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Improving Truck Trip-Generation Techniques Through Trip-End Stratification

JAMES D. BROGAN

Most existing urban truck-travel demand-forecasting techniques stratify truck trips into only two categories for modeling purposes—trips made by light trucks and trips made by heavy trucks. The rationale behind this stratification is that the trip-making characteristics of the two truck types are quite different and thus should be analyzed independently. The purpose of this research was to determine whether additional stratification of truck trips aids in improving the reliability of truck trip forecasts. Several additional stratifications were considered, including stratifications by vehicle type, trip purpose, and destination land use. Comparisons of truck trips stratified by vehicle type for three cities showed no improvement due to the stratifications. In general, the overall unstratified models were more statistically adequate, and the independent variables that were most significant in the stratified equations were comparable with those that appeared in the total truck model. Similar results were obtained when total internal truck trips were stratified according to trip purpose. The stratifications by trip purpose did show, however, that goods-related trips have a strong relationship with either commercial or retail employment, while service-type trips are most strongly related to measures of total employment. Results from the stratification by land use at destination, in which total truck trip ends were categorized as either industrial trips (those made to various types of industrial and manufacturing land uses) or consumer-related trips (those made to land uses associated with the resident population of a study area), showed some improvement over the more general overall models. In two of the three case studies, in fact, significant differences were noted between the stratified and unstratified results, in terms of both the types of independent variables employed and the statistical reliability of the regression equations themselves.

Most existing urban truck-travel demand-forecasting techniques stratify truck trips into only two categories for modeling purposes--trips made by light trucks (trucks that have only two axles and four tires and that usually weigh less than 10 000 gross lb) and trips made by heavy trucks (trucks that have more than four tires and that weigh more than 10 000 gross lb). Additional stratifications are sometimes made, for example, by subdividing heavy trucks into "medium" trucks (those that have no more than two axles and that weigh 10 000-20 000 lb) and "heavy" trucks (those that weigh more than 20 000 lb) (1). For the most part, however, the two-category breakdown is the one most frequently made.

The rationale behind the stratification by light and heavy vehicles is, of course, that the trip-making characteristics of the two types are quite different; therefore, they should be analyzed independently. Trip-length characteristics of the two truck types do, in fact, show considerable differences; this is indicated by the trip-length distribution and friction-factor values for the two truck types reported in previous research (2,3).

The purpose of this research was to determine whether additional stratification of truck trips aids in improving the reliability of truck trip forecasts. Several additional stratifications were considered: (a) additional stratifications by vehicle type (for example, panel and pickup trucks, other two-axle trucks, three-axle single-unit trucks, and all combination units), (b) stratification by trip purpose, and (c) stratification by land use at destination.

Testing for truck trip-generation modeling improvements through the additional truck trip stratifications involved the analysis of both external and internal truck-survey trip records from the origin-destination study files in each of several case-study cities. Zonal-level truck trip ends for each of the proposed trip stratifications by the various parameters listed above were sorted and accumulated, and regression equations were developed for the stratified data. Comparisons with the original unstratified regression equations (in terms of both the statistical adequacy of the regressions and the significant independent variables in the relationships) were made in order to reveal any improvements resulting from the stratifications.

The study begins by considering the effect of truck trip-end stratification in multiple-regression analysis by the three parameters listed above--truck type, trip purpose, and land use at destination. A proposed stratification of truck trips is then presented and the applications of the stratified regression relationships to truck-travel demand forecasting are discussed.

STRATIFICATION BY VEHICLE TYPE

The stratification of truck trips by vehicle size has been shown to be a logical approach to truck trip-generation analysis because of the unique trip-making characteristics of various types of trucks. Truck size is also important, however, in terms of facility design (for both geometric and pavement considerations), environmental impact analyses, fuel- and energy-consumption studies, and highway revenue forecasts from estimates of truck vehicle miles of travel.

The traditional stratification of truck trips into those made by light and heavy vehicles, however, when used to develop multiple-regression relationships to forecast truck trip ends, has generally yielded unsatisfactory results. Correlations usually have been low; standard errors have been quite high; and, in general, the equations have tended to be so complex and unwieldy as to make forecasting extremely difficult.

It was felt, therefore, that the investigation of additional truck trip stratifications based on vehcle size might result in improved and simplified truck trip-generation models. Accordingly, truck trip origin-destination data were obtained from three case-study cities--Gastonia, North Carolina; Flint, Michigan; and Saginaw, Michigan--and stratified multiple-regression relationships were developed by truck type and compared with the overall unstratified regression equations for each city. The results of the stratifications by vehicle type for each of the three cities are summarized below.

Gastonia

Two separate trip stratifications by vehicle type were developed. The first stratification broke down the total truck population into panel-and-pickup trucks versus other-than-panel-and-pickup trucks. The second stratification considered all single-rear-tire trucks separately from all other-than-single-rear-tire trucks. Results of the two stratifications for internal and external truck movements are given in Table 1.

It can be seen from Table 1 that the stratifica-

Table 1. Gastonia internal and external truck trip destinations by truck type.

Regression Equation	Overall F	R^2	Standard Error ÷ Mean	Mean ($\bar{Y}$)	Correlation Coefficient[a] r_{12}	r_{13}	r_{23}
Internal Destinations							
Panel and pickup = 41.6 + 2.35 (HE) + 0.10 (TE)	61.3	0.3622	1.0309	87.84	0.506	0.468	0.313
Other than panel and pickup = 34.6 + 0.76 (RE) + 0.23 (LIDU)	52.1	0.3252	1.1619	71.92	0.527	0.227	0.016
Single rear tire = 47.6 + 1.14 (RE) + 0.33 (TDU)	55.2	0.3384	1.0286	123.95	0.504	0.283	−0.016
Other than single rear tire = 22.0 + 0.30 (RE) + 0.71 (HE)	44.6	0.2924	1.3644	35.80	0.508	0.459	0.618
Total = 77.7 + 1.54 (RE) + 0.54 (LIDU)	59.6	0.3555	1.0163	159.75	0.536	0.269	0.016
External Destinations							
Panel and pickup = 12.21 + 0.14 (RE) + 0.02 (TE)	91.1	0.4577	0.8003	20.31	0.609	0.546	0.468
Other than panel and pickup = 4.28 + 0.19 (HE) + 0.01 (TE)	47.7	0.3066	1.1224	8.86	0.428	0.468	0.313
Single rear tire = 12.57 + 0.15 (RE) + 0.02 (TE)	95.5	0.4693	0.7946	20.97	0.622	0.545	0.468
Other than single rear tire = 4.05 + 0.16 (HE) + 0.01 (TE)	42.0	0.2802	1.1649	8.19	0.394	0.459	0.313
Total = 17.4 + 0.20 (RE) + 0.03 (TE)	91.7	0.4592	0.7960	29.16	0.601	0.558	0.468

Note: HE = highway employment; TE = total employment; RE = retail employment; LIDU = low-income dwelling units; TDU = total dwelling units.

[a] r_{12} = between dependent variable and first independent variable; r_{13} = between dependent variable and second independent variable; r_{23} = between independent variables.

tions by panel-and-pickup versus other-than-panel-and-pickup and single-rear-tire trucks versus other-than-single-rear-tire trucks did not improve the truck trip-generation results. In fact, both stratifications actually increased the standard error of the estimate as a proportion of the mean, and only one stratified equation--that for panel-and-pickup truck destinations--had even the slightest increase in the value of R^2. The value of overall F, significant at the 0.01 level for all equations, was increased in only one of the stratified equations--again that for the panel-and-pickup equation.

Only five independent variables appear in the five equations, indicating little underlying difference between the stratified trip types. Retail employment, for example, was the most significant independent variable in four of the equations. In general, the panel-and-pickup and single-rear-tire truck equations were more acceptable than the equations for the larger trucks. The equation for other-than-single-rear-tire trucks, in fact, may be difficult to interpret because of the existence of colinear variables (the correlation between the two independent variables is higher than the correlation of either of them with the dependent variable). The net effect of the stratification by truck type for internal truck destinations was that the regularity of small trucks was much more apparent than that of the larger, dual-tired single-unit and combination vehicles. Modeling of the movements of these heavier vehicles would thus seem much more risky.

Similar conclusions may be reached regarding the regression relationships for the external truck movements. Once again, significant regressions were achieved in all cases, but little improvement resulted from the stratifications. The value of R^2 was higher than that for the unstratified equation in only one instance, and standard errors as a proportion of the mean were actually increased in three of the four stratified equations. Only three independent variables were represented in the five equations; either retail or highway employment was the most significant variable, and total employment was the second variable to enter the equations in all cases.

An additional constraint placed on the stratification of the external truck movements was the fact that there were comparatively few destination trip ends for the larger trucks. As a result, the regression relationships for these movements are even more questionable.

Flint

Truck trip data for the Flint urbanized area allowed a total of three stratifications to be considered--single-unit vehicles with single tires versus other-than-single-unit vehicles with single tires, single-axle vehicles versus other-than-single-axle vehicles, and single-unit trucks versus combination (tractor-trailer) units.

An examination of the Flint results showed that the three straight truck equations (single-unit vehicles with single rear tires, single-axle trucks, and single-unit trucks) all contained the same independent variables (total employment and total automobiles) as the total truck equation. In addition, the single-unit equations all had approximately the same statistical adequacy (in terms of R^2 and percentage of standard error) as the overall equation, and there seemed to be no confounding effects due to colinearity among the variables.

Where all the Flint stratifications by vehicle type failed, however, was in their attempts to model the trip ends for heavier trucks. The equations for all three of these categories (other-than-single-unit vehicles with single tires, other-than-single-axle trucks, and combination units) were quite weak and had considerably lower values of R^2, high standard errors of the estimate, and quite low, although still significant, overall F values. The independent variables in the "other-than" categories, moreover, while significant from a statistical standpoint, sometimes did not seem logically correct. For example, while the use of commercial employment as an important predictor of trip ends for heavy trucks may make sense in the equation for other-than-single-unit vehicles with single tires, it is difficult to see the relationship of total dwelling units to trip ends for heavy trucks, as one of the regression equations indicated.

In summary, it can be said that no improvement was observed for either the internal or external truck trip-destination models in Flint when stratified by various combinations of vehicle type. Although one portion of the stratification always yielded results comparable to the overall, unstratified equation, the complementary equation was always much poorer; the overall result was to make the entire stratification no better, and often worse, than the original unstratified equation.

Saginaw

Stratifications identical to those used in Flint

Table 2. Gastonia internal truck trip destinations by trip purpose.

Regression Equation	Overall F	R^2	Standard Error ÷ Mean	Mean ($\bar{Y}$)	Correlation Coefficient[a]		
					r_{12}	r_{13}	r_{23}
Goods = 50.1 + 1.10 (RE) + 0.33 (LIDU)	64.1	0.3726	1.0470	104.07	0.564	0.242	0.016
Service = 27.8 + 1.15 (HE) + 0.07 (TE)	39.8	0.2694	1.1904	55.68	0.395	0.443	0.313
Total = 77.7 + 1.54 (RE) + 0.54 (LIDU)	59.6	0.3555	1.0163	159.75	0.536	0.269	0.016

Note: RE = retail employment; LIDU = low-income dwelling units; HE = highway employment; TE = total employment.

[a] r_{12} = between dependent variable and first independent variable; r_{13} = between dependent variable and second independent variable; r_{23} = between independent variables.

were employed in the analysis of the Saginaw data. Thus, three stratifications were made and compared with the overall equation for truck trip destinations.

Results of the vehicle-type stratification for internal truck trips in Saginaw showed that, once again, although significant regressions were achieved, no improvement in the equations resulted from the stratifications. The minimal increases in the coefficient of multiple determination and the slightly lower values of the standard error of the estimate as a proportion of the mean for the single-unit categories in the first two stratifications were more than offset by complementary inverse changes in these values for the corresponding "other-than" equations. In addition, in only three of the six stratified equations did independent variables other than those in the unstratified equation enter.

Similar conclusions may be reached regarding the stratification of the Saginaw external truck trip destinations. In this case, none of the stratified equations contained independent variables other than those that appeared in the original unstratified equation. Values of R^2 and percentage of standard error, moreover, did not show overall improvement due to the stratifications, even though the individual single-unit equations were improved somewhat. In general, however, the stratifications by vehicle type once again were no better than the original unstratified equation.

STRATIFICATION BY TRIP PURPOSE

Stratification of vehicle trips by trip purpose has long been a practice in the modeling of passenger movements. Although the trip-purpose stratifications employed in passenger-travel demand forecasting are dictated primarily by the trip-distribution model requirements (4), decisions must be made at the trip-generation stage as to the number and type of trip-purpose stratifications to employ.

Considerations in the stratification of passenger trips by trip purpose include not only the number of trips in each category but also the trip-length distributions of each trip purpose and the ability to forecast future trips in each category separately (4). Thus, the total number of trip purposes may range from eight or more in large urban-area studies to as few as three (home-based work, home-based other, and non-home-based trips) in the smaller urban areas.

Transferring the above reasoning to an analysis of goods-movement vehicle trips indicated that some stratification of truck trips by trip purpose should be investigated. Although a number of stratifications by trip purpose are theoretically possible, it is necessary to limit the total number of purposes both because of the comparatively small number of truck movements taking place and also because of limitations on the number of trip-purpose categories traditionally collected in an origin-destination survey.

Truck trip data available for this research were thus grouped into two general trip-purpose categories--goods-related trips (trips whose primary purpose is the pickup or delivery of goods) and service-related trips (trips in which the vehicle is used in connection with some type of service function). Data from two of the case-study cities used in the truck-type analysis--Gastonia, North Carolina, and Flint, Michigan--were also available for use in stratification by trip purpose, although only for the internal truck survey.

Gastonia

Two stratification categories by trip purpose for the internal truck trip destinations in Gastonia were created. "Goods" movements consisted of trips coded to pick up goods, deliver goods, pick up and deliver goods, and garage address. "Service" truck destinations included the trip purposes of service call, vehicle repair, and personal business.

A comparison of the trip-purpose stratification for Gastonia with the overall unstratified equation is given in Table 2. Goods truck destinations, which made up about two-thirds of the total truck destinations, are seen to be best predicted by the same independent variables presented in the overall model. The coefficient of multiple determination for the goods model is somewhat higher than that for the overall equation; the standard error as a proportion of the mean, however, is higher for the stratified goods model.

The significant independent variables in the service model are highway employment (defined as employees in establishments that primarily serve highway users, such as motel, restaurant, and service-station employees) and total employment; neither of these variables appears in either the overall or the goods-related equation. The R^2 value for the service category, however, is quite low; the standard error as a proportion of the mean is somewhat higher than that in the other two equations; and the overall F value, though still significant, is considerably lower than those for either the total or the goods model. The stratification by trip purpose may be of some value, nevertheless, since it shows the relationship of goods-related trips to measures of retail employment and the importance of service functions, such as those related to highway service stations, as a predictor of service-related truck trips.

Flint

The internal truck trips in Flint were similarly grouped into two general trip-purpose categories. The goods movements included trips coded to pick up goods, deliver goods, pick up and deliver goods, and base of operations. The service category included trips coded to and from work, shopping, personal business, service and other work-connected trips, and vacation.

Results of the stratification by trip purpose for

Table 3. Internal truck trips by land use at destination.

Regression Equation	Overall F	R^2	Standard Error ÷ Mean	Mean ($\bar{Y}$)	Correlation Coefficient[a] r_{12}	r_{13}	r_{23}
Flint							
Industry-oriented = 37.6 + 0.20 (OE) + 0.13 (ME)	420.1	0.7292	1.5410	82.48	0.269	0.847	0.196
Consumer-oriented = 73.3 + 0.59 (CE) + 0.36 (TDU)	140.8	0.4745	0.6723	255.38	0.505	0.584	0.260
Total = 98.2 + 0.14 (TE) + 0.34 (TA)	146.4	0.4841	0.7450	337.86	0.568	0.339	−0.107
Saginaw							
Industry-oriented = 6.12 + 0.36 (TCE) + 0.09 (TE)	223.0	0.6380	1.7209	34.23	0.277	0.775	0.110
Consumer-oriented = 11.9 + 0.38 (TDU) + 0.37 (CE)	232.1	0.6472	0.7268	102.72	0.721	0.442	0.122
Total = 23.6 + 0.43 (TDU) + 0.12 (TE)	192.1	0.6029	0.8183	136.95	0.544	0.557	0.005
Columbus							
Industry-oriented = 16.2 + 0.29 (INE) + 0.18 (CTUE)	135.6	0.2625	2.1129	25.95	0.431	0.336	0.143
Consumer-oriented = 54.6 + 0.51 (INE) + 0.18 (CGE)	203.6	0.3482	1.1537	93.20	0.370	0.494	0.099
Total = 71.7 + 0.82 (INE) + 0.19 (CGE)	210.1	0.3554	1.1383	119.15	0.455	0.429	0.099

Note: OE = other employment; ME = manufacturing employment; CE = commercial employment; TDU = total dwelling units; TE = total employment; TA = total automobiles; TCE = transportation and communication employment; INE = industrial nonmanufacturing employment; CTUE = communication, transportation, and utility employment; CGE = commercial and government employment.

[a]r_{12} = between dependent variable and first independent variable; r_{13} = between dependent variable and second independent variable; r_{23} = between independent variables.

the internal Flint truck trips indicated that goods destinations are most highly related to commercial employment, while service-related destinations are most highly correlated with values of total employment and total automobiles, the same variables that appeared in the total truck equation. Neither stratified trip-purpose category, however, showed a significant improvement over the original total truck-destination equation. The service equation did show a somewhat higher value of R^2 and a higher overall F value but at the expense of a correspondingly higher value of the standard error as a proportion of the mean.

STRATIFICATION BY LAND USE AT DESTINATION

Detailed stratifications of urban goods movements have recently been proposed that relate to the land use classification at the destination end of a goods-movement trip. Fresko, Shunk, and Spielberg, for example, proposed a classification that consists of location-oriented goods trips that serve the basic employment facilities in an urban region versus resident-oriented goods movements that serve the needs of the resident population in the area (5). Similarly, Saunders categorizes goods movements as those attracted to either industrial land uses (industry, open space, transportation and utilities, and vacant) or nonindustrial or consumer-oriented land uses (commercial, public buildings, residential, and services) (6). Finally, Hutchinson proposes grouping all goods movements into two distinct classes--interindustry and household-based movements (7).

As a final truck trip-end stratification category, internal truck trip records from three case-study cities--Flint and Saginaw, Michigan, and Columbus, Ohio--were stratified into two categories according to the land use at the destination: industry-oriented truck trips and consumer-oriented truck trips.

Flint

For Flint, industrial trips consisted of those whose destination land use codes were manufacturing; transportation, communication, and utilities; wholesale trade; resource production and extraction; and undeveloped land and water areas. Consumer-oriented land uses included residential, retail trade, services, and cultural, recreational, and entertainment.

Results of the regression analyses for the truck data stratified by land use at destination are given in Table 3. The stratification shows that industrial destinations are best predicted by manufacturing and other employment variables. Consumer-oriented destinations, on the other hand, are most significantly related to what might be considered consumer-related variables, that is, measures of commercial employment and total dwelling units. Both stratified equations are quite different from the overall equation, which predicts total truck destinations from a combination of industrial-related (total employment) and consumer-related (total automobiles) variables.

In addition to the logical structure of the equations stratified by land use at destination, the statistical strength of the separate equations seems improved over that of the unstratified equation. The values of the overall F, for example, show that the industry-oriented equation is significant at a much higher level of confidence than either of the other equations. The consumer-oriented equation, on the other hand, has a lower F value than the overall equation and hence cannot be used with as much confidence. The two values are so close (146 versus 141), however, and the industrial-oriented F value is so high, that there can be little doubt that the stratification by land use at destination has, for the Flint data, resulted in some improvements over the traditional unstratified equation. All of the criteria for determining improvements have not been met, however, since the value of R^2 for the consumer-oriented equation is somewhat lower than that of the overall equation and since the standard error as a proportion of the mean for the industrial equation is quite a bit larger than that of the unstratified equation.

Saginaw

For Saginaw, the industrial category contained manufacturing, nonmanufacturing industry, commercial-wholesale, and other open-space land uses. The consumer-related category consisted of residential, commercial-retail, services, public and quasi-public buildings, and public and quasi-public open-space land uses.

Results of the land use stratification for

Saginaw are given in Table 3 along with the overall truck equation. It can be readily seen that this stratification has also resulted in some improvements over the overall equation, in terms of both the logical placement of the independent variables and the statistical strength of the stratified equations.

Industrial truck trips are strongly related to total employment (a large majority of which is industrial employment) and transportation and communication employment. Consumer-related truck trips, in contrast, are best predicted by total dwelling units and values of commercial employment. Finally, from a statistical standpoint, the values of the overall F for both of the stratified equations are significant at higher levels of confidence than that for the total truck equation. The standard error as a proportion of the mean for the industrial equation increased, however.

Columbus

In contrast to the results for the Flint and Saginaw land use stratifications, the stratification for Columbus (see Table 3) apparently has not resulted in improved, or even different, prediction equations. The independent variables in the industrial category--industrial nonmanufacturing employment and communication, transportation, and utility employment--are intuitively logical; industrial nonmanufacturing employment, however, also enters the equation used to predict consumer-related truck destinations.

Statistical results for the three equations for Columbus also indicate no improvement due to the stratification. The overall F value is higher for the total truck equation than for either of the stratified equations. Correspondingly, values of R^2 are naturally higher for the overall equation, and the standard errors are lower.

One possible explanation for the failure of the Columbus case study to indicate any improvement when stratified by land use at destination is the fact that the number of independent variables available for use in the study may have been too great. A total of 33 variables, including 9 employment and 16 floor-space or site-area variables, was available on a zonal basis. The effect of this fine level of detail may have been an inability of only two variables to account for significant amounts of variation in the stratified truck trip equations.

SUMMARY

The purpose of this research has been to investigate the effects of various stratifications of truck trip ends on the reliability of truck trip-generation equations. Three stratification criteria have been employed. Truck trip ends were first stratified by vehicle type, that is, single-axle trucks versus other-than-single-axle trucks, single-unit trucks versus combination units, and so forth. The regression equations for the stratified data were then compared with the corresponding regression model for the overall truck trips and any improvements, either in the adequacy of the independent variables entering the model or in the statistical validity of the model itself, were noted.

Comparisons of truck trips stratified by vehicle type for three case-study cities showed no improvements due to the stratifications. In general, the overall unstratified models were more statistically adequate, and the independent variables most significant in the stratified equations were comparable to those appearing in the total truck model.

Similar results were obtained when total internal truck trips were stratified according to trip purpose. In this case, two general categories were employed. Goods-related trips were those that had as their primary purpose the pickup or delivery of goods. Service-related trips had as their primary purpose the performance of a service function, such as vehicle repair or a service call. The stratification by trip purpose, which was investigated for data from two case-study cities, indicated no overall improvements when compared with the overall model. The stratifications by trip purpose did show, however, that goods-related trips have a strong relationship to either commercial or retail employment, while service-related trips are most strongly related to measures of total employment. These relationships perhaps could be improved further by deleting those trips made by small trucks for personal business reasons. An additional area of investigation could focus on the similarity of stratification results over several urban areas. This approach was not possible by using the limited data base available for this study. Such comparisons, moreover, would have to be made over areas that use identical truck trip-purpose categories.

The final criterion on which truck trip ends were stratified was related to the land use at the destination. By employing a stratification suggested by the literature on urban goods-movement forecasting, total truck trip ends were categorized as either industrial trips (those made to various types of industrial and manufacturing land uses) or consumer-related trips (those made to land uses associated with the resident population of a study area, such as residential, retail services, and cultural or recreational). These results for three case-study cities showed some indication of improved results compared with the overall models. In two of three case studies, in fact, significant differences were noted between the stratified and unstratified results, in terms of both the types of independent variables employed and the statistical reliability of the regression equations themselves. Improvements were not discernible in the third case, although this may be a result of a plethora of independent variables that do not individually contribute significantly to the model.

The relative success of the truck trip models stratified by land use at destination suggests that this approach might be an appropriate area of pursuit if any long-range modeling of urban truck trip generation is desired. Additional improvements in the adequacy of the stratified models may be realized by the elimination of zones that have zero observed trip values, as well as those that contain unique truck trip generators. This type of refinement, of course, requires that the analyst have an intimate knowledge of the area under investigation, which was not the case with this research.

Applications of this type of modeling of urban truck-travel demands, of course, are in the long-range planning area. Improved modeling of truck trips in this time frame may be most appropriate both for evaluating the consequences of alternative future land use plans and for facilitating the development of truck-route systems and other networkwide improvements.

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Stability Tests and Enhancements in Trip Distribution for Subarea and Corridor-Level Planning

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This paper describes the investigation of three key issues in the stability of trip distribution modeling as a means toward development of a more robust model that would form the linchpin of a state-of-the-art subarea planning tool, the thoroughfare analysis process. The three issues addressed are (a) stability across trip purpose, (b) stability under subarea focusing, and (c) stability through time and changing development patterns. A set of base models is initially calibrated in much the same way as in conventional fixed-zone modeling. These models are then subjected to a series of stability tests and, where necessary, model enhancements are introduced for further testing. Model refinements are introduced to obtain greater stability with respect to trip purpose and subarea focusing.

This paper describes research into the stability of trip distribution modeling; its goal is to develop a robust model for highly detailed planning at the subarea or corridor level, for both short-range and long-range purposes. The objective is to extend the state of the art in trip distribution to form the pivotal component of the thoroughfare analysis process (TAP), a planning package that is supported by a multilayered data base and that possesses an automatic subarea focusing feature. The structure of the TAP and its application in diagnostic analysis and evaluation at the subarea level are documented by Howe, Ryden, and Penny (1).

Subarea focusing is the means by which the data base for an urban or regional study area is disaggregated to finer detail within an area of interest and aggregated externally to permit cost-effective analysis in greater detail within the area of interest. Such a capability permits a more rigorous, systems approach to subarea planning, e.g., planning the principal and minor arterial network-supporting freeways, diagnostic analysis of transportation systems at the community level, evaluation of community-level transportation system management (TSM) and capital projects, and more detailed long-range analysis of alternative capital investments for corridor improvements.

The stability of trip distribution under focusing was initially addressed by Nihan and Miller (2). The initial calibration of a trip-distribution model for the TAP package was described by Howe and Gur (3). Extending previous work, the research described in this paper examines the stability of the TAP gravity-form distribution model from the following perspectives:

1. Stability across trip purpose--The research described in this paper led to a modified gravity formulation to attain greater stability under multipurpose modeling, which is essential to treatment of separate trip types in diagnostic analysis and evaluation.
2. Stability under subarea focusing--This issue is critical to subarea systems modeling in general. In this case, research pointed to incorporation of additional model parameters to compensate for variation in zone size.
3. Stability over time and changing development--Research indicated a marked degree of stability over a 13-year period of substantial growth and shifts in socioeconomic activity. This finding is important to the use of systems modeling for planning medium- and long-range capital alternatives.

As a starting point, trip distribution models were calibrated on base-year (1964) data that represent a uniform zone structure for a two-county study region, much as one would develop models for conventional planning on a fixed-zone structure. These base models were then subjected to a series of stability tests that addressed the above issues, and model enhancements were made as needed to attain improved robustness.

MODEL FORMULATION AND BASE CALIBRATION

Model Formulation

The trip-distribution model discussed in this paper is ALDGRAV, a gravity-model formulation adapted from the Access and Land Development (ALD) model originally developed by Schneider (4-6) and further discussed by Kaplan (7). The model embodies the following basic assumptions:

1. Probability maximization is applicable to the distribution of trips.
2. For a given group of trip makers, the sensitivity to the disutility of travel is not a single value but ranges over a continuum.
3. The total disutility of travel incurred by the trips produced from a given zone must be finite.

The basic gravity model formulation may be expressed as

$$V_{ij} = V_i[G(F_{ij})A_j/\Sigma_r G(F_{ir})A_r] \quad (1)$$

where

- V_{ij} = the number of trips produced by zone i and attracted to zone j;
- V_i = the total number of trips produced by zone i;
- $G(\cdot)$ = the travel (decay) function, representing the rate at which attractiveness declines with increasing travel disutility;
- F_{ij} = the disutility of travel from zone i to zone j; and
- A_j = the attractiveness (number of attractions) for zone j.

The travel disutility (F_{ij}) used in the model is a combination of three elements: $F_{ij} = F_{ij}{}^1$ + FPENO + FPEND. $F_{ij}{}^1$ is a linear combination of travel time, travel distance, and tolls derived directly from minimum-impedance skim trees. FPENO and FPEND are fixed penalties assessed to each trip at its origin and destination. These penalties reflect the terminal impedances encountered in making a trip (e.g., parking cost, walk time).

For intrazonal travel, the minimum-impedance skim tree travel disutility ($F_{ij}{}^1$) is zero. The intrazonal disutility is estimated by using intrazonal travel cost per kilometer and the area of the zone.

In application, the model is doubly constrained; i.e., Equation 1 is iteratively adjusted to balance the trips received by each zone to the input number of attractions.

Specific gravity formulations are distinguished by different forms of the travel function $G(\cdot)$. Examples include the following:

1. The inverse power function, $G(F) = F^{-a}$;
2. The negative exponential function, $G(F) = \exp(-aF)$; and
3. The gamma density function, $G(F) = [F^{a-1} \exp(-F) \div \gamma(a)]$.

The travel function used in ALDGRAV is somewhat more complex than the above functions, but it can be related to the negative exponential function as follows: If the second basic assumption above is replaced by the simplified assumption of a single value (a) for traveler sensitivity, one derives the gravity model (Equation 1) by means of the negative exponential travel function. This model has been derived from entropy maximization principles by Wilson (8). The ALDGRAV formulation, however, is based on the theoretically more complete second basic assumption, which leads to integration over a range of sensitivity values and results in the gravity form that has the ALDGRAV travel function

$$G(F) = [K_2(2\sqrt{aF})/4aF] \quad (2)$$

where K_2 is the modified Bessel function of second kind and second order, and a is a value representing an average traveler sensitivity. Compared with the negative exponential function, the Bessel function has a faster decay rate for very small disutility values and more gradual decay over larger disutility values. Also, it can be shown that the expected distance remaining to be traveled, conditional on trip length $\geq$d, is the same for all d that has the negative exponential function but increases with d for the Bessel function.

Base Model Calibration

The ALDGRAV model was calibrated separately for each of four trip purposes: home-based work (HBW) trip, home-based nonwork (HNW) trip, non-home-based (NHB) trip, and truck and taxi (TNT) trips. The calibration dealt exclusively with vehicle (automobile-driver) trips rather than with person trips. The zone structure used in the base calibrations is comparable to that used in conventional fixed-zone modeling: 504 zones represent a study region of 6500 km^2 (2500 $miles^2$), with approximately 5 million total vehicle trips daily in 1964.

Origin-destination data from a 4 percent survey in 1964 were converted to a production-attraction format and summarized to obtain observed trip tables and trip ends. (For HBW and HNW trips, the production end is the home end; for NHB and TNT trips, the production end is the origin.) The observed trip ends were input to the calibrations in order to study trip distribution in isolation from possible trip-generation errors. For calculation of travel disutility, or impedance, a 1964 network was used to construct zonal-interchange matrices for travel time, distance, and direct cost (tolls). The disutility measure used in ALDGRAV comprises a weighted combination of time, distance, and cost, plus fixed penalties assessed at the production and attraction ends according to area type.

The region was stratified into four area types: (a) major central business district (CBD) (Dallas and Fort Worth), (b) CBD fringe and outlying CBD, (c) remaining urbanized area, and (d) rural. The parameters to be calibrated were (a) the multiplier constant a in Equation 2, (b) the fixed penalties FPENO (production-end) and FPEND (attraction-end) associated with each area type, and (c) the cost per kilometer (C/KM) used to calculate intrazonal impedance, which is also stratified by area type.

Calibration of ALDGRAV is accomplished in a structured cut-and-try fashion. The a parameter is first adjusted to obtain the correct overall average trip length. The fixed penalties can then be used to adjust trip length by area type. Finally, the C/KM parameters are adjusted to obtain the correct interzonal percentages by area type.

The calibration criteria, used in comparing estimated and observed trip tables, consisted of the following:

1. The average interzonal trip length and the percentage of trips that are interzonal, by area type;
2. Aggregation to 39 districts and summary;
3. Assignment of the district-level trip table to a spider network to examine screenlines; and
4. The standard deviation and coefficient of skew for the zonal trip-length frequency distributions.

The first criterion is geared to obtain the correct vehicle kilometers of travel (VKT) in traffic assignment, since

Table 1. Standard deviations and coefficients of skew.

Trip Type	SD (km)	Coefficient of Skew[a]	Trip Type	SD (km)	Coefficient of Skew[a]
HBW			NHB		
Observed	9.89	1.85	Observed	8.71	2.77
Estimated[b]	10.00	1.90	Estimated[b]	7.65	2.24
HNW			Estimated[c]	7.97	2.46
Observed	8.05	3.13	TNT		
Estimated[b]	6.55	2.07	Observed	9.71	2.09
Estimated[c]	7.69	2.55	Estimated[b]	9.47	2.05

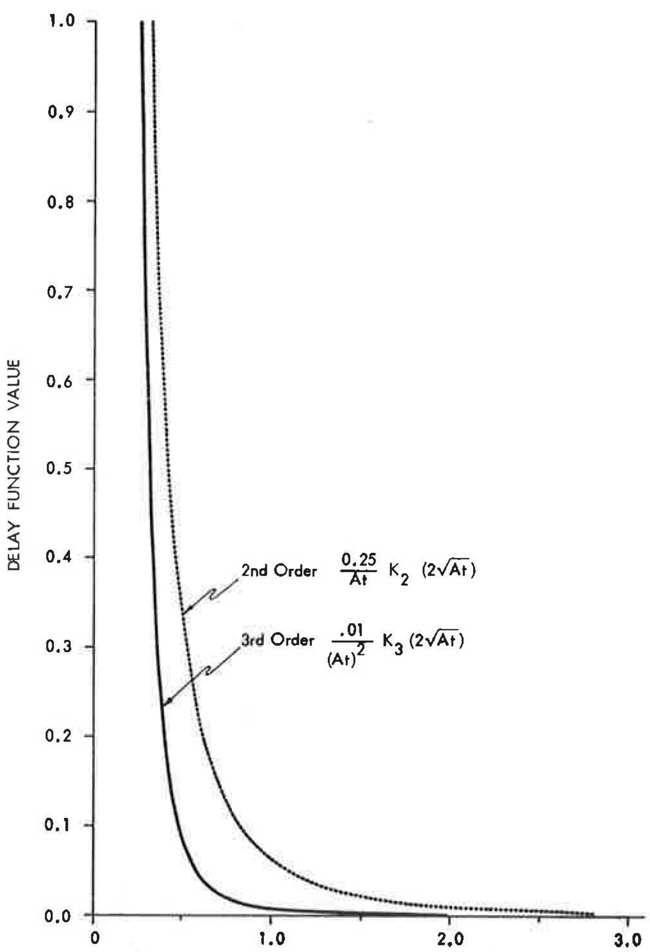
Note: 1 km = 0.62 mile.

[a]Coefficient of skew = $\sum_{i=1}^{n} (X_i - \bar{x})^3 / (n-1)SD^3$.

[b]With second-order Bessel function.

[c]With third-order Bessel function.

Figure 1. Second-order and third-order Bessel functions.



$$VKT = \text{average interzonal length} \times \text{interzonal percentage} \times \text{number of trips} \quad (3)$$

As described in the next section, the fourth criterion was particularly helpful in determining the distinctive nature of HNW and NHB trips and in pointing the way to model enhancements to better handle these trip types.

STABILITY ACROSS TRIP TYPE

Refinements to Better Handle HNW and NHB Trips

The base calibration of ALDGRAV initially used the modified Bessel function of second order and second type (Equation 2) for all four trip types. The results for HBW and TNT were generally accurate with respect to interzonal percentage and length, as well as the district-level summaries. The HNW and NHB results, however, were inconsistent. For these trip types the interzonal percentage and length were correct, thus theoretically guaranteeing correct VKT, yet the district-level spider assignment gave estimated screenline volumes that were too high. In fact, the estimated volumes were too high in general on the spider network, indicating that the model was estimating too many interdistrict trips, despite its calibration to give the correct number of interzonal trips.

It appears that the HNW and NHB categories comprised fewer long (interdistrict) trips than could be estimated by the base model calibrated to the correct average length. The HNW category, for example, includes subtypes that are very short (e.g., local shopping trips) and very long (e.g., recreational trips). It was thus surmised that the observed trip length must have a more skewed distribution than that estimated by the base model. To test this hypothesis, the standard deviation and the coefficient of skew for the trip-length distribution were introduced as calibration criteria. Comparisons shown in Table 1 confirmed that, for HNW and NHB, the skew coefficients derived by the base model (second-order Bessel function) were too low.

On the basis of these observations, it was decided to modify the ALDGRAV program to permit selection of Bessel functions other than the second order for use as the travel function. For HNW and NHB trips in particular, the desirable features would be a steeper slope for small impedance values and a more gradual, nearly flat slope for larger impedance values. The heightened sensitivity to smaller impedances would promote more short trips, while the relative insensitivity to larger impedances would promote more long trips. As shown in Figure 1, the modified Bessel function of the third order and second type possessed the desired features. Different forms of the Bessel function and their usefulness in trip distribution are discussed in Kurth, Schneider, and Gur (9). The third-order function was introduced and tested as the travel function for HNW and NHB, with substantial improvements, particularly for HNW. The skew coefficients obtained by means of the third-order function are also shown in Table 1.

It should be noted that an alternative approach to handling skewed distributions is to adopt a long-short stratification or a more-detailed breakdown of trip purposes (e.g., treat shopping trips separately from social and recreational trips). In this case, the gains in accuracy must be weighed against the additional data requirements and costs in modeling and processing.

Results

The results of the base model calibration (after modification to use third-order HNW and NHB travel function) are shown in Table 2. The interzonal percentage and average length are shown, stratified by area type and by production versus attraction. In almost all cases, the estimated value is within 5 percent of the observed value, assuring highly accurate estimation of VKT (see Equation 3), assuming correct trip generation.

The model parameters determined by the calibration are shown in Table 3 to illustrate the substantial difference in parameters across trip purpose and across area type. It should be noted that thus far the fixed penalties FPENO and FPEND

Table 2. Vehicle trip-length distribution summary.

Category	HBW[a]		HNW[b]		NHB[b]		TNT[a]	
	Observed	Estimated	Observed	Estimated	Observed	Estimated	Observed	Estimated
All trips	701 522	701 521	1 734 359	1 734 363	900 514	900 523	489 077	489 077
Interzonal (%)	92.4	90.7	68.8	65.3	79.7	79.4	75.7	74.6
Avg interzonal length (km)	14.31	14.37	9.50	9.76	10.11	10.00	11.32	11.69
SD (km)	9.89	10.00	8.05	7.70	8.71	7.97	9.71	9.47
Coefficient of skew	1.85	1.90	3.13	2.55	2.77	2.46	2.09	2.05
Area 1								
Productions	1748	1748	3471	3471	76 582	76 582	32 031	32 031
Interzonal (%)	100.0	99.3	98.4	99.5	99.3	98.9	97.0	97.9
Avg interzonal length (km)	6.95	6.90	6.81	6.71	8.69	8.53	6.32	6.32
Attractions	101 559	101 664	77 159	77 247	67 907	70 111	31 999	33 889
Interzonal (%)	100.0	100.0	99.9	100.0	99.2	98.8	97.0	98.1
Avg interzonal length (km)	13.81	13.53	12.31	11.66	8.53	6.85	6.35	6.48
Area 2								
Productions	183 988	183 989	410 740	410 741	303 339	303 348	148 725	148 725
Interzonal (%)	93.1	92.8	71.4	68.3	81.4	81.3	76.7	76.5
Avg interzonal length (km)	10.98	10.90	7.81	7.73	8.79	8.79	8.89	9.19
Attractions	223 901	224 031	549 975	553 410	306 474	313 430	148 837	154 097
Interzonal (%)	94.4	94.1	78.7	76.5	81.6	81.9	76.7	77.3
Avg interzonal length (km)	13.02	13.61	8.29	8.71	8.65	8.87	9.03	9.85
Area 3								
Productions	468 737	468 737	1 207 388	1 207 391	491 580	491 580	268 865	268 865
Interzonal (%)	92.9	90.8	68.3	64.2	76.4	75.6	74.3	72.3
Avg interzonal length (km)	14.71	14.76	9.56	9.68	10.79	10.55	12.47	12.74
Attractions	349 964	349 675	1 021 882	1 024 082	496 400	493 429	268 498	266 290
Interzonal (%)	90.5	87.6	62.5	57.8	76.6	75.7	74.3	72.0
Avg interzonal length (km)	15.00	14.87	9.50	9.82	10.85	10.98	12.37	12.81
Area 4								
Productions	47 047	47 047	112 760	112 760	29 013	29 013	39 456	39 456
Interzonal (%)	83.8	81.2	63.9	64.1	66.5	71.4	63.6	64.8
Avg interzonal length (km)	24.56	25.77	15.89	18.77	19.45	19.85	19.50	21.44
Attractions	26 096	26 151	85 343	79 624	29 733	23 553	39 743	34 801
Interzonal (%)	70.8	66.1	52.3	49.2	67.3	64.8	63.9	60.1
Avg interzonal length (km)	19.74	19.60	16.48	16.39	19.53	18.92	19.40	20.26

Note: 1 km = 0.62 mile.

[a]Based on second-order Bessel function. [b]Based on third-order Bessel function.

Table 3. Calibrated parameters.

Category	HBW[a]	HNW[b]	NHB[b]	TNT[a]
a (¢$^{-1}$)	0.0196	0.0080	0.0071	0.0161
FPENO (¢)				
Area 1	117	125	185	50
Area 2	73	26	60	30
Area 3	53	10	33	30
Area 4	15	0	0	0
FPEND (¢)				
Area 1	117	70	25	0
Area 2	73	0	0	0
Area 3	53	0	0	0
Area 4	15	0	0	0
C/KM (¢/km)				
Area 1	37.2	33.0	57.2	22.5
Area 2	13.1	57.2	49.8	23.1
Area 3	10.3	57.8	49.8	21.3
Area 4	15.5	46.7	46.1	29.3

Note: 1 km = 0.62 mile.

[a]Second-order Bessel function. [b]Third-order Bessel function.

have been treated strictly as parameters; i.e., no attempt has been made to relate these to underlying real-world penalties, such as parking cost and terminal time. Possible relationships will be explored in future work as a means toward providing sensitivity to parking management, automobile-free zones, and other TSM policies that affect trip-end impedance.

STABILITY UNDER SUBAREA FOCUSING

Test Design

The models described in the previous section were calibrated on a zone structure appropriate for regionwide analysis, specifically 504 intermediate-sized regional analysis areas (RAAs). The issue addressed in this section is the stability of trip distribution under focusing of the zone structure for detailed planning within subareas.

As is shown in Figure 2, a subarea was selected and a focused zone structure delineated for its analysis. The subarea, comprising 299 fine-grained traffic survey zones (TSZs), is surrounded by a buffer of 154 intermediate-sized RAAs; the rest of the region is aggregated to 34 districts. For testing trip distribution in this subarea context, observed trip tables and trip ends were derived from 1964 data for the focused zone structure, and matrices for travel time, distance, and cost were similarly constructed.

The stability test consisted of applying the base models to the subarea and examining possible discrepancies arising from variation in zone size. Of primary concern were the interaction between the subarea and the rest of the region, and stability in the number of interzonal trips emanating from zones of varying size. For analytical purposes, trips were stratified into four classes: (a) subarea-subarea, (b) subarea-external (all zones outside the subarea are collectively denoted "external"), (c) external-subarea, and (d) external-external.

Comparison criteria for assessing the accuracy of the subarea-external interface included (a) number of trips falling in each class, (b) average trip length for each class, and (c) the contribution by each class to VKT within the subarea. (To measure subarea VKT, a special matrix was constructed by reskimming distance over subarea network links only. Multiplication of this matrix by a trip table yields subarea VKT on each interchange.) In addition, the interzonal percentages were examined for class 1 (small zones) and class 4 (dominated by the very large zones) trips.

Figure 2. Subarea definition.

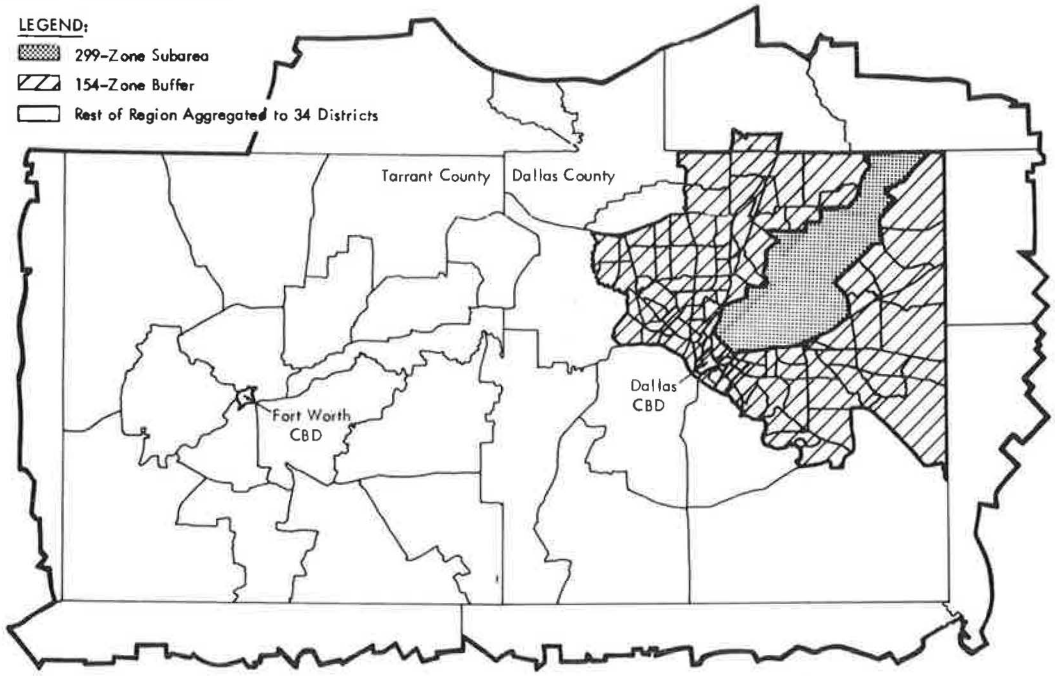


Table 4. Stability under subarea focusing for HBW and HNW trips.

Category	HBW Trips Observed	HBW Trips Base Model	HBW Trips Model with Zone-Size Parameters	HNW Trips Observed	HNW Trips Base Model	HNW Trips Model with Zone-Size Parameters
All trips	701 553	701 553	701 554	1 733 998	1 733 998	1 733 998
Interzonal (%)	78.1	68.1	76.5	49.3	61.9	50.9
Avg interzonal trip length (km)	17.82	17.23	18.11	12.82	15.45	13.35
Subarea VKT	810 552	798 906	803 192	1 049 858	966 989	984 073
Error (%)[a]		-1.4	-0.9		-7.9	-6.2
Subarea-subarea	34 665	33 682	34 075	166 616	175 817	173 059
Interzonal (%)	96.7	97.4	97.3	92.5	80.1	85.3
Avg interzonal trip length (km)	5.87	6.19	6.16	3.61	3.45	3.45
Subarea VKT	178 573	185 361	186 497	533 127	469 050	492 234
Error (%)[a]		+0.8	+0.9		-6.1	-3.8
Subarea-external	64 522	65 505	65 112	59 211	50 010	52 768
Avg interzonal trip length (km)	15.19	14.32	14.73	13.35	11.11	10.53
Subarea VKT	358 321	354 252	350 018	266 955	184 144	195 835
Error (%)		-0.5	-1.0		-7.9	-6.7
External-subarea	24 939	25 458	26 609	40 531	50 953	48 836
Avg interzonal trip length (km)	19.32	17.89	18.47	13.90	15.00	13.79
Subarea VKT	132 027	124 963	130 316	168 748	219 719	209 381
Error (%)[a]		-0.9	-0.2		+4.9	+3.5
External-external	577 427	576 908	575 578	1 467 640	1 457 218	1 459 335
Interzonal (%)	73.6	61.3	71.5	40.9	57.1	43.3
Avg interzonal trip length (km)	19.08	18.74	19.58	15.05	17.77	15.85
Subarea VKT	141 631	134 331	136 361	81 027	94 076	89 848
Error (%)[a]		-0.9	-0.6		+1.2	+0.8

Note: 1 km = 0.62 mile.

[a]Calculated as percentage of total observed subarea VKT.

Base-Run Results

A set of base runs was first made by applying the models from the regionwide calibration directly to the subarea. Base runs were made for HBW, HNW, and NHB trip purposes.

For HBW trips (see Table 4), base-run estimates for number of trips and for subarea VKT, by trip class, were quite accurate. The base-run average length is too short, however, for subarea-external and external-subarea trips. Further, the interzonal percentage for external zones is too low. It was hypothesized that both problems could be corrected by increasing the interzonal percentage for large zones, thus generating more travel from outlying districts and thereby reducing the excessive "pull" between the subarea and nearby external zones.

For HNW trips (see Table 4), the base run estimated too many subarea-subarea trips and too few subarea-external trips, while the subarea-subarea VKT was underestimated. These results are seemingly explained by the underestimated interzonal percentage for subarea zones. Also, there were too many external-subarea trips, a probable result of the excessive interzonal percentage for large zones. The proposed solution was to increase the

Table 5. Percentage change in intrazonal cost per kilometer stratified by zone size.

Trip Purpose	Zone Size 0-0.65 km^2	0.65-2.6 km^2	2.6-10.4 km^2	10.4-41.6 km^2	>41.6 km^2
HBW	-11	+4	+28	+48	+107
HNW	+40	+20	+16	-4	-27
NHB	+28	+19	+13	-10	-32

Notes: 1 km^2 = 0.38 $mile^2$.
The percentages of increase or decrease from the regionwide C/KM values are applied to each area type.

HNW interzonal percentage for small zones and to decrease it for large zones.

The NHB base-run results showed discrepancies similar to those for the HBW base run, although the NHB base run was more accurate overall. Similar adjustments to interzonal percentages were prescribed.

Model Refinements and Subsequent Results

In order to make the desired adjustments to the interzonal percentage by zone size, the intrazonal C/KM factor was stratified by zone size within area type. The C/KM factors directly affect the interzonal percentage by making intrazonal travel more or less attractive. An increase in C/KM results in an increased interzonal percentage and vice versa. It was hypothesized that travel speed of intrazonal trips and, thus, the C/KM vary with the zone size.

The parameter modifications are represented in Table 5. For HBW trips, the C/KM was increased for larger zones in order to increase the interzonal percentage for larger zones. For HNW and NHB trips, the C/KM for large zones was decreased in order to reduce the interzonal percentage for large zones, while the C/KM was increased to obtain higher interzonal percentages in the small zones.

Table 4 shows the results obtained by these refinements. Substantial improvements can be noted with respect to the discrepancies in the base-run estimates. For HBW trips, the estimated average lengths for subarea-external and external-subarea trips more closely approximate the observed values. For HNW trips, the breakdown of trips and subarea VKT, by trip class, are somewhat improved, although some discrepancies can still be discerned. Results for NHB trips were similar to those observed for HNW trips. For all three trip purposes, model refinements resulted directly in much-improved interzonal percentages, with concomitant improvements in most of the remaining values.

Interpretation and Implication of Refinements

The work described in this section suggests that (a) direct transfer of a conventionally calibrated gravity model to a focused zone structure may result in discrepancies because of variation in zone size and (b) refinements to permit explicit treatment of zone size in intrazonal calculations may lead to significant overall improvement in accuracy. To deal effectively with this problem, however, further experimentation with different subareas will be necessary for development of a generalized strategy for setting parameters by zone size. A number of factors specific to the subarea studied in this section may have affected the results: assumptions made in defining layers of zonal detail, layers of network detail, the construction of approach links and calculation of approach-link impedance, and possibly other factors pertaining to the type and location of the subarea within the study region.

Table 6. Temporal stability comparisons.

Trip Type	1964 Observed	1964 Estimated	1977[a] Observed	1977[a] Estimated
HBW				
Total trips	701 522	701 521	1 139 920	1 119 436
Interzonal (%)	92.4	90.7	95.0	90.5
Avg interzonal length (km)	14.31	14.37	16.79	17.31
HNW				
Total trips	1 734 359	1 734 363	2 233 497	2 907 725
Interzonal (%)	68.8	65.3	75.0	73.4
Avg interzonal length (km)	9.50	9.76	11.35	11.89
NHB				
Total trips	900 514	900 523	1 581 566	1 588 449
Interzonal (%)	79.7	79.4	82.8	82.0
Avg interzonal length (km)	10.11	10.00	12.89	11.66

Note: 1 km = 0.62 mile.

[a] Differences between observed and estimated total trips for 1977 may be caused by inaccuracies either in the small-sample home-interview survey (observed) or in the 1964-based synthetic trip-generation rates (estimated). Actually, the corresponding totals are quite close except for the HNW category, where underreporting of trips in the home-interview data is suspected.

One approach to a generalized strategy would be to tie the parameter adjustments by zone size to measurable real-world phenomena. For example, the reduced large-zone C/KM values adopted for HNW and NHB trips could possibly be related to the fact that in large zones the intrazonal trips are longer and thus attain faster and more efficient speeds, in turn implying lower real-world costs per kilometer.

TESTS FOR TEMPORAL STABILITY

Test Design

For long-range analysis of capital alternatives, either at the regional or at the subarea level, it is essential that trip-distribution models possess stability through time and changing development patterns. The models described above were calibrated by using 1964 survey data. To test the models for temporal stability, it was decided to apply them in a recent (1977) base-year setting.

During the 13-year lapse between base years, the North Central Texas study region underwent substantial growth and shifts in socioeconomic development. Population grew by 41 percent, industrial employment by 33 percent, and service employment by 97 percent. Considerable urban sprawl occurred, and a number of suburban towns grew into medium-sized cities during this period. In preparation for the 1977 test runs, vehicle trip ends were derived from 1977 socioeconomic data by means of synthetic trip generation. A 1977 highway network was used to construct zonal-interchange matrices for travel time, distance, and cost. The zone structure selected for the test was the intermediate-level 504-RAA set typically used in regionwide analysis.

To provide a comparison with observed 1977 trip patterns, regionwide HBW, HNW, and NHB average trip lengths and interzonal percentages were derived from a small-sample home-interview survey (the Urban Area Citizens Survey) made in 1977 (10). The travel data, taken from 1158 households representative of the study region, included 10 500 trip records. The regionwide values were used as the primary criteria for comparison; more-detailed comparisons were not attempted because of the sparseness of the observed trip data for 1977 and because 1977 estimates for specific trip interchanges could be significantly affected by errors in the synthetic trip generation.

Results

The test results are shown in Table 6. The increase in total trips from 1964 to 1977 reflects, of course, the growth in development during this period. The substantial increases in the observed trip lengths, for all three trip purposes, reflect the increased dispersion of activity. Despite these changes, however, application of the 1964-based models to 1977 data closely approximates the observed regionwide trip lengths and interzonal percentages for 1977. It appears that there are no significant biases, except possibly for NHB average trip length, which is underestimated by 10 percent.

CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

From the stability tests described in this paper, the following conclusions are drawn:

1. Trip lengths for HNW and NHB trips appear to have more-skewed distributions than those for HBW and TNT trips, which may be a reflection of a short versus long dichotomy within the HNW and NHB categories.
2. Incorporation of a family of travel-function curves, e.g., the Bessel family, selected according to the underlying degree of skewness, appears to be a cost-effective approach to attaining stability across trip type.
3. To attain stability under subarea focusing, refinements to permit explicit treatment of zone-size variation are desirable, if not absolutely necessary.
4. It appears that a key determinant of stability under focusing is the calculation of intrazonal trips, and refinements to allow stratification by zone size appear to be a promising avenue to improved stability.
5. Limited testing indicates that the models described in this paper possess an encouraging degree of stability through time and development patterns.

At least two pressing needs for further research can be identified. The first concerns the fixed penalties, FPENO and FPEND, assessed at the production and attraction end, respectively. If these parameters can be successfully related to real-world trip-end impedances such as parking cost and walking distance, it will be possible to capture the sensitivity of trip distribution to such TSM policies as preferential parking, automobile-free zones, and parking cost strategies. Second, further experimentation with subarea focusing is required to derive generalized rules for handling variation in zone size. The discussion in the section on stability under subarea focusing suggests an approach to improved stability under focusing, but the parameter values derived there may be dependent on the specific problem studied, assumptions concerning approach-link impedances, etc. A generalized strategy for stratifying parameter values by zone size is needed, preferably a method that permits calculation from observable phenomena.

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New Techniques for Integrating Census Bureau Data and Software with the Urban Transportation Planning System

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A technology transfer project between the U.S. Bureau of the Census and the Urban Mass Transportation Administration has made Census Bureau software products and simplified Census Bureau data-access procedures available to the users of the Urban Transportation Planning System (UTPS). The Census Bureau software systems for geocoding and computer mapping, as well as utilities for zone definition and area boundary extraction, have been integrated into UTPS

by means of the UTPS Procedure Generation System (UGEN). These software products make census data and software more accessible to the transportation planning process. Geocoding provides linkage to census data areas, user-defined data zones, and geographic coordinates. The mapping software allows quick and easy data display. New software modules for a geographic-data-management system are also being developed. These include the creation of an integrated geographic data base, access methods for the data base, and specific application packages such as address matching.

The Urban Transportation Planning System (UTPS) provides the transportation planner with state-of-the-art methods for the analysis of multimodal transportation systems. UTPS consists of software, documentation, and users' guides and manuals that cover both computerized and manual planning methods. The computer programs are flexible and user oriented; they constitute a major contribution to the current inventory of techniques at the planner's disposal (1). A recent technology transfer project between the Urban Mass Transportation Administration (UMTA) and the U.S. Bureau of the Census has added to this inventory of software by making available software for access to and use of census data.

The Census Bureau provides a wide variety of socioeconomic and demographic data, as well as geographic reference information. In the early 1970s, the Census Bureau developed several computer systems to facilitate the use of its data products. Many of these Census Bureau data and data-application products are useful in the transportation planning process. The systems for address matching and generalized record linkage (UGEO) and line-printer mapping (UCHORO and UGRIDS) have been incorporated into UTPS. Utilities for the definition of planning zones for subsequent address-matching and mapping purposes (UDIME) have also been added to UTPS. The boundary-extraction feature of UDIME is now being added to UTPS. In addition, modules of a geographic data-management system (GDMS) are currently being developed. Facilities for the creation of an on-line geographic data base (GeoModel) and for interactive address matching (ADMATCH'80) have been completed and are ready to be incorporated into UTPS.

Through UTPS, the transportation planner now has convenient access to all of these Census Bureau software products, as well as simplified access to actual census data.

CENSUS DATA IN THE TRANSPORTATION PLANNING PROCESS

Census data are reported in accordance with census geography areas. The boundaries of these areas are generally delineated along the street network and other recognizable boundaries for an area. Thus, the units by which data are reported are areas that can be identified geographically in terms of a linear network. The various census summary tapes contain the statistical data themselves. Specific data files provide data users with geographical reference information concerning the location of these areas.

Census Bureau data are reported according to census geography areas, which range from the block level to the entire United States. These areas are structured in a basic hierarchy of block, block group, tract, county, and state. None of these areas crosses the boundaries of the next-higher area. The areas may be thought of as being "nested." Each area is identified by an identification code for that area type.

There are other area types that are delineated and identified by codes, including standard metropolitan statistical area (SMSA), place, minor civil division and census county division, congressional district, area code, and postal zip code. Some of these represent aggregations of other area types, but they may cross boundaries of the basic area hierarchy.

A geographic base file/dual independent map encoding (GBF/DIME) file is a machine-readable, geographically coded reference file developed by the Census Bureau. It represents a model of the street and block network of an area, usually an SMSA. A GBF/DIME file consists of one record for each street segment. The record contains census geography-area identifiers (i.e., block, tract, county, state, and zip) for the left and right sides of the street segment and the coordinates of the endpoints of the segment. The address range for each segment is also contained on the record (2).

Any of this geographic information may be obtained for any known address within the SMSA through the process of geocoding. For any given address, the street segment on which it is located can be identified. The area code on that specific side of the street segment is then available and may be linked to the original data record that contains the address. In the same way, the coordinates of the intersection at either end of the street segment may be linked to the user's address-related data records.

Although the GBF/DIME files contain geographic coordinates for nodes only, the coordinates of any particular address or of block centroids may be interpolated from these. These points may then be mapped. The GBF/DIME file already contains all the information necessary to map the entire street network of an SMSA or any portion of it. In addition, there are Census Bureau programs that will automatically extract the coordinates of the boundary segments for specified area types. These areas may then be mapped.

DATA INTERFACE WITH UTPS

The transfer of Census Bureau software and data-use technology into UTPS was accomplished by means of the UTPS Procedure Generation System (UGEN). The software provided through this system includes address matching, line-printer mapping, zone definition, and automatic boundary extraction for mapping. Most of this software makes use of GBF/DIME files. The UGEN system handles the execution of the software necessary for any particular process and also handles the necessary manipulation of the GBF/DIME file for that process. However, the existence of the UGEN system itself is practically transparent to the UTPS user. Each application process is operated like other UTPS programs.

UGEN System

The UGEN system was designed to simplify the use of existing Census Bureau software systems that are inherently complex and to automate the specification of these processes for the UTPS user. The usual method of preparing program control cards and the necessary job-control language (JCL) statements for these processes is a labor-intensive and error-prone task. This task may be further complicated for UTPS users when the programs to execute these processes were developed for a context external to UTPS. The user generally prepares a deck of JCL cards and program parameters for an application and submits this deck to the computer-operating system as a job to be executed.

UGEN simplifies this process by acting as an intermediary between the user and the operating system. The user submits the job to UGEN, and UGEN creates a job that is submitted to the operating system. The parameters and specifications that UGEN requires in order to do this are much simpler than those required by the operating system. In the case of the UTPS user, these parameters and control words are in the format required by other UTPS programs. The UTPS user executes a UGEN program (referred to as a macro-procedure) as he or she would any UTPS program. The UGEN macro-procedure then handles the necessary JCL and executes the Census Bureau programs to perform the specific task. Thus, UGEN reduces the drudgery, complexity, and redundancy involved in the specification of sophisticated processes, as well as the learning time required to familiarize oneself with the use of these systems. The UTPS user need not be concerned with the operation of UGEN itself, since UGEN macro-procedures are called on in the same manner as those of other UTPS programs.

The Census Bureau software products that are available through UTPS are address matching, generalized record linkage, line-printer graphics systems, and utilities for the creation of user-defined zones for address matching and mapping (3). These Census Bureau products, which have been integrated into UTPS, facilitate the data input and display functions of the transportation planning process. Geocoding and zone definition facilities make census data and geographic reference information readily available for use in modeling processes. The mapping software provides automatic boundary extraction and graphic display facilities that are easy to operate.

Address Matching

Many transportation and urban planning processes use data files that contain street addresses in the records. For many applications, it is desirable to link certain geographic codes or identifiers to these files. A geographic identifier may be a census tract, a traffic zone, a school district, a Post Office zip code, a policeor fire-reporting district, a block, a congressional district, a pair of geographic coordinates, or any other identifier available. The linking of these geographic codes to data records creates a cross-reference between the data record and other data available according to these geographic areas, such as the census summary tapes or the UTPS zonal data files. Some geographic codes also provide the locational attribute needed to carry out various forms of spatial analysis and mapping.

The process of determining the proper geographic code or identifier for a location defined in terms of address is termed geocoding (or address matching). Geocoding is a special case of the record linkage problem. Record linkage involves two files: a data file that lacks certain information and a reference file that will provide that information. The process involves the comparison of each data file record with records on the reference file in order to find the best match. Once the best reference file record is found, information can be transferred, or linked, to the data file record, thereby providing it with information that it previously lacked. The basis of the linkage process is information that is present in both files, and the result is the transference of information to the data file.

The most rudimentary example of the record linkage process is file updating. In such a case the master file, or data file, must receive information from the transaction file, or reference file. The master file is examined sequentially by using a critical key (such as the record control number) to provide the basis for linkage. When the keys match for a record on each file, the information can be transferred. Another simple example of record linkage is record selection, whereby values on a data file are compared with a list of acceptable values (the reference file). If the data file record contains one of the acceptable values, it will be selected.

Geocoding is a specific application of the record linkage process. The data file, which contains the address information, is matched with a reference file that contains the geographic codes. These codes can then be added to the data file. Address matching is useful for a number of applications. For example, a company may wish to add Post Office zip codes to mailing lists that contain addresses only. The same company may wish to consolidate two mailing lists in order to remove duplicate entries. This entails removing the records that constitute the logical intersection of the two files. In practice, this involves matching, with either file serving as the reference file and with all records that match the data file being discarded. The remaining records (or match rejects) can then be merged with the data file (4).

A transportation planning application may involve geocoding any data file that contains addresses so that traffic zones or census tract codes may be obtained. Once the tract, zone, or other area identifiers have been added to the data file, files that contain data arranged by these areas may be accessed through these codes. For example, origin-destination survey data could be geocoded, thus linking these data to tract data or zone data by means of the geographic code obtained from the matching process. Any other data files containing address information could be geocoded in the same manner. Another important application of geocoding is adding geographic coordinates to a file for the purpose of computer mapping.

In general, geocoding involves linking any type of available geographic code from a reference file onto the appropriate records of a data file. Specifically, the geocoding system available through UTPS links geographic codes found on the Census Bureau's GBF/DIME files with the user's data file. By using the GBF/DIME file as the reference file, the geocoding process involves matching the address (house number and street name) of the records on the data file with the street names and address ranges of the records on the GBF/DIME file in order to obtain the record for the proper street segment. Depending on the side of the segment on which the address falls, the desired type of area code for that side can be linked with the data record. This area code may be for the block, tract, state, county, SMSA, place, minor civil division, zip, or zone identifier. In the same way, the coordinates found on the GBF/DIME file for the particular segment matched may be added to the data record. In addition to the standard census areas and coordinates found on the GBF/DIME files, the user may define planning zones in terms of census areas and may match with these zones.

Geocoding provides address data with the geographic codes needed to access related area data. It also may provide the geographic coordinates for other spatial analyses and mapping. This geographic linking for access purposes makes it easier to incorporate census data into the UTPS modeling systems. Census population, housing, and economic statistics can be accessed at any available level of geography by using the geographic codes obtained through the geocoding process. User-defined planning zones may also be accessed in the same way. Thus, for any particular address, a cross-reference can be established to any data available for the chosen area type into which the address falls--census blocks, tracts, or other planning zones.

The UTPS facility for performing address matching is UGEO, which is a UGEN macro-procedure. UGEO handles the necessary preprocessing of the GBF/DIME file and uses the Census Bureau's ZIPSTAN and UNIMATCH programs to perform address matching. UNIMATCH is a generalized record linkage system that performs all of the various record linkage tasks and the specialized task of address matching (5).

Computer Mapping

It is often desirable to map data that have locational information in order to better understand the spatial characteristics of the data distribution. For example, population or income data could be mapped by census tract to show the distribution across a county. This type of data display by area is termed choroplethic mapping. The variation in data values across areas is represented by different symbolism filling each area. A variation of choroplethic mapping is grid-cell mapping, wherein point data are aggregated to grid cells. For example, average housing values at points representing block centroids may be aggregated to a grid-cell system to show the distribution of such values across a county.

A quick and easy way to produce maps is by means of line-printer mapping packages. Such packages are fairly simple to use and, since most computer installations have line printers, this type of mapping does not require special equipment or personnel.

Two general-purpose line-printer mapping programs have been made available in UTPS through UGEN. These are EASYMAP, a choroplethic mapping program, and GRIDS, a grid-cell mapping program. Both require coordinate and data-value information and a few mapping parameters. The user must decide which of the two mapping techniques is better suited to the presentation of particular data. This choice is based on the number of unique points or areas for which data are available and on their spatial distribution. If areal information is available (such as the boundary coordinates of traffic zones, tracts, counties, or states), then the choroplethic display technique produces the most attractive presentation, provided the areas are not too small or numerous for the scale chosen. If point information is available [such as street intersections (nodes) or centroids of zones], then the grid technique produces an attractive presentation, provided the coverage of the point data is fairly complete with respect to the scale chosen.

The mapping software in UTPS allows quick, easy data display. With very few mapping parameters, choroplethic maps may be produced for area data. The automatic extraction of the boundaries of any specified set of areas frees the user from preparing an input boundary file. For instance, if planning zones had been previously defined, the boundaries could be automatically extracted, and the zone could be mapped by using any zonal data file desired. All census geography areas may also be mapped automatically in this manner. Aggregated grid-cell maps may be produced for point data. The point locations for these data may have been derived previously from a geocoding run. For example, addresses from an origin-destination survey could be geocoded to obtain node coordinates, and the resultant data could be aggregated and mapped at any specified resolution. Street networks themselves may be mapped through a combination of the proper option in either UGRIDS or UCHORO. Again, the coordinates are obtained from the GBF/DIME files.

These mapping systems are used in UTPS through the macro-procedures UGRIDS and UCHORO. Not only is the specification of data format and mapping parameters simplified through the UGEN system, but the formats of these specifications have been made compatible for the two systems. This makes it easier for a UTPS user to learn and to use these mapping packages (6-8).

Zone Definition

Census geography divides space into a system of levels of subareas by which data are collected and reported. These include block, block group, tract, city, county, place, and state. However, these particular areas may not be ideal for every application. In some cases it may be desirable to refer to data arranged by other types of areas.

A utility now available through UTPS allows the user to define zones in terms of census geography. A system of zones may be created by defining each zone as a combination of census geography areas. These zone codes may then be matched in an address-matching pass, just as other geographic areas may. The zone boundaries may also be extracted for mapping, as may other census-area boundaries.

The macro-procedure that provides these utilities is a GBF/DIME file preprocessor called UDIME. According to the options and specifications given, UDIME prepares a GBF/DIME file for geocoding with UGEO, adds zone definitions or redefinitions to this file, and extracts area boundaries for mapping. For example, a particular set of planning zones may be created in which each individual zone is defined as a combination of census geography areas. Addresses could then be geocoded to these zones, rather than to census tracts, blocks, etc. These zone boundaries may subsequently be extracted to form a boundary file for mapping by means of UCHORO.

GEOGRAPHIC-DATA-BASE MANAGEMENT SOFTWARE

Although these software products provide many spatial data-handling and planning-application functions, there is still a need for integrated modules for use in geographic-data-base management. Research and development in this area, whose purpose is to integrate such modules into UTPS, is currently under way, and a geographic-data management system for transportation planning applications is currently being developed. The data base for the system is derived from the GBF/DIME files and is based on the topological relationships inherent in these files. The data-base access methods are based on these topological relationships between map entities and the set relationships between hierarchical systems of nested areas. This data model and set of access methods is referred to as GeoModel.

The GeoModel data base may be accessed directly through any element, whereas a GBF/DIME file must be accessed sequentially. GeoModel represents the creation of a geographic data base from the information contained in the GBF/DIME files and the integration of this information with other user-supplied geographic information, e.g., zones. Such a data base can support low-level data access and manipulation by computer programmers and high-level application software that can be readily used by nonprogrammers. Application software, such as address matching and network editing, are also currently built around this data base. These data-base creation, access, and application functions are available as independent software products themselves. The following sections describe the creation of the data base and the geocoding modules that have now been delivered and will be incorporated into UTPS shortly.

GeoModel

GeoModel is a system of data structures and access methods that provide a geographic data base for a wide variety of planning functions. GeoModel consists of a data storage system; various input, manipulation, and output subsystems managed under a control language; and special-purpose application packages. The purpose of GeoModel is to provide the planner with access to an integrated, flexible geographic data base that does not dictate how the data must be structured or which sort of application must be used. The approach is not to anticipate what the user will want to do, but rather to provide a means to combine primitive access functions in many different ways. The data access facility, implemented as a language that is extensible and recursive, permits the planner to build complex access, edit, and display functions. The system may then be used in ways that the designer never anticipated. In short, the design philosophy was not to provide highly structured user application packages but to provide basic and powerful data access functions that could be developed and combined to form utilities tailored to the specific needs and applications of various users (9).

The skeleton of GeoModel is created from the Census GBF/DIME file. This file constitutes a model of a map of a street network. It contains the topological relationships between the map elements--street segments, nodes, and blocks--and the census geography-area codes for each block--block number, block group, tract, etc. The GeoModel data base maintains the topological links between map elements, as well as the set relationships between the various levels of geography. An important goal of GeoModel, however, is to insulate the planner, to whatever extent is desired, from the census-defined geography. The planner may define units that are most useful to him or her and may operate exclusively in these units.

Creation of a GeoModel Data Base

The basis for the GeoModel structure is the GBF/DIME file. A program called GMLOAD converts any given GBF/DIME-format file into the GeoModel on-line data base. Several integrated files are created, including a street-segment file, a node file, a block file, and files to support applications such as address matching. These files are interrelated according to the topological relationships on the GBF/DIME file.

Access to the data base is very flexible and, by using the data-access language or any other means developed by the user, complex data-access and manipulation capabilities may be developed. The data base may be accessed directly through any particular element (a street segment, for example) and the related elements may then be found (the bounding nodes and blocks, in this case). Basically, the information available after the initial creation of GeoModel is the same as that on the GBF/DIME file, but the GeoModel data structure makes it possible to access it directly, quickly, and in many different ways.

ADMATCH'80

ADMATCH'80 is an example of how the GeoModel data base may be accessed and used. ADMATCH'80 represents a new concept in geocoding technology. The ZIPSTAN-UNIMATCH operation is based on syntactical and pattern-recognition preprocessing. ADMATCH'80 bypasses all preprocessing and sorting, and it derives its match scores directly from the distribution of address components in a particular city. Thus, ADMATCH'80 automatically adjusts itself to the characteristics of the specific area being processed. Access to the data base is through the phrase files for street names that are to be matched with the incoming address. If the match is successful, the street-segment record for that address is retrieved.

ADMATCH'80 is an interactive address-matching system. It can match a single address or an entire address list interactively or in batch mode. In interactive mode the user will be presented with a list of match candidates for ambiguous addresses. By using ADMATCH'80 and access methods to the data base, related operations (such as intersection matching) may be performed.

SUMMARY

The integration of Census Bureau software products into UTPS has made new procedures and data access available to the transportation planner. Many of these techniques would be complex and time consuming if performed by user-developed methods or even through the use of the available Census Bureau packages. The UGEN system has simplified the use of geocoding and computer-mapping software for the UTPS user. Further developments in the area of geographic-data-management modules and related applications will make even more flexible and diversified techniques available to the transportation planner.

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Introduction to Aggregate Data Analysis by Using UTPS: UMATRIX

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The effectiveness of any transportation planning operation depends largely on its ability to acquire, manipulate, and present data. The Urban Transportation Planning System program UMATRIX, a powerful data manager, provides the transportation planner with capability in summarization, modification, and display of data. As numerous examples ranging from simple data preparation to application of complex travel-demand-forecasting models demonstrate, the UMATRIX user can access a variety of data forms and can accomplish analytical chores that have been difficult and time consuming. UMATRIX's ease of operation provides an effective and flexible tool for the transportation planner.

The effectiveness of any transportation planning operation depends largely on its data-management ability. In the evaluation of long-range strategies, the analysis of short-range tactics, or merely the observation of the status quo, a planner collects, refines, forecasts, summarizes, and reports data. The Urban Transportation Planning System (UTPS) consists of computerized and manual planning techniques developed, maintained, and distributed by the Urban Mass Transportation Administration (UMTA) and the Federal Highway Administration. New UTPS software that readily creates and manipulates particular types of data considerably reduces the time and cost of transportation planning. This paper describes one of these new programs--UMATRIX.

DATA TYPES

The planner must understand and forecast both the transportation and the demographic characteristics of the region. The data consist initially of network data (which describe the highway and transit infrastructure), survey data (household interviews, on-board surveys, cordon counts, etc.), and data from secondary data sources (Census Bureau information, marketing service summaries, etc). As the planner processes this large data base, he or she creates additional data for purposes of forecasting, plan evaluation, and decision making. Although they are of enormous variety in substance, a large portion of the planner's data falls into two categories: zonal data and interzonal data.

Zonal Data

Zonal data are collected and aggregated into some predetermined geographic "areal unit" configuration. Zonal data (whether forecast or observed) provide such information as population, average income per household, dwelling units, trip attractions or productions stratified by trip purpose, transit route miles, vehicle miles traveled, lane miles, carbon monoxide emissions, energy consumption, and total congestion time for each unit of local geography. Zonal data are read and written by numerous UTPS programs. Among these are UCEN70, MBUILD, AGM, UMODEL, and UMATRIX.

Figure 1 shows a hypothetical five-zone region; population figures are printed along with the zone number. Each zone's specific zonal population value is shown in Figure 2 as an indexed list for the zonal attribute "population". This can be imagined as a single array that has two components: an implicit row index and an explicit cell value. Stored in the array is a list of attribute values (LAV) in which each cell value contains the data for the zone whose number corresponds to the cell's row index (e.g., in cell 5 resides the value of population for zone 5--5900 persons).

Interzonal Data

While zonal data attributes are related to individual entities, interzonal or matrix data are related to a pair of entities. These matrix data relate various characteristics to a given set of origins and destinations. Often these values are summed from the individual link data that constitute the network, and each cell value represents a value for time, trips, fares, modal shares, or distances from one zone to another. Interzonal data constitute the input and output of numerous UTPS programs, notably UROAD, UPATH, AGM, and UMATRIX.

Interzonal data provide a matrix that gives a value for a trip from origin zone I to destination zone J. Figure 3 shows peak-hour home-based-work (HBW) person trip values from zone 5 of a hypothetical region to all other zones. Trips from zone 5 and all other regional trip interchanges are shown in Figure 4. In this case, this matrix of interchange values can be shown as a table of cells that has three components: a row index (I), a column index (J), and a cell value. Thus, for example, for a five-zone region, the matrix contains 25 cell values of trips between each origin and destination zone pair. Row 5 and column 3 refer to the number of peak-hour HBW person trips (230) from origin zone 5 to destination zone 3.

UMATRIX

The UTPS program UMATRIX is a powerful zonal and interzonal data-management system. It provides the planner with complete data-analysis capabilities. It accommodates the large range of data forms required for transportation planning, including matrix data, household surveys, zonal-based demographics, and network characteristics.

The UMATRIX user can access various input data types and modify, update, display, and create new data required for demand estimation, traffic assignment, and system evaluation. Its simple, algebraic command language provides the user with arithmetic (+, -, *, /) and logical (if-then-else) operations to transform and create aggregate and disaggregate data. These transformations are specified by using algebraic expressions in which the left-hand side of the expression names new data created by the expression on the right-hand side. Special functions (log, exp, transposition, etc.) are also available. In addition, "look-up tables" provide an efficient way to transform, edit, and screen survey data.

Figure 1. Zonal data: UTOWN zone population.

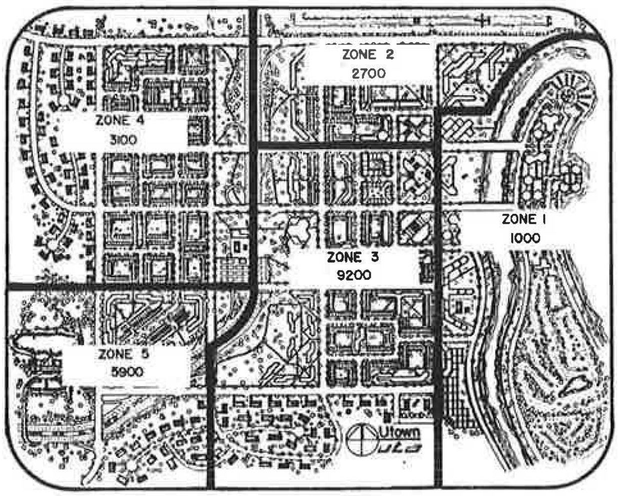


Figure 2. Zonal data for the attribute "population".

POPULATION	
1	1000
2	2700
3	9200
4	3100
5	5900

Figure 3. Interchange data: peak-hour HBW trips from zone 5.

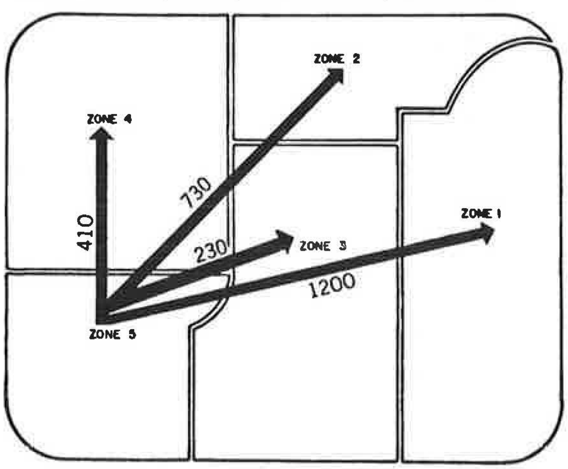


Figure 4. Interchange matrix for regional peak-hour HBW trips.

	DESTINATION 1	2	3	4	5
ORIGIN 1	200	440	270	330	120
2	1700	180	450	310	60
3	1150	1000	220	150	170
4	720	890	510	310	280
5	1200	730	230	410	250

The best way to present UMATRIX's capability is by means of examples. From basic to complex, they are

1. Arithmetic operations,
2. Logical operations,
3. Look-up tables,
4. Special LAV functions, and
5. Special matrix functions.

Arithmetic Operations

Arithmetic operations allow the planner to specify simple matrix or zonal data transformations. For example, creation of a new zonal data item, named POPDIFF [the difference between year-2000 forecast population (POP2000) and base-year population (POPBASE)], is created by means of the following expression (for simplicity the mnemonic naming convention used in the examples has been slightly altered from that actually used in UMATRIX):

POPDIFF = POP2000 - POPBASE

The following is an example of LAV subtraction for a three-zone study area:

$$\text{If POP2000} = \begin{bmatrix} 12\ 500 \\ 17\ 500 \\ 21\ 000 \end{bmatrix} \text{ and POPBASE} = \begin{bmatrix} 11\ 000 \\ 15\ 000 \\ 22\ 000 \end{bmatrix} \text{ then}$$

$$\text{POPDIFF} = \text{POP2000} - \text{POPBASE} = \begin{bmatrix} 1500 \\ 2500 \\ -1000 \end{bmatrix}$$

Subtraction, like all LAV operations, is performed on an element-by-element basis. Thus, the first element of POPDIFF is 12 500 - 11 000, or 15 000; the second element is 17 500 - 15 000, or 2500. Whether a 3-zone system or a 1300-zone system is being analyzed, the same expression is used.

For matrix data, arithmetic operations are defined in the same manner. For example, the addition of two existing trip matrices, HBW and home-based other (HBO), to create a new matrix named total trips (TT) is illustrated in the following example of matrix addition:

$$\text{If HBW} = \begin{bmatrix} 10 & 20 & 30 \\ 40 & 50 & 60 \\ 70 & 80 & 90 \end{bmatrix} \text{ and HBO} = \begin{bmatrix} 5 & 15 & 30 \\ 10 & 20 & 40 \\ 30 & 60 & 120 \end{bmatrix} \text{ then}$$

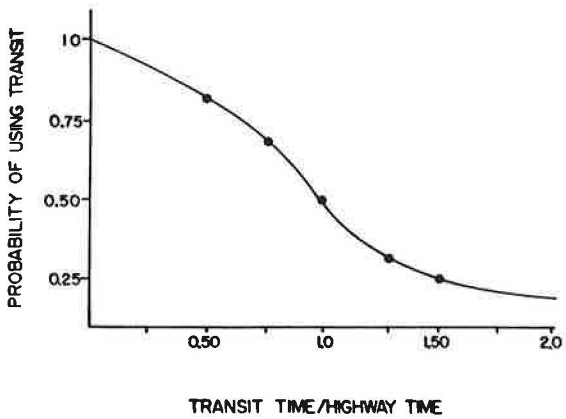
$$\text{TT} = \begin{bmatrix} 10 & 20 & 30 \\ 40 & 50 & 60 \\ 70 & 80 & 90 \end{bmatrix} + \begin{bmatrix} 5 & 15 & 30 \\ 10 & 20 & 40 \\ 30 & 60 & 120 \end{bmatrix} = \begin{bmatrix} 15 & 35 & 60 \\ 50 & 70 & 100 \\ 100 & 140 & 210 \end{bmatrix}$$

Just as for zonal data, matrix operations are performed on a cell-by-cell basis, so that the row index (I) references the current row and the column index (J) references the current column. One statement performs all operations on the two input matrices regardless of whether they are 3 x 3 or 2500 x 2500.

Logical Operations

Comparisons of zonal and matrix data are accomplished through the use of logical operations.

Figure 5. Mode split to transit.



The "IF a THEN b ELSE c" statement can discriminate values or cells (zones or interchanges) that meet or fail certain criteria. Through the use of relational operations, such as less than (<) or less than or equal to (≤), the planner can identify where certain cell values occur. For instance, if the planner wishes to identify zones in which total employment exceeds 1000 workers, the following expression could be used:

EMPGT1K = IF EMP > 1000 THEN 1 ELSE 0

Thus,

$$\text{If EMP} = \begin{bmatrix} 1500 \\ 500 \\ 1750 \\ 990 \\ 1010 \end{bmatrix} \text{ then EMPGT1K} = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \\ 1 \end{bmatrix}$$

Zones 1, 3, and 5 meet the criterion, and zones 2 and 4 fail.

Logical operators are used on matrices for criteria-based system evaluations. For example, assume that TTT = transit travel times, HTT = highway travel times, TRIPS = peak-hour person trip table, and TDTRIPS = transit-deficient person trips. If we want a trip table that contains only those trips for which the transit travel time is more than twice the highway travel time, we form the statement TDTRIPS = IF TTT >2 * HTT THEN TRIPS ELSE 0. Thus,

$$\text{If TTT} = \begin{bmatrix} 27 & 54 & 52 & 96 \\ 60 & 16 & 32 & 30 \\ 30 & 26 & 30 & 32 \\ 65 & 45 & 27 & 15 \end{bmatrix} \text{ and HTT} = \begin{bmatrix} 30 & 28 & 25 & 47 \\ 25 & 15 & 17 & 19 \\ 19 & 14 & 12 & 15 \\ 30 & 16 & 12 & 12 \end{bmatrix}$$

$$\text{and TRIPS} = \begin{bmatrix} 1000 & 1500 & 1750 & 1900 \\ 1200 & 210 & 410 & 500 \\ 1350 & 650 & 720 & 550 \\ 1200 & 230 & 410 & 190 \end{bmatrix} \text{ then}$$

$$\text{TDTRIPS} = \begin{bmatrix} 0 & 0 & 1750 & 1900 \\ 1200 & 0 & 0 & 0 \\ 0 & 0 & 720 & 550 \\ 1200 & 230 & 410 & 0 \end{bmatrix}$$

Look-Up Tables

The UMATRIX look-up tables enable the user to either create new data or alter old. Look-up tables allow the conversion of existing data values to new values, which facilitates transforming, updating, and editing. Look-up tables are lists of arguments and their corresponding converted values. In addition, the planner specifies a missing or "no-hit" conversion value for each table. This value is used every time the referenced value does not match any identified argument.

The special function LOOKUP references these tables and the data to be converted through two components--the look-up table number and an argument. Thus, for example, LOOKUP(1,POP) uses look-up table 1 to convert values drawn from zonal data in the POP category.

In the special use of look-up tables to update zonal data values, the look-up table often requires as an argument a special parameter I, the row indicator, for the cells to be updated, as well as their corresponding new values. In this case the no-hit value is usually set to zero. Therefore, if the planner wishes to update zones 3 and 4 of EMP from the example above, let LOOKUP 1 be as shown below:

Argument	Value
3	2000
4	2200
No-hit	0

The expression EMPUPD = IF LOOKUP (1,I) NOT = 0 THEN LOOKUP (1,I) ELSE EMP creates EMPUPD (which is a slight modification of EMP) by substituting the values in look-up table 1 for the zones that appear as explicit arguments in the table.

In this case, when I = 1, the look-up operation results in a no-hit, since 1 is missing from the look-up table. The value of 0 results and the value for EMPUPD is derived from EMP. The same process occurs for zone 2 (I = 2). However, when I = 3 and I = 4, a hit occurs, and the values for EMPUPD come from the look-up table (i.e., 2000 and 2200, respectively). When I = 5, another no-hit occurs, and the value for EMPUPD comes from EMP. Thus EMPUPD, which represents updated employment values, is shown below:

$$\text{If EMP} = \begin{bmatrix} 1500 \\ 500 \\ 1750 \\ 990 \\ 1010 \end{bmatrix} \text{ then EMPUPD = IF LOOKUP (1,I) NOT = 0}$$

$$\text{THEN LOOKUP (1,I) ELSE EMP creates EMPUPD} = \begin{bmatrix} 1500 \\ 500 \\ 2000 \\ 2200 \\ 1010 \end{bmatrix}$$

Look-up-table data depend on application and consist of four basic optional types: (a) positional: one conversion value exists for every explicit value of the numeric argument from 1 to the maximum argument value; (b) keymatch: conversion values exist only for explicit numeric argument values; (c) range: one specific conversion value exists for a range of argument values; and (d) linear interpolation: if no direct match is found with the argument, the two successive values that bracket it are used to interpolate for the conversion value.

Often it is necessary to input a curve, or a series of curves, to aid in the application of modal split or automobile-pollution emission models. Look-up tables can be used for these calculations. For example, let mode split to transit for HBW trips be a function of the ratio of transit time to highway time (graphically shown in Figure 5). The graph is entered in UMATRIX as a linear interpolation look-up table in the following manner:

Argument	Value
0.25	0.85
0.50	0.80
0.75	0.70
1.0	0.50
1.25	0.30
1.50	0.20
1.75	0.15
2.0	0.12

If the input trip table is named HBW and the travel time ratio is TTR, then the mode-split application is expressed as follows (where the matrix TTRIPS contains total transit trips).

$$\text{If TTR} = \begin{bmatrix} 0.75 & 0.25 & 1.25 \\ 0.50 & 0.50 & 1.30 \\ 1.25 & 1.40 & 1.30 \end{bmatrix} \text{ and HBW} = \begin{bmatrix} 1000 & 200 & 400 \\ 980 & 1000 & 900 \\ 560 & 500 & 800 \end{bmatrix}$$

then TTRIPS = LOOKUP (1,TTR) * HBW creates

$$\text{TTRIPS} = \begin{bmatrix} 700 & 170 & 120 \\ 784 & 800 & 252 \\ 168 & 120 & 224 \end{bmatrix}$$

Special LAV Functions

For purposes of summarization, the planner may wish to aggregate all data values or combine certain values according to zonal-district equivalencies. The functions SUM, COMPRESS, and EXPAND allow the planner to aggregate, replicate, or disaggregate zonal data values.

1. SUM: The SUM function simply aggregates all values within a data item and then replicates that value in the resultant:

$$\text{If POP} = \begin{bmatrix} 500 \\ 990 \\ 1750 \end{bmatrix} \text{ then TOTALPOP = SUM(POP) creates}$$

$$\text{TOTALPOP} = \begin{bmatrix} 3240 \\ 3240 \\ 3240 \end{bmatrix}$$

A common use of SUM is to create percentages, as shown below:

$$\text{If HBWPROD} = \begin{bmatrix} 450 \\ 250 \\ 400 \end{bmatrix} \text{ then HBWTOTAL = SUM(HBWPROD) creates HBWTOTAL} = \begin{bmatrix} 1100 \\ 1100 \\ 1100 \end{bmatrix}$$

For a zonal data item of total trips, data containing percentages of trip productions or attractions are created in one step:

$$\text{If HBWPROD} = \begin{bmatrix} 450 \\ 250 \\ 400 \\ 250 \end{bmatrix} \text{ and HBWATTR} = \begin{bmatrix} 250 \\ 425 \\ 425 \end{bmatrix} \text{ then PERPROD =}$$

HBWPROD ÷ SUM(HBWPROD) and PERATTR = HBWATTR ÷ SUM(HBWATTR)

$$\text{creates PERPROD} = \begin{bmatrix} 450 \\ 250 \\ 400 \end{bmatrix} \div \begin{bmatrix} 1100 \\ 1100 \\ 1100 \end{bmatrix} = \begin{bmatrix} 0.409 \\ 0.227 \\ 0.364 \end{bmatrix} \text{ and}$$

$$\text{PERATTR} = \begin{bmatrix} 250 \\ 425 \\ 425 \end{bmatrix} \div \begin{bmatrix} 1100 \\ 1100 \\ 1100 \end{bmatrix} = \begin{bmatrix} 0.227 \\ 0.386 \\ 0.386 \end{bmatrix}$$

2. COMPRESS: The function COMPRESS has two components: the LAV to be compressed and a "mapping" LAV item. In this process, a LAV of one size usually has its elements combined in such a manner as to result in a LAV that has a smaller number of elements. The mapping LAV has the same number of elements as the LAV to be compressed. Each of its cells holds the new cell index (I) of the recipient LAV, into which values from the compressed LAV are to be entered or aggregated. COMPRESS is very useful for summarizing zonal data to a more aggregate (district) geography. The example below makes this clear:

COMP = COMPRESS(POP, EQUIV) will compress POP, creating COMP by using the mapping in EQUIV thus:

$$\text{If POP} = \begin{bmatrix} 10\ 000 \\ 20\ 000 \\ 30\ 000 \\ 25\ 000 \\ 17\ 000 \\ 18\ 000 \end{bmatrix} \text{ and EQUIV} = \begin{bmatrix} 3 \\ 1 \\ 2 \\ 1 \\ 3 \\ 2 \end{bmatrix} \text{ then COMP} =$$

$$\begin{bmatrix} 20\ 000 + 25\ 000 \\ 30\ 000 + 18\ 000 \\ 10\ 000 + 17\ 000 \end{bmatrix} = \begin{bmatrix} 45\ 000 \\ 48\ 000 \\ 27\ 000 \end{bmatrix}$$

The first element of POP (10 000) has a mapping index of 3 from EQUIV; thus, it is entered in the third position of COMP. The second element of POP (20 000) is entered in the first position of COMP. The fourth element of POP (25 000) is also entered in the first position of COMP. However, the value 20 000 is already there; thus, the two values are added together. Any of COMP's elements not represented in EQUIV are set to zero (i.e., a missing zone). The size of COMP corresponds to the highest zone number that appears in EQUIV.

3. EXPAND: The EXPAND function is used to map elements of data into larger-sized data through element replication. It has two components: the LAV to be expanded and a mapping LAV that is different in size. In this case, the mapping LAV and the resultant will have the same size, i.e., the same number of cells. It is useful for transforming zonal data in order to reference a more disaggregate geography, e.g., subzone.

$$\text{If POP} = \begin{bmatrix} 45\ 000 \\ 48\ 000 \\ 27\ 000 \end{bmatrix} \text{ and MAP} = \begin{bmatrix} 3 \\ 1 \\ 3 \\ 2 \\ 1 \\ 2 \end{bmatrix} \text{ then EX = EXPAND}$$

$$\text{(POP, MAP) creates EX} = \begin{bmatrix} 27\ 000 \\ 45\ 000 \\ 27\ 000 \\ 48\ 000 \\ 45\ 000 \\ 48\ 000 \end{bmatrix}$$

In this case, the mapping LAV (MAP) describes the position of the value from POP that is entered in the appropriate position of the resultant. Thus, the first element of EX contains the third value from POP (27 000), the second element contains the first value from POP (45 000), etc. Note that, although they use the same mapping LAV, COMPRESS and EXPAND are not mutual inverses.

Special Matrix Functions

It is often necessary to transpose a matrix or to summarize matrix elements across rows and columns. To facilitate these operations, two special functions exist in UMATRIX--TR and ROWSUM. The transposition function, TR, transposes a matrix, as shown:

If $\text{MATRIX} = \begin{bmatrix} 10 & 50 & 70 \\ 20 & 90 & 30 \\ 35 & 95 & 15 \end{bmatrix}$ then OUTPUT = TR(MATRIX)

creates $\text{OUTPUT} = \begin{bmatrix} 10 & 20 & 35 \\ 50 & 90 & 95 \\ 70 & 30 & 15 \end{bmatrix}$

That is, rows become columns and vice versa. A typical application of transposition occurs when a trip table of productions (P) and attractions (A) must be split to an origin-destination (OD) trip table:

PA = P and A work-trip table; OD = O and D work-trip table; and splitting factors = 70 percent of work trips are P to A and 30 percent of work trips are A to P.

If $\text{PA} = \begin{bmatrix} 100 & 400 & 250 \\ 700 & 550 & 320 \\ 1000 & 300 & 700 \end{bmatrix}$ then OD = 0.70 * PA + TR(PA)

$$\text{OD} = 0.70 * \begin{bmatrix} 100 & 400 & 250 \\ 700 & 550 & 320 \\ 1000 & 300 & 700 \end{bmatrix} + 0.30 * \begin{bmatrix} 100 & 700 & 1000 \\ 400 & 550 & 300 \\ 250 & 320 & 700 \end{bmatrix}$$

$$\text{OD} = \begin{bmatrix} 70 & 280 & 175 \\ 490 & 385 & 224 \\ 700 & 210 & 490 \end{bmatrix} + \begin{bmatrix} 30 & 210 & 300 \\ 120 & 165 & 90 \\ 75 & 96 & 210 \end{bmatrix}$$

$$\text{OD} = \begin{bmatrix} 100 & 490 & 475 \\ 610 & 550 & 314 \\ 775 & 306 & 700 \end{bmatrix}$$

The ROWSUM operator aggregates all matrix elements across a row and then replicates that single sum across the row of the output table:

If $\text{MATRIX} = \begin{bmatrix} 100 & 150 & 200 \\ 50 & 75 & 125 \\ 100 & 100 & 100 \end{bmatrix}$ then OUTPUT = ROWSUM

(MATRIX) creates $\text{OUTPUT} = \begin{bmatrix} 450 & 450 & 450 \\ 250 & 250 & 250 \\ 300 & 300 & 300 \end{bmatrix}$

In order to obtain column sums, the transposition function must be used. In this case, transposition creates an output matrix in which the rows are the input columns and the columns are the rows of the input matrix.

Operations that combine both matrix and zonal data allow the user to perform a multitude of planning analyses, such as trip generation and mode-split model application, determination of regional accessibility, and criteria-based system evaluation.

Sometimes the planner needs matrix output that uses zonal data input for manipulative purposes. In this case, since matrix calculations are performed on a cell-by-cell basis, a matrix can be created from a zonal data item by means of column replication. For example, the expression MATRIX = POP will create a matrix in which there are as many rows as there are elements in POP and every column is the LAV POP, thus:

If $\text{POP} = \begin{bmatrix} 1500 \\ 2000 \\ 750 \end{bmatrix}$ then MATRIX = POP creates MATRIX =

$$\begin{bmatrix} 1500 & 1500 & 1500 \\ 2000 & 2000 & 2000 \\ 750 & 750 & 750 \end{bmatrix}$$

Similarly, the transposition of a LAV when equated to a matrix name yields a matrix whose rows are all duplicates of the LAV. Replication of columns or rows when matrices are being output is quite useful in the performance of accessibility analyses. For example, the planner may wish to estimate the percentage of regional blue-collar employment opportunities that are within 30 min (on the existing transit system) of each production zone. To accomplish this, a percentage blue-collar employment LAV (BCEMPPCT) must be created from BCEMP (zonal blue-collar employment data). This is done by means of BCEMPPCT = BCEMP/SUM(BCEMP). Once BCEMPPCT is created, a transit travel time matrix (TTR) is used to determine, for each production zone, whether the time exceeds 30 min. If it does, then none of the blue-collar jobs are accessible; if it does not, then the percentage employment figure must be used:

If $\text{TTR} = \begin{bmatrix} 10 & 20 & 25 \\ 15 & 8 & 35 \\ 27 & 38 & 9 \end{bmatrix}$ and $\text{BCEMPPCT} = \begin{bmatrix} 0.10 \\ 0.25 \\ 0.30 \end{bmatrix}$ then

$$\text{TR(BCEMPPCT)} = \begin{bmatrix} 0.10 & 0.25 & 0.30 \\ 0.10 & 0.25 & 0.30 \\ 0.10 & 0.25 & 0.30 \end{bmatrix}$$

ACCESSIBILITY = IF TTR > 30 THEN 0 ELSE TR(BCEMPPCT)

creates $\text{ACCESSIBILITY} = \begin{bmatrix} 0.10 & 0.25 & 0.30 \\ 0.10 & 0.25 & 0 \\ 0.10 & 0 & 0.30 \end{bmatrix}$

The transposition function is used because, as the destinations change for a given origin, the employment percentages must change accordingly. The statement ACCESS = ROWSUM(ACCESSIBILITY) creates zonal accessibility-to-employment percentages:

$$\text{ACCESS} = \begin{bmatrix} 0.65 \\ 0.35 \\ 0.40 \end{bmatrix}$$

Thus, zone 1 has accessibility to 65 percent of employment opportunities, zone 2 has only 35 percent, and zone 3 has 40 percent.

Gravity Model

Certain demand models can be readily implemented within UMATRIX, e.g., the gravity model. Let PROD be zonal productions, and ATTR be zonal attractions; TIMES has travel times and KFACT has K-factors. The traditional gravity model is effected by means of a single UMATRIX statement:

```
DISTTRIPS = PROD * TR(ATTR) * LOOKUP(1,TIMES) *
   K(FACT)/ROWSUM[LOOKUP(1,TIMES)] * TR(ATTR) *
   KFACT.
```

Look-up table 1 has friction factors for corresponding travel times. Note that the transposition of the ATTR LAV is used, since the attractions change as destinations change.

Trip-Generation Model

UMATRIX first calculates trips from each zone by using a simplistic cross-classification trip-generation model (stratified by two income levels) for HBW and then adjusts trip productions to sum to the attraction total. Zonal production estimates are based on trips per dwelling unit for each income type. The rates for income level 1 are 2.12 trips/dwelling unit; for income level 2, they are 2.54 trips/dwelling unit.

Attraction estimates are developed by using trip-attraction rates and measures of zonal activity, primarily employment. The daily work-trip attraction formula is

Person trip attractions = 1.70 * (total zonal employment).

Let DU1 and DU2 represent zonal dwelling units stratified by income, EMP represent zonal employment, and P1, P2, and ATTR represent data for productions and attractions. The generation equations can be expressed by

P1 = 2.12 * DU1.

P2 = 2.54 * DU2.

ATTR = 1.70 * EMP.

These yield three new data items that represent unbalanced trip-production levels for each zone for each income category, as well as a trip-attraction total for each zone. In this case, after applying the rates, the productions need to be summed to create regional production totals from which a normalization factor can be determined. Then, this factor is multiplied by the initial production estimates, stratified by income, to create balanced (normalized) trip values. The attraction sum-balancing procedure is shown below:

```
    TP = SUM (P1 + P2)
    TA = SUM (ATTR)
NORMAL = TA/TP
 PROD1 = NORMAL * P1
 PROD2 = NORMAL * P2
```

Impedance Calculations

For demand modeling purposes, this example can be used to create a series of HBW highway and transit impedances. The components of in-vehicle time, out-of-vehicle time, and cost are combined according to the following formula:

Impedance = in-vehicle time + (2.5 x out-of-vehicle time) + [(3600 x cost)/average zonal income],

where highway cost = ($0.15/mile x highway distance) + (0.5 x parking cost) and transit cost = out-of-pocket fare.

Assume that matrix TIV contains transit in-vehicle times, TOV contains out-of-vehicle times, and FARES contains transit fares. Matrix HIV contains highway in-vehicle times, HOV contains out-of-vehicle times, and HDIST contains distance. AVEINC has average zonal income, and PARKC has zonal parking costs in cents. Since each interchange will have a unique set of impedances, matrix output is created by using mixed zonal and matrix operations. The impedance operations are

TIMPS = TIV + (2.5 * TOV) + [(3600 * FARES)/AVEINC].

HIMPS = HIV + (2.5 * HOV) = (3600 * {(0.15 * HDIST) + [1/2 * TR(PARKC)]}/AVEINC).

Transit impedances are stored on TIMPS; the highway impedances are stored on HIMPS. Note that the transposition of PARKC appears because the parking cost is a destination charge.

Application of a Logit Mode-Split Model

To use the transit and highway impedances created above to forecast HBW mode split by means of a logit model, the following UMATRIX statement is all that is needed:

PT = 1/{1 + EX [-0.1 * (HIMPS - TIMPS)]}

where PT = probability of using transit.

SUMMARY AND CONCLUSIONS

This paper has introduced the reader to the UTPS program UMATRIX, a powerful data-base manager. UMATRIX's straightforward algebra-like command language provides the planner with an efficient and flexible planning tool. The UMATRIX user can access a large variety of data forms and can accomplish analytical chores that, prior to now, were difficult and time consuming. By allowing a large range of complex transportation planning tasks to be performed with less effort, UMATRIX gives the planner more time to devote to the important functions of system evaluation, impact assessment, and planning recommendations.

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