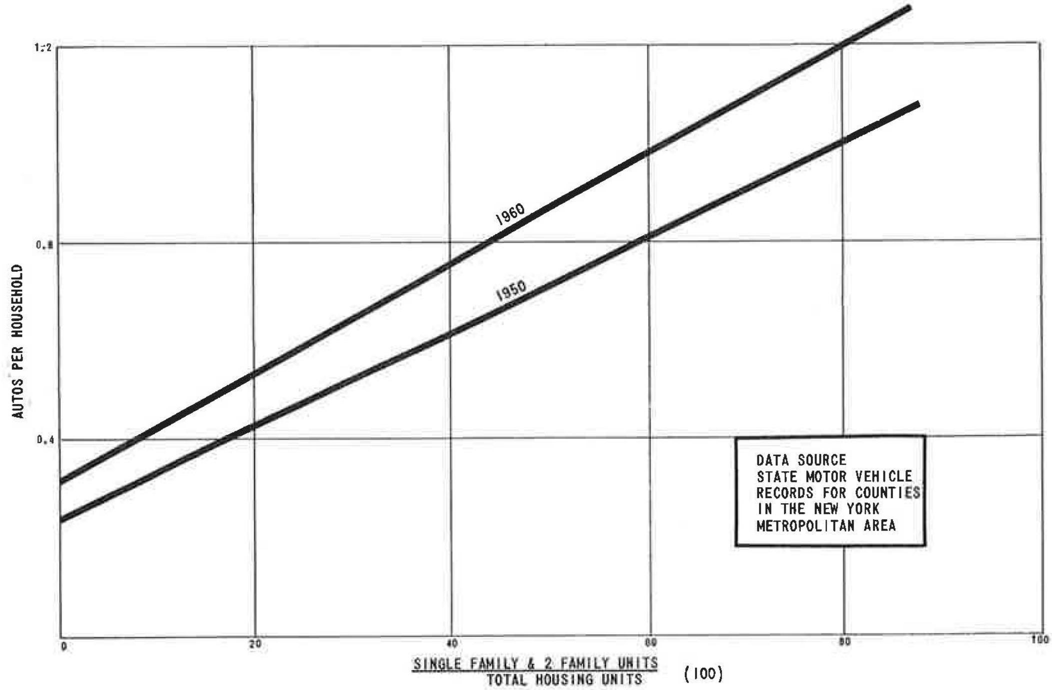

Figure 14. Autos per household vs percent (1 & 2) units per structure for the years 1950 and 1960.

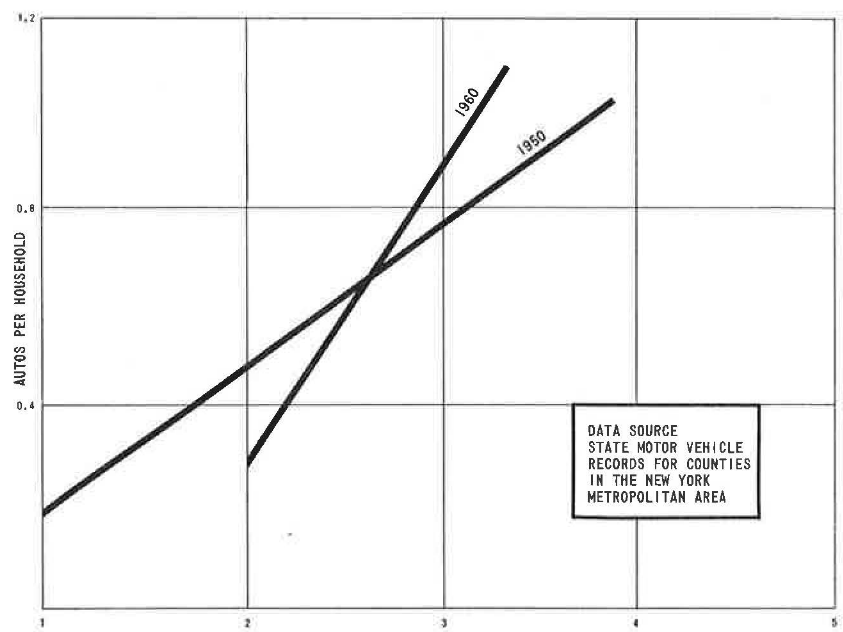

Figure 15. Autos per household vs persons per household for the years 1950 and 1960.

TABLE 5

ACTUAL AND PREDICTED 1960 AUTOS PER HOUSEHOLD

Zone	Actual 1960 Autos/Household	Predictive Variables					
		Median Household Income	% (1 & 2) Unit Structures	Persons/ Household	Median Income and % (1 & 2) Unit Structures	Median Income and Persons/Household	% (1 & 2) Unit Structures and Persons/Household
1 Bergen	1.26	1.17*	1.05	0.90	1.31	1.16	1.05
2 Essex	1.02	1.09	0.72	0.82	0.88	0.98	0.73
3 Hudson	0.77	1.06	0.64	0.81	0.77	0.93	0.65
4 Mercer	1.18	1.10	1.07	0.93	1.24	1.09	1.08
5 Middlesex	1.23	1.12	1.09	0.96	1.29	1.16	1.10
6 Monmouth	1.26	1.08	1.09	0.93	1.24	1.07	1.10
7 Morris	1.42	1.16	1.13	0.97	1.37	1.22	1.14
8 Passaic	1.09	1.08	0.94	0.85	1.08	0.99	0.95
9 Union	1.33	1.16	1.01	0.89	1.25	1.14	1.02
10 New York City	0.47	1.06	0.50	0.76	0.61	0.87	0.51
11 Dutchess	1.14	1.08	1.04	1.00	1.18	1.16	1.04
12 Nassau	1.37	1.20	1.11	1.00	1.41	1.31	1.11
13 Orange	1.06	1.04	1.04	0.91	1.13	1.00	1.04
14 Putnam	1.59	1.09	1.14	0.91	1.30	1.06	1.15
15 Rockland	1.24	1.14	1.08	1.06	1.30	1.30	1.08
16 Suffolk	1.31	1.10	1.16	1.03	1.33	1.22	1.16
17 Westchester	1.20	1.18	0.81	0.89	1.07	1.16	0.81
Root Mean Square Comparison $\sqrt{\frac{\Sigma(\text{Actual-Predicted})^2}{N}}$		0.23	0.23	0.33	0.10	0.19	0.23

Mean of Dependent Variable (Autos/HH) = 1.17 for 17 zones

*To illustrate the use of this table, the number 1.17 refers to the number of autos per household predicted by the independent variable Median Household Income.

were the counties in the New York Metropolitan Area, except for New York City which was one reading. Each point was of equal weight, since the desired result was a test of rates and not of totals. Auto ownership data were taken from state registrations. The best-fit linear regression line was derived for 1950 for each independent variable and combinations of the variables. These relationships were then used to estimate autos per household for 1960 and compared to the actual figures for that year. The results of the comparison are given in Table 5.

The results indicate that the combination of median household income and a measure of gross density yielded the smallest root mean square error[1], 0.10, or 8.5 percent. The next best combination of variables produced an error of almost twice this magnitude, 0.19. The variable persons per household produced the worst results, a root mean square error of 0.33, or 28 percent. Selected graphs from this analysis for 1950

TABLE 6

ESTIMATING AUTO OWNERSHIP, 1950

Dependent Variable	Independent Variable(s) No.	Independent Variable(s) Description	Equation	R Coeff. of Correlation	S Std. Error of Estimate	$S/\bar{X}_1$ (in percent)
Auto Ownership (X_1) Autos/Household	(X_2)	Median household income (000)	$X_1 = 0.05008 X_2 + 0.603$	0.14	0.21	22
	(X_3)	% (1 & 2) units/structures	$X_1 = 0.00958 X_3 + 0.231$	0.90	0.09	9
	(X_4)	Persons per household	$X_1 = 0.294 X_4 - 0.098$	0.33	0.20	21
	(X_2) (X_3)	Median household income (000) % (1 & 2) units/structures	$X_1 = 0.075 X_2 + 0.00965 X_3 - 0.11$	0.92	0.09	9
	(X_2) (X_3) (X_4)	Median household income (000) % (1 & 2) units/structures Persons per household	$X_1 = 0.075 X_2 + 0.00965 X_3 - 0.0001 X_4 - 0.11$	0.92	0.09	9
	(X_2) (X_4)	Median household income (000) Persons per household	$X_1 = 0.077 X_2 + 0.313 X_4 - 0.513$	0.37	0.20	21
	(X_3) (X_4)	% (1 & 2) units/structures Persons per household	$X_1 = 0.0097 X_3 - 0.019 X_4 + 0.293$	0.90	0.09	9

[1]Root mean square error $= \sqrt{\frac{\Sigma(\text{Actual - Predicted})^2}{N}}$

TABLE 7

ESTIMATING AUTO OWNERSHIP, 1960

Dependent Variable	Independent Variable(s) No.	Independent Variable(s) Description	Equation	R Coeff. of Correlation	S Std. Error of Estimate	$S/\overline{X}_1$ (in percent)
Auto Ownership (X_1) Autos/Household	(X_2)	Median household income (000)	$X_1 = 0.167\ X_2 + 0.006$	0.52	0.22	19
	(X_3)	% (1 & 2) units/structures	$X_1 = 0.011\ X_3 + 0.31$	0.88	0.13	11
	(X_4)	Persons per household	$X_1 = 0.611\ X_4 - 0.94$	0.66	0.20	17
	(X_2) (X_3)	Median household income (000) % (1 & 2) units/structures	$X_1 = 0.086\ X_2 + 0.010\ X_3 - 0.207$	0.91	0.11	9
	(X_2) (X_3) (X_4)	Median household income (000) % (1 & 2) units/structures Persons per household	$X_1 = 0.10\ X_2 + 0.013\ X_3 - 0.284\ X_4 + 0.446$	0.93	0.10	8
	(X_2) (X_4)	Median household income (000) Persons per household	$X_1 = 0.10\ X_2 + 0.498\ X_4 - 1.25$	0.72	0.19	16
	(X_3) (X_4)	% (1 & 2) units/structures Persons per household	$X_1 = 0.013\ X_3 - 0.17\ X_4 + 0.75$	0.88	0.13	11

and 1960 indicate the best-fit straight line relationships for the variables (Figs. 14-16). The equations for these graphs are given in Tables 6 and 7.

The graph of autos per household vs percent (1 + 2) units/structure (Fig. 14) shows an almost constant slope between these two variables with an increasing Y intercept with time. If a methodology is to be developed using this independent variable as a predictor of autos, then the (increasing) intercept factor must be established for the future. The graph of persons per household vs autos per household (Fig. 15) reveals the unstable

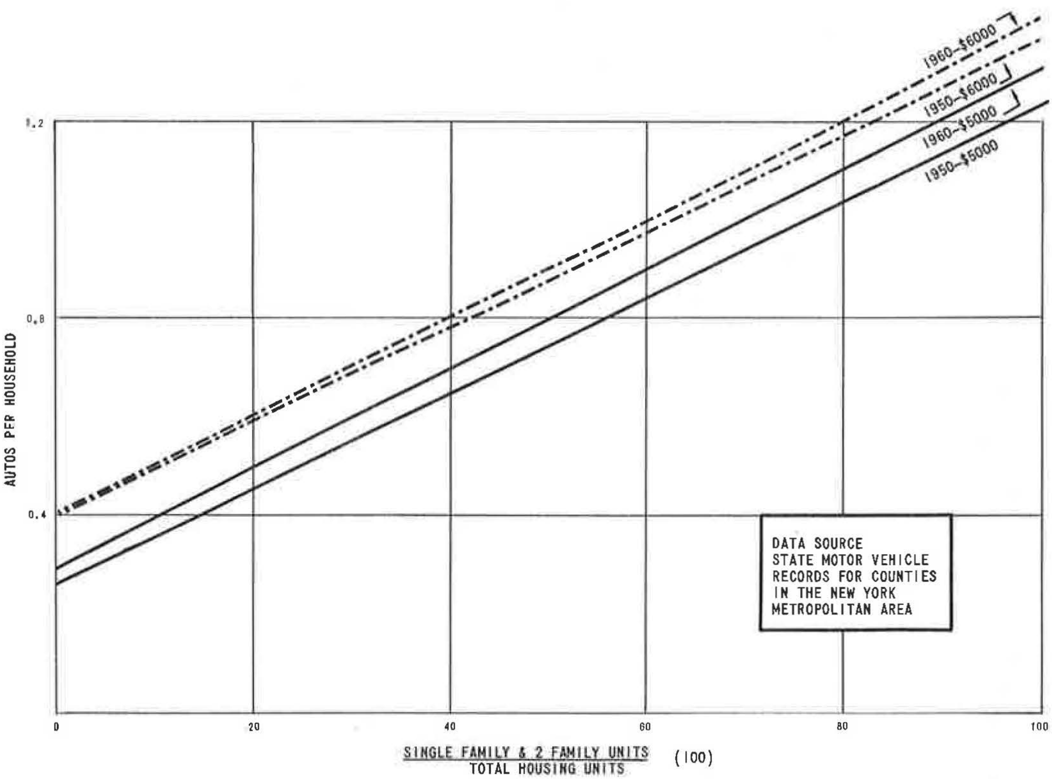

Figure 16. Autos per household vs percent (1 & 2) units per structure stratified by household income for the years 1950 and 1960.

relationship between the two variables. A decline of auto availability from 1950 to 1960 for 1 and 2 person households is indicated from the graph, which seems to be unreasonable. The graph of percent (1 + 2) units/structure (Fig. 16) stratified by median household income shows excellent correlation between the 1950 and 1960 curves for the $5000 and $6000 household income levels plotted.

FORECAST CAPABILITY

A technique selected for forecasting must be based not only on the variables' and/or model's capabilities as predictors but also on the dependability of the estimates of these independent variables.

A purpose of this report is to isolate those techniques that would yield reasonable forecasts, regardless of the difficulties of estimating the independent variables. For example, it was pointed out that an estimation of household income is considered essential in all of the recommended techniques for forecasting autos, even though the estimation of household income is thought of as somewhat of an arduous task for the analyst. Nevertheless, the results of this report indicate a need for more concentrated efforts in an analysis of this variable. Guidelines for needed work in this area include:

1. Study of the changing shape of the income distribution curve (rate of change by income groups);
2. Relationship of change of median income to change in each income group; and
3. Relationship of household income vs auto availability (are the rates constant over time or are they changing?).

Need for Evaluation

Perhaps the greatest need pointed out by this report is that of a continued evaluation of procedures for estimating auto availability. Data are needed for an area for two points in time to establish whether the procedures currently in use produce acceptable results.

The trip generation procedures and modal split models in use today are very much dependent on a measure of auto availability. Measuring the reliability and sensitivity of the techniques used in forecasting autos is essential for the effective use of these procedures.

CONCLUSIONS

1. The use of residential density measures as the sole determinant for estimating autos is not valid for predictive purposes. Autos forecast by this procedure will generally be significantly lower than the totals established by control totals.
2. Persons per household, when used as the only parameter, is not a good indicator of autos per household. In the New York Metropolitan Tri-State Region, autos per household have increased in the 10-year period between 1950 and 1960 while persons per household have decreased in this interval. This relationship has shown a positive slope in other areas (autos per household rising with an increasing persons per household), which indicates an unstable relationship between these two variables.
3. Household income may be used as the single independent variable for forecasting autos per household. Care must be exercised in using the relationship of average income changes leading to average auto availability changes since a substantial change in residential density for a zone will yield auto availability rates significantly different from those rates predicted by income alone. If the incremental growth of residential development forecast does not approximate the density configuration already in place, then the preferred methodology for forecasting autos per household is the use of the combined effect of household income and residential density.
4. The recommended procedure for establishing control totals for autos available is to develop a trend of persons per auto by county in conjunction with the setting up of maximum and minimum limits for persons per auto.

ACKNOWLEDGMENT

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Cost-Saving Techniques for Collection and Analysis of Origin-Destination Survey Data

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The traditional approach in urban transportation planning requires the collection of sufficient travel data on a sample basis to permit stability at the zonal level after expansion, analysis of zonal trip generation as a function of zonal characteristics and, until recently, distribution of generated trip ends by expansion of current patterns. With the advent of models, the trip distribution process has been largely given over to simulation rather than expansion techniques. This development represents progress toward understanding more about the urban travel phenomenon and requires far less origin-destination survey data.

This paper summarizes a suggested procedure for the use of limited O-D survey data for other phases of the travel forecasting process, with attendant savings in data collection and analysis. In the area of trip generation, it is suggested that relationships be derived directly from home interview information at the household level, rather than after aggregation of O-D survey travel data and socioeconomic and land-use data to the zonal level.

A second cost-saving technique involves eliminating the traffic zone as the basic unit of analysis for all phases of the planning process. As a result, layouts of planning areas could be made that would better serve fewer functions. Other opportunities for cost savings include alternative methods of home interview sampling, use of mailed questionnaires for parts of the truck survey, and the possibility of reducing the effort usually expended in making roadside interviews by interviewing in one direction and adhering to rigid sampling techniques.

•THE preliminary steps of an urban transportation study—data collection and analysis—have been largely unchanged for 10 or 20 years. Can we do a more effective job of analysis through variations in data-gathering techniques? Do we really need as much travel data as we have traditionally accumulated for transportation planning studies? Is it necessarily true that the smaller the traffic zone size, the more refined the result obtained? These are some of the questions considered in this paper.

Comprehensiveness has not been an objective of the authors; if this paper does no more than cause some urban transportation planners to probe more deeply into the implications of their customary procedures, it will have achieved a measure of success. We must seek greater economies in pursuing urban transportation studies while we seek greater sophistication. It is the authors' contention that these are not always antithetical goals.

THE TRADITIONAL APPROACH

Since the early 1940's the home interview type of origin-destination survey has been used to provide the basic travel data for urban transportation planning studies. Methods

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of conducting O-D surveys of this type have become a part of urban planning "tradition"—in Webster's definition, "something handed down from the past." Measured in years and months this "past" is not so long, but in terms of the number of cities in which these surveys have been made (several hundred in the United States alone during the past two decades), number of people affected (millions), and total cost (considerable), this "past" is extensive.

The three basic ingredients of a typical O-D survey of the home interview type are the dwelling unit survey, the truck and taxi survey and the roadside interview survey. In the dwelling unit survey, occupants of a carefully controlled sampling of dwelling places are interviewed to obtain detailed data about personal travel in the urban area under study. Considerable information about the occupants themselves is also recorded. In the roadside interview survey, selected drivers entering or leaving the study area are questioned about the trip that they are making into or out of the area. When the travel data obtained in each of these sample interview surveys are properly expanded and combined, a complete description of current travel in the study area is obtained.

Traffic zones are traditionally used as the basic areal units for summarizing and analyzing the vast amounts of data obtained in the interview surveys. A long list of criteria governing the manner in which the study area should be subdivided into traffic zones could be prepared, but basically they are all aimed either at minimizing the distortions that arise from aggregation of data or at conforming to areal definitions for which other data are or will be available.

Expansion of sample data from a full-scale O-D survey yields statistically reliable measures of both current trip generation and current trip distribution. Forecasting future trip generation usually involves development of trip production and attraction equations by means of multiple regression analysis, in which zonal trip ends within the study area determined from the O-D survey are related to various socioeconomic and land-use parameters of the zones. Separate equations are usually derived for various trip purposes and sometimes for different periods of the day. Future zonal estimates of the independent socioeconomic and land-use variables are introduced into trip generation equations to determine future zonal trip productions and attractions.

TRIP DISTRIBUTION

Travel patterns are the result of an immensely complicated interweaving of forces brought about by the spatial separation of people from the activities, places and other people that play a part in their lives. Growth factor procedures for forecasting trip distribution have a number of well-known limitations which are really all reflections of the fact that they "recognize" these forces without "explaining" them.

Philosophically at least, the use of models represents a considerable advance over the older techniques. Models which incorporate general theories and seek to simulate complex phenomena lead us to understanding of these phenomena. From this understanding we can hope to use the general theories with no more than a simple calibration process to account for special or unusual characteristics of the area in which they are to be applied. In transportation planning, models have been most successfully applied to trip distribution. The success of this application has led the authors to the following conclusions:

> Proposition 1—We should seek to emulate the philosophical strength of the trip distribution models in all areas of transportation planning. That is, we should try to develop procedures that will "explain," not simply "recognize" the significance of diverse factors that influence human travel behavior.
>
> Proposition 2—When we have accomplished the above, we need only calibrate to account for differences from the norm. We are not required to derive a basic theory for each particular area which we are planning. It follows that considerably less travel data should be sufficient, and therefore considerable cost savings should be possible.

With the gravity distribution model, for example, we require a set of friction factor curves. Current practice is to develop these to "fit" a particular area by trial and error procedures, but the first trial is generally to use available curves developed for some other area with similar characteristics. And when the model is calibrated the final curves are really not so very different, in general appearance anyway, from the initial curves. It has been shown that a very small random home interview sample will provide sufficient data for calibration of a gravity trip distribution model in a small urban area (1). The authors believe that further research will point to the same conclusion for larger urban areas.

At the heart of the approach suggested in this paper is the belief that a small sample will be sufficient foundation for urban travel forecasting if structured and analyzed on some other basis than traffic zones. No suggestions are made here for reducing the quantity or quality of socioeconomic and land-use data customarily considered necessary for urban transportation planning studies. As a matter of fact, many of the proposed procedures are dependent upon having such data in considerable detail and at a high level of reliability.

TRIP GENERATION

Most urban transportation studies have analyzed trip generation using multiple regression techniques on data aggregated by zones or districts. Generation equations derived in this manner usually prove to be quite reliable, and seem to explain trip production and attraction to a reasonable degree in the area for which they are developed. Assuming that these equations really do get to the causes of trip-making in the particular area for which they were developed, does the fact that equations for the same types of trips developed in different urban areas seldom bear much resemblance to one another force us to conclude that people are really that much different, insofar as their travel habits are concerned, from area to area? The authors suggest that the process of zonal or district aggregation of data is actually wasting much information collected in the interviews, and that this aggregation procedure in itself may be the cause of many of the variations between different areas. It is suggested in this paper that the household would make a better analysis unit for this purpose.

The authors believe that fewer data will be required and better results will be obtained if portions of the trip generation analysis are carried out at the household level, with each home interview representing an observation. Using this procedure, the sample size would depend primarily on the range of social and economic stratifications of the population in the area, and would be set to obtain adequate household and travel data within each stratification, without too much regard for the geographic extent of the area or its population. The same small random home interview sampling required to provide data for calibration of a gravity trip distribution model will very likely yield enough information for this type of generation analysis.

It might be well to introduce a word of caution at this point. Although the authors feel that more meaningful results are potentially available from the suggested type of analysis, the statistical measures of accuracy normally used to evaluate how good an equation is may not look as favorable. Much of the variance among samples is dampened as a result of aggregating data to the zonal level. Of course, much of the essential meaning may have been lost, too, even though the statistical correlation of zonal averages looks better.

Home-based trip production equations would be developed using home interview data pertaining to home-based trips and household characteristics. Multiple regression analyses would be carried out on an interview basis, with the number of home-based trips (perhaps stratified by purpose) per household taken as the dependent variable, and various socioeconomic or land-use characteristics of the household as independent variables. If the resulting equations were linear, they could be used directly in forecasting of home-based trip productions on a zonal basis by simply entering zonal forecast averages of the independent variables and multiplying by the forecast number of households in each zone. If nonlinear variables were involved, separate equations could be developed for different stratifications of the nonlinear variables, in which case some special treatment would be required to insure that the actual distribution of the nonlinear variables were properly incorporated into the final zonal forecasts. Or values taken by an independent variable could be stratified into several classes and each class made a dummy variable in the regression equation. Using this technique, the dummy takes on values of either 1 or zero for each observation in the regression analysis depending on whether or not the variable falls within the dummy class.

Trips with one end at home are generally considered to be produced at home, regardless of whether they are to or from home. There is great logic in so relating trip production to the people who make the trips, and to the socioeconomic and land-use characteristics of the household which are indicative of the reasons behind their desire and ability to make trips. When it comes to non-home-based trips, however, the logic of the traditional mode of analysis diminishes. Because neither end is at home, we customarily take the origin end to be the production end and seek out a relationship between non-home-based trips produced and circumstances at the production end. It is suggested that it would be more logical to consider these trips to be generated at home. Exactly as with home-based trips, it is the complex combination of circumstances that we can measure only at home that fashions the travel desires and capabilities of people to make non-home-based trips. Where they make them is, of course, another question. The authors would estimate zonal productions of non-home-based trips in two steps, first by determining area-wide totals, and second by allocation of these totals to production zones. Analysis of home interview sample data, again using each sample as an independent observation, would be employed to relate number of non-home-based trips made by household members (perhaps in more than one trip purpose category) to various socioeconomic and land-use parameters of the household. Solution of the resulting equation using area-wide forecast averages of the independent variables would produce an estimate of the number of non-home-based trips to be expected per household in the future. Multiplication by the forecast number of households would, of course, produce the total number of resident non-home-based trip productions in the area. Nonlinear variables could be handled in the same manner described for home-based trip production. Internal trips by external residents (which must be non-home-based) are usually not included in transportation studies. However, there is no reason why an estimate of the number of nonresident non-home-based trip productions in the area should not be added at this point.

An allocation function, to determine the number of trip productions within each zone in the area, could be derived from non-home-based trip production equations developed in some similar area where a full origin-destination survey had been made, yielding reasonably stable data on non-home-based trip production at the zonal level. Following this procedure, data collected in the particular area under study would be used to determine the overall significance of this type of travel, but the assumption would be made that the proportional influence of various parameters in explaining where non-home-based trips might be expected to originate is the same as in the similar area. This would seem to be a valid assumption in most cases.

An alternative means of deriving an allocation function would have to be employed, of course, if there were no reasonable non-home-based trip production equations up for adoption. One means of accomplishing this would be to break down the first step described—that of deriving an equation for the generation of non-home-based trips through relation to home parameters—into several origin purpose categories, and then distribute each purpose subtotal in accordance with the one zonal parameter that seems most reasonable.

The customary procedure in most transportation planning studies has been to derive an independent set of equations to relate trip attraction directly to various socioeconomic and land-use parameters. But O-D data from a small sample home interview survey will not provide a sufficient basis for this kind of trip attraction analysis. The authors recognize that this is a major disadvantage of the procedures suggested. Perhaps here again equations developed from a similar area, if such are available, could be used to advantage. Total attractions might then first be determined by recognizing that, over an entire area, total attractions must equal total productions plus or minus the net effect of trips crossing the external boundary of the area, and then be allocated to zones in one of the ways described for non-home-based trip productions. As far as non-home-based trips are concerned, it may not be unreasonable in some areas to assume that attractions equal productions in each zone. But, of course, such an assumption would not be valid for home-based trips.

The authors do not know of any actual transportation study where trip generation equations have been developed from unaggregated data at a household level and then used in the forecasting process. However, in a research project sponsored by the U.S. Bureau of Public Roads (2), multiple regression techniques were used to attempt to derive meaningful household trip production equations using data from 824 households spread all over the United States. Although the BPR-sponsored study was founded upon a limited nationwide sample, the findings demonstrated that this type of analysis had promise and ought to be pursued.

TRAFFIC ZONES

Traffic zones have traditionally been used as the basic unit of analysis for the entire transportation planning process. Trip data are usually coded to traffic zones, and socioeconomic and land-use data are usually inventoried on a traffic zone basis. Trip generation and distribution are also performed on a zonal basis. In traffic assignment, the trips to and from each zone are applied at a single point representing the centroid of trip end locations in the zone.

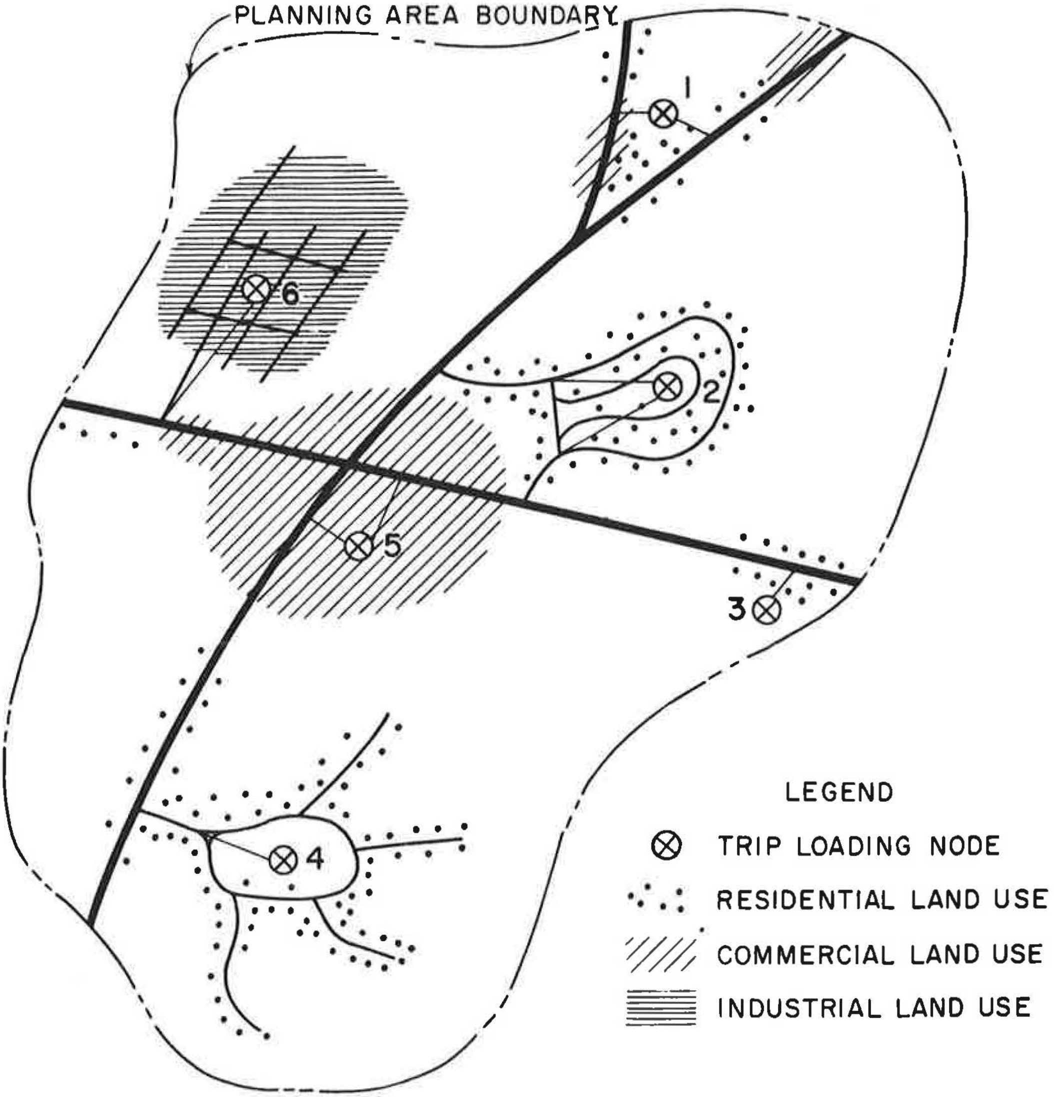
These different reasons for having traffic zones all translate into different criteria for delineating them, depending upon who is doing the traffic zone layout. Demographers are interested in availability of current and past population data; they prefer to have zone boundaries conform with areas already established by census authorities. The O-D survey data coders are interested in the ease with which addresses can be converted to traffic zone codes; they want to avoid running zone boundaries down the middle of streets, or they might even try to put entire streets in one zone or the other. The statisticians do not want the zones to be so small that sample data aggregated to the zonal level are statistically unstable. The transportation planners do not want the zones to be too large and are very concerned about the orientation of zones with respect to the transportation network. The trip generation analysts would be most concerned about homogeneity of zones, both from the point of view of character and of size.

Delineation of traffic zones in most transportation studies has been in accordance with criteria that did not permit wholesale adoption of areal units used for other purposes—for example, by the Census or by local planning bodies. Usually, when this occurs much of the value of past planning is lost and planning must be redone on the basis of the new system of traffic zones, which may not be logically and reasonably delineated from the point of view of regional planning. No layout of zones can ever satisfy everyone, but if traffic zones were not required to perform so many different functions at once, they should be able to perform certain functions better and more economically.

Traffic zones need not play a part in the trip generation analysis, and perhaps not even in the distribution model calibration process. If in neither, there would be no need to code O-D survey trip data to zones since we would be interested only in household characteristics, numbers of trips of various types (purpose, mode and time) made by household members, and the lengths of such trips—not specifically where the households were or where the trips went. Current trip generation and distribution would be simulated directly from household data. It would not be until this point then that some manageable unit of area larger than a household would be required. It is recommended that such a larger area, called a "planning area," be used.

PLANNING AREAS

Planning areas could be larger than traffic zones, and would be laid out primarily to serve the purposes of demographers, economists, geographers and planners. The transportation analysts would be concerned only with the degree of homogeneity of character for each of those parameters that affect generation of several trip categories being considered. Heavy industry and low-income, high-density residential development



PERCENTAGE BREAKDOWN OF GENERATED TRIP ENDS BY LOADING NODE

TRIP CATEGORY	1	2	3	4	5	6	TOTAL
Home Based Work							
Production	15	40	7	35	–	3	100
Attraction	5	2	1	2	20	70	100
Home Based Shopping							
Production	15	40	7	35	–	3	100
Attraction	10	–	–	–	85	5	100

Figure 1. Use of planning areas in travel forecasting.

could occur in the same planning area, but combinations of heavy industry and light industry, or of low-income, high-density residential development and high-income, low-density residential development within the same planning area would be avoided.

How then would the travel forecasting process be carried out? First, trip generation equations developed primarily from household data would be used to forecast the numbers of trip ends in each planning area. The forecast trip ends would then be disaggregated to trip loading nodes on some reasonable basis for each trip purpose category, as illustrated in Figure 1. The allocation procedure used to do this could vary widely in sophistication, just as the procedures used to allocate area-wide population forecasts, for example, vary widely in sophistication. But the objective in either case is the same—to get a fairly reliable forecast quantity for a larger area allocated to smaller areas.

Use of this concept would usually result in significant economies since all phases of the gathering of current data and the forecasting of future data would not need to conform to a single rigid system of traffic zones. Furthermore, the areal units used in the compilation and analysis of one class of data (e.g., population data) would not necessarily have to conform to the units used in the compilation and analysis of another class of data (e.g., employment data). Nor would the areal units used for current data necessarily have to conform to units used for forecasts. Several different breakdowns could be used for the forecast year, reflecting varying land-use development patterns. Of course, uniformity would be desirable where readily achievable, but the greater flexibility made possible by this approach may often provide advantages of economy and logic that far outweigh the relatively minor bookkeeping difficulties occasioned by having to keep track of more than one different system for subdividing the study area into workable planning area units.

Following the allocation of generated trip ends to loading nodes, trip distribution and traffic assignment would proceed in the normal manner. How many trip loading nodes are selected, where they are located and how they are connected to the transportation network would be left to the transportation analysts.

One of the important criteria in the selection of planning areas is the availability of data. Thus, for example, since census units are important to any study of population characteristics, they should be used as planning areas, at least for home-based trip analyses, whenever possible. Another criterion in the selection of planning areas is size. The size of individual planning areas must not be so great that a reasonably reliable allocation of any total pertaining to some characteristic of the planning area to various sectors within it cannot be made by inspection, on the basis of familiarity with the locale. It is very difficult to state this criterion in quantitative terms; its applicability in any given situation revolves around what is "reasonably reliable." This includes an appreciation of what impact a given level of imprecision in this allocation might have on the output of the transportation planning process, and also an appreciation of how significant a given level of imprecision in this allocation really is in comparison with the reliability of overall forecasts of regional activity.

DATA COLLECTION

The major advantage of the method of analysis proposed heretofore in this paper is that much less origin-destination survey information than is usually considered necessary will support it. Since data collection is one of the major items of cost in any urban transportation planning study, the implications of this fact alone are of great significance. But there are other possible opportunities for cost savings in the data collection phase that may be within reach also.

Home Interview Survey

Great care must be taken in the ordinary home interview survey to insure that samples are randomly selected from a complete statistical universe, and that sample data are expanded to account for the whole, even where there are gaps due to refusals and similar circumstances. These measures are essential when the purpose of the home interview survey is to observe and quantify a statistically sufficient sample of current travel so that the expanded sample represents the universe of current travel.

Using the type of analysis suggested in this paper, the purpose of the home interview survey would be to gather enough data to allow development of trip generation equations at the household level and to calibrate a trip distribution model.

Satisfactory calibration of a distribution model, such as the gravity model, from limited survey data appears to require that the small sample be uniformly distributed in a random fashion over the entire geographical area under study. The possibility of using a clustered sample of the same size was studied in a research project using data from the Pittsburgh Area Transportation Study (3). It was found that travel time factors developed from clustered survey data varied considerably from those developed from total study area data.

For the purposes of supporting the type of trip generation analysis proposed herein, the sample must provide sufficient observations within each socioeconomic grouping, but uniform sampling of all groupings and geographic dispersion of the sample are not required. As long as a small random uniform sample is required for gravity model calibration, it can be used, and probably will be sufficient, for sampling of household trip generation and related household characteristics as well.

If home interview survey data are to be used at the household level for the trip generation analysis, the question arises as to why the sample need be expanded at all. Current practice is to obtain trip length frequency from expanded survey data, but it would probably be just as reasonable to use trip data at the household level for this purpose also. Considerable savings could be effected if the sample did not require expansion. Moreover, if expansion is not required, do we really need the extensive and expensive measures traditionally taken in home interview surveys to insure complete, uniform, unbiased sampling of all segments of the universe? Since we are not seeking through sampling means a measure of the number of people in each socioeconomic group or in each geographic area, or a measure of area-wide trip generation or O-D trip patterns, must we encompass all corners of the statistical universe? If we are using utility records for sampling households, for instance, must we worry about the small percentage of households not served by the utility? Ordinarily we probably would because the proportion, though small, is indeterminate and we would have no basis on which to adjust expanded survey data.

These and other questions should be explored in the planning stage of the home interview survey. Perhaps collection of some additional data (e.g., stage in the family life cycle, availability of alternative transportation modes at times when specific trips were made, etc.) may be desirable to support the analysis of trip generation characteristics at the household level.

Alternative means for actually collecting the data should be investigated also. For example, several studies have reported success in making interviews by telephone (4). The Ohio Department of Highways uses a booklet which is dropped off at the sample address with a personal explanation of what is required, and later picked up and reviewed with the respondent to insure complete and accurate information.

Truck Survey

Heretofore not much has been said about analysis and forecasting of truck travel. The usual approach is to obtain travel data from interviews in a sampling survey in which the vehicle itself is the sample and an attempt is made to determine information concerning a particular day's travel.

There is a possibility that research will point the way toward a better understanding of truck trip generation leading to means of reducing the quantity of data required from an origin-destination survey. The initial step in this direction might be to separate trucks into three groups and deal with each separately:

1. First, trucks that are owned and used by individuals or families as personal vehicles should not really be considered as trucks at all in the trip generation analysis.

2. Second, a separate analysis should be made of travel by trucks that are primarily oriented toward providing services to households. These would include delivery trucks, repair trucks, refuse disposal trucks, mail trucks, and so forth. It should be possible to relate generation of trips by such vehicles to household characteristics; perhaps actual interviews would not be required at all for such vehicles, and sufficient data could be gathered to support a largely synthetic trip generation analysis through an expanded home interview survey or by special cordon counts around residential areas.

3. Third, all of the remaining trucks involved in the area's basic industries and businesses would undoubtedly have to be surveyed separately, and travel data analyzed and forecast on a zonal basis in the usual manner. It may be that there would be too much variation and too few observations from this group of trucks to support any sort of regression analysis, and that trip rate analysis by industry category would prove more satisfactory.

The authors' firm has recently completed origin-destination surveys in two urban areas in West Virginia (5, 6) in which part of the truck survey was conducted by mailed questionnaire. In both areas, questionnaires were mailed to owners of 100 percent of the non-fleet trucks (trucks registered to an owner who had no more than three trucks registered in his name). Fleet trucks were sampled and interviews conducted in the usual manner. In the larger of the two areas, a 38 percent return was received without making any follow-up mailing or telephone calls; a 27 percent return was obtained in the other area. The cost of conducting the mailed questionnaire survey was very much less than would have been required to select samples and make interviews in the normal manner. The average number of trips per interview was lower and the proportion of trucks making no trips on the travel date was higher for the mailed questionnaire survey than it was for the interview survey in both areas, but this is probably characteristic of the difference between non-fleet and fleet trucks. Research is clearly indicated to determine whether an uncontrolled sample of trucks, such as is obtained from voluntary return of mailed questionnaires, will yield unbiased trip generation and trip length frequency data.

An unusual procedure was employed by the authors' firm to collect truck travel data in a small urban area in New Hampshire (7). Here the home interview sampling rate was so great (1:5) as a result of the area's small size, that statistical stability of data relating to truck travel could be assured by obtaining origin-destination data for internal truck trips in conjunction with the home interview survey. This was accomplished with no particular problems, and at little increase in cost to the home interview survey. Special adjustments were made to account for wholly internal truck travel by external residents.

Roadside Interview Survey

In most urban transportation studies the collection of travel data at roadside interview stations on the cordon line surrounding the area represents a major portion of the total data collection effort. Careful design of questions to ask and forms on which to record answers is particularly important for the roadside interview survey because of the limited amount of time available for each interview.

An example of the kind of poorly worded question that should be avoided is the following, which oddly enough has become standard in many areas:

Question: Where is the car normally garaged?
Answer (circle one):
1. At origin inside cordon
2. At destination outside cordon
3. At neither
4. At origin outside cordon
5. At destination inside cordon

There are at least three things wrong with these answers: (a) they are confusing; (b) the specification of whether the origin or destination is inside or outside the cordon is redundant information; and (c) since the real purpose of asking the question is to find out whether or not the respondent is a resident of the internal area, if Answer 3 is given, do we know? Why not provide two answers—inside or outside—and let it go at that?

With regard to interview form design, the person who is organizing and preparing for the roadside interview survey should really have made some interviews himself, preferably in cold, wet weather at night with a large volume of traffic delayed. Many forms look fine in the office but are hard to use in the field. Poor form design is expensive, both in extra time spent in the field and in inaccurate, incomplete, or unreadable data brought back to the office.

A more rigid sampling technique might make it possible to reduce drastically the number of roadside interviews required. Roadside interview crews are customarily instructed to get all the interviews they can. There really is no control over the sample this way and we console ourselves that we make up for the resulting loss of statistical reliability by interviewing such a large percentage of the passing traffic that it can make no real difference. Fewer, more carefully selected samples would certainly result in lower costs for data collection and subsequent processing, and should produce just as reliable data.

Even greater savings would come from reducing the number of stations operated and the number of hours of operation, or from interviewing traffic in one direction only. To evaluate the feasibility of such measures, it is necessary to give careful consideration to the manner in which roadside interview data will be used in subsequent analyses and how external trips will be forecast.

Three types of trips are intercepted at cordon line stations—through trips, non-through trips by residents, and non-through trips by nonresidents. Non-through trips by residents are sampled in the internal home interview and truck-taxi surveys. Through trips and non-through trips by nonresidents can only be sampled at the cordon line.

The usual procedure for handling the duplication of resident trip data is to eliminate data pertaining to non-through trips by residents from the internal surveys. Non-through trips—by residents and nonresidents—are then distributed by the Fratar method or, in accordance with the latest recommendations of the U. S. Bureau of Public Roads (8), by a single-purpose gravity model. Through trips are customarily treated separately and distributed using the Fratar method. Duplication in the collection of data pertaining to through trips—each such trip has a chance of being intercepted twice, once at each point where it crosses the cordon line—is normally resolved by retaining all data collected but applying a one-half factor to them.

To obtain information about through trips it is necessary to interview on all the routes crossing the study area cordon line that carry an appreciable amount of through traffic. However, since through trips by definition cross the cordon line twice, we would be sure to obtain complete information if we were to interview traffic on such routes in one direction only—either inbound or outbound.

Trip data pertaining to resident travel are obtained in the internal interview surveys as well as the cordon line survey. The fact that we have duplicate sets of data to choose from is really somewhat of a luxury. If we did not have data from an external survey, we would certainly use what we had from the internal survey, probably without any qualms as to its adequacy.

This leaves non-through trips by nonresidents. What do we need to know about such trips to support the forecasting process that is normally used? We need to know how many trips there are. Insofar as total cordon line crossings are concerned, we would know this by interviewing only inbound or only outbound traffic, since total average daily inbound crossings must equal total average daily outbound crossings. In most cases it would be safe to assume that such an equality would hold for all stations individually as well as collectively.

Do we need to know trip purposes? If we follow the BPR recommendation and use a single-purpose distribution model, we do not need to know trip purposes. We must obtain from cordon line interviews information about trip lengths so that a trip length frequency curve can be developed for calibration of the distribution model. It would seem reasonable to assume that the trip length frequency distribution for inbound trips would equal the trip length frequency distribution for outbound trips. There are only two possible explanations why it would not: (a) triangular journeys with the inbound leg through one station, the outbound trip through another station, and the third leg outside the cordon line (it seems safe to assume that such journeys would not usually represent a significant part of the universe of non-through travel), and (b) triangular journeys with the third leg inside the cordon line (we customarily ignore such internal travel by external residents anyway).

It would appear then that, even without changing normal procedures for forecasting external travel, careful study should be given to the possibility of interviewing traffic in one direction only; probably inbound would be best. Through trips intercepted would not require a one-half factor; they would still be treated separately and distributed by the Fratar method. Non-through resident trips would still be deleted from the internal surveys and the assumption would be made that for every inbound non-through trip sampled at the cordon line, there is a matching outbound trip; non-through trips by residents as well as nonresidents would still be treated separately and distributed using a gravity model.

Further research is also required in the area of external travel forecasting. It is true that trip length frequency characteristics of external non-through trips may differ from those exhibited by internal trips, consequently requiring that external non-through trips be distributed separately. However, separate distribution requires separate sets of forecast trip ends, and the procedure used to split a forecast of total internal trip ends into those that must be distributed to other internal points and those that must be distributed to external points may be based on such questionable logic as to negate the benefits of separate distribution.

Other Travel Data Surveys

One disadvantage of the procedures suggested in this paper is that many of the opportunities available in the traditional approach for checking the completeness of data collection and the adequacy of models to reproduce current travel are lost. Thus, with current trip generation and distribution primarily simulated, and not enough origin-destination survey data to allow expansion to a universe of current travel against which the simulation models can be tested, how can we be sure that we have valid forecasting tools?

Comparison of ground counts with results of an assignment of simulated current travel will take on added importance as a test. But in designing an urban transportation planning study to incorporate some of the cost-saving techniques described in this paper, it will probably be necessary to conduct other data collection surveys of limited scope in order to provide the means for testing and evaluating the tools of travel forecasting in other ways as well.

Roadside interviews on a screenline running through the area would be particularly valuable in this regard. In some instances roadside interviews in major travel corridors, without necessarily forming a screenline, might be helpful. Collection of travel data at some of the principal employment and shopping centers or other major trip attractors in the area, perhaps by utilizing a postcard survey, should also be considered. A similar limited survey of transit riders might also be indicated.

CONCLUSION

The authors do not pretend that the cost-saving techniques discussed in this paper are any more than ideas, as yet largely untried. But many are felt to be worthy of immediate consideration, in planning for new transportation studies particularly. Other ideas presented are admittedly pure speculation and require careful evaluation through detailed research.

As stated early in this paper, the authors' main objective has been to stimulate the thinking of transportation planners in the direction of greater economy and to plant the idea that more economical techniques need not mean sacrificing any degree of reason and reliability in the planning process. Indeed the very techniques that will save money may lead the way to better planning.

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Discussion

JAMES J. McDONNELL, Chief, Urban Transportation Branch, U.S. Bureau of Public Roads—As in any other endeavor, there is a need in the urban transportation planning profession to continually evaluate the procedure being used in terms of both technical adequacy and cost. Ideally, this evaluation process should be made as standard operating procedure.

The ideas suggested by the authors represent a very commendable start in the evaluation process. They could conceivably form the basis of a research program taking into consideration, of course, the previous research conducted. Some of this research is identified in the paper.

The authors' main objective was to stimulate the thinking of transportation planners in the usefulness of the procedures discussed. In my case, they have succeeded in this objective. As I see it, the procedures identified for possible change are oriented around cost savings in the trip and socioeconomic portions of the data collection phase, and the trip generation and distribution portions of the analysis phase. In order to make a full evaluation, it would seem appropriate to also include traffic assignment procedures. Furthermore, speaking from the technician's point of view, it would seem more desirable to evaluate the procedures primarily on technical consideration and relegate cost to a secondary consideration. It is my feeling that the dollars that could be saved with more streamlined procedures would be greater than those saved by optimizing procedures that we all agree are not as perfect as we would like them to be.

The element of work that would be most affected by a reduced sample of home interviews or a sample that does not measure the universe of trips would be the analysis of nonresidential trip ends. When dwelling unit interviews are analyzed on a one-by-one basis, it is possible, as the authors have pointed out, to determine trips per dwelling unit, trips per car, trips per person, and the other commonly used residential trip generation rate factors; however, when limited surveys are used for a nonresidential trip generation analysis, it has been found that there is difficulty in establishing a stable universe for nonresidential trip ends. Therefore, it would be necessary to determine, for example, shopping trip ends from some other survey oriented to that need. Work trip ends could be determined from interviews conducted at work sites, provided there is the necessary cooperation. I contend that such an approach would be unsatisfactory to the statistician and also very expensive.

As the authors point out, the home interview survey has been with us for a long time. I look on its durableness as an indication of its merit. When an urban area is contemplating improvement programs that will result in the investment of millions of dollars of public funds, the dollars that go into a data base seem to me to be money well spent. It can be argued that the introduction of simulation models should have made our need for voluminous travel data less essential. Well, it has for certain areas of the process such as residential generation and trip distribution; however, the data also allow us to take a much more sophisticated look at other parts such as modal split and nonresidential trip generation analysis. These areas tax the data stability of even the "comprehensive" home interview survey data.

The procedures suggested by the authors show much promise when used in the continuing phase of the urban planning process. The continuing phase consists of five elements. They are surveillance, continuing reappraisal, service, research, and annual report.

The surveillance function is basic to the entire continuing process. Yearly maintenance of land-use and socioeconomic data as well as essential traffic and transportation data is the key to the continuing process. A trip end estimate based on changes in population and employment and other factors that have been determined in the initial phase to be significant in trip generation should be made on an annual basis. If this surveillance is done, then the procedures suggested by the authors could be developed to update and reevaluate the models and plans developed in the initial study.

Checks could be made of the models developed in initial studies by assigning the resultant trips to a current network and comparing them, as the authors suggest, to ground counts accumulated across screenlines and to vehicle-miles of travel checks by district and by facility type. At that time, the surveys required should be oriented to the refinement of initially developed models. It may be decided that the trip distribution model is the model that needs refinement and not the trip end models. If such is the case, then a survey could be developed to satisfy the need and for the reevaluation work, the old trip end models could be utilized. Such models may require adjustment in subsequent years and at that time a survey to satisfy a single purpose could be developed.

Specifically then such surveys would be structured around the solving of problems that have been identified in the reappraisal element of the continuing process. Any such methods should require a careful evaluation by the entire staff involved in the urban planning study.

These authors have brought thoughts and ideas to this forum. They should be evaluated in detail by other researchers in this country and the results of such work should be presented at future meetings of the HRB. It is through such research that worthwhile planning methods will develop for the use of persons conducting urban transportation planning studies.

RICHARD J. BOUCHARD, Director, Rhode Island Statewide Planning Program—Cost-saving techniques for O-D surveys have been a familiar topic of discussion at HRB meetings in recent years. In 1960, Robert Davidson, then with Boston University, reported on a very small sample survey which was used to develop a trip distribution model for the Boston region (9). Since that time, a large number of reports (for example, 10, 11, 12) have been presented documenting the validity of the smaller samples for purposes of developing such distribution models. But it appears that continuing discussion along these general lines is still necessary because even today large sums of money and, perhaps more important, large quantities of precious time are being spent in conducting, adjusting, and analyzing large-scale surveys.

The authors have set forth a number of suggestions which are said to reduce the time and costs involved in such surveys. While many of these proposals seem to be well presented and objectively discussed, the significance of some of them warrants appraisal.

The authors, for example, suggest that because of the rapid development of trip distribution models, current data needs are governed by the trip generation phase of the transportation planning process. They recommend that generation analyses be conducted on a household-level basis rather than on a zonal-level basis as a more realistic means of developing standardized trip generation equations which could be calibrated for any area of the country. While this recommendation may merit further exploration, its significance may well be questioned.

This discussant believes that trip generation has been made overly complicated because of a desire to "explain" too precisely the interrelationships between travel and the various characteristics which supposedly generate travel. Seven, eight, and even nine variable equations to generate total person work trips are not uncommon today. These equations have been justified because they explain an absurdly large percentage of the variation in those trips. On the other hand, two variable equations used to explain the same type of trip-making have also been used, but with more limited success in terms of their ability to explain current variations in trip-making.

The point, however, is that if the same statistically reliable measures are accepted in the trip generation phases as are already presumably accepted in the distribution and assignment phases, perhaps more rapid progress could be made in developing trip generation models which are standardized, at least to a degree comparable to present trip distribution and assignment models.

Three factors seem to support a less rigid statistical analysis of trip generation equations. First, it is certainly debatable whether the increased number of independent variables required to enhance the statistics of the equations are justified when one keeps in mind that all of these independent variables must be forecast 20 or 25 years hence. Second, it is doubtful whether the basic survey data can justify the attainment of rigid statistical results. Third, it would appear to be easier and more valid to compare one or two variable equations from various study areas throughout the country than it would be to compare equations with a larger number of variables. And this comparison is necessary if a standardized trip generation theory is ever to be developed.

So while the suggestion that something must be done to reduce the data needs of the trip generation phase is valid, the key to this reduction may well lie in acceptance of a lesser amount of statistical reliability. Once this notion has been accepted, then secondary improvements, such as use of the household rather than the zonal level, would be worthy of investigation.

In line with this, another thought might also be registered. The authors have correctly suggested that there are certain areas where the recommended procedure fails—notably with the production and attraction of non-home-based trips and with the attraction of all other types of trips. To combat this significant failure, the authors suggest that relationships be borrowed from other study areas. If these relationships are to be borrowed it would seem that the "standardization" previously mentioned must have been reached, at least to a greater degree than apparently has been reached to date.

The authors make a second principal recommendation in calling for the elimination of traffic zones and the establishment of so-called planning areas with multiple loading nodes.

It is somewhat unclear just what the significance of this proposal may be, particularly when considered in conjunction with the previous recommendation concerning trip generation at the household level. The authors suggest using the household-level trip generation equations at the planning area level, and disaggregating the results to trip loading nodes on some rational basis. If the basic premise that a household-level equation can be applied to an area representing a large number of households is accepted, then it makes little difference whether the equation is applied to the traffic zone level as is now customary, or is applied to the planning area level and disaggregated to a traffic loading node as suggested by the authors.

The authors suggest that their procedure is an improvement because it would eliminate the customary concern about standard data collection units and it would be possible, for example, to assemble population data on a census tract level and employment data on the individual establishment level. This may be so, but the simple fact remains that trips must eventually be allocated to a loading node and this loading node must represent a small traffic drainage area if the traffic distribution and assignment processes are to yield realistic results. Consequently, it makes little difference whether the trips are disaggregated from the planning area level to the loading node as suggested by the authors, or the social, economic, and land-use data are disaggregated from the data collection area as is now customary where the collection units are not standardized.

The authors further suggest that this procedure is an improvement because the planning area boundaries could be changed over the course of time and therefore could be adjusted to better reflect alternate land development patterns in the forecast year. The same course of action is possible with traffic zones today if the basic premise that the household-level equations can be applied to an areal unit representing large groups of households is accepted. In other words, whether you deal with a planning area and multiple loading node concept or with a traffic zone concept appears to be somewhat immaterial.

The authors make several other suggestions in their paper which bear some comment. They suggest, for example, that it may not be necessary to expand survey data to the total universe. This suggestion appears valid. In fact, in two recent surveys (13, 14) conducted in Rhode Island, the data were not expanded and the results have been entirely favorable. Connecticut has also followed the same procedure in at least two surveys (15, 16), and similar conclusions were reached.

A telephone survey and postcard questionnaire are mentioned by the authors as possible alternative methods of collecting data. Experience in Rhode Island indicates that both methods are satisfactory for collecting origin-destination survey data (17) and that significant cost savings can be realized by employing such techniques.

The authors' suggestions on truck surveys and roadside surveys, for the most part, seem appropriate and worthy of implementation without additional investigation.

Finally, the authors make the point that, as sample sizes are reduced, the value of a good volume-counting program becomes more critical. The importance of this statement, regardless of the amount of O-D data collected, must be recognized by any planning program which desires to be active in providing highway design figures.

In summary, the authors have presented a number of suggestions, many of which are quite valid and quite significant. These should be implemented with a minimum of further delay. They have also presented two suggestions which may be questionable as to their significance and validity. These should be further investigated in the near future, perhaps by the authors, and the resulting facts and figures presented as soon as possible.

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AUSTIN E. BRANT, JR., and DANA E. LOW, Closure—The authors wish to express their appreciation to the discussants for their thoughtful consideration of the paper.

Mr. McDonnell emphasizes the important point that any changes in procedures used in the transportation planning process must be evaluated from the technical standpoint as well as on the basis of costs. The aim should be to improve quality while reducing costs, but we cannot ignore the fact that highly sophisticated procedures which utilize large volumes of data and complex methods of analysis may not really result in a better product.

Mr. McDonnell suggests that special surveys would be needed to establish a stable universe for nonresidential trip ends. The data already available should, of course, be fully utilized. Area-wide totals for attracted trips can be determined since total attractions must equal total productions, corrected for trips crossing the area boundary. Detailed employment data are available in the records of employment security agencies. Research projects, such as Keefer's studies of airports, shopping centers and industrial plants (20), can be used to estimate attractions. While an approach which uses data from many different sources and which accepts models developed in other studies may not be statistically satisfying, it should be more than adequate for engineers and planners who realize that the entire transportation planning process is based on forecasts of socioeconomic data 20 to 30 years in the future. The degree of error inherent in such forecasts will far outweigh any statistical errors introduced by using streamlined procedures.

The authors have not attempted to indicate that the home interview survey has been in use so long that it is now outmoded. Dwelling unit interviews form an essential part of the procedures we have proposed. The use of models, however, reduces the requirements for the type of data obtained in the home interview survey. Admittedly, the proposed procedures may reduce the statistical validity of simulation for certain types of travel, but very often these types form only a small part of total travel and have a very limited effect on forecast design hour volumes.

Mr. McDonnell's suggestions that the proposed simplified procedures be applied to the continuing phases are most appropriate.

Mr. Bouchard points out that trip generation equations can be made overly complicated by incorporating an excessive amount of variables. This is very easy to do, of course, in multiple regression analyses. After working with computers for some time, one may lose sight of the common-sense relationships between cause and effect. The development of objective standards for trip generation would seem to be a fertile field for research. Mr. Bouchard also brings out the point that all independent variables must be forecast far into the future. These forecasts may range from the hopes of land-use planners for the types of development that they would like to see occur in the future to trend-line extrapolations of what has occurred in the past.

Mr. Bouchard comments on the proposed use of planning areas in lieu of traffic zones. When small traffic zones are used, those responsible for land-use planning are required to subdivide their data collection and forecasts into small geographic areas.

While land-use planners can forecast the type of developments which will occur in large areas, it is unreasonable to expect them to select exact sites for industrial developments, shopping centers and the like. Forcing land-use planners to use traffic zones does not improve the accuracy of the result and may be misleading. What is proposed is that land-use planners forecast for areas which are within their capabilities and that subdivision into smaller areas, or allocation to loading nodes, be done as part of the transportation analysis. The authors believe that it does make a difference in cost whether or not socioeconomic data are compiled and forecast on the basis of small areas, defined in a consistent manner for all variables. The disaggregation can be accomplished at less cost as part of the transportation analysis. Perhaps the difference is one of semantics, but the proper use of words can often clarify concepts.

Mr. Bouchard reinforces the statements in the paper concerning the value of a good volume-counting program. The authors have not been engaged in any study where there were too many counts of traffic volumes or transit passengers.

The authors feel that they have accomplished their first objective—to stimulate the thinking of experienced transportation planners concerning the methods and procedures they use, even though these methods and procedures have been in use for many years.

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Transit Pathfinder Algorithm

ROBERT B. DIAL, Alan M. Voorhees and Associates, Inc.

This paper represents one element of the initial phase in the development of a package of computer programs to assist in mass transportation planning. These programs provide a flexible means of predicting ridership on each line of a proposed multimode transportation system within a given land-use configuration. This paper describes an IBM 7090 computer program and its enabling algorithm which finds minimum time paths through a large multi-modal transportation system. The program's capabilities and its underlying assumptions are summarized, and terms are defined. Step-by-step descriptions and flow charts are presented of the widely used Moore "tree-building" algorithm and of the transit "pathfinder," an extension of the former algorithm accommodating the peculiarities of transit minimum paths.

•FOR purposes of long-range planning, analyses of the efficiencies and economies of a proposed transit system require knowledge of the expected path of passengers traveling between any two points on the system. The best approximation of this path is the minimum weighted time path, wherein the times to traverse various link types are weighted to reflect differences in the values the transit user places on the time spent walking, waiting or riding by various modes.

Heretofore, the transportation planner has not had the means, i.e., a computer program, to find minimum paths joining nodes of a large intra-regional transit network. No available program accepted an economical network description which allowed sufficient size and detail. Existing programs either permit only a very small network and require a real-time fixed arrival schedule at each transfer point (2), or they require summarized "trunk line" descriptions in which route discrimination and transfer information are lost. Further deficiencies result from the inability of these programs to cope realistically with wait and transfer time. All of these factors have seriously handicapped the transit system analyst.

CAPABILITIES OF THE PATHFINDER PROGRAM

The pathfinder program reduces the number and degree of the problems confronting the transit planner. Among the program's important characteristics are the following:

•The transportation network is input as two items: a link description and a line description. The former is similar to coded networks read by existing highway network analysis programs (4). The latter resembles a bus schedule. System description and updating are greatly facilitated by dual files.

•The transit network is stored in the computer as a set of "trunk-line links." Each trunk-line link is defined as (a) a pair of nodes, (b) a time, (c) a mode, and (d) a set of line numbers representing all routes traversing the link in the given time via the given mode. This permits the computer to accommodate a vastly larger network than if it had to list each line/link combination explicitly. The trunk line description also reduces computer running time. Although the program uses a trunk line description, no information is lost. Its output lists all line numbers on every minimum path.

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•Transfer penalties need not be explicitly listed. Previous methods required the analyst to code links which represented the possibility of transfer between two lines. The traverse time associated with each of these links accounted for the wait time. The number of these transfer links rose factorially, precluding a complete network description. The pathfinder program does not use transfer links. It assumes that all line number pairs at a given node constitute legitimate transfer possibilities, and that the time spent transferring depends only on the frequency of the recipient line. (This is discussed below.) Thus the majority of both intra- and intermode transfers can be handled implicitly, requiring only each line's frequency as input.

•The minimum paths can be required to satisfy user-specified constraints. The user can preclude transfer between certain modes. Any of the 64 possible ordered modal pairs can be specified as either a legitimate or illegitimate transfer. The user may also put an upper limit on the amount of time to be assessed for a transfer to a given mode, as well as the total number of transfers on a minimum path. Wait times can be similarly constrained.

•Eight modes (walk, auto, and six transit modes) can be accommodated, and the time spent on each can have a different cost factor, as can the time spent waiting or transferring. In order to implement information uncovered on the different unit values a passenger places on the time he spends on rapid transit vs that on a local bus vs that walking, etc., the program allows the user to weight these components of travel time in the selection of minimum weighted time paths.

•The program can analyze a large network. Due to the peculiarities of a transit network, any description of it in a simple node-link form becomes quite large, and the size of the problem the program can handle is of prime importance. The pathfinder's limitations are quite relaxed and permit even the largest networks to be described in fine detail. The program can process a network with the following limiting characteristics (many of the limitations are results of required interface with other programs): (a) 2800 transfer points (nodes); (b) 11,000 trunk-line links; (c) 31 lines on any one link; (d) 8 modes; and (e) 255 (optionally) round-trip lines (routes) within each of 6 modes. The implicit size of the network becomes evident when it is noted that the 11,000 links with the attendant line limitations can account for over 32,000 line/link combinations and over a quarter of a million transfer links.

When appropriate coding procedures are established and adhered to, the program's limitations do not pose any significant constraints. We are, nonetheless, anxious to recode the program for a larger capacity IBM System/360. Not only could the maximum parameters be increased, but running time could be improved and new wrinkles added.

ASSUMPTIONS OF THE ALGORITHM

There are two principal assumptions underlying the pathfinder algorithm:

1. That the time to traverse a trunk line link is constant, and
2. That the time spent waiting to transfer is satisfactorily approximated by one-half the inverse of the frequency of the recipient line(s).

Assumption 1 states that link times cannot change during the pathfinding process. The time to traverse a given link must be the same for all paths. The algorithm by itself cannot adjust for such things as volume-dependent ("capacity-restrained") speeds or times. This is a common assumption in network algorithms (1).

Assumption 2 states that, in the absence of an inviolate, real-time schedule of arrivals of each line at each node, the algorithm can assume a "random" arrival of the bus (or train, or walker) from which the transfer is to be made. Indeed, a more complicated assumption could be made, but it is not worth the effort.

The program could assume an actual bus schedule as input. But in so doing it would be imposing a hardship both on itself and on the planner. First, it would require the planner to produce these schedules for systems proposed for use 20 years hence—an exercise of questionable value. Second, the minimum time through a fixed schedule of stops varies with the time of departure from the home node. To find the minimum time over all departure times is an exercise of considerable worth, but only to computer suppliers, insofar as long-range transit planning is concerned. For the planners the marginal cost/marginal utility ratio is nearly infinite.

Obviously, the planner must be able to provide an estimate of each line's frequency. This is the minimum requirement. It puts a handle on wait times and is needed to estimate capital and operating expenditures.

Thus the algorithm assumes that if a transfer is to be made from route A to route B, and route B's frequency is 5 buses per hour, then the expected wait time is one-tenth of an hour or 6 minutes. Further, whenever a transfer can be made to more than one route at the same point, the assumed transfer wait time is one-half the sum of the departing lines' frequencies. For example, if at a given point a minimum path requires a transfer to either route B or route C, and route B frequency is 5 buses per hour and route C goes by once an hour, then the transfer penalty assessed is $0.5/(5+1) = 1/12$ hour or 5 minutes.

Assumption 2 makes the transfer wait time independent of the arriving line(s). An important corollary results: If a minimum time path from point A to point C requires a transfer at point B, then this path begins by using the minimum time path to B. The algorithm is free to "forget" the initial origin point of a path involving transfers, provided it "remembers" the point at which the last transfer occurred. Because a minimum time path to the transfer point is known, the entire path can be traced back. For example, if the minimum time path from A to C had a transfer at B, this path would be described simply as "Take line(s) X at B." The observer, i.e., volume loading program, would note that B was not the home node A, and it would seek out the minimum path to A, namely, "Take line(s) Y at A," and the path would be complete.

This is a descriptive economy, and it provides the algorithm with a means of keeping down the number of transfer possibilities to be examined. As clarified below, the only transfers to be examined at a given point are those from a minimum path to that point.

DEFINITIONS

At this point the discussion of the pathfinder algorithm requires a few definitions of terms already used, so as to eliminate any ambiguities which henceforth might prove confusing.

The algorithm works with a network description composed of line frequencies and trunk-line links. Line frequencies are simply the average number of buses per unit time for each of the lines (routes) in the transit system. Each line can have only one frequency. If a round trip route has a different frequency outbound than inbound, then the two directions must be coded as separate lines.

The only purpose for frequencies in the pathfinder program is to assess transfer penalties. A transfer penalty X is a function of a set of line numbers S:

$$X(S) = \frac{0.5}{\sum_{k \text{ in } S} F(k)}$$

where F(k) is the frequency of line k, and the sum is taken over all lines k which are contained in the set of line numbers S.

A trunk-line link (TLL) has three immediate constituents:

1. An ordered pair of nodes,
2. A traversing time, and
3. A set of line numbers.

1. Nodes are junctions in a network at which transfers occur. There are always exactly two nodes associated with a TLL, and each is identified with a unique number. The same number must always be used when referring to the node. The first node of a pair is called the A-node and the second is called the B-node. A TLL is always "one-way." The flow is always from the A-node to the B-node. The highest node number permitted by the program is 2800.

2. Traversing time is simply the time needed to traverse the TLL. All transit lines listed with a TLL must provide identical service between the TLL's A-node and B-node. When there is more than one level of service between two nodes which would otherwise constitute a single TLL, the analyst must code a second "dummy" link to which he can assign the lines providing the second level of service. The highest time permitted is 64 minutes.

3. A set of line numbers constitutes the final element of a TLL's definition. Each link has a simple listing of all the lines which traverse it in the same time. Lines are coded as integers between 1 and 255.

MECHANICS OF THE MOORE ALGORITHM

As mentioned earlier, the pathfinder algorithm is an extension of the widely used Moore algorithm (3). Because of their similarity, a description of the latter greatly facilitates a description of the former. Therefore, the Moore algorithm is discussed, flow-charted and used in an example.

The task of the Moore algorithm is to "build a tree." A tree is the set of links comprising the minimum paths from a given "home node" to all other nodes in the network. Assuming there exists a unique minimum path to each destination node, the term "tree" is quite appropriate. The uniqueness assumption implies there can be one and only one link entering each node. Thus when all minimum paths are plotted the result is a series of "branches," spreading as they move away from the home node.

The Moore algorithm finds the number-of-nodes-minus-one links in a tree in the order of their "distance" (measured in time) from the home node. A link's distance from the home node is defined here as the minimum time to go from the home node to its B-node. The algorithm starts by finding the closest link, which must have the home node as its A-node. This link is placed in the tree along with its corresponding "distance." The remaining process consists simply of selecting the link closest to the home node among all links connected to links already in the tree but not in the tree themselves. Each link's distance from the home node is calculated by adding the distance to its A-node's tree link to its own link traverse time. The link closest to the home node is placed in the tree, and the process repeated. The process stops when nodes-minus-one links have been placed in the tree.

The flow chart of Figure 1 is an example of a computer program of the Moore algorithm. Although not intended to reflect an optimal code, it is realistic enough to use with the network of Figure 2 to build a tree from home node A. The resulting tree

DICTIONARY

VARIABLE	EXPLANATION
N(I,J)	B-NODE DEFINING J'TH EXIT LINK FROM NODE I
T(I,J)	TIME ON LINK FROM NODE I TO NODE N(I,J)
LINKS(I)	TOTAL NUMBER OF EXITS FROM NODE I
TREE(I)	TERMINAL LINK IN MINIMUM PATH FROM H TO I
H	HOME NODE
C(I)	NUMBER OF LINKS IN SLOT I OF TABLE
TABLE(I,J)	B-NODE OF LINK WHOSE CUMULATIVE TIME IS I (THIS IS THE LINK SEQUENCING TABLE)
MAXN	TOTAL NUMBER OF NODES IN SYSTEM TO
NODE	COUNTS THE NUMBER OF NODES WHICH MINIMUM FROM H HAVE BEEN FOUND

Figure 1. Flow chart of Moore algorithm implementation.

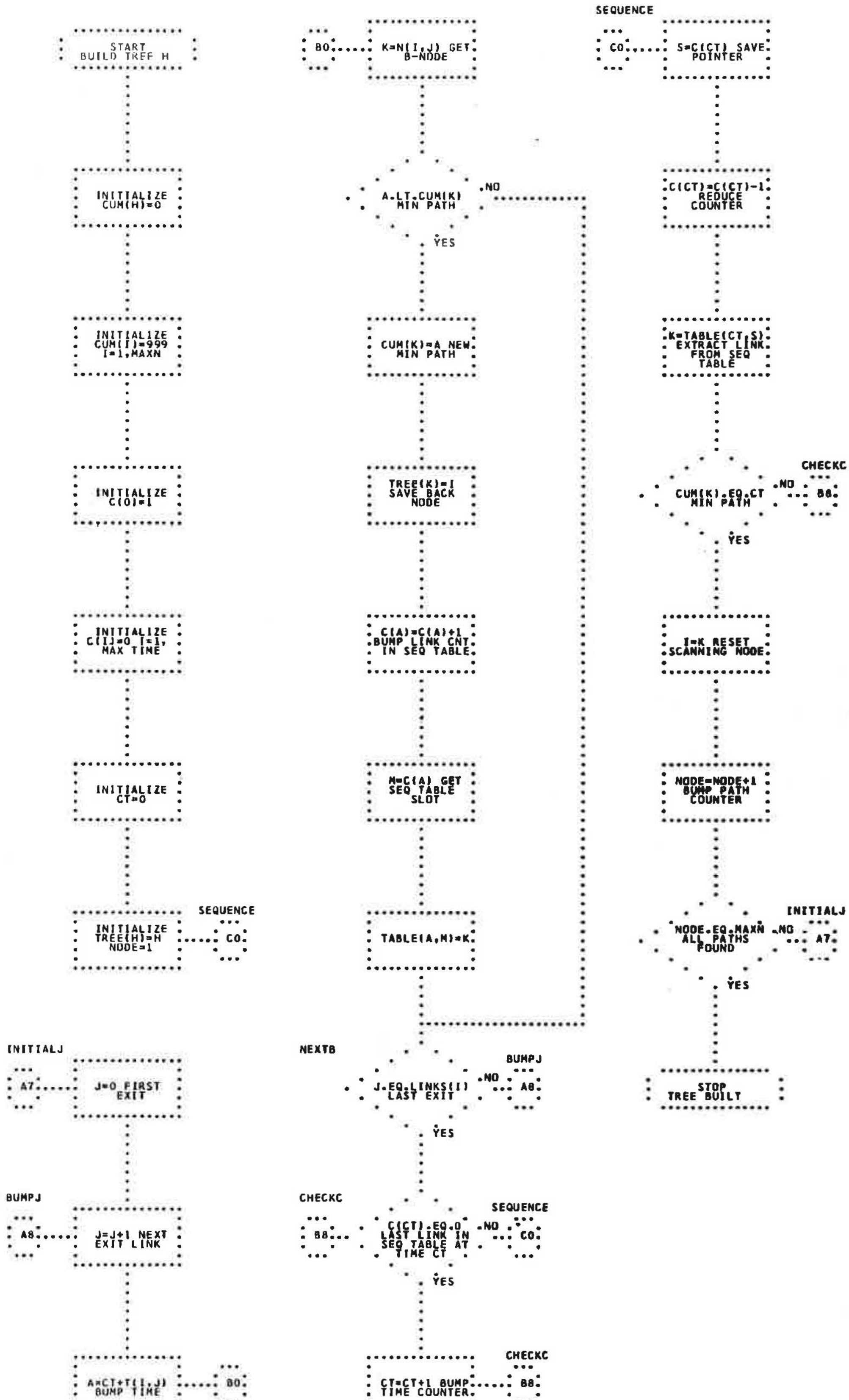

Figure 1. Moore algorithm (continued).

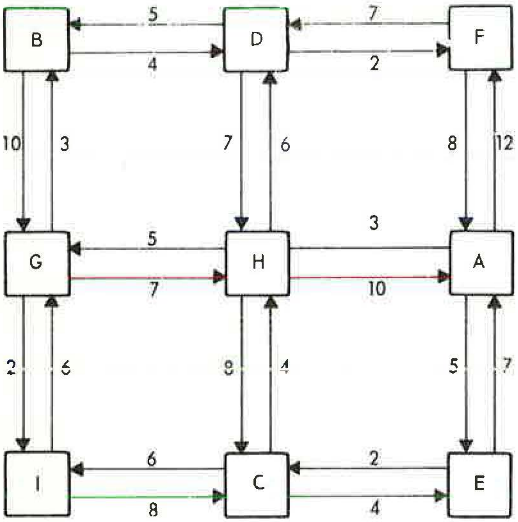

Figure 2. Sample network showing node labels and traverse times.

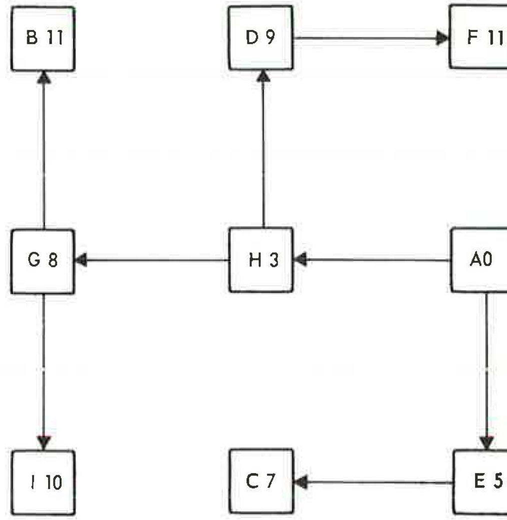

Figure 3. Tree (with cumulative times).

and the "distances" (i.e., cumulative times) to each node via the minimum path appear in Figure 3 and Table 3. Tables 4 and 5 are "scratch" tables. Tables 1 and 2 describe the network in a computer-oriented fashion. (This same example with slightly different notation and algorithm coding is found in Ref. 3 with a detailed discussion.)

Figure 2 is a graph of a network which employs letters for node labels and arrowheads to indicate the direction of flow. Each (one-way) link has its traverse time shown in arabic numerals. Table 1 describes this network by tabulating each node's exit links. This table, whose elements are called N(I, J) in the flow chart, shows all links exiting any given node. It is entered by finding the column of the node of interest and reading across to find the B-nodes of all links which have the given node as an A-node. N(I, J) is therefore the B-node of the Jth link which has I as an A-node.

Table 2 simply lists the times associated with the links in the corresponding positions of Table 1. The flow chart in Figure 1 refers to this table by the symbolic name of T, and T(I, J) is the time associated with the Jth exit from A-node I.

TABLE 1

N(I, J): LINK DESCRIPTION

a \ i	1	2	3	4
A	E	F	H	–
B	D	G	–	–
C	E	H	I	–
D	B	F	H	–
E	A	C	–	–
F	A	D	–	–
G	B	H	I	–
H	A	C	D	G
I	C	G	–	–

TABLE 2

T(I, J): LINK TRAVERSE TIME

a \ i	1	2	3	4
A	5	12	3	–
B	4	10	–	–
C	4	4	6	–
D	5	2	7	–
E	7	2	–	–
F	8	7	–	–
G	3	7	2	–
H	10	8	6	5
I	8	6	–	–

TABLE 3

CUMULATIVE TIMES VIA MINIMUM PATH

J	CUM(J)	TREE(J)
A	~~99999~~ 0	HOME NODE
B	~~99999~~ 11	G
C	~~99999~~ ~~11~~ 7	~~H~~ E
D	~~99999~~ 9	H
E	~~99999~~ 5	A
F	~~99999~~ ~~12~~ 11	~~A~~ D
G	~~99999~~ 8	H
H	~~99999~~ 3	A
I	~~99999~~ ~~13~~ 10	~~C~~ G

TABLE 4

"SCRATCH" TABLE

CT	TABLE(CT,K)
2	
3	~~H~~
4	
5	~~E~~
6	
7	~~C~~
8	~~G~~
9	~~D~~
10	~~I~~
11	~~C~~, ~~B~~, ~~F~~
12	F

TABLE 5

"SCRATCH" TABLE

I	CT	NODE
~~A~~	~~0~~	~~1~~
~~H~~	~~3~~	~~2~~
~~E~~	~~5~~	~~3~~
~~C~~	~~7~~	~~4~~
~~G~~	~~8~~	~~5~~
~~D~~	~~9~~	~~6~~
~~I~~	~~10~~	~~7~~
~~B~~	~~11~~	~~8~~
F	11	9

Three other tables are used in the flow chart. TREE(I) contains the A-node of the final link in the minimum path from the home node to node I. TABLE (I, J) holds the B-node of the J th link whose distance from the home node is equal to I minutes. C(I) is a count of the number of links in the Ith time slot of TABLE.

Explanation of the Moore Algorithm Flow Chart

1. Initialization consists of setting all minimum path times arbitrarily high except for the home node's, which is set to zero. The link sequencing table is emptied, and one link is entered into it representing the "minimum path" to the home node H. This dummy link is also placed in the tree table at location TREE(H). NODE, which counts the number of nodes for which the program has found a minimum time path, is set equal to one. The cumulative time value CT is reset, and control transfers to step 3 below.

2. After a link has been placed in the tree, all links connected to it are examined for possible entry into the link sequencing table. For each of the exits from the new tree link, a "distance" is calculated by adding the current cumulative time CT to the exit link's traverse time T(I, J). Its B-node is then examined to see if a shorter path to it has already been found, i.e., if CUM (B-node) is less than the distance just calculated. If it is, the link is ignored. If the new distance is less than that in the CUM table, the CUM table entry is updated, CUM (B-node) = CT + T(I, J), and the link's A-node, I, is placed in the tree, while its B-node is entered into the link sequencing

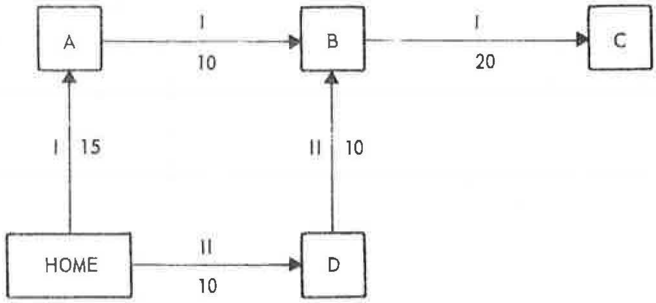

Figure 4. Simple transit network (frequency of Line I is 5/hour, of Line II, 5/hour).

table at a position corresponding to CT + T(I, J). Step 2 is repeated until all exits from node I have been examined, at which time control passes to step 3.

3. This step extracts links from the link sequencing table. Remember that the entities in this table are B-nodes and their position in the table corresponds exactly to the B-node's distance, i. e., cumulative time, from the home node. The program removes the first link at or below position CT in the table. CT is then updated to this node's position in the table. If this B-node's cumulative time is equal to its positional value, i.e., CUM(TABLE(CT, J)) = CT, then this is a minimum path link, in which case control returns to step 4. If CUM(TABLE(CT, J)) is less than CT, then the link is ignored and step 3 is repeated.

4. This step enters a link into the tree. It increases the value of NODE (the number of nodes to which minimum paths have been found) by one, and transfers control to step 3, if all nodes have not been reached. Otherwise, it stops; the tree is complete.

PECULIARITIES OF TRANSIT TREES

The Moore algorithm is an efficient means to build a tree, thanks to the fact that once a minimum time path to a node is found, the node can be ignored for the remainder of the tree-building process. Any minimum path crossing that node will use the same (minimum) path up to the node, regardless of the path's ultimate destination.

Transit trees lack this property. A node can lie on two or more minimum paths, none of which uses the same path from the home node to the common node. The simple network of Figure 4 illustrates this fact. (In this example, as in all subsequent graphs of a transit network, the following conventions are used: boxed letters represent nodes, arabic numerals represent link traverse time in the direction of the arrow, and the roman numerals represent line numbers of routes which traverse the trunk line link in the same time.) Assume that the headways of lines I and II are equal, and each is 12

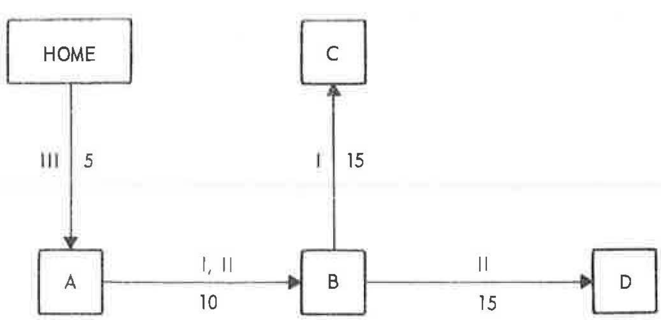

Figure 5. Entire transit network (frequency of Line I is 4/hour, of Line II, 2/hour, of Line I and Line II, 6/hour).

minutes. The transfer penalty to change from line II to line I at node B is therefore 6 minutes, and the total time to go from Home to C via this path is 46 minutes (plus the initial wait time for line II). On the other hand, by getting on line I at home, the trip to C takes 45 minutes (plus the initial wait time for line I, which is the same as line II's). Thus the minimum to C passes through B via a different path than the minimum time path to B, which is to get on line II at Home.

While transfers to a line require the pathfinder algorithm to examine reentries to a node after the minimum path has been found, the algorithm must also cope with another nuisance, namely the penalty for "transferring from" a line. This occurs with the diminishing of a line selection group. Assume that Figure 5 is an entire transit network. Then obviously the minimum path to any node except A requires a transfer at A. If I and II's headways are respectively 15 and 30 minutes, then the minimum paths to B, C and D will each arrive at B in a different cumulative time. But any Moore-type algorithm, including the proposed version, will arrive at B exactly once. It will find a path to B requiring a total of 15 + 5 = 20 minutes. The 5 minutes are for the transfer at node A, where 6 buses go by each hour.

However, for any trip destined for C, only two usable buses go by B each hour, since the minimum time to go to C is obviously realized by transferring to line I at node A. Thus the time to get to B for any trip heading for C is 15 + 7.5 = 22.5 minutes. Similarly, the minimum path to D crosses B 15 + 15 = 30 minutes after leaving home. Therefore each of the three paths requires a different time to B, although the algorithm gets them there at the "same" time of 25 minutes.

An easy solution exists; the algorithm simply adjusts the cumulative time to B for each exiting path at the time it is generating the exit links from B to place in the link sequencing table. Because it knows on what lines it arrived at B, it knows the value of the current transfer penalty. It subtracts that penalty and adds the penalty for "transferring" to the through lines as it adds the link's traverse time to the cumulative time. The actual computation is described later.

Although the above problems are easily solved theoretically, it is important to realize that there are practical repercussions. The pathfinder has to work much harder than the Moore algorithm. While it does nearly the same actions, it performs them with much greater frequency. Many more links have to be examined. It will always have a fuller link sequencing table, and will have to analyze twice as many links for each link drawn from the table. The effect is significant in terms of running time.

MECHANICS OF THE PATHFINDER ALGORITHM

Differences between the Moore algorithm and the pathfinder are results of transfer penalties. For this reason, the way the program uses them will be elaborated on here. A transfer penalty measures the effect of waiting time, and it can seriously affect a path. Waiting time can occur at the start of a path and also at transfer points en route, whenever a minimum path requires line changing.

To the algorithm a transfer penalty X, as discussed earlier, is merely a function of a trunk-line link or, more simply, a function of the frequencies of the lines on the trunk-line link. In particular, it is a certain number of minutes, equal to one-half the inverse of the sum of the frequencies of the link's lines. For example, if link k has line numbers II, VII and XII whose frequencies are three, five and one bus per hour, the link k's transfer penalty is

$$\begin{aligned} X(k) &= 0.5/(F(II) + F(VII) + F(XII) \\ &= 0.5/(3 + 5 + 1) \\ &= \tfrac{1}{18} \text{ hours} \\ &\cong 3.3 \text{ minutes} \end{aligned}$$

The algorithm incorporates the transfer penalty function X as it puts links into the link sequencing table. For each link extracted from the table, it analyzes all links exiting from its B-node. For each of these exit links it enters in the sequencing table one or both of the following links (assume that L is the link extracted from the sequencing table, and E is a link exiting from L's B-node):

1. Link 1 is (almost) always generated. It represents "through" paths and is comprised of (a) the A-node of L; (b) the B-node of E; (c) the lines which are common to L and E; and (d) the time equal to the cumulative time plus E's link time minus L's transfer penalty plus E's transfer penalty, i.e., CT + T(E) - X(L) + X(E).

2. Link 2 is only generated the first time a link with L's B-node is extracted from the table, and then only if T(Link 1) is greater than T(Link 2). Link 2 represents "pure transfer paths," and has the following elements: (a) the A-node of E; (b) the B-node of E; (c) the lines on E but not on L; and (d) the time equal to the cumulative time plus the time to traverse E plus the transfer penalty for E, i.e., CT + T(E) + X(E).

Explanation of the Pathfinder Algorithm Flow Chart, Figure 6

1. Initialization is exactly analogous to that of the Moore algorithm, wherein a dummy link is placed in the zeroth position of the link sequencing table. The remainder of the table is emptied. Minimum path times to all nodes is set arbitrarily high except for the home node, whose time is set to zero. The cumulative time pointer CT is set to zero, and control goes to step 3.

2. This step merely finds the uppermost link in the link sequencing table. The search begins at the CT th slot and continues downward (upward in minutes) until a non-empty slot is found. CT is reset to the slot value containing the first link found and control transfers to step 4. If no link is found this means some nodes are not connected to the home node, and tree-building stops.

3. This step extracts a link, called Y, from the link sequencing table. The variable I represents this link's B-node, and its line number set is called R. All links exiting from I, except for U-turns, are examined for line numbers in L. A link is generated

DICTIONARY

VARIABLE	EXPLANATION
CUM(I)	TIME FROM HOME NODE TO NODE I VIA MINIMUM PATH
SEQ(I,J)	J'TH LINK IN TIME SLOT I OF SEQUENCING TABLE
C(I)	NUMBER OF LINKS IN SLOT I OF SEQUENCING TABLE
LINK(I,J)	J'TH EXIT LINK FROM NODE I (LINK TABLE)
LINKS(I)	NUMBER OF EXITS FROM NODE I
MAX(I,J)	MAXIMUM FUNCTION SELECTS LARGEST VALUE OF I,J
CT	CUMULATIVE TIME POINTER
AND(I,J)	LOGICAL AND FUNCTION
COMP(I)	LOGICAL COMPLEMENTATION FUNCTION
DIFF(I,J)	LOGICAL DIFFERENCE FUNCTION,AND(I,COMP(J))
NULL	THE EMPTY SET
TREE(I)	LAST LINK(S) IN MINIMUM PATH(S) FROM HOME TO I
MAXN	HIGHEST NODE NUMBER
MAXT	HIGHEST TIME PERMITTED IN LINK SEQUENCE TABLE
X(I)	TRANSFER TIME FUNCTION (PENALTY TO LOAD)
H	HOME NODE
A(I)	A-NODE FUNCTION FETCHES A LINKS ANODE
B(I)	B-NODE FUNCTION FETCHES LINK I'S B-NODE
L(I)	LINES FUNCTION FETCHES LINK I'S LINES
T(I)	TIME FUNCTION FETCHES LINK I'S TIME

Figure 6. Flow chart of pathfinder algorithm implementation.

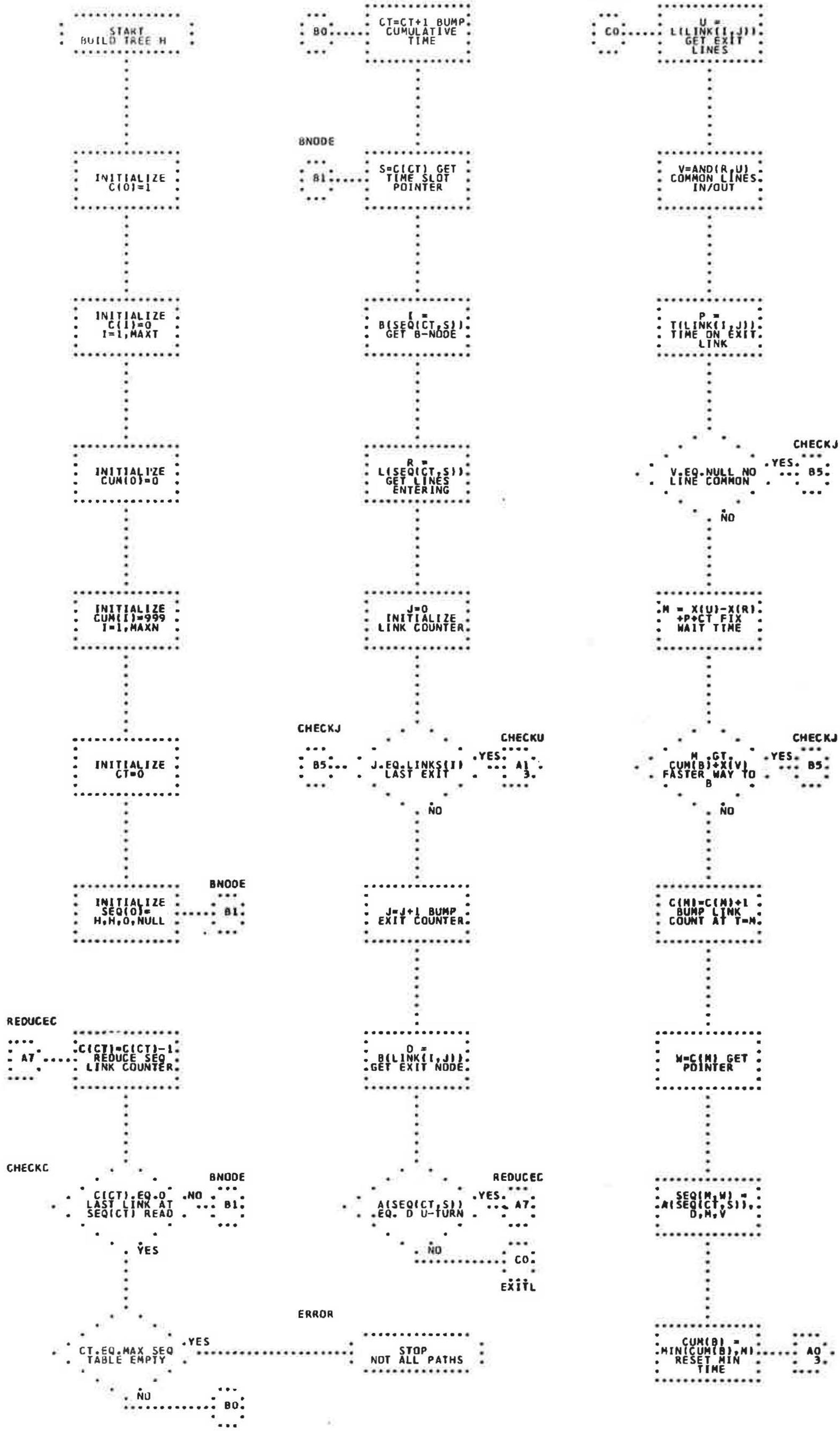

Figure 6. Pathfinder algorithm (continued).

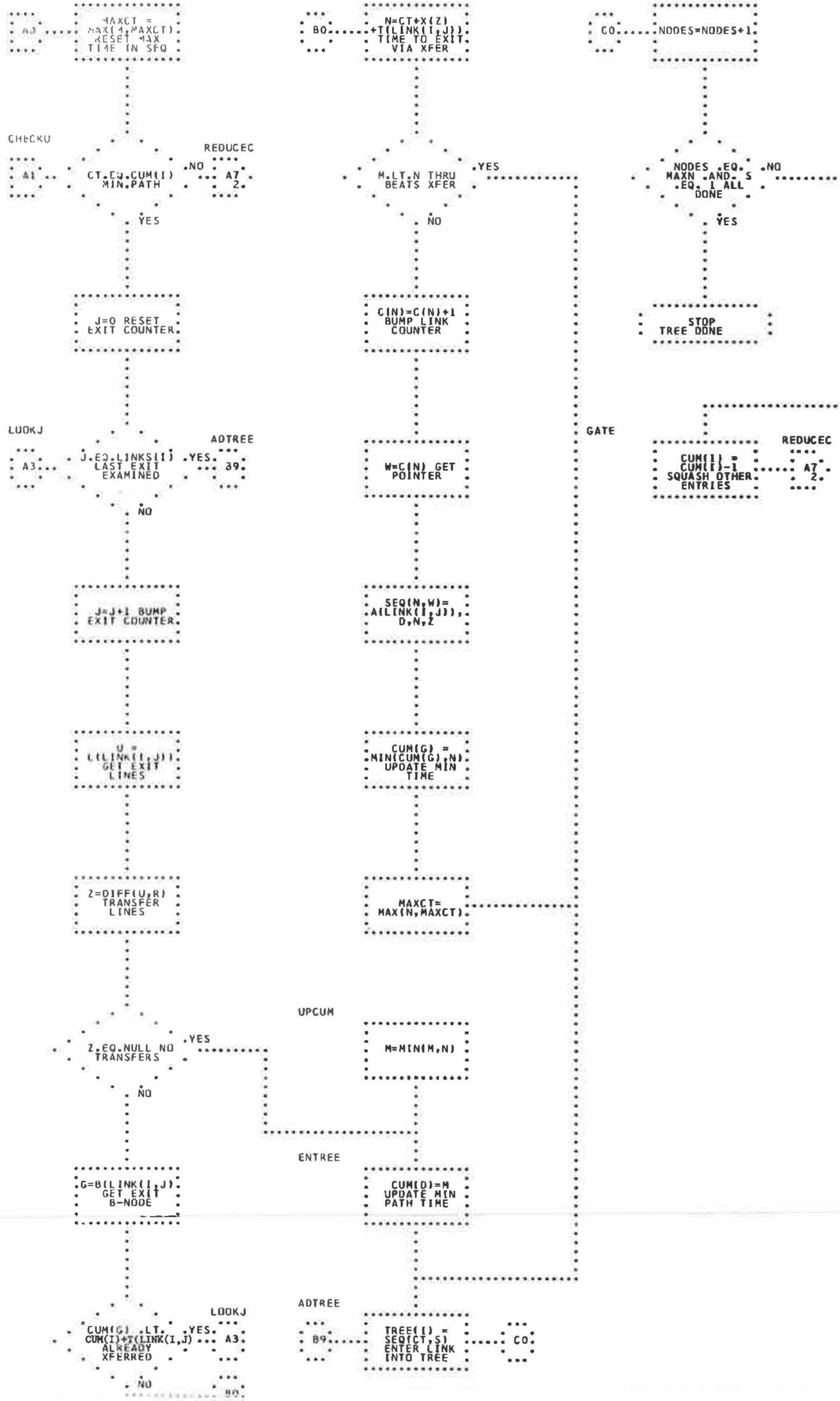

Figure 6. Pathfinder algorithm (continued).

for each exit and placed in the cumulative time table. The description of this through link appears earlier, where it is called "Link 1." (The algorithm only generates this link whenever there are line numbers common to both Y and the exit link under examination.) The algorithm next examines the minimum path time to I, stored in CUM (I). If this is the same as CT, the slot in the link sequencing table at which Y was stored, then Y comprises the last leg of the minimum path to I. In this case transfer out of I must be examined, and control goes to step 4. Otherwise step 4 is skipped and control goes to step 2.

4. Step 4 generates the transfer paths out of node I. It is reached only when Y is on the minimum path to I. The transfer path link's description appears earlier, where it is called "Link 2." (Step 4 is not executed if Y is the last link in the tree, i.e., the number of links found equals the number of nodes in the network. In this case the tree is built and the program stops.) A transfer link to I is only generated whenever the cumulative time to its B-node, CUM (B-node), is greater than the time to get to I via the transfer link. When all exiting transfers from I have been examined, the procedure continues at step 5.

5. This step merely adds the link Y to the tree. It increments the total number of links in the tree by one and checks if it has found a link for every node. If so, it is finished with the tree, and the program ends. If not, CUM (I) is set to a value below the minimum path time to preclude any other link being put in the tree for this node. The program then returns to step 2 to extract the next ranking link from the sequencing table.

It should be noted that a different method of storing the tree has to be used in the pathfinder program than was used for the Moore algorithm. The reason is that the transit network requires a far larger description and link sequencing table. The sizes of these tables are such that no room is left in core storage to contain the entire tree, and its links must be "written out" as they are found.

Notation

Because the pathfinder algorithm is more complicated in its detail than the Moore algorithm, an extended notation is used in its flow chart to keep the number of boxes down and still provide a thorough idea of the processing. While the basic element of the Moore algorithm was a B-node, the pathfinder handles cumbersome trunk-line links. It fetches them, stores them, creates them, and discards them. To facilitate their symbolic manipulation, the following notation is employed in the flow chart:

If K is a trunk-line link it is often written as

$$K = A, B, T, L$$

where A is an A-node number, B is a B-node number, T is a time, and L is a line number set. For example, if the graph of the link P is

$$\boxed{Q} \xrightarrow[7]{II,\ V,\ X} \boxed{R}$$

then this link is written as

$$P = Q, R, 7, S$$

where S is a set comprised of lines II, V and X.

The individual elements of a trunk line link are extracted with the "functions" A, B, T and L where A(K) is K's A-node number, e.g., A(P) = Q; B(K) is K's B-node number, e.g., B(P) = R; T(K) is K's time, e.g., T(P) = 7; and L(K) is K's line number set, e.g., L(P) = S = II, V, X.

As line number sets have to be compared and created, the following notation is useful: If A, B and C are sets of line numbers, then

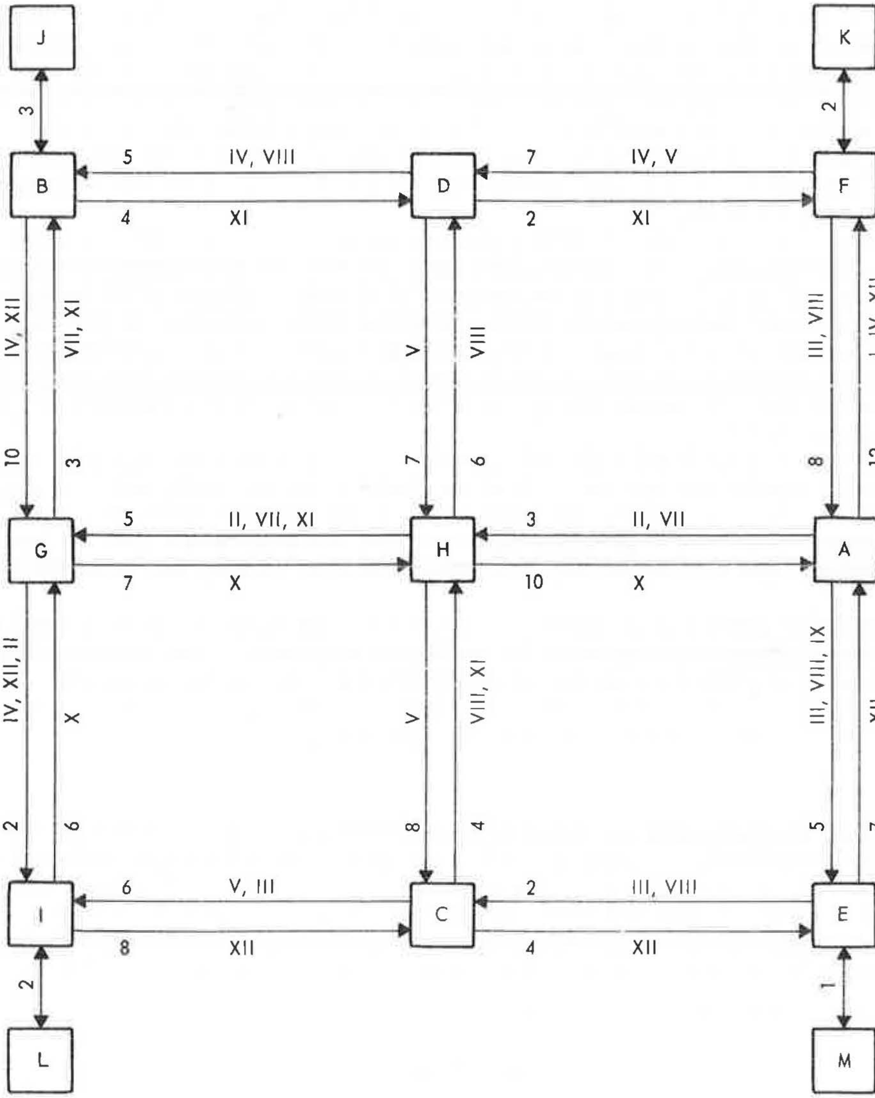

Figure 7. Hypothetical transit network (letters are node identifiers, arabic numbers are link times, roman numerals are bus line (route) numbers, and double-headed arrows are walk links).

A = NULL means that A has no line numbers
C = A means C has all and only those line numbers in A
C = COMP (A) means C has only those line numbers not in A
C = AND(A, B) means C has only those line numbers in both A and B
C = DIFF(A, B) means C has only those line numbers in A but not in B

The minimum or maximum of a pair of numbers is often desired. The following notation is used in the flow chart:

A = MIN(T, S) means A equals the smaller of T and S
A = MAX(T, S) means A equals the larger of T and S

Transfer penalties are frequently calculated in the algorithm. A shorthand method of indicating this computation is used in the flow chart. The penalty for transferring to lines contained in the set A is denoted as X(A). Its value is equal to one-half the

TABLE 6

TRANSIT NETWORK DESCRIPTION (NET) COMBINED LINK-TIME-LINE TABLE

From node
To node
Link Time
Line number set

A	E, 5(III, VIII, IX)	F, 12(I, IV, XII)	H, 3(II, VII)	
B	D, 4(XI)	G, 10(IV, XII)	J, 3(0)	
C	E, 4(XII)	H, 4(VIII, XI)	I, 6(III, V)	
D	B, 5(IV, VIII)	F, 2(XI)	H, 7(V)	
E	A, 7(XII)	C, 2(III, VIII)	M, 1(0)	
F	A, 8(III, VIII)	D, 7(IV, V)	K, 2(0)	
G	B, 3(VII, XI)	H, 7(X)	I, 2(IV, XII)	
H	A, 10(X)	C, 8(V)	D, 6(VIII)	G, 5(II, VII, XI)
I	C, 8(XII)	G, 6(II, X)	L, 2(0)	
J	B, 3(0)			
K	F, 2(0)			
L	I, 2(0)			
M	E, 1(0)			

inverse of the sum of the frequencies of all lines in A. For example, the penalty for transferring to the lines on link P above is

$$\begin{aligned} X(L(P)) &= X(S) \\ &= X(II, V, X) \\ &= 0.5/(F(II) + F(V) + F(X)) \end{aligned}$$

where F(II) is line II's frequency, etc.

EXAMPLE

The transit network shown in Figure 7 is tabulated in Table 6. In the network, nodes J, K, L are assumed centroids, and the links connecting them to the system are walk links. As above, roman numerals represent line numbers and arabic numerals are time. There are no line numbers associated with the walk links. The line frequencies listed in Table 9 complete the system's description.

The pathfinder algorithm is used to build a tree from node J. A worksheet describing the principal calculations comprises Table 11, which tabulates the computations in generating candidates for the link sequencing table. Tables 7, 8 and 10 are the working tables used in the tree-building process. Tree-building consists of adding links in the table called TREE until one link is present for each node. Figure 8 portrays the final tree.

TABLE 7
WORKING TABLE

DEST. NODE	CUMULATIVE TIME
I	CUM(I)
J	0
K	~~16~~ 15
L	~~23~~ 22
M	~~32~~ 31
B	~~3~~ 2
D	~~12~~ 11
F	~~14~~ 13
G	~~19~~ 18
H	~~24~~ 23
A	~~26~~ 25
I	~~21~~ 20
C	~~33~~ ~~32~~ 31
E	~~31~~ 30

TABLE 8
WORKING TABLE

LINK NO.	LAST LEG ON MINIMUM PATH
I	TREE(I)
1	J–J(0) 0
2	J–B(0) 3
3	B–D(XI) 12
4	B–F(XI) 14
5	F–K(0) 16
6	B–G(IV, XII) 19
7	B–I(IV, XII) 21
8	I–L(0) 23
9	D–H(V) 24
10	F–A(III, VIII) 26
11	F–E(III, VIII) 31
12	D–C(V) 32
13	E–M(0) 32

TABLE 10
WORKING TABLE

TIME SLOT	LINK SEQUENCING TABLE
T	SEQ(T)
0	~~J–J(0)~~
~~1~~ 21	~~B–I(IV, XII)~~
2	
~~3~~ 23	~~J–B(0), I–L(0)~~
~~4~~ 24	D–H(V)
5	
~~6~~ 26	~~F–A(III, VIII)~~
7	
8	
9	
10	
~~11~~ 31	~~F–E(III, VIII)~~
~~12~~ 32	~~B–D(XI), D–C(V), E–M(0)~~
~~13~~ 33	B–C(12), F–C(III, VIII)
14	~~B–F(XI)~~
15	
16	~~F–K(0)~~
17	
18	
19	~~B–G(IV, XII)~~
20	

TABLE 9
LINE FREQUENCIES

LINE NO.	FREQUENCY (BUSES HR.)
I	6
II	10
III	5
IV	2
V	6
VI	5
VII	3
VIII	3
IX	10
X	6
XI	6
XII	3

TABLE 11

WORKSHEET FOR TRANSIT TREE-BUILDING EXAMPLE

Step	Extracted Link	Generated Link	Time Calculation	Entered into Sequencing table?
0	-	J-J(0)	0	Yes
1	J-J(0)	J-B(0)	3	Yes
2	J-B(0)	B-G(IV, XII)	3+10+X(IV, XII) = 13+6= 19	Yes
		B-D(XI)	3+4+X(XI) = 7+5 = 12	Yes
3	B-D(XI)	D-H(V)	12+7+X(V) = 19+5 = 24	Yes
		B-F(XI)	12+2 = 14	Yes
		D-B(IV, VII)	12+5 =17 >2	No
4	B-F(XI)	F-K(0)	14+2 = 16	Yes
		F-A(III, VIII)	14+8+X(III, VIII=22+4 = 26	Yes
		F-D(IV, V)	14+7 = 21> 12	No
5	F-K(0)	None	-	-
6	B-G(IV, XII)	B-I(IV, XII)	19+2 = 21	Yes
		G-I(II)	19+2+X(II) > 21	No
		G-H(X)	19+7+X(X)=26+5=31>24	No
7	B-I(IV, XII)	I-L(0)	21+2 = 23	Yes
		B-C(XII)	21+8+X(IV, XII)+X(XII)=29-6+10=33	Yes
8	I-L(0)	None	-	-
9	D-H(V)	D-C(V)	24+8 = 32	Yes
		H-A(X)	24+10+X(X) = 25 + X(X)> 25	No
		H-G(II, VII, XI)	24+5+X(II, VII, XI)=21+X(II, VII, XI) > 18	No
		H-D(VIII)	24+6+X(VIII)> 12	No
10	F-A(III, VIII)	A-H(II, VII)	26+3+X(II, VII) >24	No
		A-F(I, IV, XII)	26+12+X(I, IV, XII)> 14	No
		F-E(III, VIII)	26+5 =31	Yes
		A-F(IX)	26+5+X(II) >13)	No
11	F-E(III, VIII)	E-M(0)	31+1=32	Yes
		F-C(III, VIII)	31+2 = 33	Yes
		E-A(XII)	31+7+X(XII) > 25	No
12	D-C(V)	D-H(V)	32+6=38 >24+X(V)	No
		C-H(III)	32+6+X(III) > 24+X(III)	No
		C-E(XII)	32+4+X(XII) > 31+X(XII)	No
		C-H(VIII, XI)	32+4+X(VIII, XI) > 24+X(VIII, XI)	No
13	E-M(0)	None	-	-

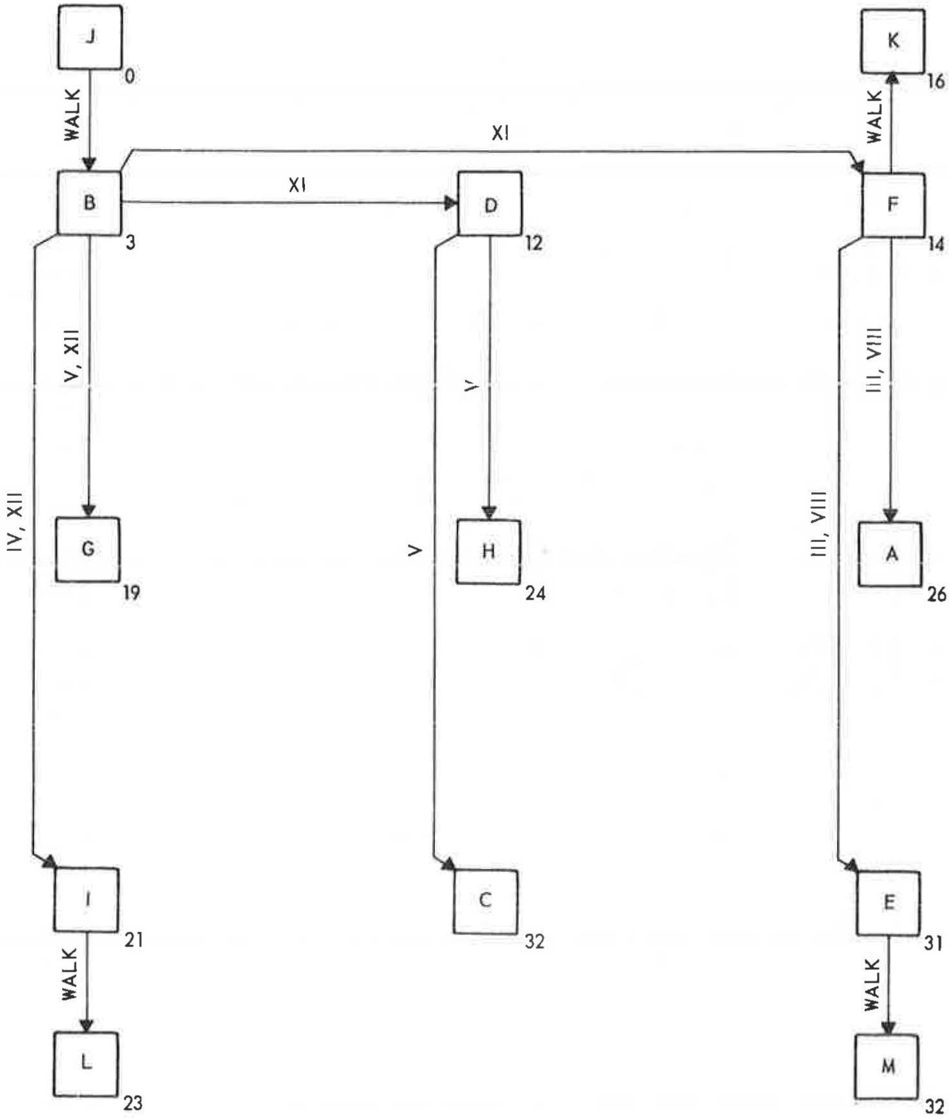

Figure 8. Minimum paths from home node J (letters are node identifiers, roman numerals are line numbers, and arabic numerals are total times from home node).

To follow the example, the reader should read Table 11 from top to bottom. The first column tabulates the links extracted from the link sequencing table in the order they are extracted. Each is entered into the tree. The second column lists the transfer links and through links exiting the B-node of the link extracted from the link sequencing table. Note that there is usually more than one link generated for each taken out. The third column shows the "distance" (time) calculation. First is posted the cumulative time to the extracted link's B-node. Next is shown the link traversing time, followed by a symbolic representation of the transfer penalty. A yes or no in the last column indicates whether or not the generated link was entered into the link sequencing table.

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Sampling Methods for the Collection of Comprehensive Transit Passenger Data

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This paper outlines a method of sampling transit service to obtain comprehensive data on passenger usage. Three examples of surveys using this sample design are described—a bus and streetcar survey in the Pittsburgh area, and railroad and bus surveys in the New York area. Differences in the surveys due to refinements in sample design and variations in the data desired are explored. Comparisons of the results of these surveys with complete enumerations at selected points are examined.

•A PORTION of comprehensive transportation planning that has been somewhat neglected in the past is the planning for transit facilities and services. Much of this neglect has often been due to the separation of transit planning and the other parts of the comprehensive transportation planning process, with the responsibility for transit planning often being held by a separate agency. More recently, the need for an overall transportation planning process has been seen and transit planning has become an integral part of the program of the comprehensive transportation study.

This broadening of function has required that additional tools of data collection and analysis be developed. It is the purpose of this paper to describe one of these tools—the on-board sample survey method for obtaining transit usage data. Much of the data traditionally collected for a comprehensive transportation study are applicable to transit planning as well as highway planning. The home interview survey provides the same type and level of information about transit trips as it does about highway travel. Land-use surveys are not restricted in use to planning for any one mode of transportation. Although no survey paralleling the cordon line interview survey of highway travel is usually made, it is an extremely rare study area that has a significant number of external transit trips.

The major area in which new survey techniques have had to be developed is the collection of "on the ground" data measuring the actual operation of the transit system. For the purposes of the transportation study, the traditional data collection methods of transit operators are not adequate, and a new approach is necessary. Transit operators have traditionally used two measures of passenger usage, revenue passengers as derived from fare box receipts, and peak load point passengers as observed by field personnel. Each of these measures is seriously deficient as an indication of system usage. Revenue passengers based on fare box receipts can be associated with the geography of the system only in a rough way, as it is almost never reported in greater detail than by route. (Rapid transit systems with station fare collection are an exception.) Thus, the best information that can be derived from this source is the number of passengers by corridor for a largely radial system without through routings. Where a grid of routes or a substantial number of radial routes passing through the central area exists, even this is nearly impossible. In addition, where a zone fare system or any other system

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of differential fares is in effect, the adjustment of revenue receipts to reflect patronage is usually made by some overall allocation formula, which is often seriously misleading for a particular route.

Peak load point passenger counts are commonly used for purposes of preparing route schedules. These counts are taken at the highest volume point on a line as determined subjectively, and are analogous to a screenline count for highway traffic. Radial lines will almost always have a peak load point at or near the edge of the central area, so that a cordon around the central area is often available. Nonradial lines will have peak load points at scattered locations, so that usually no pattern of count coverage would be available for a grid system. Again, only partial geographical coverage is possible using this information, while the level of detail concerning the service passing a given point is greater than is needed for system planning work.

After considering the shortcomings of the standard methods of transit data collection, a method of data collection designed specifically for the uses of comprehensive transportation studies was indicated, based on the needs for transit data in such studies. The first need is for a measure of transit usage that can be used to corroborate data collected in a home interview survey. Another principal use of the data is in the development and verification of transit trip distribution and assignment models. The data also have uses in assessing the performance and efficiency of the transit system as currently operated. For all of these purposes, it is necessary to have a measure that is comprehensive, i. e., that permits assertions to be made about the entire transit system or subsystem. This measure should also be designed to be capable of subdivision, both geographically and by time period.

With these needs in mind, a general method of survey procedure has been developed that is not rigid, but can be varied to produce results suited to the problem at hand. The method relies on the fact that a transit system operates a fixed or largely fixed (over the short run) schedule of service. This service has to be specified in complete detail for operating purposes. Such information is sometimes available in the familiar public timetable, but it is usually necessary to obtain operating timetables, equipment assignment lists and other relevant material for sample frame preparation.

The basic procedure requires that the transit service be divided and ordered into units suitable for the selection of a sample. A systematic sample is then drawn, and an observation procedure for determining the desired information is developed and applied to the sample. The results of this procedure are then expanded to a total figure by use of the ratio of sampled service to all service. The ratio used for the expansion need not be based on the same division as that used for selecting the sampling frame. Generally, a more detailed examination of the service is possible for the determination of the expansion ratio.

While in theory this sounds extremely simple, there are many pitfalls inherent in the procedure, in both a logical and operational sense. It will thus be of interest to examine three surveys that have been conducted using this method. The first was run by the Pittsburgh Area Transportation Study in the spring of 1959. The information required of this survey was the total number of mass transportation passenger trips by common carrier transportation, excluding suburban railroad passengers. This information was to be used merely as an accuracy check of the PATS home interview survey trip reporting, so that no elaborate data collection procedures were necessary. The procedure used in this project was first to prepare a sampling frame of vehicle trips (bus and streetcar). Transit service was divided into nine expansion areas based on geographic area, vehicle type and CBD orientation as follows:

1. Streetcars, North, Entering CBD;
2. Buses, North, Entering CBD;
3. Streetcars, West and South, Entering CBD;
4. Buses, West and South, Entering CBD;
5. Streetcars, East, Entering CBD;
6. Buses, East, Entering CBD;
7. Buses, North, West and South, Not Entering CBD;

8. Pittsburgh Railways Buses and Streetcars, East, Not Entering CBD; and
9. Other Buses, East, Not Entering CBD.

Within each expansion area, vehicle trips were ordered by company, route number, subroute or branch, direction and time. Each trip was assigned a sequential number based on the above ordering. Thus sequence number 00001 would apply to the first outbound trip on the main route of the route with the lowest number in the first expansion area. In all, 16,603 trips were listed in this fashion, a random start was made and a 1 percent sample, or 166 trips, were selected for data collection.

Since the desired information was passenger origins, each sampled trip was ridden to observe the number of passengers that originated on it. Fieldwork was very straightforward. A form with a heading section describing the trip was prepared including time, route, boarding point (usually at some location near the end of the previous trip if a previous trip was scheduled to be made by the same vehicle), start and end point of the count, and points at which time was to be observed. The field personnel were required to observe passenger origins (defined as all boarding passengers except those presenting transfers), times at terminal and intermediate points and the vehicle number. The last two items were used for assessing the quality of the fieldwork. Times were used for checking adherence of the sampled trip to the scheduled time. If the trip was substantially late due to vehicle breakdown or traffic conditions, the assignment was rescheduled. Vehicle number was intended for use if a question arose as to the actual presence of the enumerator aboard his assigned vehicle. The assignment of a particular vehicle to a trip could be checked with the operating company's records, making it possible to determine, if necessary, whether or not an enumerator had actually been aboard the vehicle with a fair degree of certainty. Although not necessary in this survey, this check has been quite helpful in settling cases of suspected non-performance of duties by enumerators.

Processing of the information was relatively simple. Since the sample selection frame and the expansion frame were identical, it was merely necessary to multiply the observed passenger origins by the ratio of sampled trips to total sequenced trips, by expansion area. Thus a sample count of 3,684 passenger origins was expanded to a total of 369,096 passenger origins. While this number was not verified independently, it appeared to be in reasonably close agreement with home interview passenger trip origins, after corrections for services not included in the survey were made (school buses and inclined planes).

Some major shortcomings were found in the design and operation of this first survey based on service sampling. Most important, the ability of the enumerator to observe passenger movements was seriously underestimated. Thus, in addition to boarding passengers, departing passengers could have been recorded and exact stop locations could have been noted rather than the sequential numbers used. With this information, and some coding work, many measures of transit system behavior could have been derived, including trip length, vehicle occupancy, a total measure of passenger miles, as well as passenger origin and destination location and density patterns.

Other problems were more of an operational nature and did not affect the amount or quality of the data collected. Use of the vehicle trip as a sampling unit posed two such problems. The first was that the enumerator had a difficult time locating the particular trip that he was assigned to ride. Not all terminal locations could be specified exactly, so that in some cases a trip had to be assigned more than once until it could be located. Also, it was often quite difficult to locate the correct trip on routes with frequent service, particularly as small delays were common and buses were at times out of their proper sequence. In such cases it was necessary to stop several buses and obtain from the driver either their run number or scheduled leaving time, whichever was applicable, in order to determine the right vehicle.

A second problem associated with the trip sample was the productivity of the enumerator obtained with this system. Since each trip was sampled independently of all other trips on a route, it was almost impossible to schedule the enumerator's work in such a way that more than half of his time was actually engaged in fieldwork. Thus, for any sampled trip with one end in the CBD, it was necessary to ride a trip not in the sample in the opposite direction, either to get to the starting point or to return. In practice, the productivity was much lower, with an average of only two hours of actual counting possible out of a normal day due to the peaking of sampled trips in the morning and evening, and the large amount of unproductive travel time that was necessary to reach some non-CBD-oriented samples.

The sample of service method of obtaining transit passenger usage information has in addition been used on two surveys in the New York region. Both of these were conducted by the Tri-State Transportation Commission. One was a survey of suburban railroad service, conducted in the summer of 1963. The other covered the regularly scheduled bus operations in the Tri-State region, and was conducted in the period from the spring of 1964 to the winter of 1965. While the principles underlying the method were the same as those of the Pittsburgh survey, many changes were made, both to correct defects in the original design, and to adopt the procedure to produce the desired results.

The purpose of the suburban railroad survey was to obtain the volume of passengers over each segment of a railroad line both for the 24-hour day and for peak periods. To obtain such detailed information a more carefully controlled expansion base as well as a higher sample rate or rates were needed. Thus, it became desirable and readily feasible to use a variable sample rate. Since individual route and segment information was desired, the sample rate should reflect the density of service on the individual routes. Thus a 20 to 50 percent sample was used, depending on the amount of service on the route or group of routes under consideration. In some areas a complete count had to be taken, because there was not sufficient service operated to use a sampling procedure.

To permit a more carefully controlled expansion of the survey findings, it was decided to use a different base for expansion of the survey than was used for sample selection. The expansion base used was the seating capacity of the service operated over each route segment for a given time period. Obviously, this is not a quantity that could be sampled in an operational manner. Although it would be possible to assign an enumerator to count the passengers in every third seat, it would be far simpler and less expensive to take a complete count of a larger segment of service. Thus a method for approximating the seating capacity for sample selection purposes had to be designed. Unlike buses or streetcars, which are single, rather small units, readily enumerated by one man, suburban trains vary widely in size and at best are difficult to observe satisfactorily. Thus, a sample unit had to be devised based on the limitations of the enumeration system. It was decided that a count of passengers taken as the train moved between stations provided sufficient information for the purposes of the study, and required far fewer people than would a count taken of passengers boarding and alighting. This is because an accurate boarding and alighting count requires one man per pair of adjacent vestibules, or the inspection of tickets. Thus a 7-car train would require 6 enumerators, assuming the front vestibule of the lead car and the rear vestibule of the last car are not used. It was determined by some experimental fieldwork that an onboard count can be taken at a rate of slightly over one car per minute. Thus the controlling factor is the time between stops, as well as the train length. The 7-car train in the example would require 1 man, if station stops were 7 minutes or more apart, and more typically two men, if station stops were 3 to 4 minutes apart. While the method of enumeration adopted provided sufficient information for the survey, information on the boarding and alighting points of passengers, and thus station usage, was not obtained. For some applications, this type of information may be desirable and would require a different enumeration procedure.

After the method of enumeration was decided upon, a sample selection scheme compatible with it was laid out. This scheme consisted of dividing all service into sampling units or blocks, a block being defined as the position of a train that could be assigned to one enumerator following the one-car-per-minute rule mentioned. The service to be sampled, i. e., the suburban service on the Long Island, New Haven and New York Central railroads, was first divided into sampling groups by railroad, route and type of service. Trains in each group were then listed in direction and time order and the

RR XYZ

Train No.	Leave	Arrive		Consist	Block No.	Sample No.
201	8:09 AM	9:30 AM	LV	2AC MU	1	0001
203	9:46	10:40	LV	2AC MU	1	0002
17	10:14	11:37	EM	4RSC-1 Grill-1 Parlor	1	0003
209	12:10 PM	1:06 PM	LV	3AC MU	1	0004
451	3:07	4:39	XA	2RSC-1 NRSC	1	0005
211	3:44	5:40	LV	3AC MU	1	0006
213	4:27	5:22	LV	4AC MU	1	0007
453	4:41	6:19	EM	4NRSC-Bar C-5RSC	2	0008-0009
57	4:45	6:04	EM	5RSC-Grill-1 Parlor	1	0010
215	4:52	5:45	LV	6AC MU	2	0011-0012
217	5:16	6:12	LV	8AC MU	3	0013-0014-0015
219	5:41	6:44	LV	9 Old MU	3	0016-0017-0018
499	5:44	6:02	WY	7AC MU	2	0019-0020
23	6:00	7:15	EM	2RSC-Diner-2SL-SL Lge	1	0021
221	6:12	7:07	LV	4AC MU	2	0022-0023

Figure 1. Sample train listing sheet.

number of blocks determined for each train. Each block was then given a sequential number. Figure 1 shows a sample train listing sheet. Note that the number of blocks per train will vary with respect to the train length quite noticeably. This example is designed to show a mixed type of service, with local suburban trains and medium distance trains carrying suburban passengers intermixed. Information on normal train lengths and consists was provided by the railroads.

The sequential numbers chosen to be sampled were based on a series of random starts in a group of 10 numbers. Thus, if a 40 percent sample was to be chosen, 4 random starts were taken, and the final digits thus determined were selected from each group of 10 sequence numbers. Each block was then included in a work assignment for an enumerator. Work assignments were laid out so as to maximize utilization of personnel, but due to the highly peaked nature of railroad service only 3 to 4 hours of fieldwork per man day was possible. Field work was straightforward, with each enumerator making a count of his assigned block between all station stops. In addition, each enumerator was to record a complete count of the train at the point where it crossed the river boundaries of Manhattan. A list of car numbers on the train was also made, to verify, if necessary, the presence of the enumerator on the train as well as to provide a more exact record of seating capacities for use in establishing the expansion ratio. Trains with substantial observed deviations from normal train length were reassigned, as well as trains that were significantly behind schedule.

In order to expand the sample, a complete record of seating capacity was needed for the universe of service. An approximation of capacity could be obtained from the equipment assignment lists used to prepare the sampling frame, but it was desired to make a more accurate estimate. Therefore capacity was established based on the trains actually observed in the counting process. As has been noted before, car numbers were observed for all trains, along with a notation as to whether or not the car was open to passengers. Capacity of each car was obtained from equipment rosters supplied by the railroads, or from the "Official Register of Passenger Train Equipment." All trains not falling in the sample were also observed. Those trains that crossed into Manhattan had complete counts taken at the crossing point, while the unsampled trains that did not enter Manhattan were inspected only for car numbers at a major terminal.

Capacity was defined as the total number of seats in cars open to passengers at the inner terminal. In a few cases where cars were added or removed at intermediate points, trains are assigned different capacity values over several parts of the system. Capacity of the sampled blocks was handled in the same manner as described for system capacity. Volumes were calculated by means of the expansion ratio described for the previous survey:

$$\text{Passenger volume} = \frac{\text{Observed passengers}}{\text{Sampled capacity}} \times \frac{\text{Total capacity}}{\text{Sampled capacity}}$$

The expansion was performed based on the sum of each value for the route segment and time period of interest.

Two tests of the accuracy level of this survey were designed into the procedure. The first was a comparison of the complete count made at the Manhattan boundary with the expanded sample count taken at that point. Table 1 shows the results of this comparison. The general comparison is very good, with the largest difference in the 9 groups being 3.6 percent. Note, however, a slight tendency for the expanded sample to be slightly biased upward from the complete count. An overall comparison of +2.0 percent for all service was obtained, and 6 of the 9 subgroups compared had expanded sample volumes higher than the complete count volumes recorded.

A more detailed comparison of the results of the sample counting process was obtained for the Port Washington branch of the Long Island Rail Road. A complete count was taken of passengers on the branch in a way that made it possible to divide the count into five subsamples of 20 percent each. A comparison of the expanded volume derived from each subsample with the complete count showed that the expansion of subsample 1 produced almost the same number of passenger-miles as the complete count. Subsamples 2, 3 and 4 were respectively 9, 2 and 1 percent higher than the complete count, and subsample 5 was 10 percent lower. The counts entering Manhattan followed a similar pattern, with the expansion of subsample 1 being almost the same as the complete count, subsamples 2, 3 and 4 being 6, 1 and 3 percent higher, and subsample 5 being 9 percent lower. It appears that variations in both passenger-miles and the Manhattan entry count parallel each other. All samples varied in the same direction in both quantities, and remain within 3 percent of each other at all times. Also, looking at the detailed results of the comparison (Table 2), descrepancies remain in the same range throughout the length of a line, except for the low-volume outermost links where a greater dispersion can be observed.

TABLE 1

ENTRY COMPARISON FOR EXPANDED SAMPLE VS 100 PERCENT COUNT

Terminal	Complete Count	Expanded Sample	Percent Difference
Penn Station (LIRR)			
8-9 AM Inbound	31,651	32,002	+1.11
7-10 AM Inbound	52,782	53,305	+0.99
24 Hour-2 Direction	136,943	140,049	+2.27
Grand Central (NHRR)			
8-9 AM Inbound	14,674	14,882	+1.42
7-10 AM Inbound	22,286	22,198	-0.39
24 Hour-2 Direction	62,394	64,670	+3.65
Grand Central (NYCRR)			
8-9 AM Inbound	19,139	19,110	-0.15
7-10 AM Inbound	27,776	28,206	+1.58
24 Hour-2 Direction	69,923	69,855	-0.97

TABLE 2

PORT WASHINGTON BRANCH SUBSAMPLE COMPARISON

Station	Sample 1			Sample 2			Sample 3		
	100% Volume Count	Expanded Volume Count	Exp/100% Ratio	100% Volume Count	Expanded Volume Count	Exp/100% Ratio	100% Volume Count	Expanded Volume Count	Exp/100% Ratio
Penn Station-Woodside	30651.0	30718.9	1.0022	30651.0	32561.5	1.0623	30651.0	31055.3	1.0132
Woodside-Elmhurst	31833.0	31829.1	0.9999	31833.0	34637.1	1.0881	31833.0	31896.8	1.0020
Elmhurst-Corona	31905.0	32109.3	1.0064	31905.0	34668.2	1.0866	31905.0	31889.8	0.9995
Corona-World's Fair	31900.0	32104.4	1.0064	31900.0	34658.5	1.0865	31900.0	31889.8	0.9997
World's Fair-Flushing	31655.0	32316.1	1.0209	31655.0	34644.6	1.0944	31655.0	31826.5	1.0054
Flushing-Murray Hill	32962.0	33488.0	1.0160	32962.0	35976.5	1.0914	32962.0	32678.2	0.9914
Murray Hill-Broadway	32098.0	32767.7	1.0209	32098.0	34654.4	1.0796	32098.0	31903.1	0.9939
Broadway-Auburndale	30596.0	31401.4	1.0263	30596.0	33448.4	1.0932	30596.0	30624.4	1.0009
Auburndale-Bayside	29524.0	30320.6	1.0270	29524.0	32207.9	1.0909	29524.0	29297.6	0.9923
Bayside-Douglaston	26439.0	26976.3	1.0203	26439.0	28646.7	1.0835	26439.0	26814.2	1.0142
Douglaston-Little Neck	24678.0	24814.9	1.0055	24678.0	27483.5	1.1137	24678.0	25615.1	1.0380
Little Neck-Great Neck	22777.0	22339.1	0.9808	22777.0	25716.2	1.1290	22777.0	25710.8	1.1288
Great Neck-Manhasset	13055.0	12044.8	0.9226	13055.0	14579.6	1.1168	13055.0	15307.0	1.1725
Manhasset-Plandome	7029.0	6598.5	0.9388	7029.0	8523.1	1.2126	7029.0	7844.6	1.1160
Plandome-Port Washington	5529.0	4974.9	0.8998	5529.0	6891.2	1.2464	5529.0	6376.6	1.1533

Station	Sample 4			Sample 5		
	100% Volume Count	Expanded Volume Count	Exp/100% Ratio	100% Volume Count	Expanded Volume Count	Exp/100% Ratio
Penn Station-Woodside	30651.0	31693.5	1.0340	30651.0	27868.5	0.9092
Woodside-Elmhurst	31833.0	32504.7	1.0211	31833.0	28783.7	0.9042
Elmhurst-Corona	31905.0	32524.0	1.0194	31905.0	28672.2	0.8987
Corona-World's Fair	31900.0	32524.0	1.0196	31900.0	28662.3	0.8985
World's Fair-Flushing	31655.0	32461.7	1.0255	31655.0	28805.3	0.9100
Flushing-Murray Hill	32962.0	32837.8	0.9962	32962.0	29720.1	0.9016
Murray Hill-Broadway	32098.0	31792.0	0.9905	32098.0	28847.1	0.8987
Broadway-Auburndale	30596.0	30508.6	0.9971	30596.0	27430.1	0.8965
Auburndale-Bayside	29524.0	29573.1	1.0017	29524.0	26148.0	0.8856
Bayside-Douglaston	26439.0	25583.0	0.9676	26439.0	23280.2	0.8805
Douglaston-Little Neck	24678.0	23556.5	0.9546	24678.0	21629.8	0.8765
Little Neck-Great Neck	22777.0	22062.8	0.9686	22777.0	19301.1	0.8474
Great Neck-Manhasset	13055.0	13045.8	0.9993	13055.0	11662.3	0.8933
Manhasset-Plandome	7029.0	7159.0	1.0185	7029.0	5990.6	0.8523
Plandome-Port Washington	5529.0	5486.2	0.9922	5529.0	4643.9	0.8399

The two tests indicate that the results of surveys using this method can be used with a considerable degree of confidence. In general, it appears that the results obtained are well within the normal (day-to-day) variability level of the information sought. In the one area where excessive variation was observed—the outer end of the Port Washington branch—it was accounted for by the low total volume observed and the low sample rate (20 percent) used. The lesson to be drawn is that the sample rate used in this test (the lowest used in the survey) was too small to provide a high level of accuracy on the lowest volume segments of this service. However, the estimated and actual volumes in this area did not vary by more than around 1,500 persons per day, which for many purposes would be a sufficiently accurate estimate.

The second survey using the sample of service method was the bus passenger survey taken by Tri-State in 1964. Here the information desired was bus passenger-miles of travel by geographic area. Although this survey is not yet completely analyzed, a description of the methods used is possible.

Looking back to the 1959 Pittsburgh work, it was apparent that a vehicle trip sample would present almost insurmountable selection problems, as well as requiring a large amount of geographic coding of both sample and universe data to produce the desired geographic breakdown. Since the geographic coding appeared inevitable, a sample frame was sought that approximated the distribution of bus movements, yet was operationally simple to use. The sample unit decided upon was the active vehicle. This is a somewhat arbitrary concept. It is defined as a bus in service at the time when the maximum number of buses are in service that are based at the facility under consideration.

Perhaps working through the preparation of the sample frame will be helpful. First the bus service is ordered by major geographic area (state, county, etc.) based on the garaging location of the vehicles. Within this order, bus service is separated by company and division or garage. The garage thus becomes the primary subdivision of service within which the sample is drawn. For each garage, the maximum number of buses required to operate the service is determined. This number represents the total sample frame for the garage. The detailed sample frame is determined as follows. The number of buses on each route at the time of day when the maximum number of buses is required from the garage is computed and is used to determine the number of lines in the sample listing. Buses are then listed by route in order of their first departure from the garage until the number of lines indicated is reached. The return time to the garage is listed for each of the departures. The remaining buses departing from the garage are tied to previously listed departures on a first-in, first-out basis, within route if possible. A 30-minute minimum time between arrival and departure at the garage is required. Generally, the final arrival cannot be more than 23 hours 30

Sample No.	ON AM	OFF AM	ON PM	OFF PM	ON EX	OFF EX
8243	5:25	7:50 PM				
8244	5:45	8:30 PM				
8245	6:05	9:00 PM				
8246	6:20	10:20 AM	4:30	6:25		
8248	6:25	12:50 AM				
*8248	6:35	11:10 AM	(Route 23)		(4:35 PM	7:15 PM)
8249	6:55	10:00 AM	2:30	9:10		
8250	7:05	9:10	1:55	8:10		
8251	7:20	9:20	2:15	12:15 AM		

Figure 2. Master sample list.

minutes later than the initial departure. When it is impossible to remain within the route structure and follow the above rules, the remaining portions of the service on a route may be listed with another route in the same garage. For example, this would occur when a route using its maximum number of buses in the afternoon peak operates from a garage having a maximum bus requirement during the morning peak. In some cases, buses are not specifically assigned by route, so that a whole garage may be treated as one route. The result of this procedure is a listing for each garage by route showing the departure and return times of each active vehicle. A sample of this listing is shown in Figure 2. Sample vehicles to be used in a count program can be selected by numbering the list of active vehicles sequentially and selecting a sample using every nth sample number. In 1964 a 5 percent sequential sample was selected using every 20th line starting with sample number 0008.

The use of the active vehicle as a sample unit was decided upon primarily for operational reasons. A sample of bus trips would more closely approximate the desired sampling quantity of bus miles, since only variations in route length would cause the two quantities to differ. With the active vehicle sample, differences occur due to extent of utilization during the day, as well as due to variations in route length. In addition, the use of a trip sample would permit stratification by direction and time of day as well as by route, which was not possible in the vehicle sample.

However, a bus trip sample would be very difficult to handle in an operational sense. The work required in stratifying and delineating the sample would be increased by a very substantial amount, as there would have been at least 10 times the number of units in the sampling universe. More important, the fieldwork involved in a trip sample would be much more time-consuming and difficult to organize. Deadheading time and time between assignments would be increased from about 10 percent of total paid time for field personnel to over half of the total, based on Pittsburgh experience, thus doubling the cost of fieldwork for a given sample size. In addition, it was much simpler for enumerators to locate buses at the beginning of a day's run at the garage than it would be to have to locate a particular trip at the end of a line, four or five times during the day, especially during rush hours and at crowded locations such as subway transfer points, where it might be necessary to go down a line of buses and inquire of the driver as to the run number or leaving time of each bus until the correct one is located. It would be expected that a substantial number of assignments would not have been completed due to the enumerator's inability to located the correct trip, thus adding even more to the costs of the survey.

While final results of the bus survey have not yet been completed, the question of the degree to which the sampling device, using the active vehicle as the sampling and

TABLE 3

COMPARISON OF EXPANDED SAMPLE COUNT WITH COMPLETE COUNT ON BRONX-MANHATTAN, AND BROOKLYN AND QUEENS-MANHATTAN SCREENLINES

Category	Bronx-Manhattan Screenline	Brooklyn and Queens-Manhattan Screenline	Combined Screenline
Number of routes	12	7	19
Number of buses crossing screenline	4362	1630	5998
Buses sampled	212	70	282
Percent of buses sampled	4.86	4.29	4.70
Passengers counted in sample	3206	1682	4888
Average passengers per bus	15.12	24.03	17.33
Total passengers (expanded from sample counts)	65,965	39,167	103,965*
Total passengers (from screenline count)	67,038	35,184	102,222
Percent difference	-1.60	+11.32	+1.27

*Computed based on total sample count and number of buses, not sum of estimates for individual screenlines.

enumeration unit, succeeded in representing the total universe of bus miles has to some extent been solved. In the Tri-State bus survey, 391 sample buses were observed. These buses traveled a total of 38,653 miles. The total bus movement (excluding school and charter buses) in the region was 799,037 miles, divided into 7824 active buses. Thus the sampled bus miles represent 4.84 percent of the total bus miles as compared with an intended 5 percent sample. When data are available, the stability of this ratio will be examined for smaller areas.

Due to the size of the survey, no comparison of sample results with a complete enumeration was possible. However, two tests of the accuracy of the results are available. For test purposes, two 5 percent samples were taken in Staten Island. When results are available for both of these samples, they will be compared to get some idea of the stability of the results. Another test possibility is to compare the results of the sample survey at a screenline with independent complete counts taken at this screenline. A series of counts taken in the fall of 1963 at the crossings between Manhattan and Brooklyn, Queens and the Bronx were available for this purpose. The results of this comparison are shown in Table 3. The comparison is almost too good to believe, except for the Manhattan-Queens and Brooklyn screenline, where as a result of the small size of the sample, substantial deviation might be expected. Results on this screenline are still good, particularly considering that only 4 of the 7 routes fell into the sample and 3 of 6 samples were on one route. Additional comparisons of this type will be made for other screenlines as data become available.

It appears that the sample of service method can be used to satisfactorily obtain data on the usage of transit systems, and that the level of detail and accuracy desired can be achieved by control of the sample size and method of observation. However, it must be cautioned that no exhaustive test of the accuracy of this sampling method has been made using an entire service area as a base, and all evaluations made up to this time have been based on partial data.

A Network Evaluation Procedure

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A novel traffic assignment method is presented which greatly increases the number of network alternatives that can be evaluated at a given cost in computer time. Based on slight variations of the usual minimum path tree-building and traffic loading procedures, the method makes it possible to consider only the effects of new or improved network links, rather than complete networks, when evaluating alternatives of some basic (existing or future) network configuration. The same values for each alternative, such as interzonal travel times and flows on links, are obtained as if each network alternative were treated separately. Furthermore, such values as savings in travel time between any pair of zones, flow changes, and total vehicle hours are directly obtained. In addition, the procedure readily provides interzone travel times via a link or links, even if these do not contribute to the minimum time or cost path, and this information can be used for improved (more realistic) but still rather efficient capacity restraint and traffic diversion procedures. The present report describes the essential parts of the process and a procedure for evaluating sketch-plan network alternatives.

•THE network evaluation method described in this report utilizes several special network properties which make it possible to assess large numbers of transportation projects such as new bridges, freeways, or rapid transit lines without requiring a complete traffic assignment process for each alternative combination of projects. It is capable of evaluating a large number of network alternatives in the same amount of time it would take to evaluate a single alternative using standard procedures (e.g., the Bureau of Public Roads or TRAN/PLAN traffic assignment programs), and still obtain not only the same information at a comparable level of detail, but also additional data as well.

When using the procedure, the usual traffic assignment process is applied only to a "basic" network configuration, while additional routines make it possible to concentrate on possible effects of network changes, such as new or improved links, when evaluating the various alternatives. The procedure will provide the following data for each network alternative:

1. Interzonal travel times via minimum time paths;
2. Traffic flows on links;
3. Savings in travel time between all pairs of affected zones, due to some improvement to the basic network (inclusion of project or combination of projects);
4. Changes in traffic flows for each network alternative, i.e., the flow diverted to or from all existing and future facilities due to network changes;
5. The origins and destinations of all flows on any new facility in a network alternative;

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6. The total travel time required to satisfy given travel demands for a network alternative, and the difference in the total travel time between each alternative and the basic network;

7. Information regarding the degree to which several transportation projects (new or improved links) compete or cooperate in carrying traffic, and the area affected by any project; and

8. Interzonal travel time via any link or links, even if these are not on the shortest path.

The following input data are required:

1. Network description for each "basic" network;
2. Network changes needed for converting a base network into a network alternative; and
3. A trip desire (origin-destination) table.

The interzonal travel times for a "basic" network can be obtained first and used to determine a trip table by means of suitable land-use and traffic generation and distribution models. This trip table can then be used in conjunction with all the network alternatives which do not differ too significantly from the basic network. In case of the significantly different alternatives, it would be necessary to rerun the trip demand models, or, in the intermediate case, only a new trip distribution process would be required. The trip tables are actually only utilized as weighting factors for determining flows and cumulative travel times, and the decision as to whether the same trip table should be used for each alternative, or whether the trip tables should be adjusted for each alternative network, has to be left to the user.

The network evaluator procedure and related computer program, as developed for the San Francisco Bay Area Transportation Study, was envisaged primarily as a simple, efficient, and inexpensive management tool, suitable for testing and evaluating very large numbers of possible highway, transit, or multimode network alternatives. It will be used mainly to limit the large amount of possible alternatives to the more promising ones, to be evaluated in greater detail by means of a different process. The main emphasis was, therefore, on quantity rather than quality, as is usual in sketch planning. The general method, as described in the following parts, could, however, be just as well used in a detailed transportation planning process, and the development of suitable computer programs is presently being considered.

In developing the model, the author was mainly influenced by the general network methodology as presented by Ford and Fulkerson (1), and benefited greatly from many discussions concerning the transportation planning process with J. W. McBride, Technical Director, Bay Area Transportation Study Commission. The benefit/cost evaluation method is partly based on Kuhn's work (2) and Ridley's dissertation (3). It would be difficult to enumerate all the authors who contributed to the state-of-the-art in the field of traffic assignment, which, of course, forms the basis of the model.

MODEL DEVELOPMENT

Network Properties

The network evaluator utilizes a special tree-building procedure for determining the minimum paths that will use a specific project link. The procedure is an extension of the well-known dynamic programming (or Moore) shortest path algorithm, the only difference being:

1. Two or more "project" nodes—either the end nodes of a "project" link, or several nodes, such as the interchanges of a segment of freeway or the stops of a transit line segment—are used as origins at the start of the process, so that two or more disjointed tree branches are obtained.
2. Each node is labeled by a subset (tree branch) number to indicate from which node the branch originated.

The procedure is just as efficient as the fastest standard tree-building process and has the same computer core requirements.

At the end of the tree-building process a project tree is obtained, consisting of two or more branches, so that each node is connected with the closest project node. In case of equal travel times (it is, of course, also possible to minimize distances, costs, or some other value), one or the other project node is selected.

The project tree has the following properties (the properties mentioned hold strictly true only for symmetrical networks; similar ones apply to asymmetrical networks):

1. No two nodes belonging to the same subset can be connected by a minimal path that would include the project link, since their connection via the last common node on their branch cannot be longer than the sum of the shortest distances between them and the closer project node.
2. Only the paths between the nodes of different branches could possibly have been improved by the inclusion of the project link. Therefore, only these connections will have to be tested.
3. The minimal path between nodes, each belonging to separate subsets, via the project link(s) can easily be determined by summing the times from the two project nodes and the time required to cross the project link(s). The project link time, therefore, does not enter the actual tree-building process and can be varied depending on various conditions; for instance, it could be adjusted to reflect traffic flows, different tolls, etc.

Any standard minimum-path, tree-building routine can be used to determine a project tree by either (a) representing the project as a special centroid, connected to the two or more project nodes by "dummy" (zero-time) links, or (b) adjusting the routine so that the several project nodes can serve as "home" nodes, i.e., be initialized at zero and become the simultaneous origins of a single tree. Though it would be a simple matter to carry the subset number which identifies the origin node to each network node as it is reached in the tree-building process, it is more efficient to determine the subset numbers by means of a subsequent labeling routine.

Project Tree Routine Input and Notation

Network N is composed of nodes i, connected by links (i, j) with travel times $t(i, j) \geq 0$. Associated with each node i is a number $t(i)$. The nodes i can be divided into complementary subsets X, $\bar{X}$ such that $N = X \cup \bar{X}$. The project is represented by project nodes p = a, b, c, d, ... which form a chain of links (a, b), (b, c), (c, d), ... The project nodes and links are connected with the network.

Step 1—Initialization: Set all $t(p) = 0$ and all remaining $t(i) = M$ (high value). Assume that all nodes with $t(i) < M$ form a subset X of "reached" nodes, with the remaining nodes forming a complementary subset $\bar{X}$.

Step 2—Consider all links (i, j) connecting the node(s) i that have been assigned to the set X in the preceding step to nodes $j \in \bar{X}$, and calculate values $t'(j) = t(i) + t(i, j)$. Place the values $t'(j)$ in a sequence table, i.e., a table ordered by value $t'(j)$.

Step 3—Select the minimal $t'(j)$ from the sequence table. If $\min(t'(j)) < t(j)$, go to Step 4, otherwise remove $t'(j)$ from the sequence table and repeat Step 3. If the sequence table is empty, STOP.

Step 4—Set $t(j) = t'(j)$ and reassign the node j from the set X to the set $\bar{X}$. Place the link (i, j) into the next position of a tree trace vector.

Step 5—If the set $\bar{X}$ is empty, STOP, otherwise return to Step 2.

At the end of the process, the $t(i)$ values will give the travel time, via fastest route, to the node i from whichever project node p is the closest. The tree trace obtained in Step 4 is just a listing of all links (i, j) that form the project tree, in the sequence in which they entered the tree, i.e., ordered by increasing $t(j)$ values. The links can be identified by their addresses (positions) in the link table (network description). The tree trace is used as input to a labeling routine which determines for each node i the project node p from which it has been reached and, furthermore, is also used in the loading and unloading routines.

Labeling Routine

1. For each node i, initialize a value $\ell(i)$ in the following manner: (a) For each project node p set $\ell(p)$ at different non-zero values. For instance, $\ell(a) = 1$, $\ell(b) = 2$, $\ell(c) = 3$, $\ell(d) = 4, \ldots$; (b) Set all remaining $\ell(i) = 0$.
2. Starting at the first link, scan through the whole tree trace, setting $\ell(j) = \ell(i) + \ell(j)$.
3. Sort all centroids (nodes which represent a zone) by their $\ell(i)$ values, so as to form subsets of centroids S(a), S(b), S(c), S(d),..., each comprising the centroids reached from the project nodes a, b, c, d,....

The above algorithm can also be used to determine which nodes have been reached from any project node via some other node or nodes k. This is done by setting $\ell(k)$ equal to some unique non-zero value in Step 1, even though k is not a project node. In this case, it is convenient to use the numbers formed by the series 2^n (n = 1, 2, . . .) as labels for all "initially tagged" nodes. Any sum of the label values then forms a unique identifying number which can be used to determine for any node i the "tagged" nodes or links through which it was reached and the project node p from which any particular branch of the tree originated.

Single-Link Projects

Assume now that the interzonal travel times for some "base" network have been determined by the standard method, and that an alternative network is to be evaluated. The alternative is formed by all links of the base network plus a project link (a, b).

The travel time between any pair of centroids u and v could have been improved only if there exists a shorter route between u and v via the project link (a, b), since that was the only change in the network.

All that needs to be done, therefore, is to build a single project tree, simultaneously from the project nodes a, b. In the case of symmetric networks, i.e., $t(i, j) = t(j, i)$, a time saving will have been obtained for any centroid pair (u, v), $u \in S(a)$, $v \in S(b)$ if

$$t(u) + t(v) + t(a, b) < t(u, v) \tag{1}$$

where t(u) is the minimum-time path between nodes u and a, t(v) is the minimum-time path between nodes v and b, t(a, b) is the estimated travel time on the project link (a, b), and t(u, v) is the minimum time between nodes u and v on the basic network.

In case the condition (1) has been met, the value of the time-saving d(u, v) can be determined as

$$d(u, v) = t(u, v) - t(u) - t(v) - t(a, b) \tag{2}$$

Assuming all-or-nothing loading, the project link (a, b) will get the flow f(a, b):

$$f(a, b) = \Sigma f(u, v)\text{: summed over all } (u, v) \text{ such that } d(u, v) > 0 \tag{3}$$

If the flow f(a, b) is greater than the planned capacity of the project link, the value t(a, b) can be appropriately increased. The time-saving d(u, v) for any affected pair of centroids will be decreased by the same amount so that some d(u, v) will become zero or negative and Eq. 3 will produce a decreased flow f(a, b). Capacity restraint relationships can, therefore, be introduced into the process without requiring a new tree-building procedure.

It must be stressed that not all pairs of centroids (u, v), $u \in S(a)$, $v \in S(b)$ need be evaluated for time savings, since if some centroid u does not achieve any time saving, obviously no centroid on the branch behind it need be considered in the time-saving evaluation. This greatly reduces the number of calculations which have to be performed.

The time savings in a network where not all links are symmetrical, i.e., some $t(i, j) \neq t(j, i)$, are determined in the following manner. Using the standard tree, as built for a centroid u on the "base" network, determine the closer project node—say it is node a. Then for subsequent centroids v of some other subset—say S(b)—check whether

$$t(u,a) + t(v) + t(a,b) < t(u,v) \tag{4}$$

If yes, then the time saving is determined as

$$d(u,v) = t(u,v) - t(u,a) - t(v) - t(a,b) \tag{5}$$

where $t(u,a)$ is the minimum-path travel time from centroid u to project node a on the base network.

Note that for

$$t(u,a) + t(a,b) > t(u,b) \tag{6}$$

no time saving can be achieved for centroid u on routes to the centroids of the subset S(b) via the project. The travel times on the project link can also be different in both directions, when criterion (4) is used.

The centroids of the two subsets S(a) and S(b) have to be evaluated in both directions, but otherwise the process remains basically the same. It must be stressed that even for asymmetrical networks only a single project tree is required, built by the algorithm in the "outbound" direction.

Multi-Link Projects

Multi-link projects are treated in much the same manner as single-link projects, except that each centroid should be evaluated in conjunction with the centroids of all other centroid subsets. For instance, given a two-link project (a, b), (b, c), the centroid u of the group S(a) is evaluated against the centroids of the group S(b), in which case the criteria (1) or (4) are used, and against the centroids of group S(c) with the value $t(a,c) = t(a,b) + t(b,c)$ replacing the $t(a,b)$ of (1) and (4). Again, symmetrical networks need be evaluated in only a single direction, asymmetrical networks in both directions.

It is possible that the existence of a shorter path via some other project node in the direction of travel, rather than via the closest project node, will lead to errors if the above algorithm is applied to long chains of multi-link projects. The error becomes negligible if an actual project is broken up into several straight-line segments. This approach has been found to be more practical than the inclusion of additional checks in the evaluation routine.

Multi-Project Alternatives

Projects can interact in a complex manner, since various projects can either compete for traffic, or cooperate in carrying traffic, or as often occurs, do both at the same time, depending upon the origins and destinations of the various trips. The total time savings due to the inclusion of several projects, therefore, cannot be assessed directly from the time-saving tables of the individual projects.

Take, for instance, two projects A and B. Depending upon their location and other network values, some zone pair interchanges will not benefit from either of the projects, others from just one of them, and still others from both. With regard to this last possibility, a particular zone pair (u, v) could be in "series" and the time saving achieved by both projects will be greater than any achieved singly and

$$d(u,v)\,[AB] > d(u,v)\,[A];\; d(u,v)\,[B] \tag{7}$$

where the capital letters in brackets indicate the project alternative being evaluated—that is, the projects which were added to the base network to form an alternative.

The projects could also be "parallel" with regard to some other zone pair (u, v), then

$$d(u, v)\,[AB] = \max\,(d(u, v)\,[A];\ d(u, v)\,[B]) \tag{8}$$

and the projects "compete" with regard to time savings, but cooperate in the sense of increasing the capacity on the routes between centroids u and v.

The procedure, as discussed so far, can be used to evaluate several projects by the inclusion of one project after another. For instance, if a network alternative formed by the base network and projects A, B and C are to be evaluated, it might be conveniently done by first evaluating project A, then adjusting the interzonal travel times of the base network by including the achieved time savings to produce a new "base" network. Then it would be possible to evaluate the additional effect of project B by building a project tree for B, with the links of project A included in the base network. After a second adjustment, the final effect of the inclusion of project C could be evaluated.

In this approach, three project trees were built in order to evaluate three alternatives to the base network N, and travel times, time savings, etc., will have been obtained for networks N + A, N + AB, and N + ABC.

If it is desired to evaluate project C by itself, it would now be necessary to return to the base network N by removing the project links, building a project tree for C, and evaluating it against the original base network.

A more efficient way of handling the above problem would be:

1. Evaluate project C against the base network N,
2. Evaluate project A against the base network N,
3. Evaluate project B against the network N + A, and
4. Evaluate project C against the network N + AB.

As can be seen, the greatest computational savings can be achieved if the various alternatives form logical combinations of projects, where each alternative differs from some other alternative which is of interest by only a single project. Luckily, this is also convenient from the planning standpoint. Since not all projects can be built simultaneously, we are interested not only in the effect of a large number of projects, but also in the order in which the projects should be built, so as to maximize the benefit at each stage of completion.

Whenever the alternatives to be evaluated can be set up in such logical chains, the improvement in efficiency of the procedure suggested here, as against the standard approach, is quite obvious. For instance, using the standard approach, the evaluation of 20 alternatives of a 1000-zone network requires the building of 20,000 trees (at, say, one second of computer time each), their loading (if flow comparisons are desired), and 20 evaluations of 1000 × 1000 interzonal travel time tables. The suggested procedure will require the building of only 1020 trees and the evaluation of substantially less than 1000 × 1000 values for each alternative. Also the flow changes on the network and project links can be obtained in a more efficient manner, as will be discussed later.

The number of computations to be performed in the evaluation phase differs with each individual case, but as a rough estimate for a single-link project, it can be assumed that in a 1000-zone network, perhaps 400 zones would be reached from one project node and 600 from the other, and that after evaluating possibly 100 × 150 "closer" centroids no time savings will appear, and the evaluation can be discontinued. Multi-link projects require the evaluation of several subsets of centroids, but the number of centroids in a subset is smaller. It can, therefore, be claimed that the travel-time effects of a network improvement can be obtained in a matter of seconds, rather than tens of minutes, on the same computer.

If it is desired to evaluate a combination of projects without evaluating the subsets, still as many project trees as there are projects have to be built, but some economies can be achieved in the evaluation phase. If it is desired to evaluate the combination AB, all the project links would be added to the base network N before the project trees are built. The evaluation of the first project, say A, will indicate the time savings that can be obtained by going via A or AB, whichever route is the best. The evaluation of project B will then indicate the additional savings, due to B, over the network N + A, but at no time will the individual improvements due to projects A or B over the base network N be considered.

Another point which should be made now is that the "base" network must invariably be the network with the worst connections in any group of alternatives. If a freeway will improve travel along its corridor but somewhat disrupts travel across the corridor, the links that are "cut" by the freeway will also have to be missing in the base network. These can then be added to evaluate the "existing" network, and then again removed, and the freeway links added to evaluate the freeway against the base network. This approach will provide both the positive and negative effects of the studied project.

Flow On Links

The manner in which the traffic flows on project links can be obtained by summing the flows between all pairs of zones with a time saving due to the project has been mentioned previously. In case the change in flows, due to the inclusion of one or more projects, is required for all links of the network, it becomes necessary to "load" the flows between all affected pairs of zones on each project tree and to unload all affected base trees. A loading and unloading routine which simultaneously determines all the flow changes on a project or network tree has been devised. In the case of multi-project alternatives, the flows will be rerouted to the project tree for which the maximum time saving has been obtained. The loading of the project trees will provide the additional flows on the project links themselves and on the links of the "outbound" branches behind them. The tree of every centroid for which a time saving has been obtained has to be loaded with the flows "toward" the respective project nodes where the rerouted flows enter the project, and the same flows have to be unloaded from the base network routes. This can be done in a simultaneous operation.

The loading and unloading process is relatively efficient by itself and, of course, not all centroid trees will have to be treated. Nevertheless, though more efficient than the standard process, the suggested procedure does not have as obvious an advantage as was the case in obtaining travel time values. It is, therefore, suggested that link flows or flow changes for the whole network be obtained only for some alternatives, and only the flows on the projects themselves or on significant "existing" links, treated as projects, for the remaining alternatives.

Benefit/Cost Evaluation

A major purpose of any transportation study is the evaluation of all important transportation projects such as bridges, transit lines, tunnels, and freeways, on the basis of their benefits and costs, taking into account other social, political, and general economic factors.

Since various projects can compete for traffic, or cooperate in carrying traffic, often doing both at the same time, depending on the origins and destinations of the various trips, the total benefit of several projects cannot be assessed as the simple sum of the benefits of these projects taken individually. This is in direct contrast to the total cost of these projects which will, in general, be the sum cost of the individual projects.

Since available investment funds are always limited, not all projects can be built, and it therefore becomes imperative to evaluate the costs and benefits of as many realistic project combinations and alternatives as possible. The sum of all possible project combinations is, however, an extremely high number, equal to 2^n, where n is the number of projects. Thus, there are in theory more than 1000 possible project combinations for 10 projects, more than 1,000,000 for 20 projects, and more than 1,000,000,000 for 30 projects. Obviously, only the more promising alternatives will be evaluated.

The project tree and time-saving evaluation steps described in the preceding section will provide data for any desired network alternative (project combination). They can be used to determine the total time spent in the system to satisfy given travel demands, or the time savings or losses when compared to some other alternative, or to the base network. This is done by multiplying interzonal traffic flows and travel times or time savings, and summing the resulting values. The benefit/cost evaluation process described here is suitable for a gross evaluation of hundreds of alternatives.

The cost (in dollars) of a network alternative is the sum of the costs of all new projects in the given alternative, such as construction costs, operating and maintenance costs, dislocation costs, etc., adjusted to a common scale suitable for purposes of comparison. The adjustment should utilize discounting and different interest rates, to take into account the fact that projects will be built at different times in the future under different financing schemes. Additional factors that can be evaluated in dollars, such as revenue (bridge tolls, transit operation profits) or accident costs, can easily be included. As can be seen, some costs could be negative (i.e., revenue), but in general a total project cost will be positive (outlay).

Benefits will be measured in time units, the major benefit being the cumulative time saving in man-hours for satisfying given travel demands due to a project or project combination. The use of a time/cost space for a comparison of benefits and costs of alternatives has several advantages. In the first approach evaluation of a large number of alternatives, the human mind can relatively easily operate with two values, and in urban transportation those of cost and time are probably the most meaningful ones. It is difficult to combine the various cost elements, but the combination of cost and time values on the basis of a time/cost factor is still more difficult. In the contemplated evaluation process the two basic measures of time and cost are therefore left separate until the final analysis. For comparing a limited number of alternatives, the ingredients that went into the study of the "cost" (such as construction, operating costs) and time saving (e.g., travel, terminal time) of several alternatives can, of course, be called for and viewed in detail.

The benefit/cost evaluation process can best be shown on a small example. Assume that all combination possibilities of four projects, A, B, C, and D, have been evaluated and their benefit in time savings and costs, as shown in the accompanying Table 1, have been plotted in Figure 1.

The costs of the individual projects are A:30, B:10, C:20, D:20 units. The maximal benefit is obtained by building all four projects, which also entails the largest investment costs. The sequence in which the projects should be constructed so as to maximize benefits at any stage of completion is indicated (Fig. 1) by the line 1-10-11-13-9 for the project sequence B, C, D, A. If, for instance, only thirty units of investment were available, then project combination 11 (projects B, C) should be chosen. In the case that, due to aesthetic, political or other considerations, project combination 12 (B, D) is selected instead, the implication would be that these "intangible" considerations have at least a value of 10 units of benefit.

TABLE 1

BENEFITS AND COSTS OF ALL COMBINATIONS OF FOUR-PROJECT EXAMPLE

Seq. No.	Projects	Benefit	Cost
1	0	0	0
2	A	40	30
3	A, B	50	40
4	A, C	50	50
5	A, D	70	50
6	A, B, C	80	60
7	A, B, D	80	60
8	A, C, D	70	70
9	A, B, C, D	100	80
10	B	10	10
11	B, C	60	30
12	B, D	50	30
13	B, C, D	90	50
14	C	20	20
15	C, D	50	40
16	D	30	20

It must be emphasized that the evaluation procedure suggested here is only to be used for a rapid determination of the network alternatives which should be investigated in greater detail, not as a tool for reaching any final decision as to an "optimal" alternative. Nevertheless, the benefit/cost values for network alternatives can conveniently be utilized for a more detailed analysis which, despite the fact that the data are gross, might be helpful in eliminating the less promising alternatives. For instance, the marginal effect of adding a particular project to, or removing it from, some project combination can easily be determined from the graph (Fig. 1). Another value which can easily

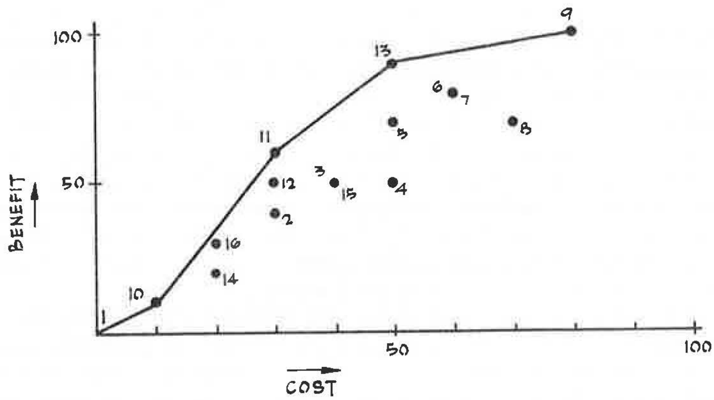

Figure 1. Benefits and costs of project combinations identified by sequence number (see Table 1).

be found is the maximum benefit cost ratio r_{max} which is the point of tangency to a line leading through the origin (0 benefit, 0 investment cost). This is shown in Figure 2 for the same example. The alternative with the highest benefit/cost ratio for any particular value of time r is the one farthest from the r line (Fig. 2).

It is difficult to evaluate all combinations of a larger number of projects. The following procedure is therefore recommended. Determine a priori some project combinations which should be evaluated, rank the results in the benefit/cost space, and then possibly decide on other combinations which should also be evaluated. It is, of course, always possible that some "optimal" combinations might be missed. This problem has been considered by Kuhn (2) and Ridley (3), with particular regard to transportation, and by Weingartner (6) as a general capital budgeting problem. The author has described a matrix method (5) which, on the basis of some simplifying assumptions, can evaluate all combinations of a larger number of projects. Since the procedure suggested in this report is only used for the secondary task of evaluating network alternatives, but not for the primary task of determining in some exact manner alternatives that should be evaluated, these methods will not be discussed in detail.

THE NETWORK EVALUATOR PROGRAM

The procedures described in the preceding sections were incorporated into three basic computer routines supervised by a monitor program. The functions of the three routines are:

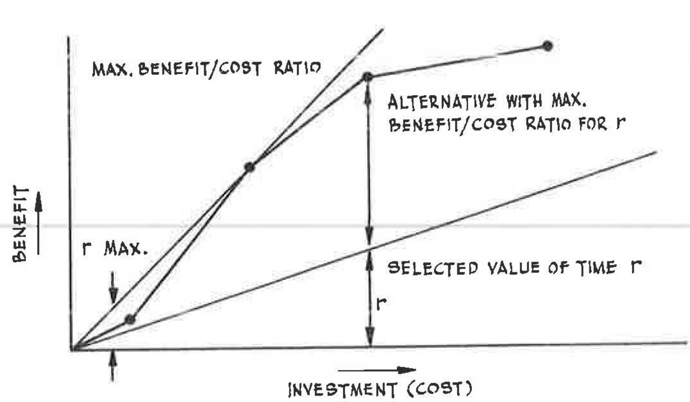

Figure 2. Values on the project evaluation curve.

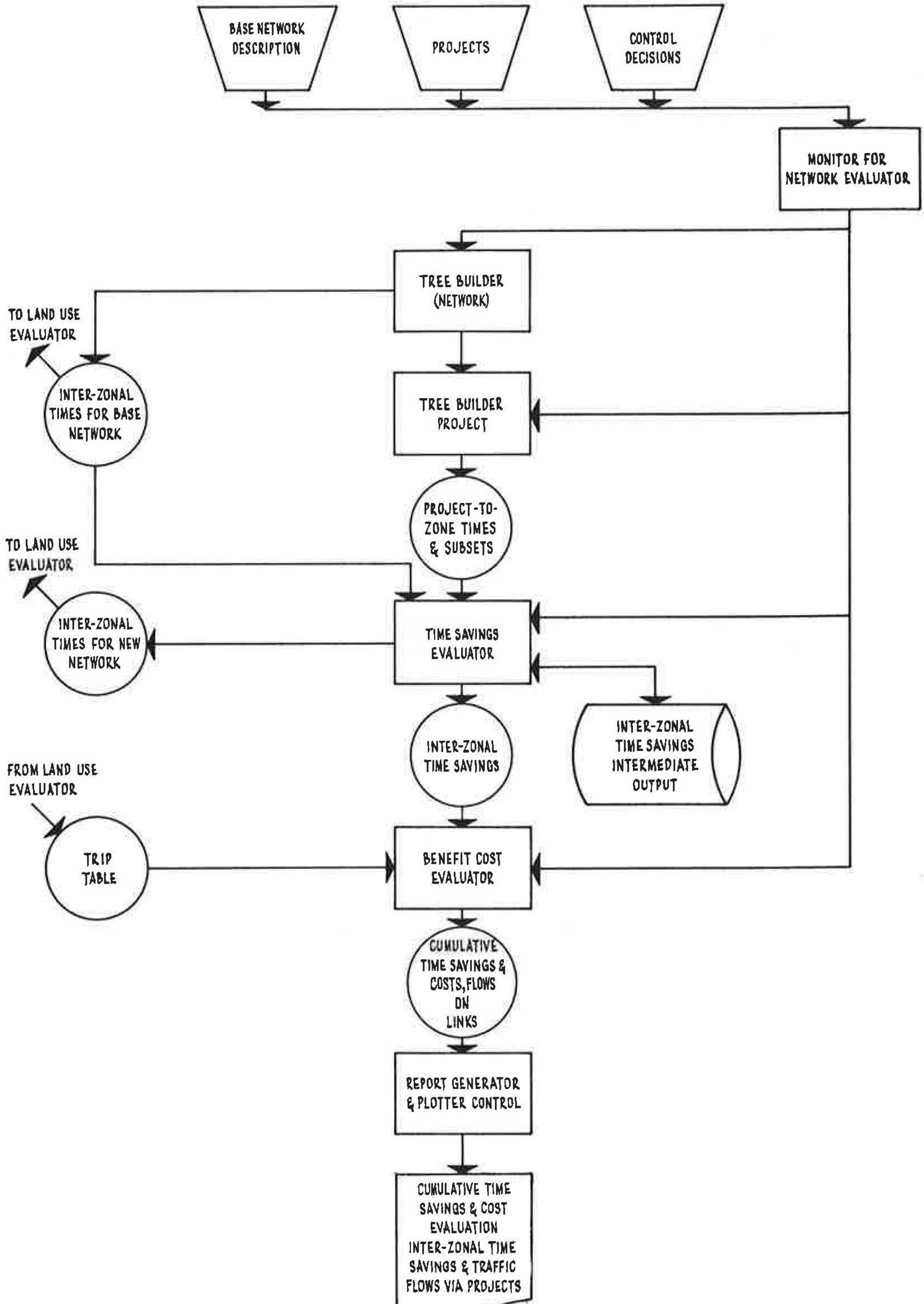

Figure 3. Network evaluator.

1. Tree Builder—To build minimum paths for all zones of the base network (network tree builder) and for all projects of a network alternative (project tree builder) as specified by the monitor;

2. Time-Saving Evaluator—To determine time savings between all pairs of affected zones for each network alternative; and

3. Benefit/Cost Evaluator—To determine the cumulative time savings and costs of each network alternative and the flows on project links (directly) and/or network links by means of the loading and unloading subroutine.

The monitor controls the interaction of the programs and the sequence in which the network alternatives and projects within an alternative are processed.

The network evaluator interacts with a land use evaluator by providing it with the interzonal travel times required for accessibility calculations. In turn, the land use evaluator and related traffic generation, distribution, and modal split programs are used to obtain one or more trip tables for the network evaluator. The operation of the network evaluator is independent of the other programs and they could be replaced by any other procedure which would provide a trip table.

The flow chart (Fig. 3) relates the routines and indicates the source data and output. The report generator programs are used for formatting the output and printing it.

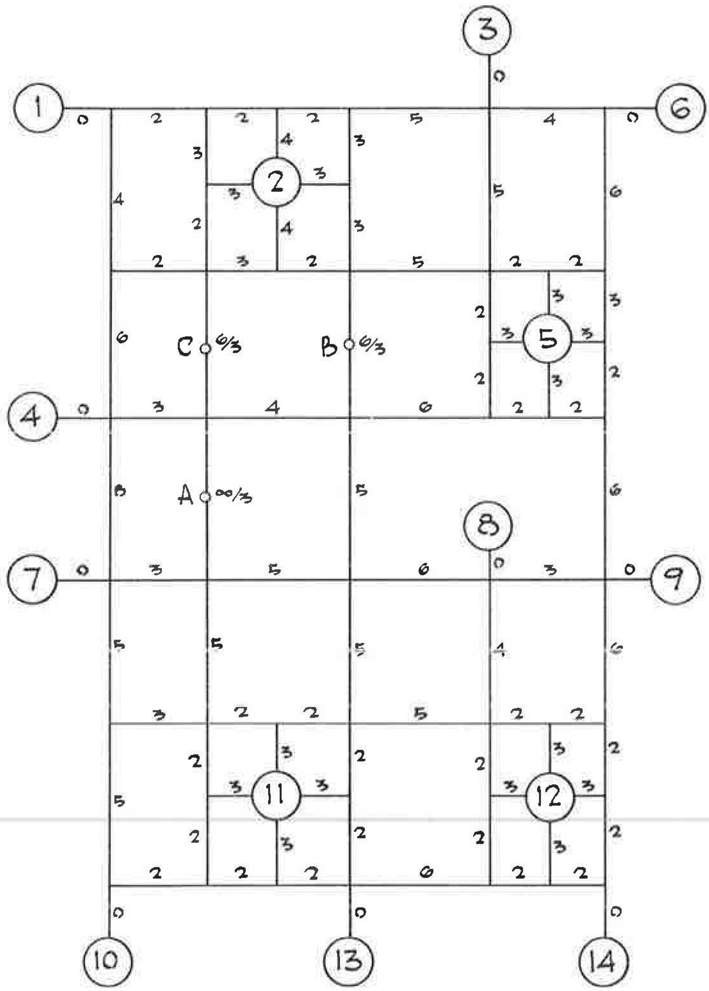

Figure 4. Project selection—test network.

EXAMPLE

The first version of the network evaluator program has been tested on a small 14-zone example (Fig. 4) with all combinations of three single-link projects evaluated. The values on the links are travel times. The three projects (A, B, C) have two values—a before-completion travel time and an after-completion travel time. As can be seen, projects B and C are improvements of existing links, while project A is a completely new link. The project tree for project A is shown in Figure 5. The nodes can be separated into two groups (subset 1 and subset 2), depending on the project node from which they were reached. The subset numbers on the printout indicate not only the project end from which a centroid was reached (last digit), but also whether some other project lies on the branch. The network is symmetrical, and a symmetrical trip table was assumed. Only the flows on the project links were determined. A cost of 20, 8, and 6 units was assumed for, respectively, the projects A, B, and C, and the resulting benefit/cost values were plotted.

The following flows were determined on the project links:

Alternative A: Flow on project A = 450
Alternative B: Flow on project B = 370

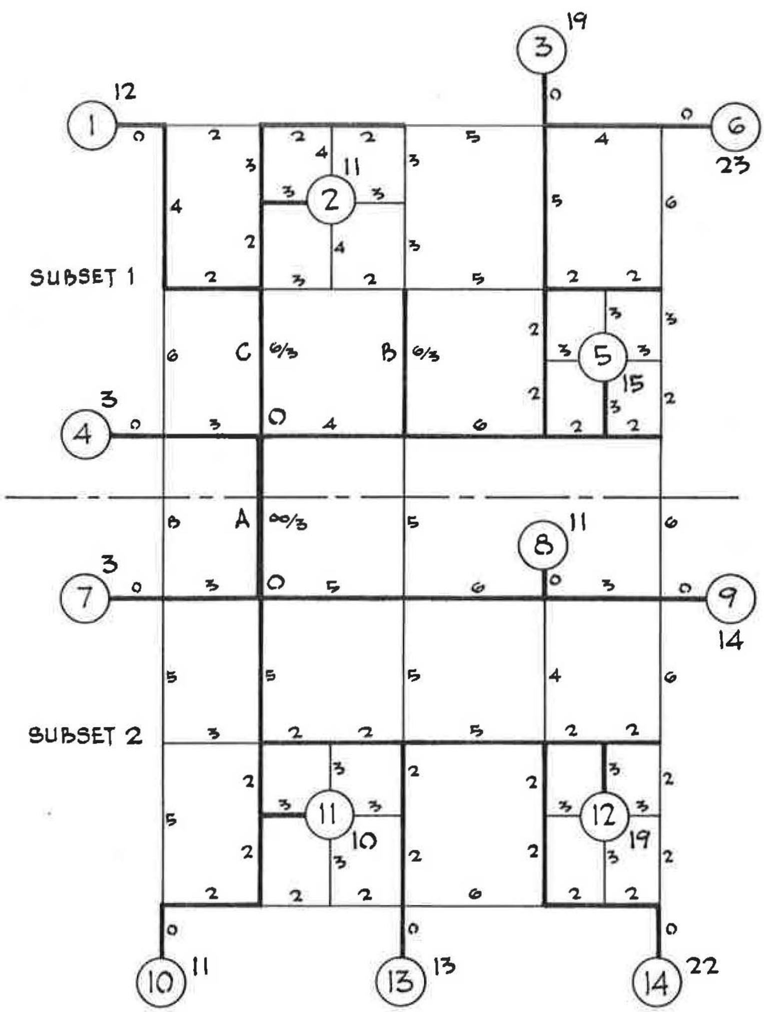

Figure 5. Minimum path tree for project A.

Alternative C:	Flow on project C = 210
Alternative AB:	Flow on project A = 390
	Flow on project B = 330
Alternative AC:	Flow on project A = 530
	Flow on project C = 390
Alternative BC:	Flow on project B = 260
	Flow on project C = 170
Alternative ABC:	Flow on project A = 470
	Flow on project B = 220
	Flow on project C = 270

CONCLUSIONS

The application of the network evaluator to gross planning, providing "relative" rather than "absolute" evaluations, has been emphasized in this report. The recent development of computer time-sharing and of display methods by means of cathode-ray tubes is leading toward a new type of man-machine interaction. The efficiency of the suggested procedure, or any similar approach, when dealing with the effects of slight changes to a network makes it possible for a transportation planner, sitting at a suitably designed console, to become familiar with an area by testing out various alternatives and directly obtaining at least a gross estimation of the effect of any decision. More detailed information could be called for whenever desired. The overall computer time requirements can remain within reasonable bounds, and yet the planner could reject obviously wrong alternatives within a few seconds and concentrate on the promising ones, call for increasingly detailed outputs, and study the effect of additional small variations of plans. Much remains to be done, yet both the computer hardware and the software capabilities are available, and the way toward this type of transportation planning is clearly open.

It remains to mention briefly the possible applications of the suggested procedure toward a more detailed evaluation of networks. The manner in which the speed on a project link can be varied to reflect expected traffic conditions has already been mentioned. Actually, it is possible to use the capability of the network evaluator to separate the travel times on "project" or "critical" links from those on the remaining links to form the basis of efficient capacity restraint and traffic diversion procedures. By assuming specific capacity restraint characteristics for the critical (bottleneck) links of a network, it becomes possible to assign traffic to these competing or cooperating links so as to balance flows in order to minimize individual or total travel times in accordance with Wardrop's two principles. In other applications, it would be possible to test the effect of differential tolls; determine how flows are affected if different tolls are placed on parallel facilities and a particular distribution is assumed for the value trip-takers place on time; study the effects of various emergency situations, such as stalled vehicles on a bottleneck link; and test different strategies which would cope with these situations. Analytical and graphical procedures utilizing the network evaluator routines for treating the above problems have been devised and are described elsewhere (7).

ACKNOWLEDGMENT

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Intercity Traffic Projections

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•THE projection of intercity highway travel was made as a part of the highway needs and fiscal studies prepared for the States of Arizona and Illinois. The projections provided information for development of functional classification systems of streets and highways. Also, the traffic volumes and trip length data were utilized in the development of future physical needs of the various facilities.

In each state basic origin-destination data were available; however, different types of analyses were required to develop the current year trip matrix. In Arizona, the State Highway Department had conducted extensive interviews along all of the major highway facilities. Comprehensive transportation studies provided data for the three largest cities. Growth factors were developed to project traffic to 1985 levels.

The statewide multiple screen line origin-destination survey conducted by the Illinois Division of Highways provided the basic source of data. As established by the Mississippi Valley Highway Conference, the screen lines were spaced at one degree longitude and one degree latitude. Also, data were available from the Chicago Area Transportation Study. Generation-distribution equations were developed and applied to ascertain existing and future trip interchanges. In the following sections the basic procedures utilized in the two states are presented.

ARIZONA

The State Highway Department conducted extensive O-D interviews from 1957 through 1961 on the state highway system in rural locations, as shown in Figure 1. These interviews intercepted the major intercity traffic movements and furnished comprehensive data of all travel patterns. The results of the study provided fundamental information for development of the 1965 travel patterns. In addition, recent interviews made by the State Highway Department in the Navajo Indian Reservation area provided data, and external cordon interview data from the urban area studies conducted in Phoenix, Tucson, and Yuma were also used. The data, when adjusted to 1965 levels, were sufficient to provide a zone-to-zone trip matrix similar to the existing traffic patterns. Traffic was assigned to a network consisting of all major intercity routes and comparisons were made of the assigned volumes and the existing traffic volumes as indicated on the flow maps prepared by the highway department.

Projections of travel patterns to 1985 were based on anticipated population growth and vehicle registration. In addition, the recreation traffic was particularly analyzed in view of anticipated increased visits to the various parks, dams, and national forests.

The statewide O-D surveys conducted in 1957 through 1961 by the Arizona Highway Department resulted in about 450,000 interviews at more than 100 interview stations on principal intercity highway routes. The transstate movements were summarized in a 1965 report (1).

Data were also available from the Valley Area Traffic and Transportation Study for which interviews were taken in the fall of 1964. The Yuma Area Transportation Study (2) and the Tucson Area Transportation Study (3), undertaken in 1961, provided additional interview data.

The 1965 and 1985 trips were assigned to major highway networks representing principal corridors of travel. Vehicle-mile and trip length analyses were undertaken

Paper sponsored by Committee on Origin and Destination.

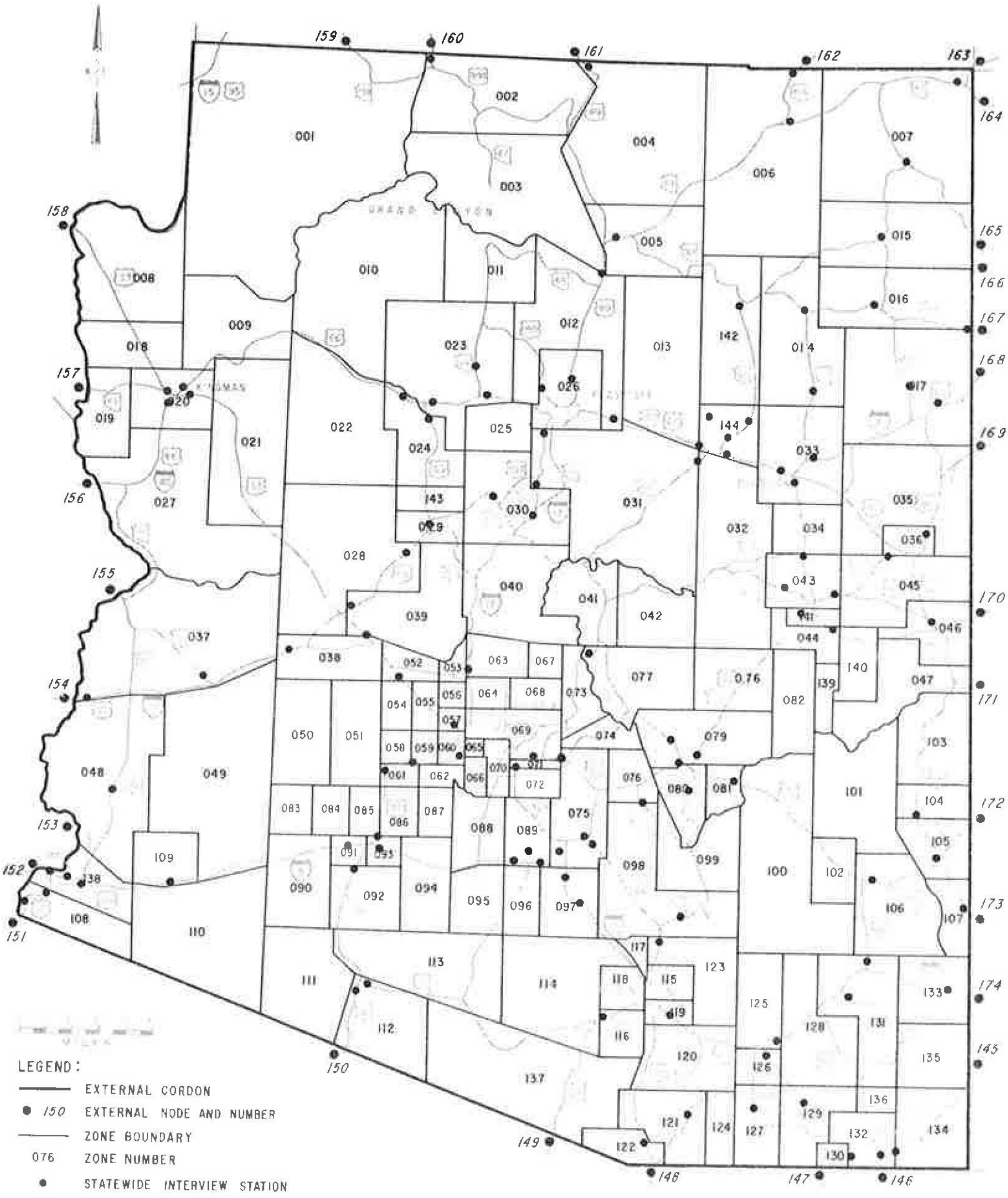

Figure 1. Arizona highway system.

for each route to assist in the determination of future corridor needs. A flow chart indicating the analysis procedure is shown in Figure 2.

Development of 1965 Travel Patterns

In the following paragraphs the analyses utilized to develop the existing year (1965) trip matrix are presented. Traffic was assigned to the highway network and comparisons were made with measured or recorded traffic volumes.

Traffic Zones—The state was divided into 144 traffic analysis zones, as shown in Figure 1. The zones were designated on the basis of population and vehicle registra-

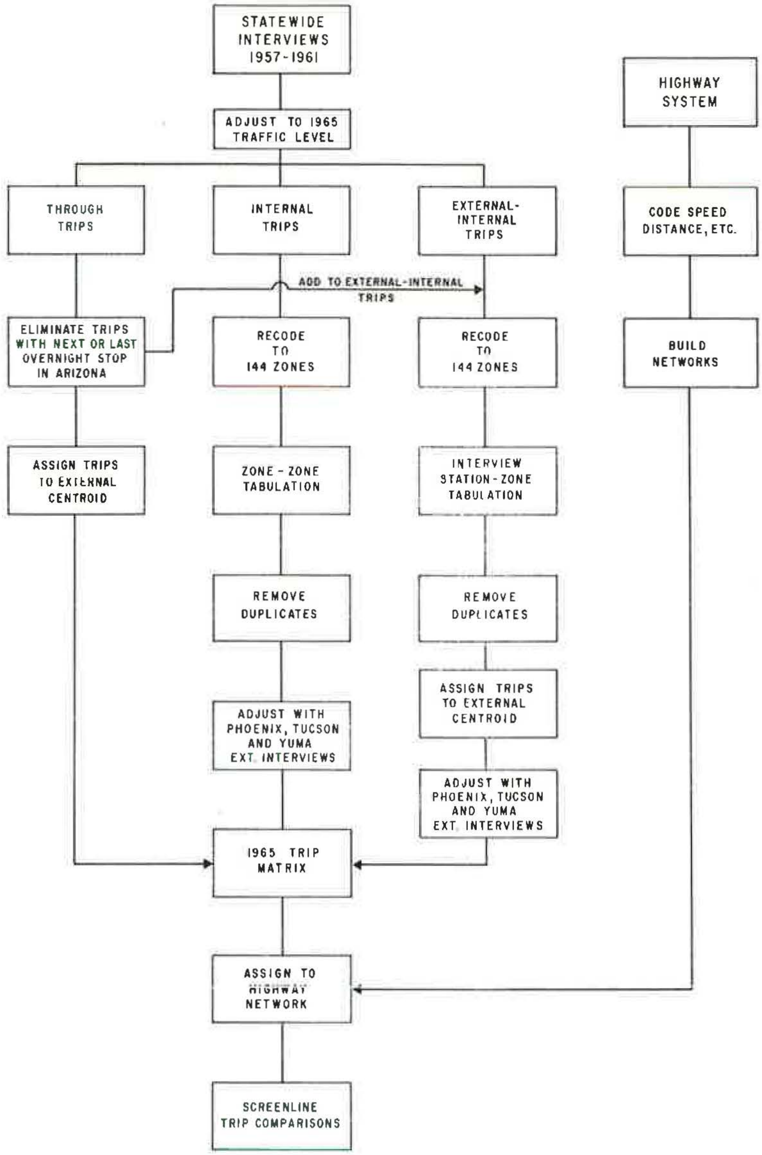

Figure 2. Analysis procedure, Arizona.

tion, which provided for distribution of volumes on the assignment network. External stations were established at 30 state-line entry points.

Population and Related Projections—Significant trends indicate increasing dependence of the state's economy on motor vehicle transportation. The large metropolitan areas are growing, covering more territory with low-density urban populations. Automobile registrations are increasing at a more rapid rate than population, and commercial vehicle registrations are increasing at a rate greater than automobiles. Personal incomes are also increasing and resulting in further demand for automotive transportation. Both rural and urban populations are largely dependent on motor vehicles.

It is anticipated that the statewide population of 1,300,000 in 1960 will increase to 3,100,000 by 1986, an increase of 138 percent. A substantial increase in vehicle registration is also anticipated between 1965 and 1986, gaining from 830,000 to about 2,000,000 vehicles. Employment is expected to increase from 454,000 in 1960 to 1,100,000 in 1986, an increase of 135 percent. Total personal income is estimated to increase by 152 percent between 1965 and 1986, from $3.7 billion to $9.4 billion.

Traffic Assignment Network—The 1965 traffic assignment network consisted of about 8,094 miles and about 1,001 miles of centroid connectors. This included primarily the US-numbered highways and the major state highways, the primary intercity traffic carriers. Time, speed, and distance were ascertained to describe each link of the highway assignment network. The assigned speeds ranged according to the area and the type of traffic facility. The speeds assumed were 30 mph for the centroid connectors to 60 mph for freeways. All of the zones and the entry points throughout the state were included in the assignment network. For the analysis of the proposed freeway corridors, time and distance networks were established. The standard traffic assignment computer programs were included in the analyses.

Basic Tabulations—The 455,000 interviews procured in the 1957 through 1961 study period were adjusted to 1965 daily traffic levels. Factors were applied to both summer and winter interviews for each of the 106 interview stations. The interview stations were divided into three basic categories—internal, combination, and border. The border stations were those located at state boundaries. The internal stations were somewhat removed from the border and the data were used for trips which had the origin and destination in Arizona. Some of the border stations had to be classified as combination stations since they were located several miles from the state line. Travel intercepted at these stations consisted of internal, external-internal, and through movements.

The origins and destinations within Arizona were recoded to the 144 zones and a series of analysis tabulations were prepared utilizing the basic O-D data. Internal movements were ascertained using data from the internal and combination stations. The basic tabulation included low zone (recoded number), high zone (recoded number), interview station, trip purpose, and season.

The interview station was included to facilitate the removal of duplicates. For example, trips between Tucson and Phoenix could be intercepted several times on the same route and also on parallel routes. This required a manual analysis to remove the duplicates and also provided a system for averaging the movements along a particular route. In all cases the data were developed on a seasonal basis by trip purpose. Because of the nature of the many scenic and recreational attractions in Arizona, specific zone-to-zone trip interchanges were found on many routes. For example, several routes of travel were utilized for trips between Tucson and the Grand Canyon area. This basic tabulation and analysis resulted in the development of a zone-to-zone matrix for trips originating within and ending within Arizona.

The second tabulation summarized through trips intercepted at combination and border stations. The tabulation included route of entry and route of exit (state-line designation assigned by state highway department), interview station, trip purpose, and season. This summarized the transstate movements, i.e., where the origin and ultimate destination were outside of the state. Realizing that many stops had been and would be made along the way, two additional tabulations were prepared. Trips which included an overnight stop in Arizona were recoded and included in the external-internal trip matrix to depict average daily traffic. The last overnight stop in Arizona was considered the zone of origin or destination. The remaining trips were considered as through trips in the analyses. The routes of entry and exit were recoded to the appropriate external centroid (numbers 145-174 as indicated in Fig. 1) consistent with the assignment networks.

To ascertain the external-internal movements a summary was developed from combination and border stations. It included interview station, route of entry, purpose, and season. The manual analysis included the removal of duplicate trips and the merging with data developed from the recoding of external trips with overnight stops.

Thus, three trip tables were prepared and summarized depicting the basic movement of internal, external-internal, and through trips. Total trips were as follows:

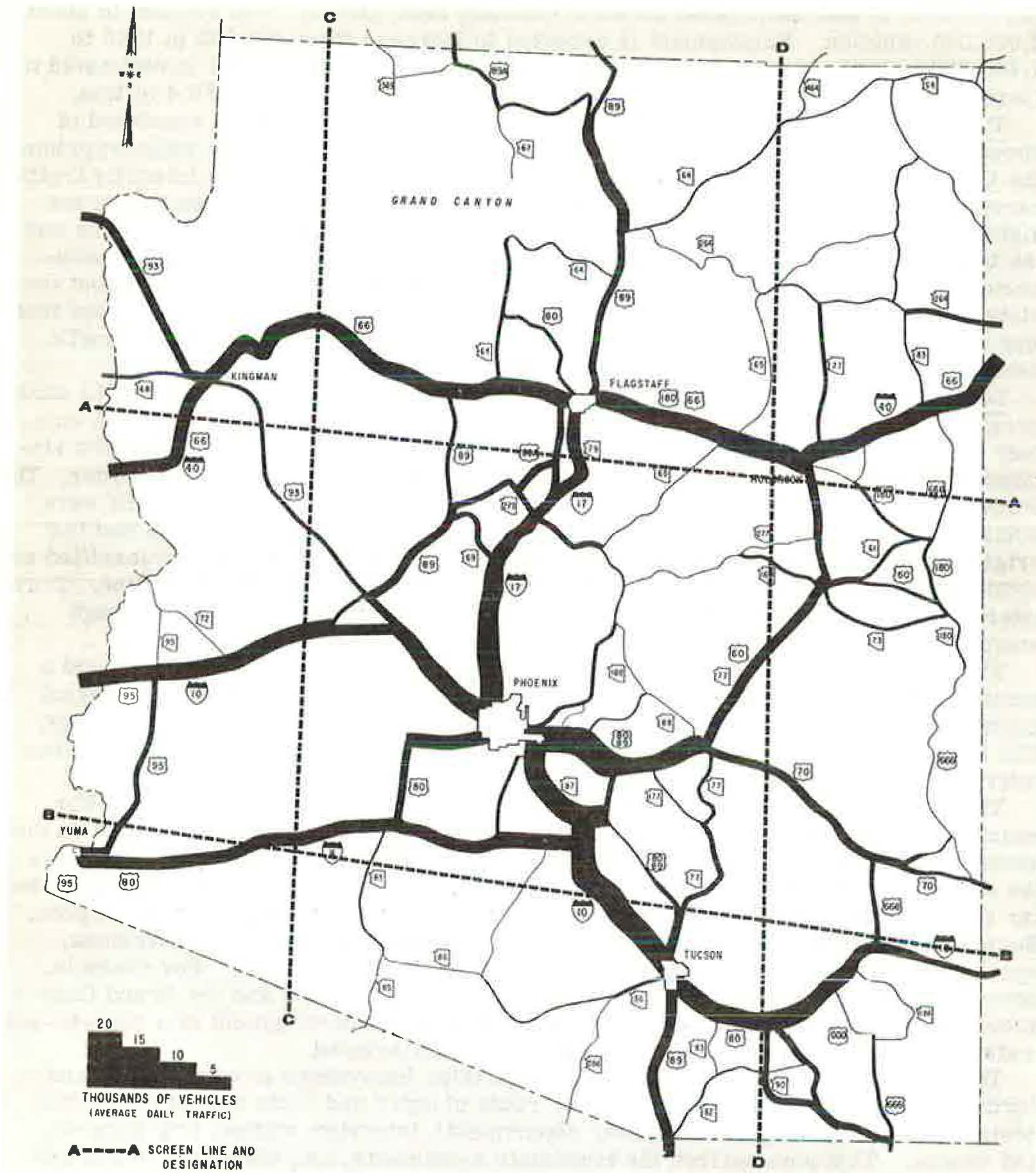

Figure 3. 1965 traffic assignment, Arizona.

Internal	94,285
External-internal	33,858
Through	4,661
Total	132,804

Traffic Assignments—The three sets of data (internal, external-internal, and through trips) were combined into one matrix. The zone-to-zone matrix was utilized to prepare assignments to the existing year highway network. The standard minimum path time network was utilized for making the assignments. It is realized that all interzonal trips did not follow the same paths; however, very close correlations with actual volumes were found along the major routes in the critical travel corridors.

TABLE 1

1965 TRAFFIC VOLUME COMPARISON

Screen Line[a]	Traffic Volume	
	Measured Traffic[b]	Assigned Traffic
A East-west—south of Kingman, Flagstaff, and Holbrook	14,144	17,130
B East-west—south of Safford, north of Tucson, south of Casa Grande and Gila Bend, but north of Yuma	18,793	19,910
C North-south—boundary between Yuma County and Maricopa County, and between Mohave and Coconino Counties	15,164	16,100
D North-south—eastern part of state, parallel to, but west of US 666	22,009	20,950

[a]Screen lines are shown in Figure 3.
[b]Source: Arizona Highway Department, Planning Survey Division.

The assigned 1965 traffic volumes for the basic highway system are shown in Figure 3. The actual assignment network included additional routes to facilitate the zone-to-zone interchange. However, the figure depicts the major corridors of travel.

For comparison purposes, two east-west and two north-south screen lines were established. The actual and estimated volumes recorded across these screen lines are given in Table 1. Based on these and other analyses, it was concluded that the trip matrix properly reflected the 1965 level of intercity travel. It is realized that all trips are not included in the trip matrix; however, sufficient data were available to predict the major desire lines.

Vehicle-Miles and Trip Length—The 132,804 trips in 1965 resulted in about 12,781,000 vehicle-miles of travel. As given in Table 2, internal trips accounted for 54 percent of the vehicle-miles of travel and the average trip length was 73 miles. External trips averaged 149 miles. For all trips the average was 96 miles.

TABLE 2

1965 TRAVEL CHARACTERISTICS

Characteristic	Type of Trip		Total
	Internal	External	
Trips:			
Number	94,285	38,519	132,804
Percent	71	29	100
Vehicle-miles:			
Number	6,928,000	5,753,000	12,781,000
Percent	54	46	100
Average trip length, miles	73	149	96

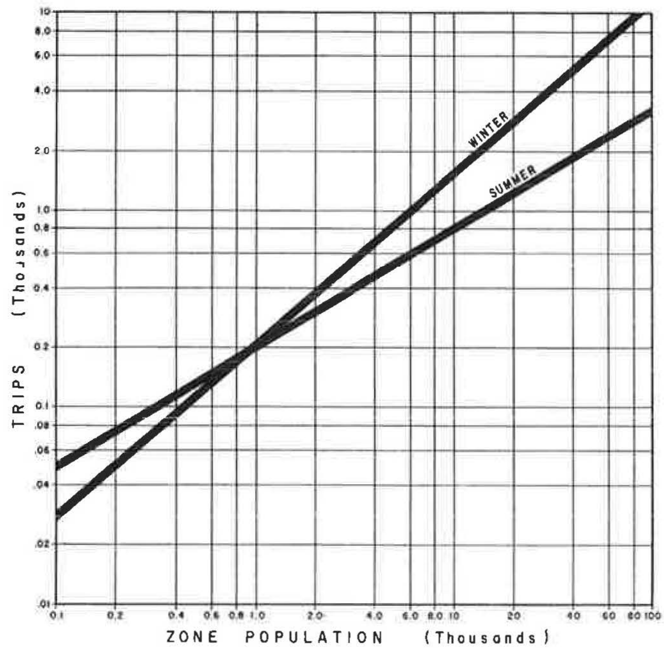

Figure 4. Internal trips, work, Arizona.

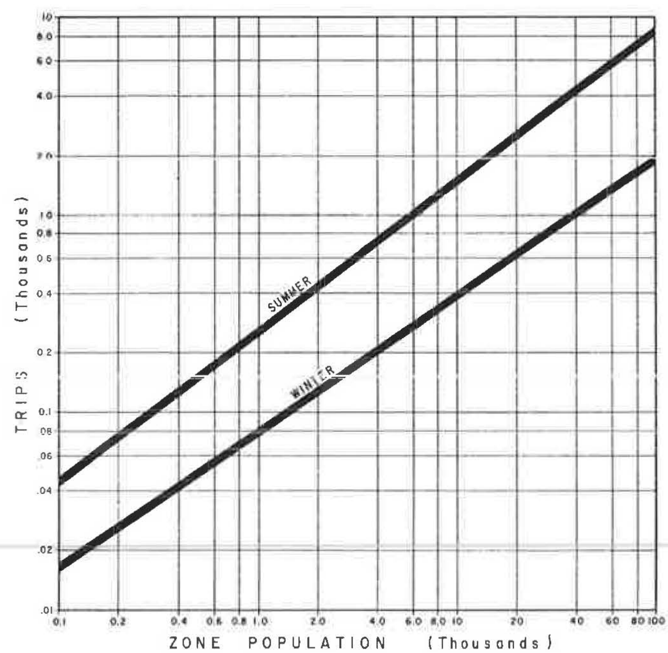

Figure 5. Internal trips, recreation, Arizona.

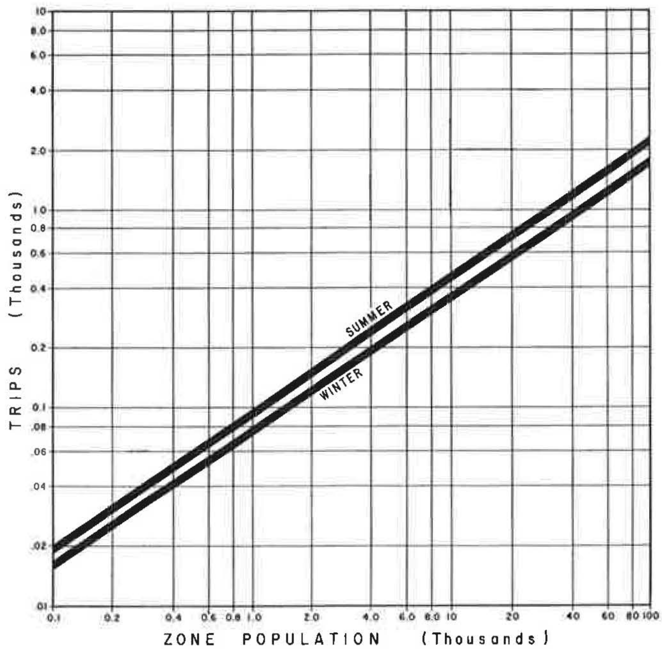

Figure 6. Internal trips, other, Arizona.

1985 Trip Projections

Utilizing the population projections, anticipated vehicle registration increases, and the expected number of visits to recreational areas, 1985 trips were developed.

Internal Trips—A growth factor technique was utilized to develop the appropriate projections for both internal and external traffic. In Figures 4, 5, and 6, the 1965 trip generation is depicted for each purpose by seasons. These are illustrated for the basic internal trip purposes of work, recreation, and other. The generation rates were used to determine the basic growth factor for each zone. This factor was further modified by the increase in vehicle registration which is expected to occur in each county. Therefore, the growth factors for the trips to and from each of the 144 internal zones

TABLE 3

INTERCITY TRIP PROJECTIONS, ARIZONA

Type of Trip	Number of Trips		Percent Increase
	1965	1985	
Internal:			
Work	46,648	93,190	100
Recreation	37,075	100,332	170
Other	10,562	20,370	93
Total internal	94,285	213,892	127
External:			
External-internal	33,858	79,280	134
Through	4,661	11,073	139
Total external	38,519	90,353	135
Total trips	132,804	304,245	129

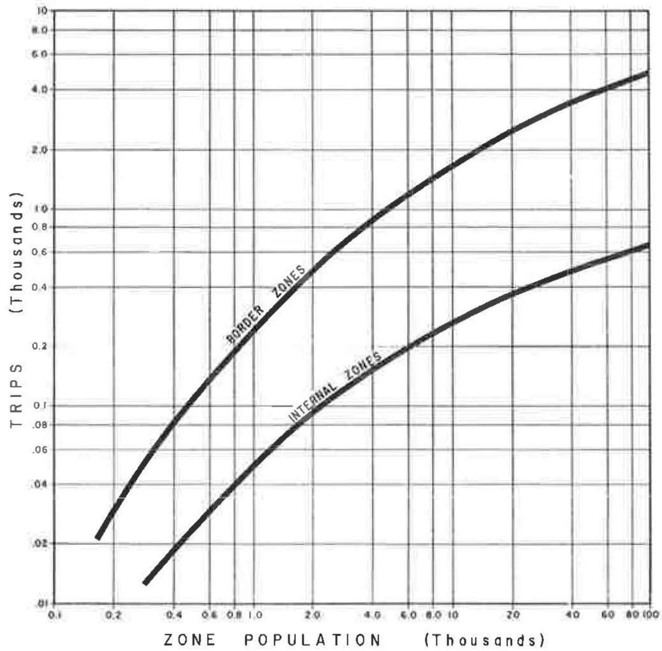

Figure 7. External-internal trips, Arizona.

were based on the estimated population change modified by the future vehicle registration for each county.

For the recreation trips, estimates of the increase in visits were made for the national parks, the national recreation areas, and other facilities. These increases were assigned to the appropriate zones. For the zones which did not have the recreational facilities, the population, vehicle registration and overall increase in vehicle-miles of travel were utilized in the calculation.

As given in Table 3, it is estimated that all internal trips will total 213,892 by 1986. This would represent a 127 percent increase in total internal travel. Work trips are anticipated to increase 100 percent whereas a 170 percent increase is anticipated for recreation trips. Other trips will increase from 10,502 to 20,370, a gain of 93 percent.

External Trips—For external trips, growth factors were developed for each entry point based on trends in growth and estimated increases. Factors were also applied to each zone based on 1965 external trips compared to zone population. The zones were divided into two categories, internal and border. The border zones located at or near the external stations generated trips at a much higher rate than the internal zones, as shown in Figure 7. The growth factors for the external stations and for the internal stations were balanced to develop an overall external matrix.

It is anticipated that the external travel will increase 135 percent, from 38,519 in 1965 to 90,583 in 1985. The through trips should total approximately 11,073 in 1985, an increase of 139 percent. The external-internal travel is expected to be 79,280 trips in 1985, as contrasted with 33,858 in 1965. The total intercity travel movements are expected to be 304,245 in 1985, representing an overall growth of 129 percent over the 132,804 in 1965.

Traffic Assignments—Travel assignments to the major freeway and highway networks are shown in Figure 8. The basic traffic volumes have been adjusted (1.15 factor) to reflect the influence of establishing an Interstate freeway in a particular corridor. It has been assumed in the assignments that the Interstate System will provide the basic framework of the future highway network.

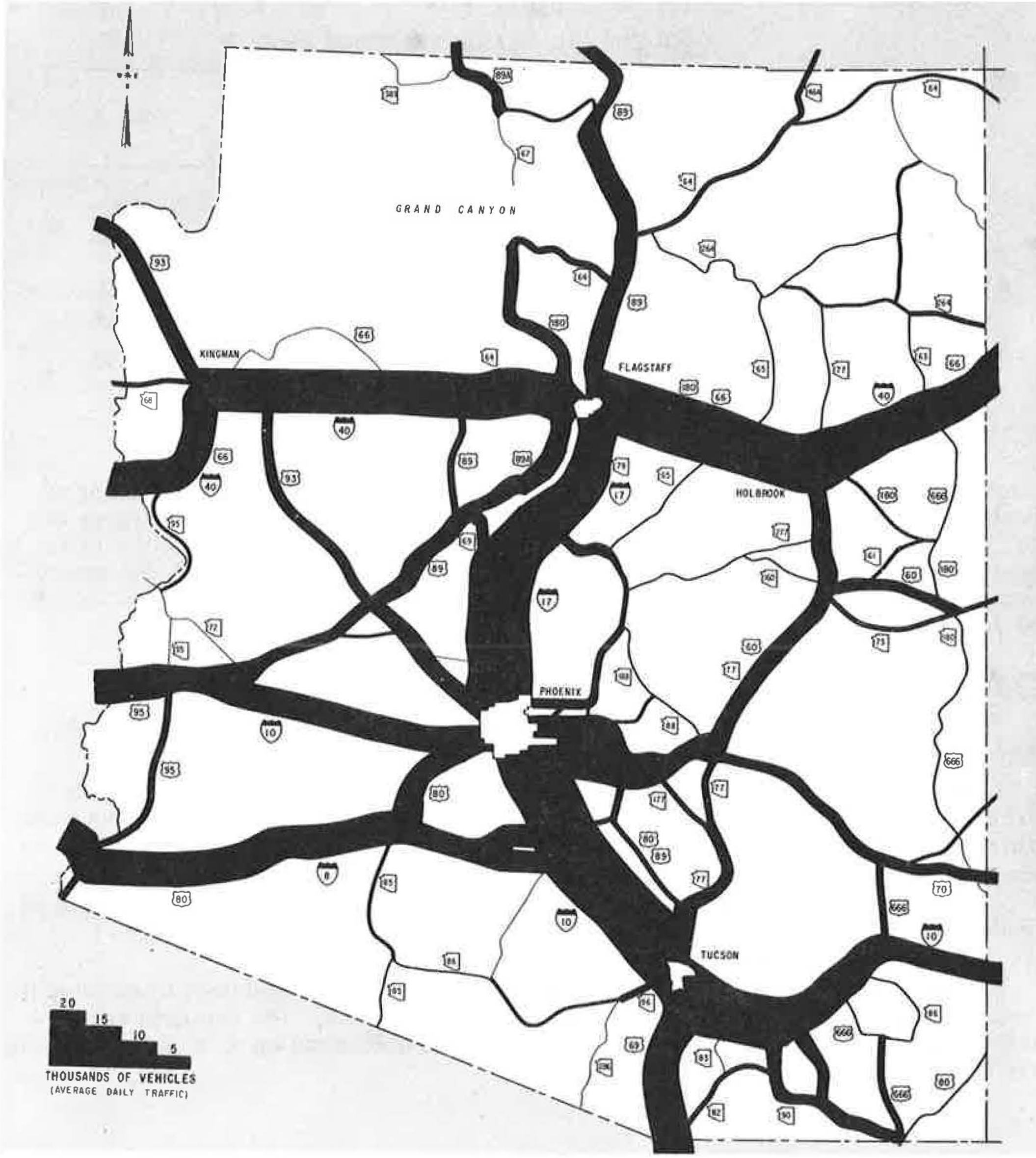

Figure 8. 1985 traffic assignment, Arizona.

1985 Travel Characteristics

About 70 percent of the 1985 trips will be internal and 30 percent external. The internal trips will produce 16,421,000 vehicle-miles of the total 30,138,000, or about 55 percent. The average trip length for internal trips will be 77 miles as compared with 152 miles for external trips. Combining these, the average trip length will be 99 miles. Therefore, internal trips will account for 70 percent of the total trips but only 55 percent of the total vehicle-miles of travel, as given in Table 4.

The distribution of travel for 1985 was calculated for the several types of facilities. The highway facilities were subdivided into connectors, other routes, and the Interstate System, as given in Table 5. The connectors reflect the travel between the zone centroid and the basic highway network. It is anticipated that internal trips will produce

TABLE 4

1985 TRAVEL CHARACTERISTICS

Characteristic	Type of Trip: Internal	Type of Trip: External	Total
Trips:			
Number	213,892	90,353	304,245
Percent	70	30	100
Vehicle-miles:			
Number	16,421,000	13,717,000	30,138,000
Percent	55	45	100
Average trip length, miles	77	152	99

a total of about 16,421,000 vehicle-miles of travel. Of this amount, 6,535,000 or 40 percent will utilize the freeway system. About two-thirds of the external travel will be accommodated by the freeway system and will account for 9,061,000 of the 13,717,000 vehicle-miles. For total travel, it is estimated that there will be 30,138,000 vehicle-miles of travel daily. Of this, slightly more than half, 15,596,000 vehicle-miles, will be accommodated by the Interstate System.

Trip Length Analysis

Vehicle-miles of travel were ascertained for each network link and traffic zone. The following procedure was employed using future trips and networks:

1. A matrix of interzonal vehicle-miles of travel was developed by multiplying the 1985 interzonal trips by interzonal distances utilizing the traffic assignment network. This produced a tabulation of vehicle-miles of trips having an origin or destination in each zone.
2. A table of zones "ranked" according to vehicle-miles of travel originating in or destined to each zone was developed.
3. Vehicle-miles were assigned to highway networks.
4. Average trip length on each highway network link was ascertained by dividing the vehicle-miles on a given link by the assigned traffic volume. The assigned vehicle-miles represent the total vehicle-miles from origin to destination of all trips traversing the link.

TABLE 5

1985 DISTRIBUTION OF TRAVEL

Type of Facility	Type of Trip: Internal		Type of Trip: External		Total	
	Vehicle-Miles	Percent	Vehicle-Miles	Percent	Vehicle-Miles	Percent
Connectors	1,248,000	8	411,000	3	1,659,000	5
Other routes	8,638,000	52	4,245,000	31	12,883,000	43
Interstate System	6,535,000	40	9,061,000	66	15,596,000	52
Total	16,421,000	100	13,717,000	100	30,138,000	100

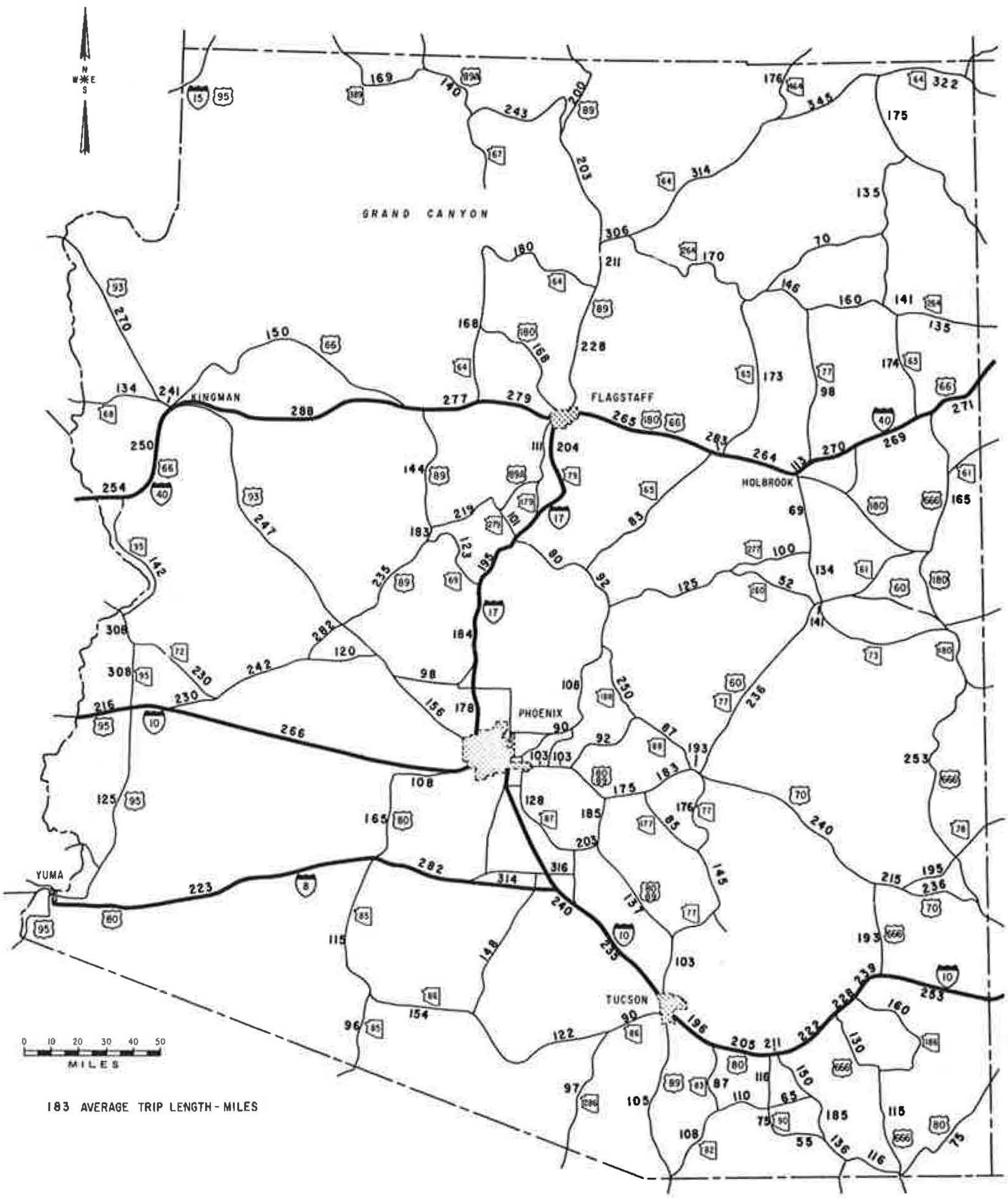

Figure 9. 1985 relative average trip lengths, Arizona.

The relative average trip lengths calculated for various sections of the proposed highway system are shown in Figure 9. As anticipated, the highest average trip lengths will occur on the Interstate System, which will be located in the primary corridors of long-distance travel. The relative average distance will be more than 200 miles on all parts of the Interstate System. The average distance will be about 100 miles on the other major highway systems.

Intrazonal trips were not included in the calculations. Also, the distances for external trips were measured from the state-line points of entry or exit to the zone centroid.

ILLINOIS

The basic procedure followed in the study consisted of synthesizing existing travel patterns and utilizing population, vehicle registration, and available origin-destination data. Zone-to-zone trip interchanges were calculated for all intercity movements. Traffic was assigned to a network consisting of all major routes, and comparisons were made of synthesized and recorded existing traffic volumes along east-west screen lines. Projection of travel to 1985 was based on estimated growth in population and vehicle registration.

The statewide multiple screen line O-D survey conducted in 1959 by the Illinois Division of Highways provided the basic source of data (4). This consisted of extensive O-D surveys on principal intercity highway routes. Interview stations were located on north-south and east-west screen lines throughout the state. They were part of a grid system with one-degree longitude and one-degree latitude spacing as established by the Mississippi Valley Highway Conference. This study was part of a cooperative project to develop basic O-D data for the Midwest region. Data were produced relative to trip origin, destination, purpose, and mode of travel.

Data were also available from the Chicago Area Transportation Study (CATS) concerning external trips. Basic projections and freeway assignments prepared as part of CATS were also utilized for the state-line stations in the area. The volumes projected by CATS on major routes crossing the Illinois-Indiana border were included in the analyses.

The state also interviewed at several locations on the state boundary and included the data in the multiple screen line tabulation. These include data obtained for the Mississippi River Bridge stations located between St. Louis and East St. Louis.

Separate analyses were prepared for trips which originated and ended within the state (internal), trips which had one end outside of the state (external-internal), and for trips which had both the origin and destination in other states (through).

The 1964 and 1985 travel patterns were assigned to the existing and proposed major highway networks. A vehicle-mile and trip length analysis was undertaken for each route to assist in the determination of future highway needs. A flow chart indicating the analysis procedure is shown in Figure 10.

Development of 1964 Travel Patterns

In the following paragraphs, procedures employed to develop the existing year (1964) trip matrix are presented.

Traffic Zones—The state was divided into a total of 526 traffic analysis zones, as shown in Figure 11. This consisted of groupings of townships within the 102 counties, approximately five zones per county. The City of Chicago was subdivided into seven zones for analytical purposes. External stations were established at 59 state-line entry points. In some instances two or more routes were combined, but all significant routes were intercepted.

Population and Related Projections—Population estimates were prepared for each county and zone in the survey area for the years 1960 and 1985. This report revealed a statewide population of 10,081,000 in 1960, which can be expected to increase to 13,851,000 by 1985, an increase of over 37 percent.

Between 1960 and 1985 it is anticipated that the vehicle driver-age population will increase from 6,104,000 to about 8,736,000, an increase of about 43 percent. A significant and even greater increase in vehicle registration is also anticipated. The 1985 total automobile registration is anticipated to reach 6,990,000, an increase of 112 percent over 3,296,262 in 1960.

Traffic Assignment Network—The 1964 traffic assignment network (about 11,500 miles and about 6,500 miles of centroid connectors) consisted primarily of the US-numbered and major state highways, the main intercity traffic carriers. Time, speed, and distance were ascertained to describe each link of the highway assignment network. The distances were determined from route logs and state maps. The assigned speeds ranged according to the area and type of facility. The assigned speeds were 30 mph for centroid connectors to between 50 and 60 mph for freeway corridors. Turn penalties

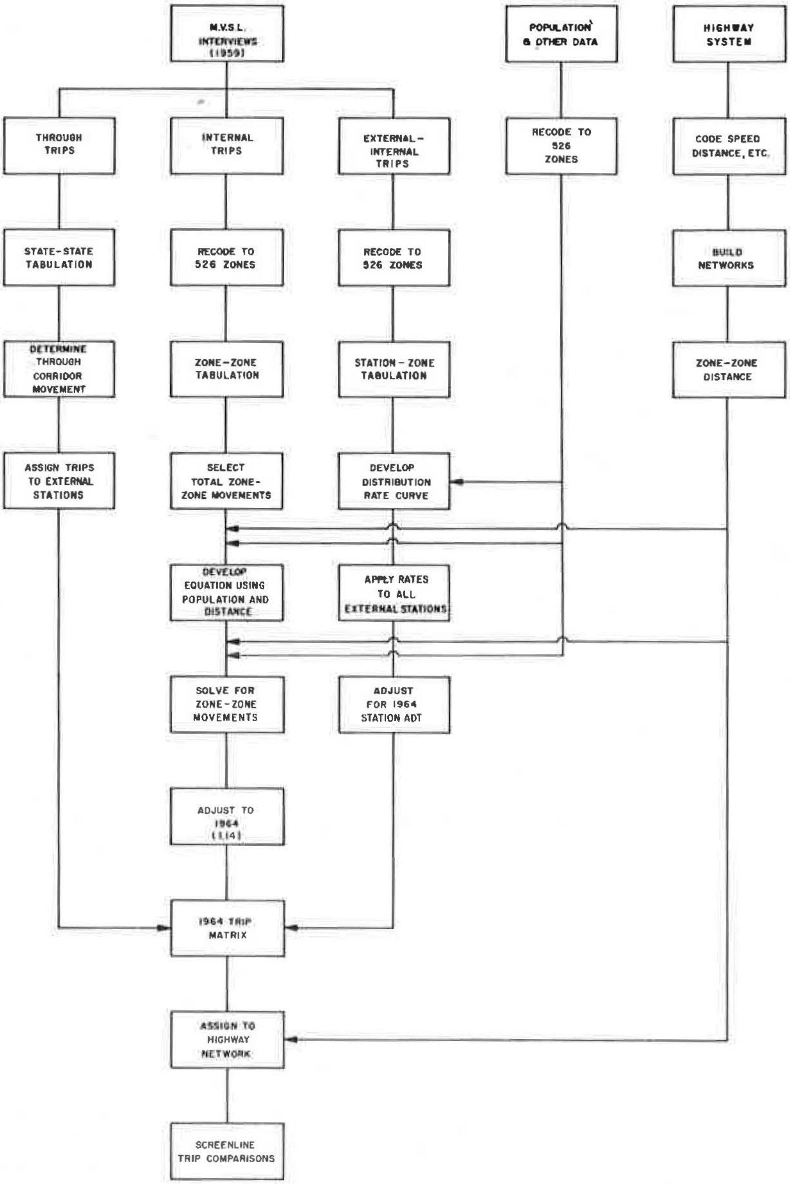

Figure 10. Analysis procedure, Illinois.

and prohibitors were not used. Centroids were established for each of the 526 traffic zones and the 49 state-line stations which were connected to the highway system. For the analysis of proposed freeway corridors both time and distance networks were established.

Internal Trips—The screen line interview stations provided extensive data on intercity traffic movements. However, it was not possible to develop from these data an overall zone-to-zone trip matrix because of the screen line spacing. With 526 zones there was a possibility of about 140,000 zone-to-zone trip interchanges. Therefore, correlations were developed to synthesize the principal movements.

Interview data were stratified by mode of travel and trip purpose. The interview results were recoded to conform with the 526 zones. A tabulation was prepared listing

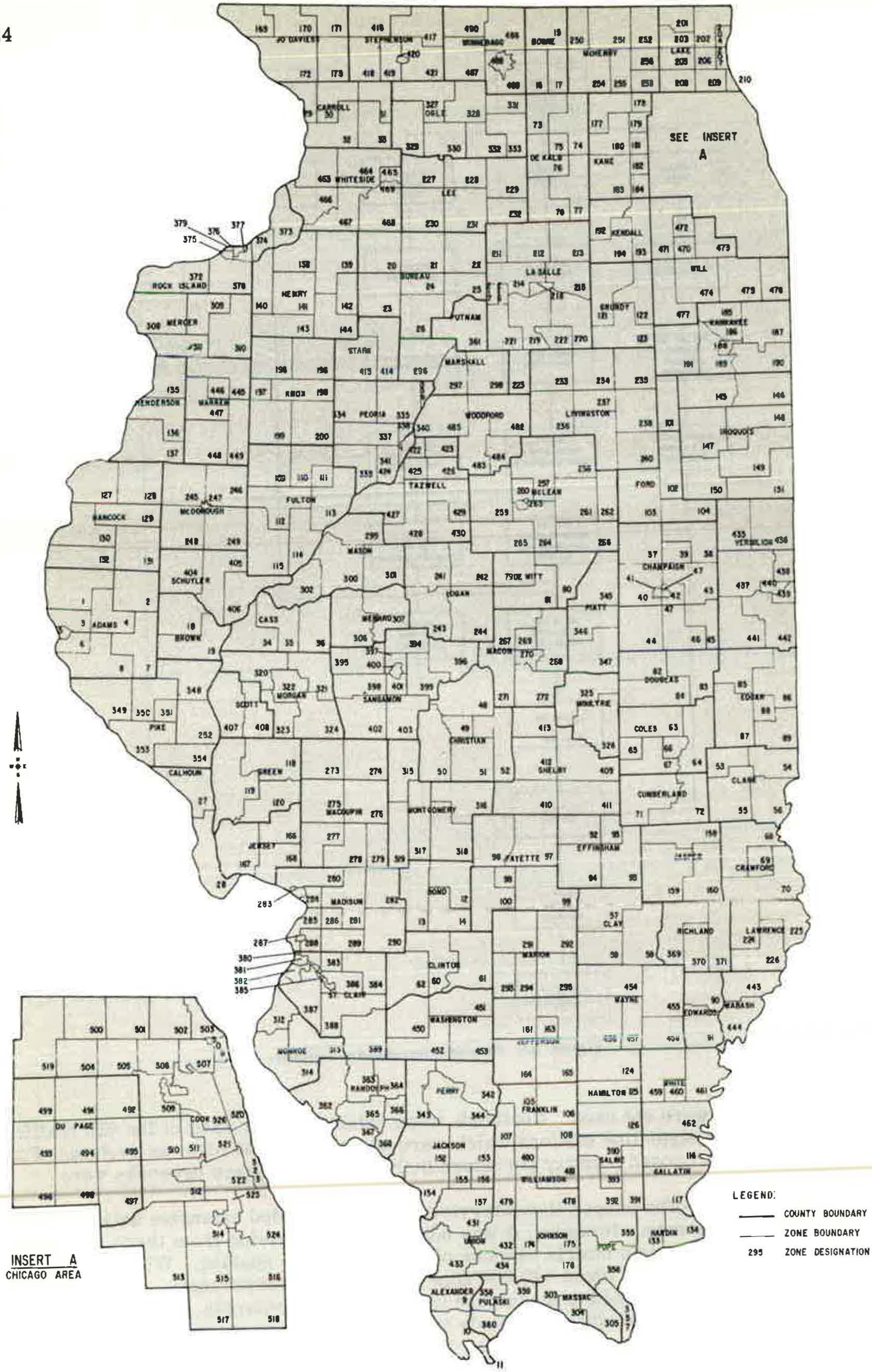

Figure 11. Traffic analysis zones established for statewide traffic projections, Illinois.

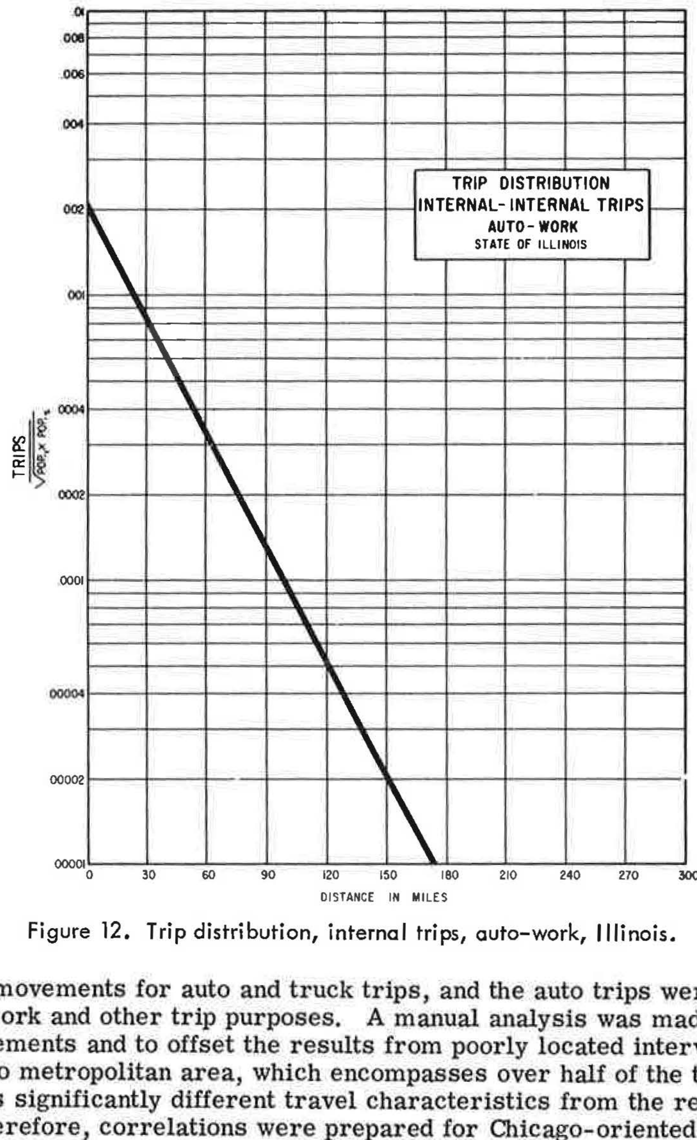

Figure 12. Trip distribution, internal trips, auto-work, Illinois.

zone-to-zone movements for auto and truck trips, and the auto trips were further stratified by work and other trip purposes. A manual analysis was made to eliminate duplicate movements and to offset the results from poorly located interview stations.

The Chicago metropolitan area, which encompasses over half of the total state population, has significantly different travel characteristics from the remainder of the state. Therefore, correlations were prepared for Chicago-oriented trips (one or both trip ends in Chicago) and non-Chicago trips (both trip ends outside the Chicago area).

It was assumed that the traffic interchange between two zones was dependent on the zonal populations and the highway distance between the zones. The "skim distance trees" of the coded network provided the highway distance between zones. A special computer program was prepared which related the distance, populations, and zone interchange, and determined the appropriate equation. Thus the analysis simultaneously produced both trip generation and zone-to-zone distribution.

Driver-age population was also considered in the analyses, but total zone population provided the best correlation. The basic equations for non-Chicago trips are as follows:

Type of Trip	Equation
Auto driver, work	$T(1\text{-}2) = 0.0026 \sqrt{P_1 P_2} \; e^{-0.035D}$
Auto driver, other	$T(1\text{-}2) = 0.0032 \sqrt{P_1 P_2} \; e^{-0.038D}$
Truck	$T(1\text{-}2) = 0.0023 \sqrt{P_1 P_2} \; e^{-0.035D}$

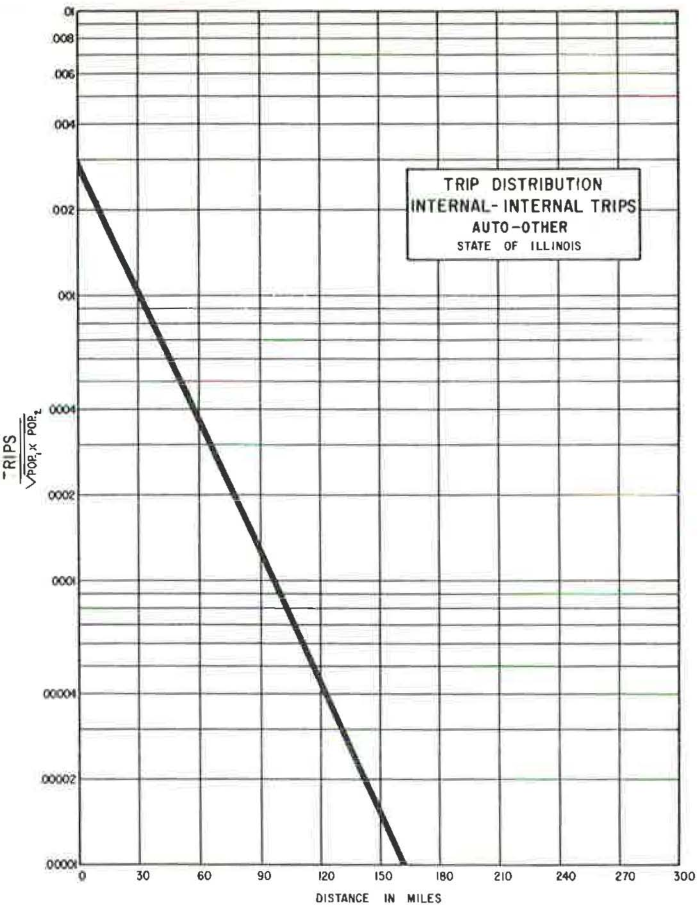

Figure 13.

where:

P_1 = Population of Zone 1;
P_2 = Population of Zone 2;
T(1-2) = Trips between Zone 1 and Zone 2; and
D = Highway distance between Zone 1 and Zone 2.

The basic relationships developed are presented in Figures 12, 13, and 14 for the three different types of trips for non-Chicago trips. The trip interchange between the two zones was divided by the square root of the product of populations and was related to the distance between the two zones. Quite similar relationships were developed for auto driver-work and auto driver-other and for truck trips. There was a significantly sharp decrease in the trip interchange between population centers as the distance between them increased. This provided a good means of reflecting "isolation" of some cities. For cities of similar size, the trip interchange at 30 miles would be three times the rate at 60 miles and almost nine times the interchange rate for 90-mile trips.

Significantly higher intercity trip production rates were found for non-Chicago trips (neither zone located in the Chicago area). The Chicago-oriented trip interchange rate was about 45 percent to 55 percent of the non-Chicago trip rate, depending on trip purpose.

Based on these correlations, the population of each zone and a table of distances between each zone pair were developed, and through the use of a computer program

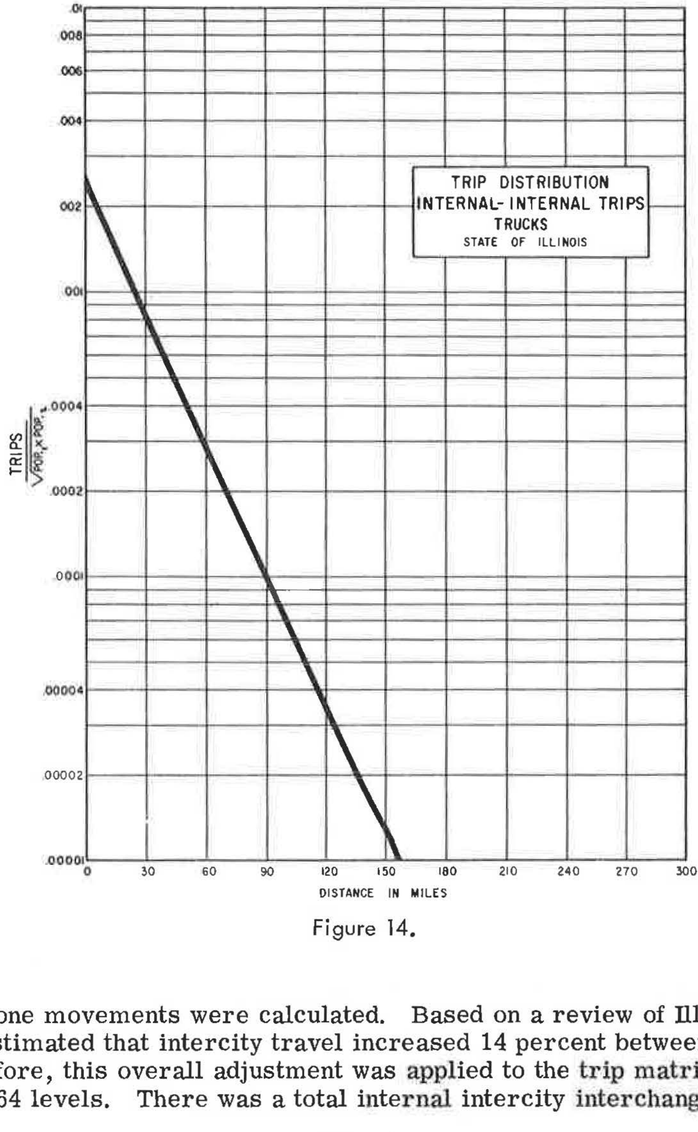

Figure 14.

all zone-to-zone movements were calculated. Based on a review of Illinois travel data it was estimated that intercity travel increased 14 percent between 1959-60 and 1964. Therefore, this overall adjustment was applied to the trip matrix to develop traffic for 1964 levels. There was a total internal intercity interchange of 677,825 trips in 1964.

External-Internal Trips—On a typical 1964 weekday there was a total movement of 418,000 vehicles as measured at 49 stations along the state boundaries. Of this total, 374,000 trips were external-internal movements, and about 44,000 were through trip movements.

Primary external state-line movements occurred in the Chicago area at the Illinois-Indiana border, north of Chicago at the Wisconsin boundary, and across the Mississippi River bridges in the St. Louis-East St. Louis and Quad City areas.

Stations were grouped for the St. Louis area and also the Quad City area. The volume in the St. Louis-East St. Louis area totaled 83,600 vehicles per day in 1964, and a total of 53,000 vehicles crossed the Mississippi River in the Quad City area. In the Chicago area three stations were established with a total volume across the Illinois-Indiana line of 71,000 vehicles a day.

For selected interview stations located at or near the state line, the internal-external trips per 1,000 population were related to the distance between the station and the destination zone to develop a relative distribution rate. Separate analyses were undertaken for stations near the large metropolitan areas of Chicago and St. Louis

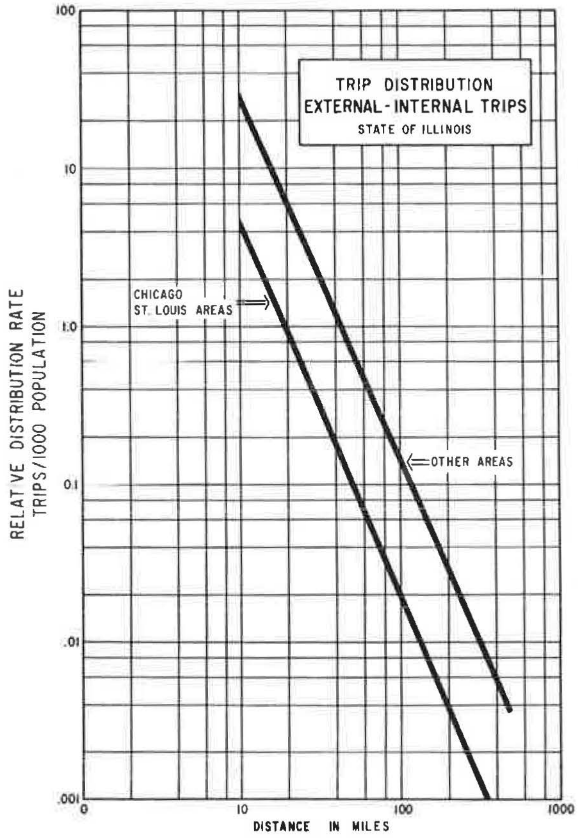

Figure 15.

since the distribution rate for these stations was lower than for other areas. As shown in Figure 15, for the Chicago and St. Louis areas the trip distibution rate at a distance of 20 miles was about one-sixth of that found in other areas. For the Chicago and St. Louis areas the lower distribution rate by zones near an external station reflected several adjacent zones with intense population densities; for other areas the route may serve only one major zone in the immediate vicinity of the station.

Equations were not developed for external-internal trips; however, the calculated distribution rates were used to manually distribute the estimated 1964 volume of about 374,000 trips between external stations and internal zones. The recorded volumes were used as control totals after applying the distribution rates.

Through Trips—Through movements represented only a small part of the intercity trips; however, their longer trip length and restriction to only a few corridors created significant movements along some routes.

The available data were adequate to determine the through trip movements. However, a manual analysis was required to establish station-to-station movements since the interview data did not include points of route of entry or exit at the state boundaries for the trips. Therefore, the external movements were assigned to the appropriate stations based on the percent of the state-to-state movement occurring at each station with the recorded through volumes along major routes used as a comparison.

1964 Traffic Assignments—The three sets of synthesized data (internal, external-internal, and through trips) were combined into one matrix of 1964 intercity trips. The zone-to-zone matrix was utilized to prepare assignments to the existing (1964) year network to provide comparisons with actual intercity traffic volumes. This is the most important test since the primary purpose of the projection is the determination of travel volumes in key corridors. These data were converted for computer input and standard minimum path assignment programs were used. (The zone-to-zone trip matrix was converted into Memory J format. The assignment procedure utilized minimum time between zones via the highway network.)

The actual and estimated volumes recorded at the east-west interview screen lines established in the multiple screen line study were as follows:

Latitude (deg. N)	1964 Volume (actual)	1964 Volume (estimated)
38	20,000	15,381
39	32,200	31,978
40	42,450	37,831
41	44,900	55,272
42	14,900	13,248
Total	154,450	153,710

Screen line comparisons for the four screen lines are given in Table 6.

1985 Trip Projections

Utilizing population projections and anticipated vehicle registration increases, the 1985 trips were developed.

Internal Trips—Several factors will determine the magnitude of future intercity trips. First, the overall state population is estimated to increase from 10,081,000 in 1960 to 13,851,000 in 1985. Vehicle registration will more than double. There has been a steady increase in traffic along the intercity routes as improvements have been implemented. It is anticipated that this growth will continue at a rate less than the overall vehicle registration but substantially higher than population. The overall travel growth is expected to be about 86 percent, an average of 3 percent compounded annually.

Utilizing the projected populations for each zone and the generation-distribution equations, the 1985 zone-to-zone internal trip interchanges were calculated. An adjustment factor was applied to account for increased vehicle registration and use to achieve an overall increase of 86 percent. Based on these analyses there will be an estimated internal movement of 1,256,025 trips in 1985 as compared to 677,000 in 1964.

External-Internal Trips—Anticipated 1985 daily traffic volumes were estimated for the 49 external stations. Projections made by the CATS study, the Lake County Transportation Study, and by the highway departments of Wisconsin, Iowa, Missouri, Kentucky, and Illinois for the Interstate and other highways were reviewed. The estimates were

TABLE 6

SCREEN LINE COMPARISONS

Screen Line[a]	Location	1964 Volume[b] (actual)	1964 Volume (estimated)
1	South of Ill. 13	12,750	11,930
2	North of US 40 and Ill. 16	36,550	34,040
3	North of US 136 and US 24	46,850	47,110
4	North of Ill. 116	50,200	56,760
Total		146,350	149,840

[a]Screen line locations are shown in Figure 11.
[b]Source: Traffic Volume Map, State of Illinois, prepared by Bureau of Planning, Division of Highways, Department of Public Works and Buildings.

TABLE 7

ESTIMATED INTERCITY TRIPS, ILLINOIS

Type of Trip	Year		Increase (percent)
	1964	1985	
Internal-Internal	677,825	1,256,025	86
External-Internal	374,031	791,593	112
External-External	43,112	114,782	167
Total	1,094,968	2,162,400	97

also based on volume trends at each station and the anticipated population growth of the particular region of the state. It is estimated that the total state-line volume will increase from 418,000 in 1964 to about 906,000 in 1985, an increase of 118 percent.

Utilizing the trip rates developed for 1964 traffic, external-internal trips were distributed to the traffic zones. Factors were applied to adjust to the estimated station control total. The total external-internal volume in 1985 is estimated to be 791,593 vehicles compared to 374,031 vehicles in 1964.

Through Trips—A 1985 through movement of 114,800 is anticipated as compared to 43,000 trips in 1964. Through trips were estimated for each station and distributed utilizing the Fratar method, which takes into consideration future station volume and the existing station-to-station trip interchange.

Trip Comparisons—As given in Table 7, it is estimated that the total intercity movement will be 2,162,400 trips by 1985, an increase of 97 percent over the 1964 level. The through trip volume is expected to increase at the highest rate, followed by external-internal travel, which reflects a substantial anticipated increase in the use of Interstate and other major facilities. Chicago and St. Louis, which will experience relatively high population growth, and since they are located at the state boundaries, will contribute to the major increase in the external-internal trips.

1985 Traffic Assignments—Traffic has been assigned, using the minimum time path technique, to the proposed statewide system of freeways and major highways designed to serve 1985 travel demands. (The minimum time between zones via the highway network was used.) Also, trip length and vehicle-mile analyses have been made.

The assignments to the freeway and major highway networks are shown in Figure 16. The basic traffic volumes have been adjusted (1.15 factor) to reflect the influence of establishing an Interstate freeway in a particular corridor.[1] Also, factors have been used ranging from 1.30 to 1.60 for generation of additional traffic due to the provision of more superior traffic service. It is realized that volumes will increase on the urban area approaches, whereas the intercity values generally reflect anticipated rural traffic volumes.

It was assumed that the basic projection procedure accounted for the A, S, and L factors. Generation on a limited-access facility has been found to range from 30 percent to about 60 percent. This accounts for trips resulting from new developments along the route occasioned by construction of the facility, and more trips including travel mode change because of the new or greatly improved route. With the nationwide system of Interstate highways having a common identification and being located in major

[1]From The 1965 Estimate of the Cost of Completing the Interstate System, U.S. Department of Commerce, Bureau of Public Roads, 1963. The basic formula is as follows:

$$\text{Design year traffic} = AG\ (1 + SLI)$$

where

A = base year assigned traffic, G = generation factor, S = statewide percentage traffic increase, L = factor to convert statewide percentage increase(s) to the percentage increase for a particular location, and I = factor to reflect more rapid rate of growth along Interstate system when improved to Interstate standards.

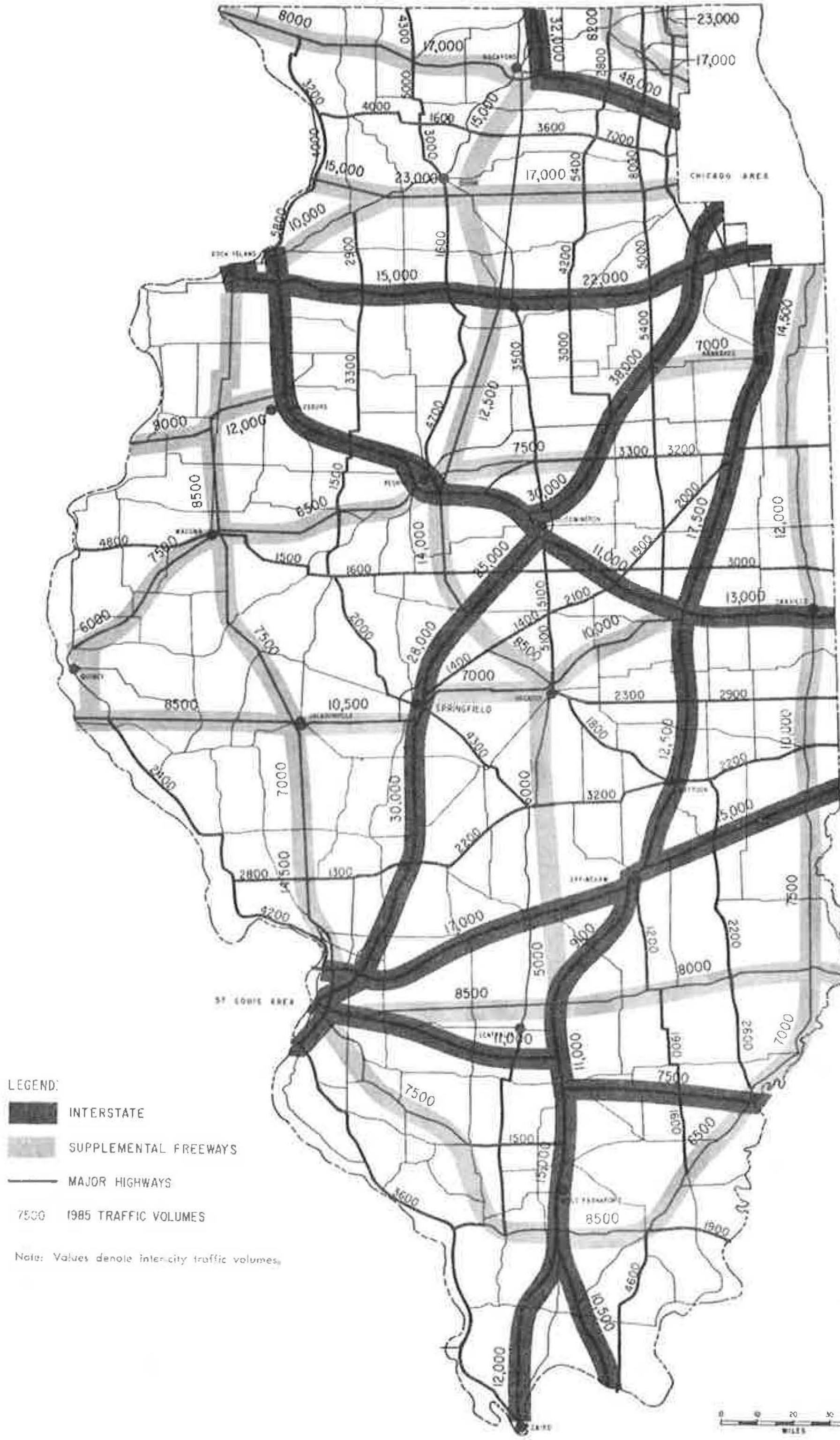

Figure 16. 1985 traffic volumes, proposed freeway and major highway corridors, State of Illinois.

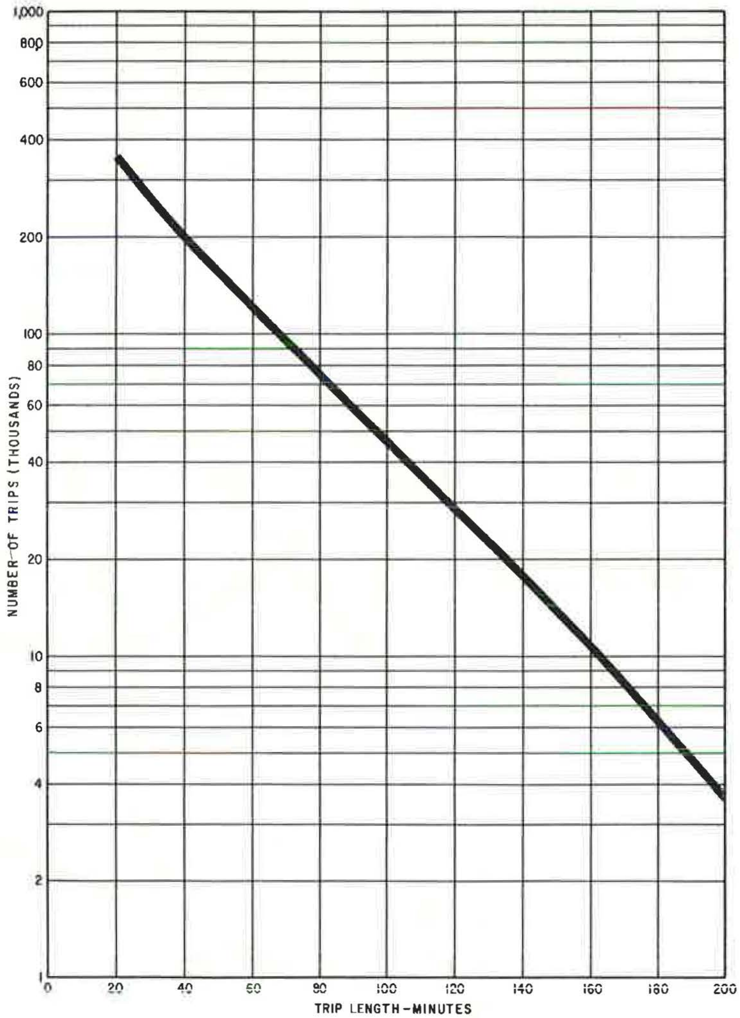

Figure 17. 1985 trip length distribution, Illinois.

travel corridors, it is anticipated that a more rapid growth will occur. Therefore, an additional value of 1.15 (the I factor) is suggested for these routes.

The relationship of trip length and time is shown in Figure 17 for 1985 conditions for the assumed network. There will be a substantial number of trips in the short time periods, rapidly decreasing for longer time and distance ranges. The average trip length for trips assigned to the highway network would be 38.6 miles and average speed would approximate 46 mph. This would produce about 83,000,000 vehicle-miles of travel. The trip length and vehicle-miles should be considered as relative. Distances from centroids to the assignment network and the elimination of many short trips due to the limited number of zones tend to increase trip length.

Vehicle-Miles and Trip Length

Vehicle-miles of travel was ascertained for each network link and traffic zone. The same procedure used for the Arizona analyses was followed in utilizing computer programs.

The 526 internal zones were divided into five groups or increments (about 105 zones in each group) according to vehicle-miles of travel. As shown in Figure 18, the first increment produced about two-thirds of the vehicle-miles and the first two increments

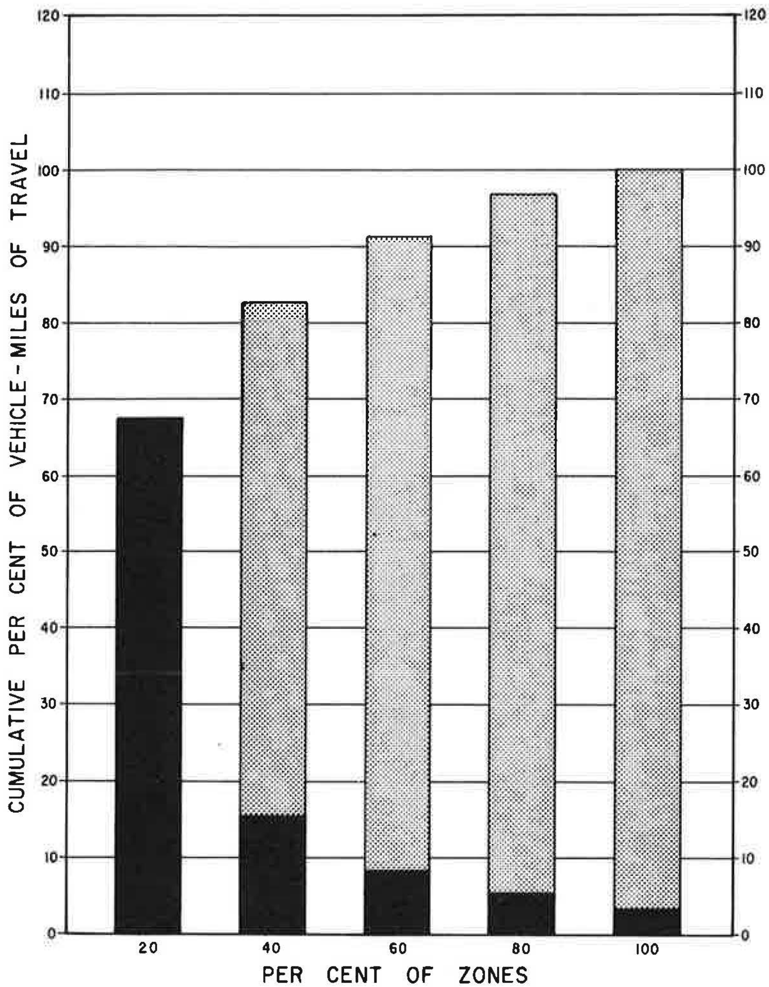

Figure 18. Interzonal vehicle-miles of travel, Illinois.

(40 percent of the zones) accounted for 83 percent of the total travel. The first three increments are shown in Figure 19 by individual zone, representing 91 percent of total travel. They are generally located in the metropolitan areas.

IN RETROSPECT

By utilizing available origin-destination data, trip matrixes were developed for the base year for Arizona and Illinois. While this did not include all of the intercity traffic trips in Arizona or all movements between zones, it did reflect the major corridors of travel. Assignments to a traffic network of highways revealed close correlations with volumes that would normally be found between cities. It is recognized that traffic volumes substantially increase adjacent to and within the urbanized area. These present and future volumes and capacities are being developed in the urban comprehensive studies, such as are under way in the Phoenix, Tucson, and Yuma areas.

The basic projection procedure involved applications of growth factors which reflected anticipated increases in population, vehicle registration, and recreational area visitation. In Illinois the equations were developed utilizing origin-destination data. These equations were also used to project travel to 1985 levels. For each state the

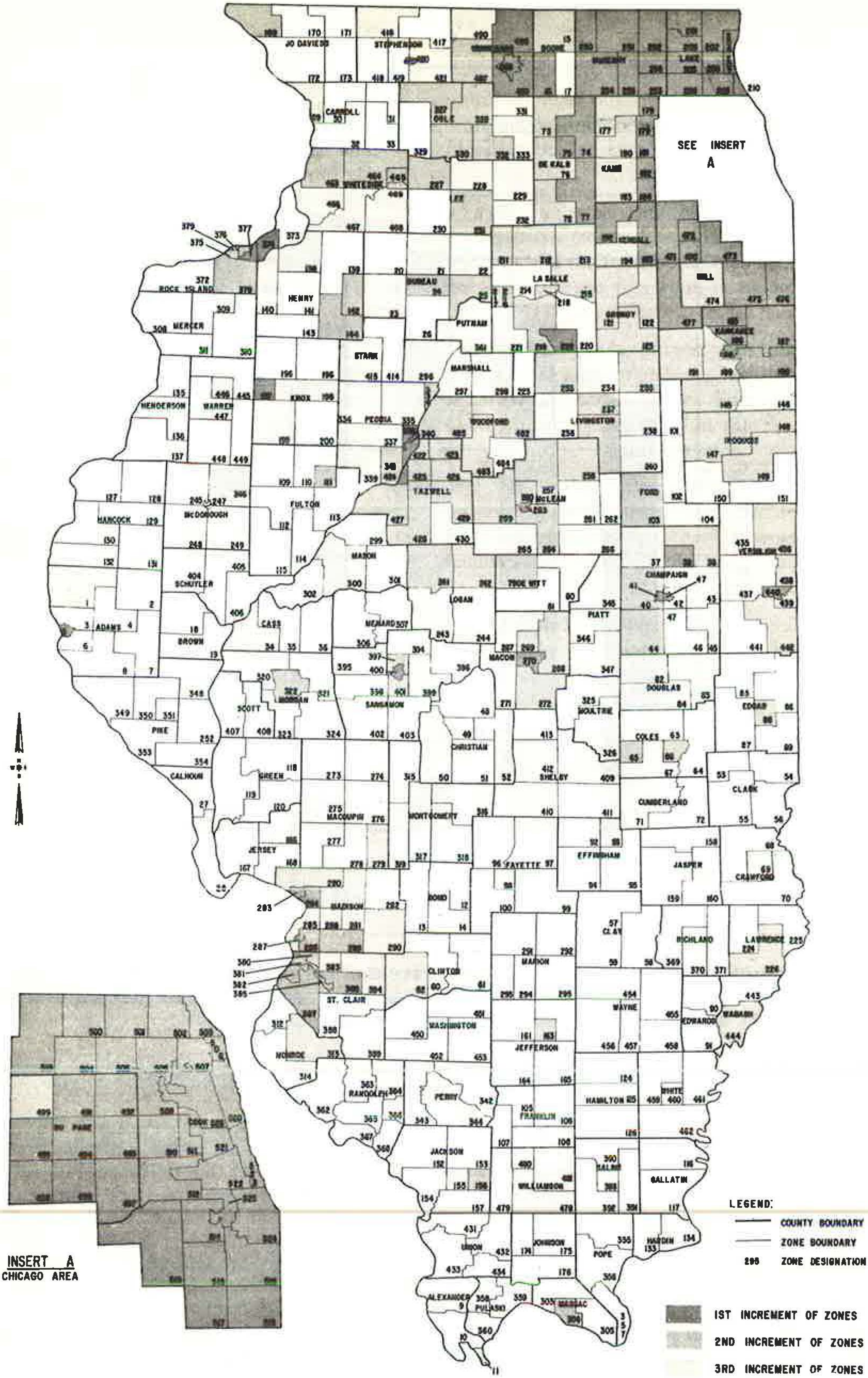

Figure 19. Relative miles of travel by zone, Illinois.

trip matrixes were prepared and assignment networks formulated to permit the testing of other alternatives of movements. Differences in growth patterns for zones also can be reflected.

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