The Traffic Assignment Process of the Delaware Valley Regional Planning Commission

THABET ZAKARIA, Sr., and JOHN FALCOCCHIO, Sr., Delaware Valley Regional Planning Commission

This paper reports on the traffic assignment process of the Delaware Valley Regional Planning Commission. It describes the concepts of traffic assignment used and it briefly explains the computer process. The DVRPC assignment is an "all or nothing" assignment which utilizes travel cost as the tree trace variable.

Four sensitivity tests were made to evaluate the inputs to the traffic assignment package and the results of each test are reported. Tests 1 and 2 were unrestrained assignments. These tests were conducted to determine if turnpike tolls and accident costs should be included as components of total travel costs. Tests 3 and 4 are restrained assignments which were made to find out the advantage of calculating the 2KD value (peak-hour fraction) for each input to the capacity restraint program on the basis of generalized route and area types.

The district assignment calibration indicates that the district simulated volumes are sufficiently accurate to serve as a guide in establishing the overall design requirements for freeways and high-type arterials.

A zone assignment, using tests 1 and 3, was made for the portion of Mercer County within the cordon area for the purpose of determining the degree of improvement in output that it has over district assignment.

The "real error" concept is introduced as a method which may be used in reporting the accuracy of the traffic assignment outputs. This method seems to be superior to the usual RMS measure used in statistics, since it takes into consideration the capacity of highways to accommodate a wide range of traffic volumes.

•TRAFFIC assignment may be defined as the allocation of trip interchanges on the routes or transportation facilities whether they are highways or public transportation facilities. Because it is concerned with the many variables involved in the travel behavior of people, traffic assignment is the most complex step in the traffic simulation model.

Since transportation facilities have certain physical capacities such as vehicles or passenger per hour or per day, a comparison between the assigned volumes (demand) and the capacity of the existing, or of the existing plus the proposed transportation facilities (supply), would clearly indicate the deficiencies or the surpluses of individual transportation facilities as well as the whole system. The knowledge of traffic supply and demand is one major criterion used to evaluate objectively the adequacy of proposed highway and mass transit facilities. This information is an end result of the traffic assignment program.

The purpose of this paper is to discuss and report the concepts and calibration outputs of the highway traffic assignment program used by the Delaware Valley Regional Planning Commission. The assignment outputs or results, are reported at the district level for the whole DVRPC cordon area and at zonal level for the portion of Mercer County lying within this area. The DVRPC cordon area includes five counties in Pennsylvania and four counties in New Jersey covering an area of about 1,200 sq mi, with

Paper sponsored by Committee on Origin and Destination and presented at the 47th Annual Meeting.

a 1960 population of 4 million people and over 2, 200 mi of highway test network consisting of less than 11 percent (230 mi) of turnpikes, freeways and high-type arterials.

TRAFFIC ASSIGNMENT CONCEPT

The traffic assignment concept used by the Delaware Valley Regional Planning Commission is based on the assumption that people are rational and behave in their travel in a way that minimizes their total travel cost. Total travel cost is defined as the sum of travel cost elements, such as operating and time costs, incurred by persons making trips between any pair of zones or districts. This concept has been adopted by DVRPC because it was found that the concept of least total time tends to overassign traffic to high-speed facilities such as expressways and high-type arterials. For example, consider two districts, A and B, which are linked only by two paths: a freeway and a high-type arterial. The following data are obtained from the trace variables that were used in the calibration of 1960 highway network.

Item		Freeway	Arterial	Difference
Distance between A and B	(mi)	4.2	3.8	0.4
Speed on route	(mph)	54.0	44.0	10.0
Time of travel	(min)	4.6	5.2	0.6
Time and operating cost (travel cost)	(cents)	26.5	24.1	2.4

These data show that the arterial link between A and B is 0. 6 min slower but 2. 4 cents cheaper than the freeway link. On the basis of the minimum travel time criterion and "all-or-nothing" assignment, all trips between A and B will take the freeway link. But all trips will take the arterial link on the basis of the minimum travel cost criterion.

A brief identification of the travel cost components, which were summed up to trace the least total cost paths follows.

1. Time Cost—The time value is the major cost component in traffic assignment. Although it is recognized that the time value is dependent on many variables—such as the time of travel, income, type of transportation facilities, purpose of trips, and age composition of travelers—DVRPC adopted $1. 50 per vehicle hour and $1. 00 per person hour. These values seem to be reasonable as average time values for all trips in the DVRPC cordon area since they produced assigned values close to the 1960 ground counts on the Delaware River toll bridges and on a few expressways and turnpikes. Since the distance and speed are known for each link in the highway network, the computer determines consecutively the time for each link, time cost, and its aggregated time via all possible routes, and from the latter computes the time cost for each route according to the unit time cost established.

2. Operating Cost—The operating cost to auto users includes the cost of fuel, oil, tires and maintenance. The DVRPC has adopted the auto operating cost estimated by Hoch for the Chicago Area Transportation Study (4). This operating cost per vehicle mile can be established as a factor of speed. Like time cost, operating cost can be obtained by the computer since the speed and distance for each link are known.

3. Turnpike and Bridge Tolls—Turnpike and bridge charges are two other elements of travel cost. They are coded manually on the links where auto drivers must pay them. Bridge tolls, if any, are added to the operating cost and included in all the sensitivity tests. But turnpike tolls are included in a separate test to find out whether or not these tolls are to be considered as a predictive variable in the assignment model. Also, turnpike tolls are coded into the link data card for providing cordonwide summaries of tolls.

4. Accident Cost—Another element of travel cost is accident cost which is considered in tracing the least total travel cost paths in order to test the effect of accident cost on freeway assigned volumes. Like time and operating costs, accident cost can be computed for each link since the distance and speed are coded.

Table 1 shows travel cost component used for traffic assignment at various selected speeds.

TABLE 1
1960 TRAVEL COSTS IN THE DVRPC REGION

Average Speed (mph)	Cost (cents per veh-mi)			
	Operating	Accident	Time	Total Travel
10	4.62	4.30	15.00	23.92
15	3.84	2.70	10.00	16.54
20	3.39	1.80	7.50	12.69
30	2.91	0.80	5.00	8.71
40	2.74	0.40	3.75	6.89
50	3.28	0.30	3.00	6.58
60	3.90	0.30	2.50	6.70

Parking charges are excluded in all sensitivity tests because they are included in tracing the minimum travel cost paths for the trip distribution model. The rationale for excluding parking charges from traffic assignment program is that they are paid by auto users in the district of destination regardless of the routes they choose in their travel.

Two other elements of travel cost not considered in the DVRPC assignment program are the inconvenience and discomfort costs. These two elements are the least known in travel behavior. Although they may be important criteria in the selection of the route of travel between the districts of origin and destination, inconvenience and discomfort costs are nevertheless very difficult to quantify in dollar terms per vehicle-mile, unlike the other travel cost elements previously mentioned.

In summary, the DVRPC assignment program is all-or-nothing assignment and utilizes the concept of least travel cost. The travel cost elements used in tracing the least travel cost are time cost, operating cost, accident cost, and turnpike and bridge tolls.

COMPUTER PROCESS OF DVRPC HIGHWAY ASSIGNMENT SYSTEM

Generally, the DVRPC highway assignment system is similar to that prescribed by the Bureau of Public Roads in its Traffic Assignment Manual (1). It consists of a series of programs which allocates trip interchanges between districts or zones in a region to a relevant transportation network. This assignment process is accomplished according to the following general steps:

1. Preparation of the input data.
2. Preparation of the network.
3. Loading of traffic on the network.
4. Output of unrestrained assigned volumes.
5. Restrained assignment.

In step 1, two functions are performed: (a) the number of trips from each subarea (district or zone) to all subareas are converted into a binary magnetic tape suitable for input to step 3; and (b) the preparation of all data pertaining to network and area characteristics is accomplished by the link data preparation and build area description programs. The program of link data preparation generates the link data tape necessary for steps 2, 4 and 5. The DVRPC link data preparation program considers area (i. e., CBD, urban, suburban, rural and open rural) and route types which are the determinants of speeds, capacities and the travel cost components. The build area description program generates the area description tape necessary for step 2. This tape includes area information such as load node numbers, area code, cost-time conversion factors and turn penalty.

In step 2, two programs are run: first, the build network description program which edits and summarizes the information of the link data tape in order to be suitable for use in the computation of minimum paths and subsequently in the actual assignment of traffic volume to the network; and second, the build trees program which actually employs Moore's algorithmic procedure to compute, on the basis of least travel cost, minimum cost paths or trees through the network from each subarea centroid to all other nodes in the highway network.

The actual assignment of the simulated traffic interchanges on the links of the highway system is accomplished in step 3 by running the load network program. The DVRPC load network program conforms substantially to the all-or-nothing network loading described by the Bureau of Public Roads (1).

In step 4, the results obtained in steps 1 and 3 are summarized and represented in different forms by the output loaded network program. This program requires as input

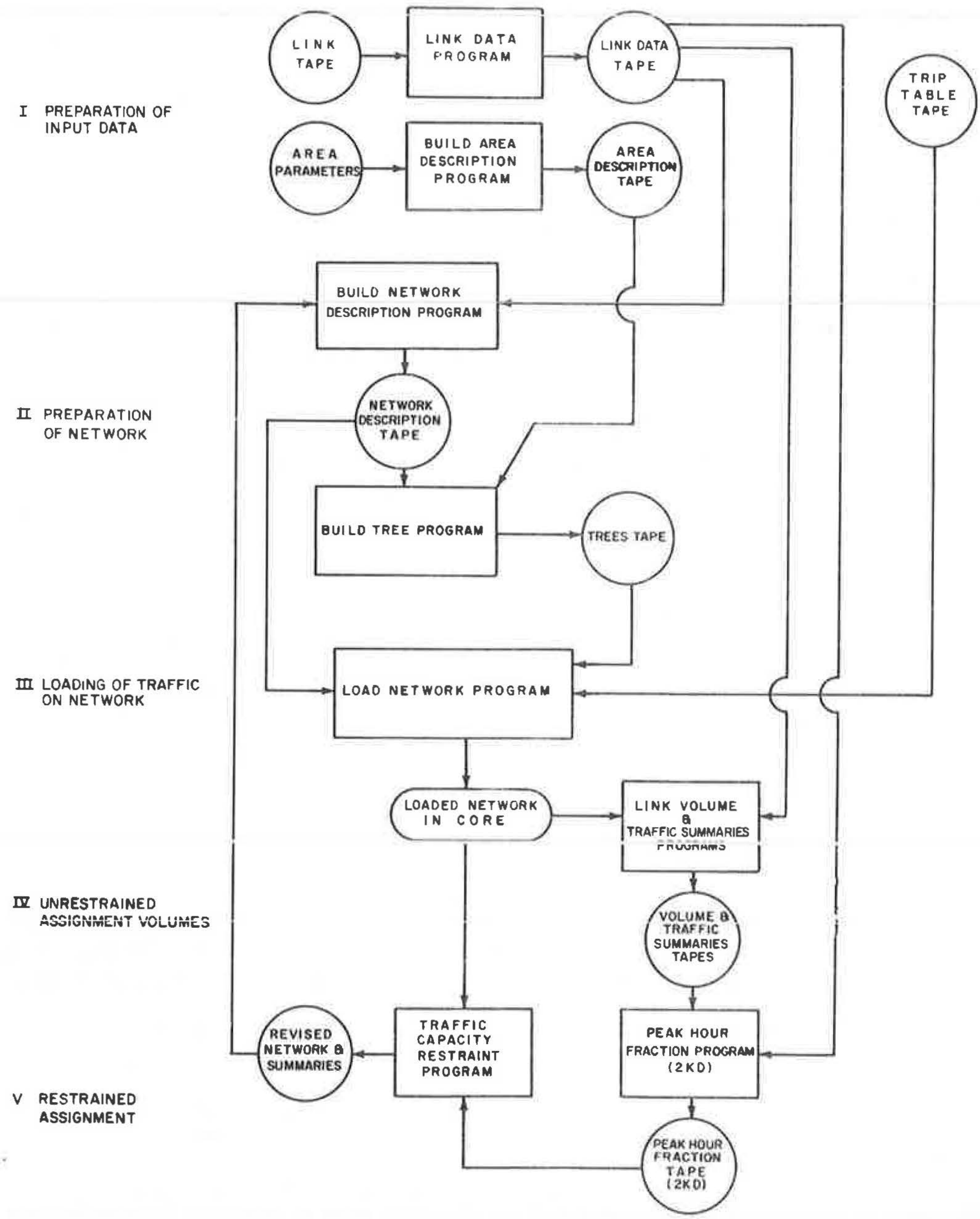

Figure 1. The highway assignment system of DVRPC.

tape the link data tape and the link and turn volumes. The program produces an output tape which is subsequently converted to sets of cards employed in printing and plotting (E. A. I. data plotter) individual link and turn volumes as well as traffic summaries such as vehicle-miles of travel, vehicle hour, vehicle time cost, vehicle operating cost, accident cost, toll charges, miles of route, vehicle speeds, total cost, and vehicle density. The restrained assignment is accomplished in step 5 which adjusts the traffic volume assigned in step 3 on the basis of the capacity restraint concept. According to this concept, new values of speed, time and route travel costs are computed. The computation of average daily restrained speed requires, as input, the following: daily duration of delay, peak-hour fraction, peak-hour speed, and off-peak speed.

The former Penn-Jersey staff developed a program for computing the peak-hour fraction from a linear regression function of home to work trips. The peak-hour fraction program uses, as input, the total assignment volumes obtained from the output loaded network program of step 4, a tape record of assigned home-to-work trips and the link data tape. By using the peak-hour fraction, the link data tape and load network tape, the capacity restraint program produces a tape containing revised network loadings, new time, operating and accident cost values as well as corresponding sets of prints and data plotter cards for detailed analysis.

TABLE 2

INPUT VARIABLES TO HIGHWAY ASSIGNMENT TESTS

Input Variables	Unrestrained Runs		Restrained Runs	
	Test 1	Test 2	Test 3	Test 4
X-var. (operating cost)[a]	LU	LU	LU	LU
Turnpike tolls	NA	A	NA	NA
Y-var. (time cost)	LU	LU	LU	LU
Z-var. (accident cost)	NA	A	NA	NA
Off-peak speed	NA	NA	LU	LU
Average daily speed	LU	LU	C	C
Peak-hour speed	NA	NA	C	C
Min. avg. daily speed	NA	NA	LU	LU
Delay rate	NA	NA	C	C
Max. delay rate	NA	NA	LU	LU
Daily duration of delay	NA	NA	C	C
Hourly capacity	NA	NA	NA	LU
2 KD value	NA	NA	LU	C
24-hr capacity	NA	NA	LU	C

Notes: LU = input obtained from look-up table, except manual coding.
NA = input not used or not applicable in test.
A = input used or applicable in test.
C = computation as specified.

[a]The other component of (X-var.) is the bridge tolls which are included in all tests.

Figure 1 is a work flow chart showing the main steps of DVRPC's highway assignment system.

TRAFFIC ASSIGNMENT SENSITIVITY TESTS

To evaluate the DVRPC traffic assignment concept, several sensitivity tests were designed and run to simulate 1960 traffic volumes. The calibration of the assignment model was made on the basis of different input specifications. Four sensitivity tests were designed and tested at the district level for the whole DVRPC cordon area, and only two sensitivity tests (tests 1 and 3) were run at the zonal level for that portion of Mercer County which is included in the cordon area.

Table 2 gives the major input variables used in each test to trace the minimum cost paths required for traffic loading. Tests 1 and 2 are unrestrained assignment runs, but 3 and 4 are restrained. Test 2 differs from test 1 in that the turnpike tolls and accident costs in test 2 are included in the computation of minimum travel cost paths in order to test the effect of these costs upon traffic assigned to high-type arterials, freeways and turnpikes. The main difference between test 3 and test 4 is that the peak-hour fraction (2KD) in test 4 is computed for each link in the system as a function of the ratio of home-to-work trips to total trips rather than those 2KD values which are input in test 3 on the basis of generalized field observations. Another difference between test 3 and test 4 is that the daily capacity is computed for each highway link in test 4 but the daily capacity is input in test 3 according to certain values specified by route and area types.

Table 3 gives the speeds which are input into the tests. Off-peak speeds have been estimated by route and area types on the basis of speed and delay runs (7). Peak-hour speeds were estimated theoretically by adding the delay rate during peak hour to off-peak speed rate; i. e.:

Peak-hour speed rate = Off-peak speed rate + delay rate in peak hours

The average daily speeds (Table 3) were used in the unrestrained assignment runs (tests 1 and 2). But for tests 3 and 4, average daily speed was computed for each link on the basis of the following relationship:

Average daily restrained speed rate = (daily duration of delay) (peak-hour fraction) (peak-hour speed rate) + [1 - (daily duration of delay) (peak-hour fraction) (off-peak speed rate)]

TABLE 3

OFF-PEAK, PEAK, AVERAGE DAILY AND MINIMUM AVERAGE DAILY SPEEDS (MPH) BY AREA AND ROUTE TYPE, 1960

Route Type	CBD				Urban				Suburban				Rural				Open Rural			
	OPS	PHS	ADS	MADS	OPS	PHS	ADS	MADS	OPS	PHS	ADS	MADS	OPS	PHS	ADS	MADS	OPS	PHS	ADS	MADS
Turnpike (0)	—	—	—	30	—	—	—	32	—	—	—	35	60	60	60	38	60	60	60	42
Freeway (1, 2)	40	25	37	30	45	30	43	32	50	36	48	35	55	45	54	38	60	60	60	42
Multi-high (8, 5) (controlled)	24	17	23	18	29	18	27	21	39	25	37	28	44	39	44	31	50	50	50	35
Multi-high (9) (uncontrolled)	22	17	21	16	27	17	25	20	37	22	34	26	42	37	42	30	50	50	50	35
Multi-low (3)	17	11	16	13	22	13	20	16	32	20	30	23	37	26	26	26	45	35	44	32
Other (4)	12	8	11	10	17	14	17	13	27	23	27	20	32	24	31	23	42	42	42	30

Notes: a. Average daily speeds (ADS) are used in tests 1 and 2 except for links manually coded.
b. Off-peak speeds (OPS) are used in tests 3 and 4 except for links manually coded.
c. The minimum values for ADS are used when the computed average daily speeds in any iteration of the restrained assignment program (tests 3 and 4), are lower than MADS.

The restrained average daily speeds computed for tests 3 and 4 were subject to the minimum average daily speeds constraint in Table 3. These minimum average daily speeds are computed by assuming that one-third of daily travel occurs at 5.0 mph and the other two-thirds occur at off-peak speeds. This assumption is made in order to determine the lowest possible daily speed on each of the heavily congested links in any area in the region.

On the basis of previous speed and delay studies, three equations were used to estimate the delay rates used in tests 3 and 4. As is evident, these delay functions are dependent on the route type of the link.

Turnpikes and freeways:

$$\text{Delay rate} = 2.5 \left(\frac{\text{daily assigned volume}}{\text{daily estimated capacity}}\right)^5$$

Multilane high-type facilities:

$$\text{Delay rate} = 3.0 \left(\frac{\text{daily assigned volume}}{\text{daily estimated capacity}}\right)^5$$

All other routes:

$$\text{Delay rate} = 3.5 \left(\frac{\text{daily assigned volume}}{\text{daily estimated capacity}}\right)^5$$

The delay rate function is subject to a constraint of a maximum delay rate, expressed as minutes per mile. Figure 2 shows the relationship between the delay rates and speeds as functions of the daily volume to daily basic capacity ratios for urban highway facilities. The minimum peak speeds on all highways are set up to be 5.0 mph when the volume-capacity ratio becomes equal to or larger than 1.2. The higher the off-peak speeds, the higher are the maximum delay rates.

In order to compute the average daily restrained speeds, the daily duration of delay was computed as a function of volume to capacity ratio. One formula was used to estimate the duration of delay during peak hours.

$$\text{Daily duration of delay} = \left[2.5 \left(\frac{\text{daily assigned volume}}{\text{daily estimated capacity}}\right) - 1\right]^{-2}$$

It is further assumed that the maximum duration of delay is 10 hours.

Highway basic rather than practical capacities were used in the capacity restrained program. For test 3 the daily basic capacities (Table 4) were used to compute the ratios of daily assigned volumes to daily basic capacities. (The V/C_b values are used in the computation of: delay rates and daily duration of delay; both are subsequently used to

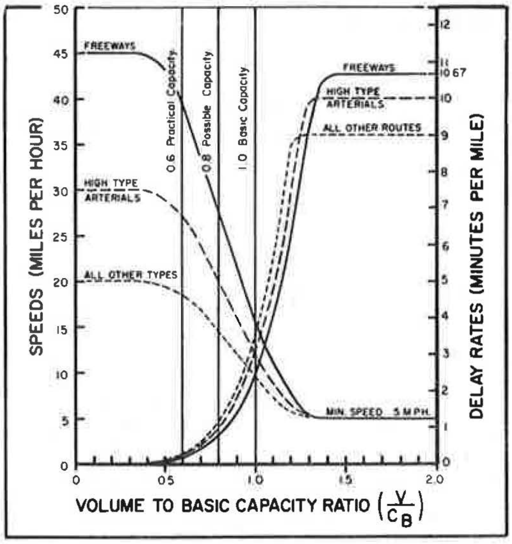

Figure 2. Delay rates and speeds related to volume-capacity ratios for urban highways.

estimate the average daily restrained speeds.) For test 4, however, the daily basic capacities were computed for each highway link as follows:

1. Estimate the peak-hour fraction (2KD) where K is defined as the ratio of two-way peak hour volume to two-way daily volume and D is the ratio of heavy directional peak hour volume to two-way peak hour volume. The value of 2KD is estimated by a linear regression function (5):

$$2KD = 0.0256 + 0.39\,(WR)$$

where

$$WR = \left[\frac{\text{home-to-work trips (assigned)}}{\text{total trips (assigned)}}\right]$$

2. Estimate the daily basic capacity by dividing the hourly capacity into the peak hour fraction (2KD); i.e.,

$$\text{Daily basic capacity} = \frac{\text{hourly capacity}}{2KD}$$

To obtain realistic values for the estimated daily capacities, upper and lower values for 2KD were established on the basis of 1960 available data of cordon and screen line traffic count stations.

Thus, if the 2KD values computed by the model were lower than 0.08 or higher than 0.20, the daily basic capacities of Table 4 were used rather than using the aforementioned formula to compute these capacities. For test 3, however, the following 2KD values were input into the link data program rather than estimating them by the regression equation.

Values	CBD's and Urban Areas	Suburban Areas	Rural and Open Rural Areas
2KD Values (arterials)	0.10	0.12	0.14
2KD Values (freeways)	0.11	0.13	0.15

TABLE 4

HIGHWAY BASIC CAPACITIES BY ROUTE AND AREA TYPES

(Vehicles per Lane)

Route Type	CBD		Urban		Suburban		Rural and Rural Open	
	Hourly	Daily	Hourly	Daily	Hourly	Daily	Hourly	Daily
Freeways (0, 1, 2)	2,500	22,700	2,500	22,700	2,500	19,200	2,500	16,700
High-type (cont.)(8)	700	7,000	900	9,000	1,320	11,000	1,680	12,000
High-type (uncont.)(9)	600	6,000	800	8,000	1,200	10,000	1,600	11,400
Low-type (3)	450	4,500	600	6,000	900	7,500	1,200	8,500
Other routes (4)	370	3,700	500	5,000	750	6,200	1,000	7,100

Notes: a. Basic daily capacities are used in the restrained assignment program (test 3).
b. Basic hourly capacities are used in the restrained assignment program (test 4).

RESULTS OF ASSIGNMENT RUNS

District Assignment Tests

The results of the four sensitivity tests are reported here and evaluated first in terms of statistical measures and then on a link-by-link comparison. The tests were conducted for the whole of the DVRPC cordon area (see Fig. 3).

Figure 3. Traffic assignment study area of the DVRPC 9 county region.

To measure the accuracy of each of the four sensitivity tests, statistical measures were run for eight types of link groups: all master count stations, all river crossings, all turnpikes, all freeways, all high-type arterials, all low-type arterials, all links in Pennsylvania, and all links in New Jersey. The statistical measures were the following:

1. The mean of ground counts ($\bar{X}$) for each link group.
2. The mean of the simulation errors ($\bar{E}_1$) and the mean of these simulation errors expressed as a percent of ground counts ($\bar{E}_2$),

$$\bar{E}_1 = \frac{\sum_{i=1}^{n} (Vai - Vgi)}{n}$$

$$\bar{E}_2 = \frac{\sum_{i=1}^{n} \frac{(Vai - Vgi)}{Vgi} \times 100}{n}$$

These measures indicate the average error of overassignment or underassignment in each link group.

3. The root mean square error in vehicles (RMS), and in percent of the mean of ground counts (% RMS).

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} (Vai - Vgi)^2}{n}}$$

$$\% \, RMS = \frac{RMS}{\bar{X}} \times 100$$

As is known in statistics, about 67 percent of the links of each group should lie within one root mean square. Of course, the lower the RMS is, the better are the simulation results.

4. The coefficient of correlation (r) between the assigned volumes and ground counts. This measure indicates the quality of fit of the simulated result to the actual counts.

$$r = \sqrt{1 - \frac{(RMS)^2}{(Sx)^2}}$$

where

n = number of links in each group considered,
Vai = the assigned volume to link i,
Vgi = the ground count to link i, and
Sx = the standard deviation of the ground counts in each link group considered.

The results of these statistical measures for the eight link groups mentioned above are given in Table 5 for each sensitivity test. Test 1 produced better results than test 2, indicating that the inclusion of turnpike tolls and accident costs in tracing the minimum paths did not improve the outputs of the unrestrained assignment program. A characteristic common to both tests is a general overassignment to all link types except for turnpikes. The best results were obtained in the assignment to river crossings and turnpikes but the assignment to freeways and arterials resulted in high simulation errors which were considerably reduced in test 3 and 4.

TABLE 5

COMPARISON OF SIMULATION RESULTS BY ROUTE AND AREA TYPES FOR TESTS 1, 2, 3, AND 4

Link Group	Test No.	Mean of Ground Count, $\overline{X}$ (veh)	Mean of Simulation Error		Root Mean Square Error		Coefficient of Correlation, r (%)
			$\overline{E}_1$ (veh)	$\overline{E}_2$ (%)	RMS (veh)	RMS (%)	
1. Master control stations	1	18, 227	3, 362	17	15, 154	83	—
	2	18, 227	3, 257	14	17, 077	93	—
	3	18, 227	-1, 264	-4	10, 898	60	71
	4	18, 227	-215	-2	9, 700	53	78
2. River crossings	1	27, 020	886	4	6, 107	23	96
	2	27, 020	1, 418	2	8, 354	31	93
	3	27, 020	2, 649	12	10, 409	38	89
	4	27, 020	2, 974	10	10, 431	38	89
3. Turnpikes	1	20, 765	-1, 470	-7	4, 875	24	49
	2	20, 765	-6, 114	-27	8, 468	41	—
	3	20, 765	795	3	3, 228	16	84
	4	20, 765	180	1	2, 804	14	88
4. Freeways	1	29, 374	8, 556	64	22, 909	78	—
	2	29, 374	12, 932	79	26, 938	92	—
	3	29, 374	7, 768	41	19, 062	65	32
	4	29, 374	8, 471	44	19, 422	66	27
5. High-type arterials	1	36, 019	22, 278	74	34, 586	96	—
	2	36, 019	30, 133	100	43, 554	120	—
	3	36, 019	8, 496	31	17, 501	48	49
	4	36, 019	9, 526	35	18, 770	52	35
6. Low-type arterials	1	17, 081	3, 003	35	16, 891	99	—
	2	17, 081	3, 218	35	16, 940	100	—
	3	17, 081	2, 213	39	12, 443	73	—
	4	17, 081	2, 542	39	12, 776	75	—
7. Links in Pa.	1	13, 907	2, 086	37	16, 290	117	—
	2	13, 907	3, 076	37	17, 231	122	—
	3	13, 907	2, 185	40	11, 766	84	—
	4	13, 907	2, 306	39	11, 996	87	—
8. Links in N.J.	1	12, 470	1, 972	21	11, 684	94	—
	2	12, 470	2, 475	27	13, 066	113	—
	3	12, 470	1, 057	15	8, 463	68	—
	4	12, 470	1, 261	16	8, 827	71	—

The calibration results of tests 3 and 4 were obtained through an iterative process.

First Iteration—The vehicle trips were loaded on the minimum cost paths which were traced on the basis of the restrained speeds that were computed by the capacity restraint program. These restrained speeds were calculated on the basis of V/C ratio in which the assigned volume (V) was taken from the output of test 1.

Second Iteration—The speeds were obtained from averaging the speeds of the first iteration and the minimum average daily speeds. The purpose for this iteration was to get maximum restrained speeds at a reasonable rate to reduce the overassignment on freeways and high-type facilities.

Third Iteration—The minimum cost paths for this iteration were traced on the basis of restrained speeds that were computed by the capacity restraint program. The volume used in the calculation of V/C ratio was taken from the second iteration.

It was found that the three iterations were satisfactory to dampen the fluctuations in tracing alternative minimum cost paths. Large fluctuations, however, were purposely controlled by inputting reasonable parameters in the equations of the restrained assignment program.

The average of the assignment outputs of the first and third iterations produced the best calibration results. The statistical measures in Table 5 indicate that test 3 resulted in better assignment than test 4. However, the assignment results of test 4 are generally comparable to those of test 3. The estimation of the peak-hour fraction (2KD) from the assignment of home-to-work trips on the highway network (which requires several computer runs) did not prove to be significantly superior to inputting values for 2KD.

The restrained tests gave the best simulation volumes of all link groups considered except for the river crossing links. The cause of this occurrence was studied and it was found that the restrained speeds produced multiple river crossings in the trace of the minimum travel cost paths. For example, the tracing of some selected trees showed

TABLE 6

COMPARISON OF ASSIGNED VOLUMES AND GROUND COUNTS AT HIGH-TYPE ARTERIALS AND LOW-TYPE ARTERIALS

Link Identification	1960 Ground Counts	Unrestrained			Restrained			
		Test 1 Diff.	Test 2 Diff.	ADS	Test 3		Test 4	
					Diff.	ADRS	Diff.	ADRS
Sections of high-type arterials:								
US 130	33, 000	+ 17	+ 27	37.0	+10	38.3	+15	39.0
US 130	46, 000	+ 57	+ 83	37.0	+21	32.2	+34	37.5
Roosevelt Blvd.	70, 000	+ 81	+ 91	37.0	- 5	32.8	-11	33.0
West Chester Pike	19, 200	+ 22	+ 22	42.0	+36	32.0	+29	42.0
Sections of low-type arterials:								
Broad Street	36, 000	- 1	+ 75	20.0	-26	16.0	-13	16.0
Chestnut-Walnut	32, 800	- 23	- 32	16.0	-12	13.0	-33	14.0
Market Street	11, 800	- 44	- 14	16.0	-38	17.0	+52	17.0
5th-6th Streets	24, 200	- 1	+ 36	20.0	+ 9	21.5	+ 5	21.5
City Line Avenue	34, 600	- 25	- 24	30.0	+14	23.0	-22	25.6
City Line Avenue	26, 000	- 20	- 21	20.0	-11	18.7	-31	19.0
15th-16th Streets	20, 000	- 26	- 13	20.0	+37	19.0	+67	19.0
Belmont Avenue	16, 600	+102	+103	30.0	- 8	27.5	+ 8	27.5
Lancaster Pike	18, 600	+152	+138	30.0	+26	25.3	+26	26.3

Notes: Applicable to Tables 6, 7, and 8.

a. Diff. = difference between assigned volume and ground count expressed as percent of ground count.
b. ADS = average daily speed.
c. ADRS = average daily restrained speed.

TABLE 7

COMPARISON OF ASSIGNED VOLUMES AND GROUND COUNTS AT TURNPIKES AND EXPRESSWAYS

Link Identification	1960 Ground Count	Unrestrained			Restrained			
		Test 1 Diff.	Test 2 Diff.	ADS	Test 3		Test 4	
					Diff.	ADRS	Diff.	ADRS
Pennsylvania Turnpike:								
Valley Forge-Norristown	20, 524	-38	-48	60.0	-39	60.0	-38	60.0
N.E. Ext'n-Ft. Washington	21, 421	- 5	-36	60.0	+ 8	60.0	+ 6	60.0
Ft. Washington-Willow Grove	21, 245	+12	-16	60.0	+16	60.0	+14	60.0
Willow Grove-Philadelphia	20, 513	+ 3	-26	60.0	+ 1	60.0	+ 2	60.0
New Jersey Turnpike:								
Bordentown-Tpke. Jctn.	32, 613	+16	-32	60.0	+17	60.0	+14	60.0
Mt. Holly-Camden	24, 902	0	-40	60.0	+11	60.0	+ 2	60.0
Camden-Woodbury	20, 919	- 8	-28	60.0	- 1	60.0	- 8	60.0
Woodbury-Swedesboro	17, 773	+10	- 5	60.0	+20	60.0	+ 9	60.0
North-South Freeway:								
NJ 47-NJ 168	21, 000	+65	+69	54.0	+70	53.9	+69	55.0
NJ 168-NJ 534	17, 200	+23	+24	54.0	+21	55.0	+21	55.0
Schuylkill Expressway:								
Valley Forge-US 202	16, 798	+16	+14	54.0	+10	52.5	+28	55.0
Maudyunk-City Line	47, 005	- 6	+ 9	48.0	- 1	48.0	+ 1	49.8
Girard-Spring Garden	88, 666	+18	+39	43.0	+12	38.8	+ 9	40.3
University-34th St.	35, 145	+ 8	+50	43.0	+25	45.0	+27	45.0
7th St.-Front St.	50, 000	+ 2	+ 7	48.0	+ 9	49.3	+11	50.0

TABLE 8

COMPARISON OF ASSIGNED VOLUMES AND GROUND COUNTS AT MASTER COUNT STATIONS AND RIVER CROSSINGS

Link Identification	1960 Ground Count	Unrestrained			Restrained			
		Test 1 Diff.	Test 2 Diff.	ADS	Test 3		Test 4	
					Diff.	ADRS	Diff.	ADRS
Master stations:								
US 202	15, 600	- 6	- 3	31.0	- 78	23.0	- 35	28.0
US 309	19, 800	+ 25	+ 59	48.0	- 11	50.0	+ 33	50.0
NJ 541	3, 000	- 18	- 27	31.0	- 17	32.0	- 19	32.0
US 30	7, 600	+ 80	+ 77	36.0	+ 62	37.0	+ 86	37.0
River crossings:								
Chester Ferry	2, 639	- 39	- 45	8.0	+ 23	8.0	- 15	8.0
Walt Whitman	50, 086	+ 1	+ 6	45.0	+ 27	34.5	+ 29	37.0
Ben Franklin	69, 104	+ 2	+ 5	45.0	0	33.0	0	38.4
Tacony-Palmyra	46, 602	+ 4	+ 9	35.0	- 5	28.0	+ 46	30.0
Burlington-Bristol	18, 738	+ 19	+ 34	30.0	+ 59	30.0	- 6	28.0
Turnpike Bridge	12, 764	- 7	- 55	60.0	- 17	60.0	- 13	60.0
Trenton Freeway	15, 833	+178	+206	50.0	+125	44.3	+124	49.6
Bridge Street	18, 922	- 65	- 76	25.0	- 70	25.0	- 72	25.0
Calhoun Street	18, 271	+ 6	+ 9	25.0	- 17	23.0	- 19	23.5
Yardley	7, 030	+ 50	+ 37	20.0	+ 29	14.0	+ 35	17.8

TABLE 9

SYSTEM CHARACTERISTICS OF THE MERCER COUNTY TRAFFIC ASSIGNMENTS

Items	Assignment	
	District	Zone
Miles of route	107	161
Highway links	182	574
Approach links	32	211
No. of internal load nodes	13	105
Average trip ends per internal load node	41, 400	7, 500
Average population per internal load node	15, 640	1, 940

that trips originating in the Trenton area with a destination in the vicinity of the Philadelphia International Airport would cross the Delaware River at the Trenton Freeway Bridge into Pennsylvania; thus proceeding in Pennsylvania along US 13 and again crossing the Delaware River at the Burlington Bristol Bridge into New Jersey and continuing the journey in New Jersey along US 130 to the Walt Whitman Bridge; and using this bridge to cross once more the Delaware to reach the destination.

In general, the district highway assignment resulted in an overassignment, which is a characteristic of a coarse network. The best assignments were made on the turnpikes and the poorest assignments were made on low-type arterials; freeways and high-type arterials were generally good.

The vehicle summaries produced by the four tests were very close to actual field data. The difference between the vehicle-miles of test 3 and those obtained from the route and intersection data collected from the field was less than 2 percent (22. 36 million vs 22. 73 million).

The link-by-link comparison of assigned volumes to ground counts for randomly selected sections of turnpikes, freeways, high-type arterials, low-type arterials, master count stations, and all river crossings, is given in Tables 6 through 8. Tests 3 and 4 produce generally lower simulation errors than the unrestrained runs of tests 1 and 2. The best results are found for turnpikes, freeways, and high-type arterials. Neither test 3 nor 4 was better than the unrestrained tests for the bridge crossing links. The reason for this discrepancy was previously given.

Overall, the link-by-link comparison indicates that the calibration of the district assignment produces simulation volumes of sufficient accuracy for establishing general design requirements of freeways and high-type highway facilities throughout the DVRPC cordon area.

Mercer County Assignment

For Mercer County, a zone highway assignment was run and compared to the outputs of the district assignments. The comparison and evaluation of the outputs of the two assignment systems were made to assess the amount of improvement made in the calibration of traffic volumes due to the characteristics of the zone system.

The zone and district systems are given in Table 9. The average number of trip ends per zone loaded on the zone network is considerably less than that loaded on the district network (7500 vs 41, 400). The zone network contains 54 additional miles of routes; this additional mileage makes the zone network much denser than the district network (182 links vs 574), and thus it provides a greater combination of route choices for trip interchanges in the area. Figures 4 and 5 show the zone size and network density of Trenton's CBD for the district and zone assignments. These maps illustrate typical differences between the zone and the district networks. The zone centroids (from which trips are loaded) are more uniformly distributed throughout the area than those of the district. In turn, each load node of the zone network is connected to the adjacent highways by more approach links than in the district system, resulting in a more uniform loading of trips. Since the cost trace variables for both the district and zone networks are identical, the differences between the simulated volumes of the zone assignment and those of the district assignment are due to the change in network density and in the size of traffic zones.

Certain capacity characteristics for links located in the suburban and rural areas were revised to describe the zone network in a more precise manner than was necessary for the district assignment; however, these changes are not considered to have a significant influence on the comparison between the zone and district systems.

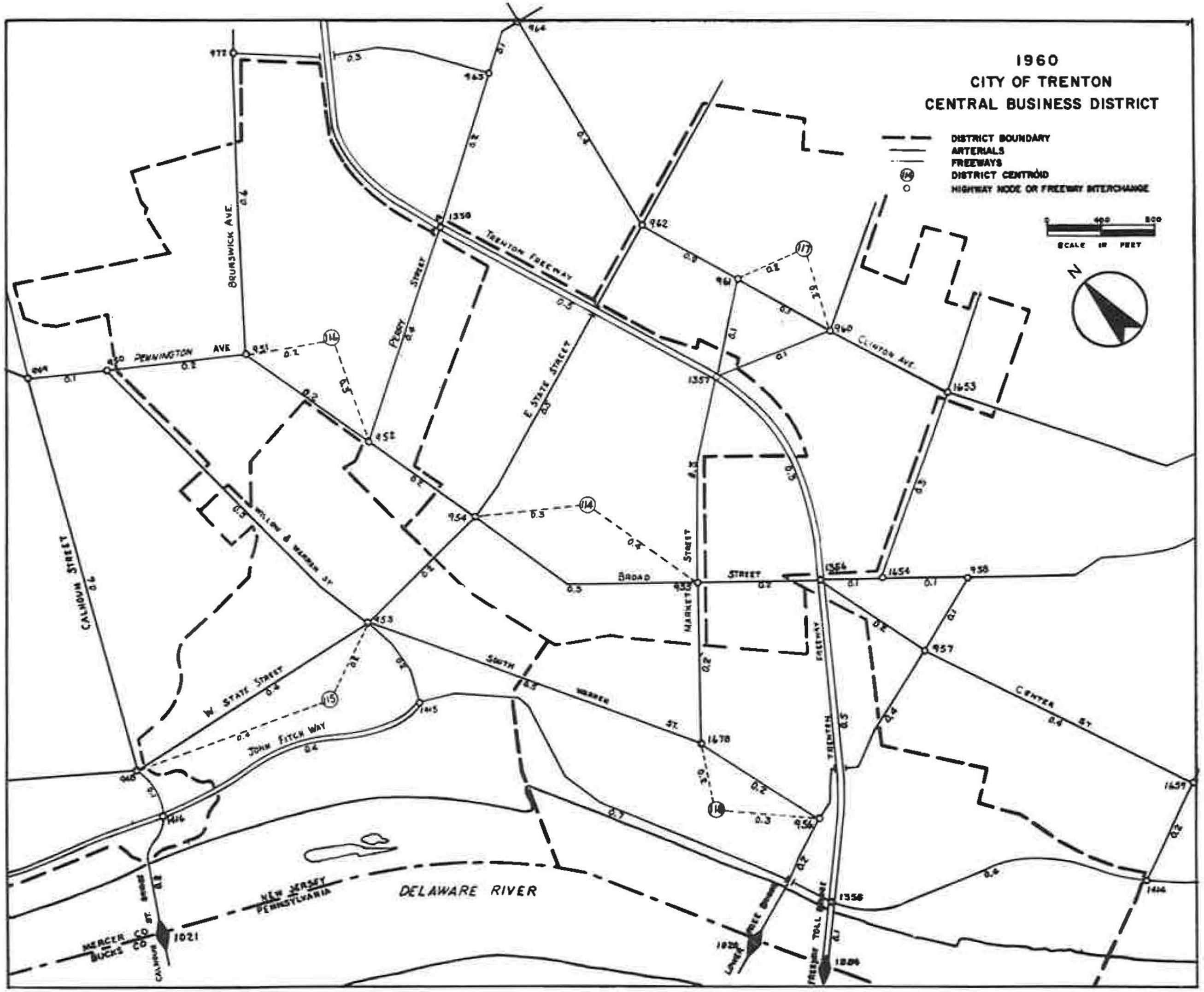
1960
CITY OF TRENTON
CENTRAL BUSINESS DISTRICT
DISTRICT BOUNDARY
ARTERIALS
FREEWAYS
DISTRICT CENTROID
HIGHWAY NODE OR FREEWAY INTERCHANGE
SCALE IN FEET
N
BRUNSWICK AVE.
PENNINGTON AVE
PERRY STREET
TRENTON FREEWAY
E. STATE STREET
CLINTON AVE.
WILLOW & WARREN ST
BROAD STREET
MARKET STREET
CALHOUN STREET
W. STATE STREET
JOHN FITCH WAY
SOUTH WARREN ST.
CENTER ST
TRENTON FREEWAY
DELAWARE RIVER
NEW JERSEY
PENNSYLVANIA
MERCER CO
BUCKS CO
FREEWAY TOLL BRIDGE

Figure 4.

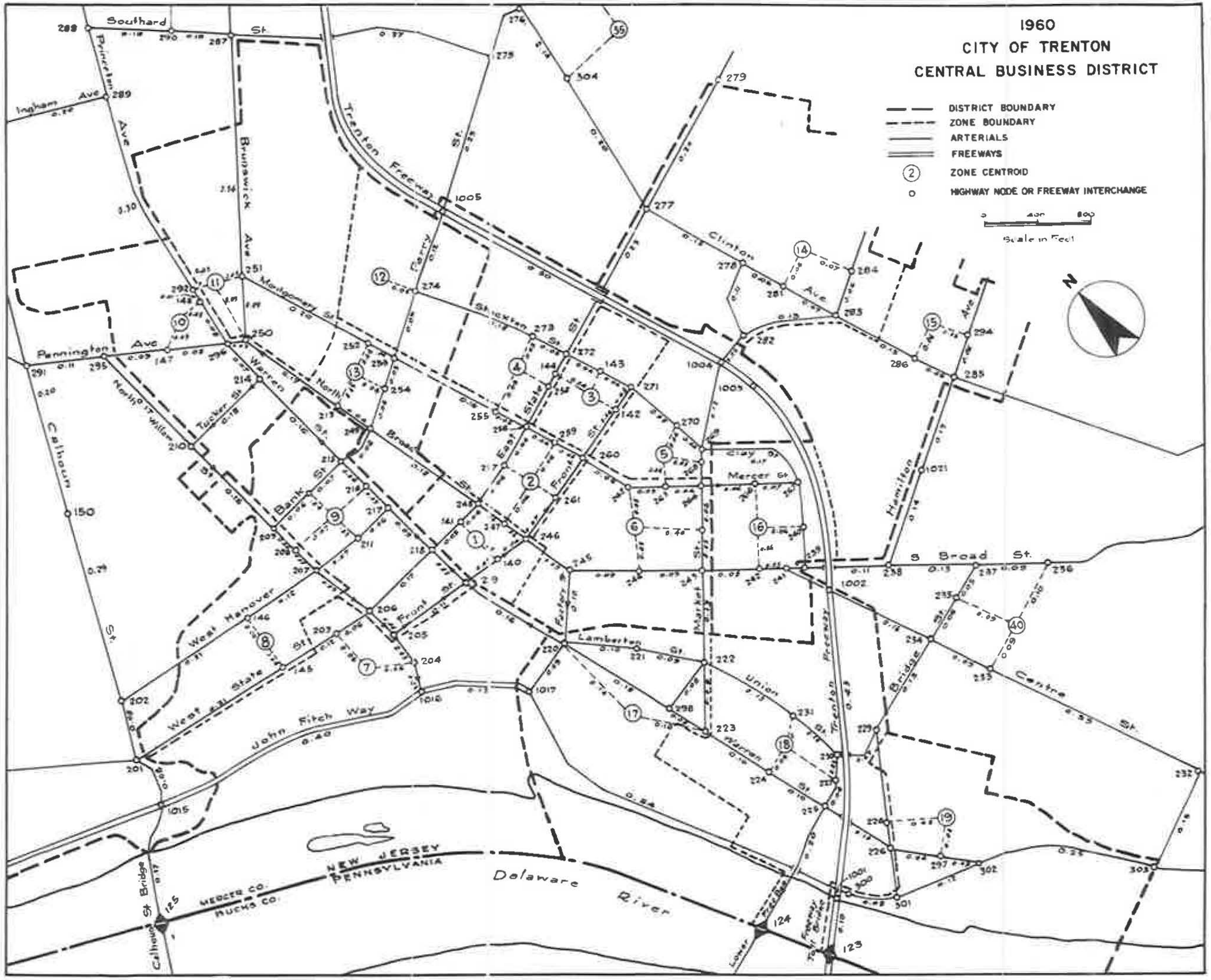
1960
CITY OF TRENTON
CENTRAL BUSINESS DISTRICT
DISTRICT BOUNDARY
ZONE BOUNDARY
ARTERIALS
FREEWAYS
ZONE CENTROID
HIGHWAY NODE OR FREEWAY INTERCHANGE
Scale in Feet
Trenton Freeway
Delaware River
NEW JERSEY
PENNSYLVANIA
MERCER CO.
BUCKS CO.
Calhoun St.
Southard St.
Princeton Ave
Pennington Ave
Brunswick Ave
Clinton Ave
S Broad St.
Centre St.
John Fitch Way
Hamilton

Figure 5.

TABLE 10

ROOT MEAN SQUARE ERRORS FOR DISTRICT AND ZONE HIGHWAY ASSIGNMENTS—MERCER COUNTY

Volume Group	Unrestrained Assignments				Restrained Assignments			
	Zone		District		Zone		District	
	RMS	%RMS	RMS	%RMS	RMS	%RMS	RMS	%RMS
0 1, 999	1, 253	111	560[a]	56[a]	1, 827	165	560[a]	56[a]
2, 000- 4, 999	5, 210	159	5, 364	162	4, 315	129	5, 171	151
5, 000- 9, 999	5, 962	83	9, 814	137	4, 573	64	5, 583	77
10, 000-14, 999	6, 524	55	14, 154	120	5, 517	46	10, 273	87
15, 000-19, 999	10, 522	66	18, 338	112	8, 997	56	11, 550	71
20, 000-24, 999	10, 428	48	16, 787	81	5, 052	24	17, 276	81
25, 000-35, 000	9, 308	31	9, 801	31	9, 488	31	7, 337	23
Freeways	5, 970	29	17, 899	87	6, 776	33	15, 977	77
High-type arterials	12, 265	67	13, 474[b]	51[b]	10, 187	53	13, 555[b]	63[b]
Low-type arterials	6, 746	76	13, 687	116	5, 468	61	9, 415	79
All links	7, 073	73	14, 000	111	5, 776	60	10, 059	79

[a]Only one link in this volume group. [b]Only three links in this volume group.

TABLE 12

REAL ERROR OF TRAFFIC ASSIGNMENT FOR MERCER COUNTY

Design Volume Range	One-Half Design Tolerance (±)[a]	Real Error (%)	
		Zone Calibration	District Calibration
0- 4, 999	99	41	52
5, 000- 9, 999	35	29	42
10, 000-14, 999	21	25	66
15, 000-19, 999	16	40	55
20, 000-24, 999	12	12	69
25, 000-34, 999	17	14	6

[a]As a percent of group mean volume; these volumes were computed on the basis of the mean of ground counts to reflect the 1960 actual traffic distribution by volume ranges.

TABLE 11

LANE REQUIREMENTS BASED ON PRACTICAL CAPACITY AND ECONOMIC VOLUME RANGES FOR PROPOSED HIGHWAY FACILITIES[a]

Range of Average Daily Design Volume	CBD			Urban			Suburban			Rural and Open Rural.		
	L	H	F[b]	L	H	F	L	H	F	L	H	F
0- 4, 999	2	–	–	2	–	–	2	–	–	2	–	–
5, 000- 9, 999	4	–	–	4	–	–	4	–	–	4	–	–
10, 000- 14, 999	–	4	–	4	–	–	4	–	–	4	–	–
15, 000- 19, 999	–	6	–	–	4	–	–	4	–	4	–	–
20, 000- 24, 999	–	6	–	–	6	–	–	4	–	–	4	–
25, 000- 34, 999	–	–	4	–	–	4	–	6	–	–	6	–
35, 000- 44, 999	–	–	4	–	–	4	–	–	4	–	–	4
45, 000- 64, 999	–	–	4	–	–	4	–	–	6	–	–	6
65, 000- 94, 999	–	–	6	–	–	6	–	–	8	–	–	–
95, 000-135, 000	–	–	8	–	–	8	–	–	–	–	–	–

[a]Based on references (2, 3).
[b]L = low-type arterial; H = high-type areterial; and F = freeway.

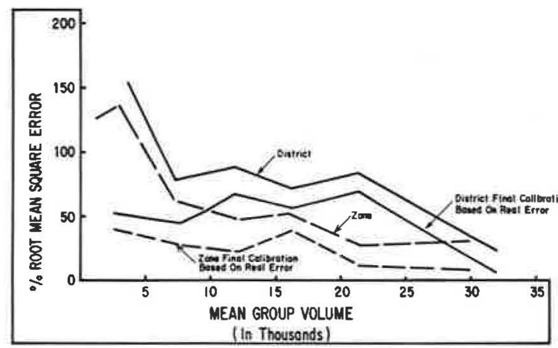

Figure 6. RMS error vs mean group volume.

The zone assignment was calibrated in four computer runs: one unrestrained and three restrained assignment runs. The average of the first and third restrained runs was found to give the best results. The same variables used in the district calibration were applied to calibrate the zone assignment. As in the case of the cordonwide district highway assignment, the evaluation of the Mercer County zone assignment and the comparison of its results with those of the district assignment were made through statistical analysis and direct comparison of ground counts to simulated volumes for selected sections of the highway system.

The statistical evaluation of the Mercer County assignments was made by comparing the assigned volumes with the ground count within selected traffic volume ranges; these volume ranges were established to reflect significant differences in lane capacity requirements. In addition, statistical measures were calculated for freeways, high-type arterials, low-type arterials, and all route types combined. The root mean square error (RMS) was used as the criterion for measuring the accuracy of the assignment. This error both in vehicles and as a percent of the mean of ground counts is given in Table 10 for the zone and district assignments. The zone assignment produces significantly better results than the district assignment since there is a reduction in RMS error for almost all link groups. The lowest RMS values were obtained for the high volume groups of 20, 000 vehicles or more. Freeways received the best assignments with an RMS of 33 percent and low-type arterials the poorest with an RMS of 61 percent. The low-type arterials usually carried an average daily volume of well below 10, 000 vehicles per day.

As it is used in statistics, the RMS value here represents the error of the traffic assignment. In measuring the accuracy of traffic assignment, however, the statistical significance of the RMS should be appraised in conjunction with the fact that while highways are usually designed to accommodate a fixed design volume, they in effect have a capacity to serve certain ranges of volume demand. For example, a six-lane freeway in the CBD can accommodate a traffic volume varying from 65, 000 to 95, 000 vehicles per day, representing a range of 30, 000 vehicles. This range is equivalent to ±RMS (15, 000) which is equal to 19 percent of the mean. It is reasoned that when a freeway is assigned a volume that falls anywhere between 65, 000 and 95, 000, the "real error" of the traffic assignment may be considered insignificant if the ground count also falls anywhere between this range.[1] The allowable design volume ranges are given by route and area type in Table 11 and they are defined here as design tolerance volumes. When these tolerances are expressed in terms of a percentage deviation of the mean of each volume group, the result is defined here as the real error of the traffic assignment. These real errors are listed in Table 12 for both the zone and district systems.[2]

In Figure 7, the overall improvement of the zone assignment results over those of district assignment is brought into focus both in terms of RMS and real error. The

[1] The real error concept does not purport to, either replace the RMS as the measure of assignment accuracy, or justify the error of traffic assignment. Rather, it is introduced to relate the RMS to practical highway design. Thus, if a six-lane freeway is designed to accommodate the mean volume of 80,000 vehicles per day when the RMS is 19 percent, then the peak-hour volume per lane will range between 1,375 and 1,740 vehicles. This range of peak-hour volume per lane is the equivalent of about 65,000 to 95,000 vehicles per day and it is acceptable for design purposes. It is seen, that although we would like to design this freeway to accommodate 1,500 vehicles per lane in the peak hour, we would not require a change in the number of lanes if the peak-hour volume per lane is between the range of 1,375 and 1,740 vehicles.

[2] The real error of traffic assignment as defined in this paper represents not only that error which is attributable to the traffic assignment process, but it also includes errors resulting from other sources such as the O and D survey, the accuracy of the ground counts, and the trip table used. The outputs of simulated volumes for future years will depend not only on the accuracy of the traffic assignment process but also on the accuracy of each component model of the traffic simulation process, such as the car ownership, trip generation, modal split, and trip distribution models.

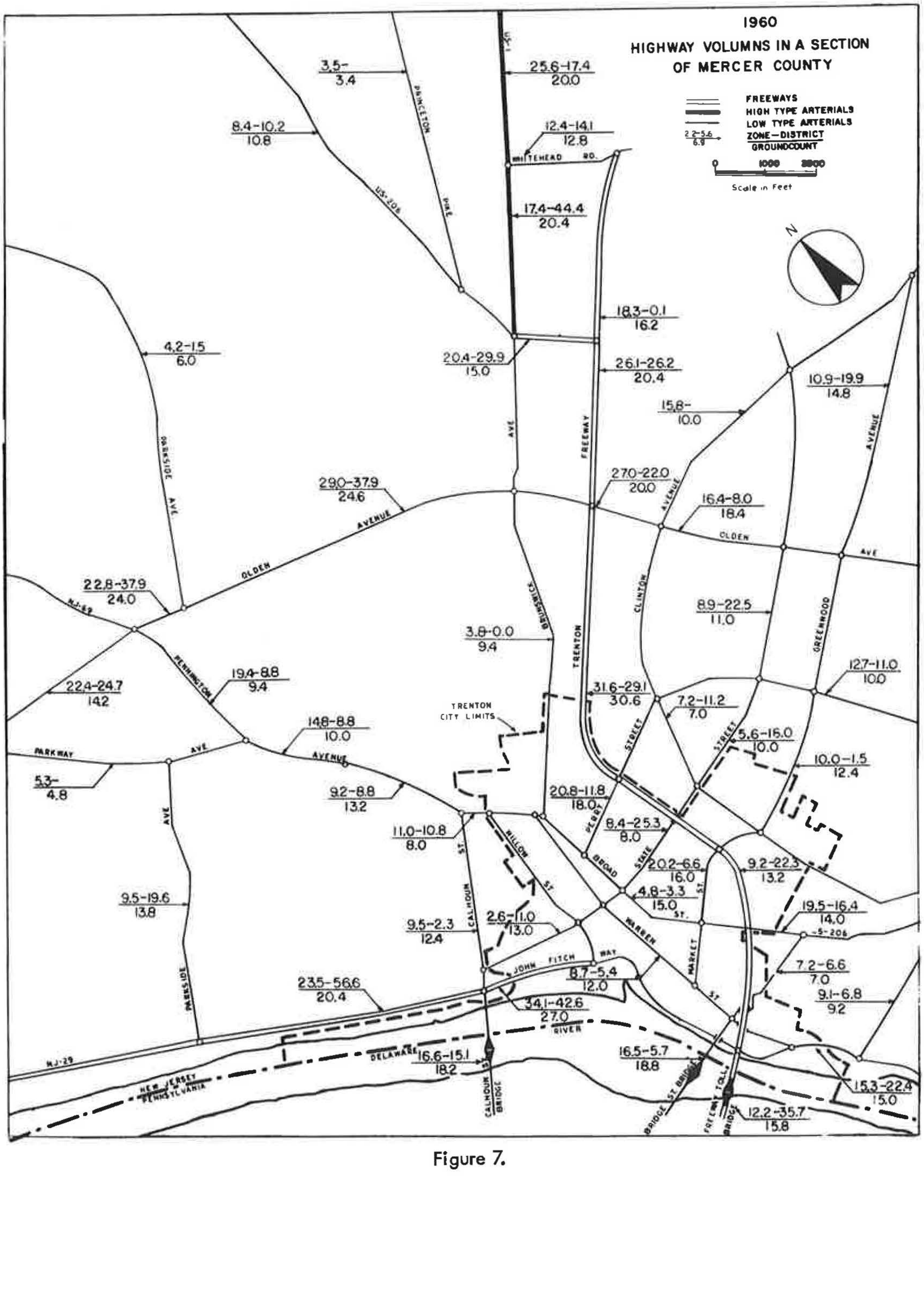
1960
HIGHWAY VOLUMNS IN A SECTION
OF MERCER COUNTY
FREEWAYS
HIGH TYPE ARTERIALS
LOW TYPE ARTERIALS
ZONE—DISTRICT
GROUNDCOUNT
Scale in Feet
N
OLDEN AVENUE
PENNINGTON AVENUE
PARKWAY AVE
PARKSIDE AVE
PRINCETON PIKE
US-206
US-1
WHITEHEAD RD.
TRENTON FREEWAY
BRUNSWICK AVE
CLINTON AVENUE
GREENWOOD AVENUE
PERRY STREET
STATE STREET
BROAD ST.
WARREN ST.
MARKET ST.
CALHOUN ST.
WILLOW ST.
JOHN FITCH WAY
NJ-29
DELAWARE RIVER
NEW JERSEY
PENNSYLVANIA
CALHOUN ST. BRIDGE
BRIDGE ST. BRIDGE
FREEWAY TOLL BRIDGE
TRENTON CITY LIMITS
3.5- 3.4
25.6-17.4 20.0
8.4-10.2 10.8
12.4-14.1 12.8
17.4-44.4 20.4
18.3-0.1 16.2
4.2-1.5 6.0
20.4-29.9 15.0
26.1-26.2 20.4
10.9-19.9 14.8
15.8- 10.0
29.0-37.9 24.6
27.0-22.0 20.0
16.4-8.0 18.4
22.8-37.9 24.0
8.9-22.5 11.0
3.8-0.0 9.4
12.7-11.0 10.0
19.4-8.8 9.4
22.4-24.7 14.2
31.6-29.1 30.6
7.2-11.2 7.0
14.8-8.8 10.0
5.6-16.0 10.0
5.3- 4.8
10.0-1.5 12.4
9.2-8.8 13.2
20.8-11.8 18.0
11.0-10.8 8.0
8.4-25.3 8.0
20.2-6.6 16.0
9.2-22.3 13.2
9.5-19.6 13.8
4.8-3.3 15.0
2.6-11.0 13.0
19.5-16.4 14.0
9.5-2.3 12.4
7.2-6.6 7.0
23.5-56.6 20.4
8.7-5.4 12.0
34.1-42.6 27.0
9.1-6.8 9.2
16.6-15.1 18.2
16.5-5.7 18.8
15.3-22.4 15.0
12.2-35.7 15.8

Figure 7.

greatest accuracy was obtained for high-volume roads and the least accuracy for low-volume roads. This conforms with the findings of other transportation studies.

Actual field survey data of route miles and traffic counts produced 1.409 million vehicle-miles; and the zone and district assignments produced 1.409 and 1.523 million vehicle-miles, respectively. The excellent agreement produced by the zone assignment is due to the system characteristics of the zone network such as additional highway mileage, smaller zone size, fewer number of trips loading from a zone load node and shorter highway links. The combination of these system characteristics, therefore, has resulted in better paths for traffic assignment.

A detailed analysis of simulated volumes is shown in Figure 7 which illustrates some freeways, high-type arterials, and low-type arterials in the fringe area of Trenton. The zone assigned volumes, the district assigned volumes and the observed ground counts are shown for each highway link. These volumes provide a link-by-link comparison of zone and district assignments. A good simulation was obtained on the Trenton Freeway by both the district and zone assignments; notable were the improvements made on the John Fitch Way, Olden Avenue, US 1, and sections of routes in the CBD such as Warren and Perry Streets. On these highway sections, the overall differences between the assigned volumes and the observed link volumes for the zone and district assignments were as follows:

Route	Zone	District
John Fitch Way	+14%	+49%
Olden Avenue	+16%	+30%
US 1	+ 2%	+42%
Warren Street	-27%	-55%
Perry Street	+11%	-34%

These results indicate that the zone simulated volumes are of significantly greater accuracy than those of the district assignment.

CONCLUSIONS

The traffic assignment process used by the Delaware Valley Regional Planning Commission is based on the concept that trip interchanges are assigned to those routes which offer the least resistance to travel. The resistance parameter used is travel cost. This represents a departure from the practice used by other transportation studies which consider travel time as the travel resistance parameter. Travel cost was used in order to minimize the amount of overassignment to freeways and expressways which normally become considerably overloaded when travel time is used.

Only the cost components which were quantifiable were included in the computation of the total travel resistance. These were the vehicle operating costs, vehicle time costs, bridge tolls, accident costs and turnpike tolls. These five cost components were then combined into two sets of total travel costs; one set including all five components and another combining only the vehicle operating costs, vehicle time costs, and bridge tolls. For each set of these travel costs an unrestrained assignment was run (tests 1 and 2) and it was found that test 1, which included only the vehicle operating costs, vehicle time costs and bridge tolls, produced better unrestrained assignment outputs. Consequently, only these three components of travel cost were the ones used in the calibration of the restrained assignment tests 3 and 4.

The results of tests 3 and 4 proved that the extra efforts associated in the calculation of the 2KD value (peak-hour fraction) did not produce more accurate assignment results than did test 3 where the 2KD's were input into the capacity restraint program. The analysis and evaluation of the assignment results of test 3 showed that the use of travel cost as the parameter of travel resistance produced simulated volumes of acceptable accuracy and that these volumes can be used as a guide in the design of major highway facilities such as freeways and high-type arterials. The RMS errors for turnpikes and freeways were 16 percent and 65 percent respectively, and 48 percent for high-type arterials.

A satisfactory calibration was obtained through the use of mechanical means built into the assignment program without the need of manual adjustments of the input variables used in the assignment package. This is considered a very desirable property since it permits a realistic evaluation of the accuracy of the calibration process and thus provides reliable estimates of future simulated volumes.

As the direct result of smaller zone size and denser highway network, the zone assignment for Mercer County produced much better simulation of traffic volumes than the district highway assignment. The real error of the zone assignment for all the link volumes groups considered varied from 12 percent to 41 percent, demonstrating that the zone calibration for Mercer County produced assignment outputs that could effectively be used in highway design.

This paper shows that the use of the real error concept in the assessment of traffic assignment outputs is valuable since it is directly related to highway lane design volumes.

We believe that when using the zone outputs for highway design the errors of traffic assignment can be reduced if the simulated link volumes are combined to reflect the general traffic demand on the particular highway.

ACKNOWLEDGMENT

The authors wish to acknowledge the contributions made by several members of the DVRPC study staff and the Traffic Assignment Subcommittee in the preparation of this paper. Special thanks are given to Richard E. Hubbell and Anthony R. Tomazinis for their constructive criticisms of the initial draft of this paper. However, the authors are solely responsible for any errors in the calculations and conclusions presented.

REFERENCES

1. U. S. Department of Commerce, Bureau of Public Roads. Traffic Assignment Manual. 1964.
2. Zakaria, Thabet. Traffic Assignment—Part I: Testing the 1960 Highway Assignment. Delaware Valley Regional Planning Commission, 1966 (unpublished).
3. Zakaria, Thabet. Economic Evaluation of Individual Highway Facilities. Delaware Valley Regional Planning Commission, 1966 (unpublished).
4. Hoch, Irving. Benefit-Cost Methods for Evaluating Expressway Construction. Traffic Quarterly, April 1961.
5. Wickstrom, G. V. Basic Relationship Between Daily Work Travel and Peak Hour Traffic. Tech. Memo. 13-9, Penn-Jersey Transportation Study, 1964; Traffic Engineering, Volume 34, No. 5.
6. Hubbell, R. E., and G. V. Wickstrom. Determining Highway Capacity. Tech. Memo. 11-4, Penn-Jersey Transportation Study, 1963 (unpublished).
7. The State of the Region. Penn-Jersey Reports, Vol. 1, p. 111, 1960.