CAPACITY OF SIGNALIZED INTERSECTIONS

Eugene Reilly, Ivan Dommasch, and Munireddy Jagannath,
Division of Research and Development, New Jersey Department of Transportation

Standardized methods for estimating capacity at signalized intersections have been sought for at least 25 years. The publication by the Bureau of Public Roads of the 1950 Highway Capacity Manual was the first extensive effort made toward this objective. In 1960, W. R. Bellis, of the New Jersey Department of Transportation, developed a more simplified technique. The results of the research discussed in this paper indicate that the techniques in the Highway Research Board's 1965 Highway Capacity Manual yield greater than 20 percent error in estimating the through capacity of the approach to a signalized intersection for at least half the locations studied. When the Bellis technique was used, less than 20 percent of the locations showed this error. Revisions were made to techniques in the 1965 Highway Capacity Manual, and 20 percent error then was found in only 25 percent of the locations studied. It was concluded that measuring the capacity of an approach in the field is preferable to estimating capacity by using the 1965 Highway Capacity Manual. A method of determining capacity from field measurements is described briefly in this paper.

•STANDARDIZED methods for estimating capacity at signalized intersections have been sought for at least 25 years. The 1950 Highway Capacity Manual (1) was the first extensive effort made toward this objective. The 1965 Highway Capacity Manual (HCM) (2) added parameters not covered in the 1950 publication. Meanwhile, many engineers were continuing to use their own techniques for capacity estimation primarily because of the HCM's lack of accuracy.

The HCM has been the subject of several studies (3, 6, 7, 8) that have investigated the applicability of the parameters, accuracy of results, and modification of the approach used to determine capacity.

A study by Reilly and Seifert (3) was conducted to determine the accuracy of the HCM's capacity estimation. The results of this study indicated that the HCM capacity estimates were inaccurate by at least 20 percent for half the approaches studied. The results indicated an inaccurate quantification of some of the parameters in the HCM for a limited study sample. As a result of Reilly and Seifert's study (3), an expanded work plan was developed to study and revise the parameters of the HCM to improve its reliability for estimating capacity. More intensive analysis was performed by the Bellis method (4) on capacity estimation.

STUDY METHODOLOGY

This paper compares the HCM and Bellis techniques to a field measurement of capacity [average loaded-cycle expanded (ALE) measurement]. ALE is considered to be the most accurate method of determining the capacity of a signalized approach, and it represents an expansion of the average number of vehicles/loaded cycle. For example, if there were an average of 20 vehicles/loaded cycle and 60 cycles/hour, ALE would be 20 × 60 or 1,200 vehicles/hour.

The HCM method combines factors for several environmental and traffic conditions and then applies these factors to a basic volume. The basic volume is determined by the approach width and parking conditions at the site.

The Bellis method is simpler. It has been modified in this study to include a factor for right and left turns. Basically, a lane capacity volume is given for each of the 4 types of approach for a specific green period. This volume is adjusted by the number of lanes, number of cycles, and percentage of trucks and turns.

Data Collection

The primary object of this study is the improvement of the reliability of the HCM parameters. It is evident that the interaction of many variables would require an extremely large sample size. The estimate of approach volume is dependent on 10 separate variables, many of which have a wide range of application. We decided to try to incorporate our data collection with another program because it would be impossible to amass the information with our own forces.

The data collected in 21 samples by 1 consultant's field crews were found to have a variety of inaccuracies which resulted in our using only 38 percent of the data collected. A second consultant volunteered input from 24 samples. Saturation flow information and HCM parameters were collected. However, only 50 percent of these data were useful in the analysis. New Jersey Department of Transportation field crews tabulated data on 106 sample sites. Some of these samples were reruns because inaccuracies were found in the original data. Sixty percent of these data were used in the final analysis.

Tables 1 and 2 give the characteristics of 122 sites. The following abbreviations are used in these tables:

Abbreviation	Definition
LF	Load factor
PHF	Peak-hour factor
CBD	Central business district
OBD	Outlying business district

Eighty-five of the sites were used in the analysis. Although 151 sites were studied originally, some were not tabulated in Tables 1 and 2 usually because LF was zero or the data were collected inaccurately.

Because of the variety and enormousness of unusable data, the original plan for the study had to be modified to accommodate the limited input that was available for the modification of so many parameters in the HCM.

Because of the lack of available 1-way streets, only approaches on 2-way streets were used. The method of collection was similar to that used in the Reilly and Seifert study (3).

Data Analysis—Highway Capacity Manual Method

The major steps in the analysis are as follows:

1. Capacity is estimated by using the adjustment factors in the HCM. This includes use of the factors for peak hour and metropolitan area population. The population used for this factor is the population of the municipality in which the intersection is located plus the population of adjacent municipalities.
2. Estimate of capacity is again computed, but no adjustment is made for PHF. The reason for not making an adjustment is that the PHF correction accounts for delays due to peaking traffic and not for reductions in capacity. Because ALE does not make subjective judgments concerning delays, the HCM estimate for capacity is computed without a PHF adjustment, thereby putting the HCM estimate on the same basis as ALE.
3. HCM parameters are studied for their rationale and accurateness (as determined

Table 1. Physical, environmental, and traffic characteristics of study locations for 2-way streets with no parking.

							Percent Turning Left		Percent Turning Right		Truck Percent		Bus Percent					
Site	Approach Width (ft)	Lanes	Location	Population (thousands)	PHF	LF	Expanded Loaded Cycle	Peak Hour	Expanded Loaded Cycle	Peak Hour	Expanded Loaded Cycle	Peak Hour	Expanded Loaded Cycle	Peak Hour	Cycle (s)	Green Time (s)	Service Volume (vehicles/ h green)	ALE Capacity[a] (vehicles/ h green)
RS-16	9	1	Residential	250	0.89	0.35	0		7		0		–	–	90	63	1,291	1,486
RS-22	9.5	1	Residential	250	0.84	0.90	31		3		2		–	–	70	26	1,402	1,455
MEP-1W	10	1	Residential	75	0.89	0.63	0	0	19	23	1	2	–	–	70	27	1,129	1,173
SB-2S[b]	14	1	Residential	75	0.78	0.51	25	27	12	10	2	1	–	–	70	26	1,035	1,246
EN-1S	14	1	Residential	250	0.79	0.27	8	9	21	23	2	3	–	–	60	26	954	1,385
MET-1E	15	1	Residential	250	0.57	0.20	5	9	17	18	2	1	1[c]	1[c]	70	28	877	1,683
MET-1N[d]	15	1	Residential	250	0.93	0.67	2	3	67	65	0	0	–	–	70	33	1,359	1,454
RS-17	18	1	Residential	250	0.79	0.46	10		11		6		–	–	70	31	1,022	1,156
SB-1E[b]	18	2	Residential	75	0.85	0.31	27	27	8	8	1	2	–	–	70	36	1,370	1,605
EM-1E	18	1 and 2[e]	Residential	250	0.85	0.78	6	5	22	23	0	0	–	–	60	24	1,852	2,014
SB-1S[b]	20	2	Residential	75	0.81	0.59	11	11	25	27	1	1	–	–	70	25	2,308	2,570
RS-14(A)	20	2	Residential	250	0.80	0.12	0		0		3		5[c]		90	31	2,520	3,314
RS-14(B)	20	2	Residential	250	0.91	0.40	0		8		4		0[c]		90	31	2,616	3,227
RS-20	20	2[f]	Residential	250	0.89	0.78	4		7		2		0[c]		90	55	1,751	1,833
RS-12	10	1	CBD	250	0.87	0.21	0		2		3		15[c]		70	39	839	1,107
RS-23[g]	10	1	CBD	250	0.81	0.27	16		0		3		11[h]		70	32	783	978
MEP-2E[d]	11	1	CBD	75	0.87	0.41	62	59	15	17	6	6	–	–	70	29	1,077	1,260
MEP-2EII[d]	11	1	CBD	75	0.84	0.18	70	60	15	18	14	7	–	–	70	29	911	1,204
EB-1S	30	3	CBD	250	0.81	0.07[i]	41	39	3	3	8	5	3[c]	12[c]	80	48	1,792	2,200
EO-4E[j]	14	1	OBD	250	0.90	0.23	23	18	18	20	8	6	–	–	60	21	577	808
EO-4S	16	1	OBD[k]	250	0.76	0.27	3	2	5	8	11	8	–	–	60	31	862	1,191
MNB-1N	18	2	OBD	100	0.90	0.12	28	34	2	3	0	1	–	–	70	31	1,330	1,708
RS-13	21	2	OBD	250	0.75	0.02[j]	0		11		0		0[c]		70	42	1,150	2,317
MET-2W[d]	22	2	OBD	250	0.87	0.39	17	15	53	52	6	6	–	–	70	21	1,420	1,827
MET-2N	26	2	OBD[k]	250	0.83	0.31	20	18	1	2	6	6	–	–	70	39	1,977	2,294

Note: 1 ft = 0.3048 m.

[a] Average loaded cycle volume expanded to full volume.
[b] Data were not used because of large variation in green phase.
[c] Near-side stop.
[d] Data were not used because few samples had more than 60 percent turns.
[e] Data were not used because this operation combined 1- and 2-lane streets.
[f] Data were not used because 2-lane approach narrows to 1 lane downstream.
[g] Data were not used because left-turn lane is also used for through movement.
[h] Far-side stop.
[i] Data were not used because load factor was too low to allow accurate expansion of loaded cycle volume.
[j] Data were not used because of excessive delays during loaded cycles.
[k] Reclassified as CBD.

Table 2. Physical, environmental, and traffic characteristics of study locations for 2-way streets with parking.

Site	Approach Width (ft)	Lanes	Location	Population (thousands)	PHF	LF	Percent Turning Left: Expanded Loaded Cycle	Percent Turning Left: Peak Hour	Percent Turning Right: Expanded Loaded Cycle	Percent Turning Right: Peak Hour	Truck Percent: Expanded Loaded Cycle	Truck Percent: Peak Hour	Bus Percent: Expanded Loaded Cycle	Bus Percent: Peak Hour	Cycle (s)	Green Time (s)	Service Volume (vehicles/ h green)	ALE Capacity[a] (vehicles/ h green)
PC-3E[b]	16	1	Fringe	250	0.85	0.13	23	20	36	33	5	5	—	—	90	33	669	851
PC-3ERE	16	1	Fringe	250	0.83	0.13	12	15	8	20	8	5	—	—	90	33	885	1,287
PC-3WRE	16	1	Fringe	250	0.84	0.35	28	28	18	18	5	5	1[c]	2[c]	90	33	1,148	1,379
RS-27	17	1	Fringe	250	0.85	0.52	0		37		6		—	—	70	28	1,000	1,184
RS-29	17	1	Fringe	250	0.83	0.41	4		12		3		—	—	70	28	934	1,184
MNB-2W	17	1	Fringe[d]	100	0.71	0.12	13	12	10	9	3	3	—	—	70	30	697	1,249
RS-27II	17	1	Fringe	250	0.84	0.24	7	4	24	26	9	8	0[c]	2[c]	70	25	675	904
RS-29II	17	1	Fringe	250	0.78	0.16	25	25	9	13	8	6	0[c]	0[c]	70	25	888	1,142
MNB-4WII	18	1	Fringe	100	0.84	0.59	5	5	8	8	1	1	—	—	70	28	1,185	1,313
MNB-4WIII	18	1	Fringe	100	0.82	0.45	2	2	12	12	0	1	—	—	70	28	1,117	1,392
MNB-4W	18	1	Fringe	100	0.88	0.33	2	3	9	10	4	3	—	—	70	35	998	1,176
SS-1N	18	1	Fringe	75	0.90	0.18	7	11	16	13	4	4	—	—	80	36	813	1,175
PC-2E	18	1	Fringe	250	0.85	0.38	8	8	14	12	5	5	—	—	90	43	1,146	1,194
PH-1N	18	1	Fringe	100	0.96	0.40	2	3	2	4	5	5	—	—	80	40	1,328	1,386
PH-1NRE	18	1	Fringe	100	0.94	0.69	2	2	2	2	2	3	—	—	80	40	1,428	1,553
PC-2ERE	18	1	Fringe	250	0.75	0.52	10	10	9	9	2	2	2[c]	2[c]	90	43	1,218	1,451
MNB-4SII	19	1	Fringe	100	0.86	0.43	31	30	11	11	1	1	—	—	70	31	850	1,094
MNB-4SIII	19	1	Fringe	100	0.80	0.41	32	33	13	11	1	1	—	—	70	31	866	1,143
MNB-4S	19	1	Fringe	100	0.83	0.45	17	16	26	21	0	0	—	—	70	25	1,157	1,372
EI-1SRE[f]	19	1	Fringe	250	0.87	0.25	27	17	26	37	47	22	—	—	90	33	760	851
EI-1S	19	1	Fringe	250	0.84	0.45	22	25	18	15	1	2	—	—	90	33	1,145	1,394
UP-1SII	20	1	Fringe	75	0.91	0.13	3	3	12	10	5	4	—	—	80	36	933	1,250
UP-1WII	20	1	Fringe	75	0.87	0.07	4	10	6	8	2	4	—	—	80	36	1,147	1,633
EI-4W	20	1	Fringe[d]	250	0.90	0.55	10	9	7	8	4	3	—	—	70	28	1,348	1,557
CC-1W	20	1	Fringe	100	0.88	0.24	7	5	14	13	3	5	—	—	70	31	962	1,324
SP-1E	20	1	Fringe	75	0.82	0.22	12	11	15	13	5	3	—	—	60	30	852	1,182
SP-1S	20	1	Fringe	75	0.89	0.28	17	18	16	20	2	1	—	—	60	23	929	1,160
RS-30-a	20	1	Fringe	250	0.81	0.41	13		17		4		—	—	70	32	1,022	1,267
RS-30-b	20	1	Fringe	250	0.83	0.58	16		14		3		—	—	70	32	1,044	1,244
RS-31	20	1	Fringe	250	0.82	0.41	4		10		4		0[c]		70	36	1,118	1,372
RS-36	20	1	Fringe	250	0.81	0.18	7		7		1		6[c]		70	36	1,104	1,333
RS-30II	20	1	Fringe	250	0.87	0.39	18	17	19	18	6	5	—	—	70	31	1,007	1,244
PC-3SRE	20	1	Fringe	250	0.92	0.15	19	15	10	7	9	11	0[c]	0[c]	90	51	954	1,259
RS-34	21	1	Fringe	500	0.86	0.75	8		25		1		0[c]		90	29	1,247	1,327
PP-1WRE	22	1	Fringe	250	0.88	0.68	11	12	6	6	1	1	—	—	60	24	1,162	1,324
PP-1W	22	1	Fringe	250	0.86	0.70	16	16	9	9	5	5	—	—	60	24	1,105	1,246
RS-38	22	1	Fringe	250	0.85	0.88	3		9		5		6[c]		70	28	1,350	1,375
RS-37	22	1	Fringe	250	0.94	0.35	7		2		1		3[c]		70	42	1,467	1,583
RS-37II	22	1	Fringe	250	0.83	0.06[g]	12	8	10	6	6	6	—	—	70	42	840	1,388
RS-38II	22	1	Fringe	250	0.94	0.63	14	12	12	13	7	7	—	—	70	28	1,140	1,235
PP-1S	23	1	Fringe	250	0.85	0.10	6	10	6	8	5	5	—	—	60	30	900	1,260
PP-1N	23	1	Fringe	250	0.83	0.65	7	8	23	22	5	5	—	—	60	30	1,058	1,185
PP-1NRE	23	1	Fringe	250	0.88	0.83	8	8	18	18	2	3	—	—	60	30	1,158	1,217
PP-1E	23	1	Fringe	250	0.87	0.56	8	7	4	4	5	5	—	—	60	24	1,172	1,371
CC-1N	24	1	Fringe	100	0.87	0.33	2	3	9	6	3	3	1[c]	5[c]	70	31	1,406	1,666
MNB-5E	24	1 and 2[b]	Fringe	100	0.84	0.47	9	8	11	12	1	2	—	—	70	25	1,381	1,618
RS-32	25	1 and 2[b]	Fringe	250	0.87	0.18	26		15		1		—	—	70	31	1,512	2,032

Table 2. Continued.

Site	Approach Width (ft)	Lanes	Location	Population (thousands)	PHF	LF	Percent Turning Left: Expanded Loaded Cycle	Percent Turning Left: Peak Hour	Percent Turning Right: Expanded Loaded Cycle	Percent Turning Right: Peak Hour	Truck Percent: Expanded Loaded Cycle	Truck Percent: Peak Hour	Bus Percent: Expanded Loaded Cycle	Bus Percent: Peak Hour	Cycle (s)	Green Time (s)	Service Volume (vehicles/ h green)	ALE Capacity[a] (vehicles/ h green)
EN-1W	18	1	Residential	250	0.88	0.15	17	14	19	16	3	3	–	–	60	28	1,004	1,400
MNB-3W	18	1	Residential	100	0.85	0.61	35	32	6	8	2	1	–	–	70	38	1,050	1,127
SB-2E[i]	18	1	Residential	100	0.85	0.24	10	8	8	8	3	2	–	–	70	37	1,159	1,496
MNB-3N	20	1	Residential	100	0.86	0.55	14	13	3	2	1	1	–	–	70	25	1,179	1,382
PP-6NRE	20	1	Residential	250	0.83	0.05[g]	12	12	0	2	0	1	–	–	60	33	727	1,491
PP-5E	20	1	Residential	250	0.82	0.15	24	30	26	25	5	5	–	–	60	19	611	1,137
PP-4W[b]	20	1	Residential	250	0.81	0.20	12	13	17	19	5	5	–	–	60	20	697	1,035
PP-5W	20	1	Residential	250	0.82	0.22	22	17	10	14	5	5	–	–	60	19	778	1,253
PP-4WRE	20	1	Residential	250	0.84	0.18	14	15	19	20	5	2	–	–	60	20	946	1,358
PP-5WRE	20	1	Residential	250	0.84	0.27	8	8	14	12	4	4	–	–	60	19	1,063	1,397
PP-4E	20	1	Residential	250	0.79	0.17	38	39	13	15	5	5	–	–	60	20	586	1,153
PP-6N[b]	20	1	Residential	250	0.72	0.17	9	6	13	11	5	5	–	–	60	33	624	993
MNB-2S	22	1	Residential	100	0.84	0.22	10	7	21	24	5	3	–	–	70	30	1,296	1,634
PP-6W	22	1	Residential	250	0.87	0.27	27	20	14	13	5	5	–	–	60	21	1,131	1,403
PP-6WRE	22	1	Residential	250	0.92	0.30	19	19	12	14	3	3	–	–	60	21	1,214	1,467
PP-2E[j]	17	1	CBD	250	0.85	0.52	0	0	10	9	5	5	–	–	90	33	740	873
MNB-1W	19.5	1	CBD	100	0.87	0.20	12	11	16	19	6	2	–	–	70	29	978	1,145
UP-1S	20	1	CBD[k]	75	0.83	0.18	5	12	11	13	4	4	–	–	80	36	1,067	1,400
UP-1W	20	1	CBD[k]	75	0.83	0.18	11	9	9	10	2	5	0[c]	3[c]	80	36	1,147	1,763
RS-33	20	1	CBD	250	0.86	0.58	0		18		5		18[c]		70	32	1,152	1,239
MEP-4S	21	1	CBD	75	0.90	0.29	0	0	0	0	6	8	5[c]	19[c]	70	42	927	1,139
MEP-4SII	21	1	CBD	75	0.88	0.10	0	0	0	0	7	5	0[c]	0[c]	70	42	783	1,190
PP-3N[j]	22	1	CBD	250	0.90	0.20	0	0	0	0	5	5	0[c]	0[c]	90	53	1,292	1,623
RS-26	25	1	CBD	250	0.91	0.10	0		12		5		4[c]		120	47	1,200	1,436
MEP-4N	26	1 and 2[h]	CBD	75	0.92	0.37	0	0	28	25	2	2	–	–	70	42	1,275	1,445
MEP-4NII	26	1 and 2[h]	CBD	75	0.88	0.12	0	0	27	28	8	6	–	–	70	42	1,102	1,346
MEP-2S	28	1 and 2[h]	CBD	75	0.86	0.24	3	4	42	38	8	6	–	–	70	36	1,307	1,703

Note: 1 ft = 0.3048 m.

[a]Expanded to full volume.
[b]Data were not used because loaded cycle data were inaccurately tabulated.
[c]Near-side stop.
[d]Reclassified as residential.
[e]Far-side stop.
[f]Data were not used because of the high percentage of trucks.
[g]Data were not used because the load factor was too low to allow accurate expansion of loaded cycle volume.
[h]Data were not used because this operation combined 1- and 2-lane streets.
[i]Data were not used because of the large variation in green phase.
[j]Data were not used because of the unusual layout.
[k]Reclassified as fringe.

from prior studies), and changes are made accordingly. Estimates of capacity again are made by using the revised factors; again, this is done without a correction factor being applied for PHF.

4. The estimates of HCM capacity derived from these 3 steps are compared to the ALE values for statistical differences.

5. ALE capacities as determined from the field conditions by those basic conditions defined in the HCM charts (2, Figures 6.8 and 6.9) as revised in the third step are adjusted. A new curve should be computed for the 1.0 LF condition with the adjusted ALE values.

The resulting set of curves and adjustment factors can be checked accurately only with an entirely new set of field data. However, the utility of the HCM method of capacity estimation is currently under question and soon may be completely revised.

Although LF data were included in the data collected, no examination of the HCM estimate at various levels of service was attempted for 2 reasons. First, it was not possible to define adequately a loaded cycle such that 2 individuals would each have equal assurance of its loaded condition. The resulting situation would reflect a wide variation in the load factor for equal service volumes. Although the level-of-service variation would be large, the average number of vehicles/loaded cycle would not be large, which would thus maintain reliable capacity estimates.

The second reason is the variability encountered in unloaded cycles. If one assumes that the loaded cycles were accurately defined, then the unloaded cycles could contain any number of vehicles up to the number needed to load a cycle.

The variability results from an inability to measure the volume-to-capacity ratio of individual unloaded cycles. For a given period of time at a given intersection, this ratio will not vary significantly. However, when many intersections studied at different periods are considered, this ratio can range from near 0 to 1. Because of this, it would be possible for 2 intersections with similar physical and environmental characteristics to have great differences in volumes with equal load factors.

Data Analysis—Bellis Method

The revisions made to HCM parameters also were made to those parameters that apply to the Bellis method. The most prominent correction was for turns. Otherwise the procedure for estimating capacity by this method is similar to that outlined by Reilly and Seifert (3).

Revisions to HCM Parameters

Turning Movements

The quantified adjustments for turns (2, Tables 6.4 and 6.5) reflect basic approach volume decreases for increases in the width of approach for 0 percent turns at 2 points of each curve. Figures 1 and 2 show the actual differences in service volume at the smaller widths. To overcome this apparent disparity for less than 10 percent turns, the turn factors of the HCM will be discarded for lower approach widths up to 10 percent turns. For example, for a 14-ft (4.3-m) approach with no parking, the factors for 16 to 24 ft (4.9 to 7.3 m) will be used for 0 to 10 percent turns; the factors for 15 ft (4.6 m) will be used for more than 10 percent turns.

Metropolitan Area Size

Three metropolitan area size choices exist for the engineer:

Figure 1. HCM turn factors for 2-way streets with no parking.

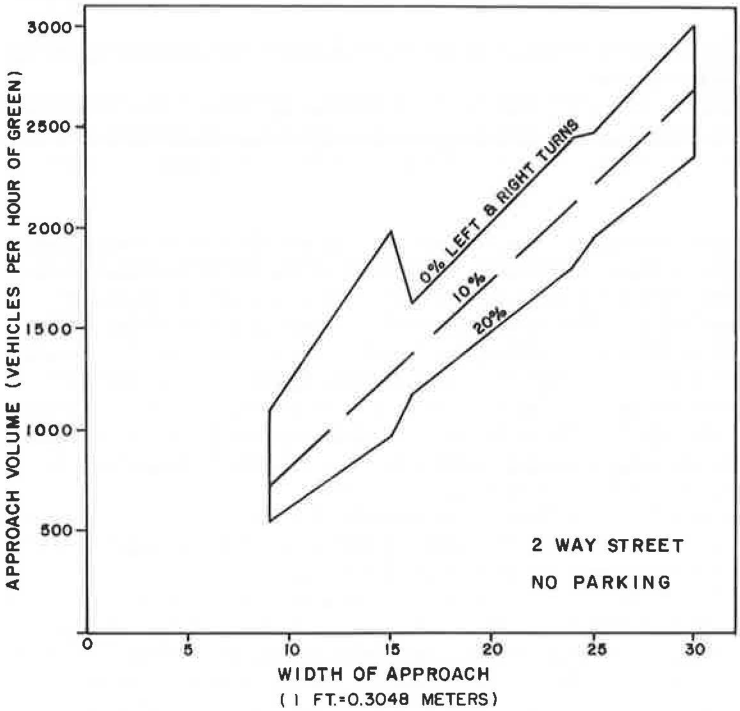
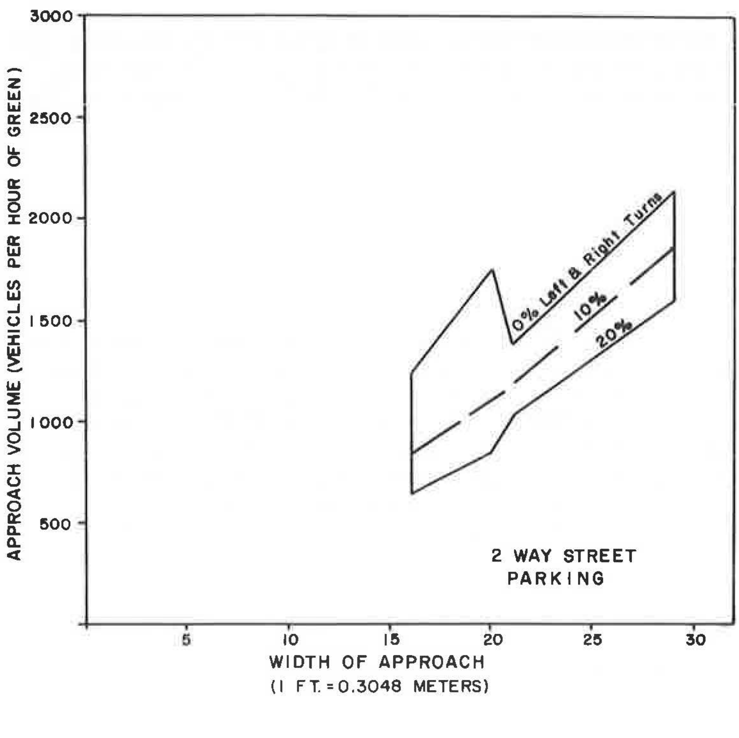


Figure 2. HCM turn factors for 2-way streets with parking.



1. Population of the municipality itself,
2. Population of the municipality and the surrounding municipalities, or
3. Population of the region in which the municipality exists.

The first 2 choices are straightforward, but judgment is called for in making the third choice. For the current study, all 3 choices were tried and the regional approach made use of 3 main areas: New York City (more than 1 million), Trenton (1 million), and Philadelphia (more than 1 million). The HCM estimate of capacity for all samples was tabulated by using each of the 3 choices but without adjusting for PHF. The mean and standard deviation then were compared for each choice.

The smallest factor used in this study was 75,000 because it is the lower limit to population found in the HCM charts.

One last difference for the peak-hour and metropolitan population factors is the adjustments for 2-way streets with no parking. These adjustments are 3 to 4 percent lower than those on all the other charts. No tests were made on the data to check this difference because it is too small in relation to the magnitude of adjustments for all other parameters.

Location Within Metropolitan Area

Two primary reasons exist for adjusting the HCM factors for metropolitan location. As indicated by Chang and Berry (7), the disparity in the basic approach volume curves between 1-way and 2-way streets is made even greater when fringe-area adjustments are applied (Figure 3). In addition, the HCM description of the various areas defines levels of pedestrian and commercial vehicle activity in the different areas. So, for this study, the following factors are used with the basic HCM curves for 2-way streets:

Location	Factor
CBD	1.00
Fringe	1.10
OBD	1.15
Residential	1.25

These factors do not consider the pressure of traffic in the busy areas, but they attempt to equalize the disparity between approaches, 1-way streets, and 2-way streets according to the HCM description of these areas.

Local Transit Buses

The Reilly and Seifert study (3) indicated that large HCM capacity estimate errors resulted when bus adjustment factors were used for near-side bus stops on streets with parking. For the study discussed in this paper, adjustment factors for near-side bus stops with parking were cut off at 1.0.

Parking Conditions

An attempt was made to overcome some of the judgment problems that exist in determining whether an approach has parking and to what extent parking affects capacity. The sites with parking are plotted by width against ALE capacity in Figure 4. A visual inspection of the distance of parking from the stop line would be incomplete without including the associated percentages of left and right turns and the indication of a bus stop.

Figure 3. HCM factor for metropolitan location.

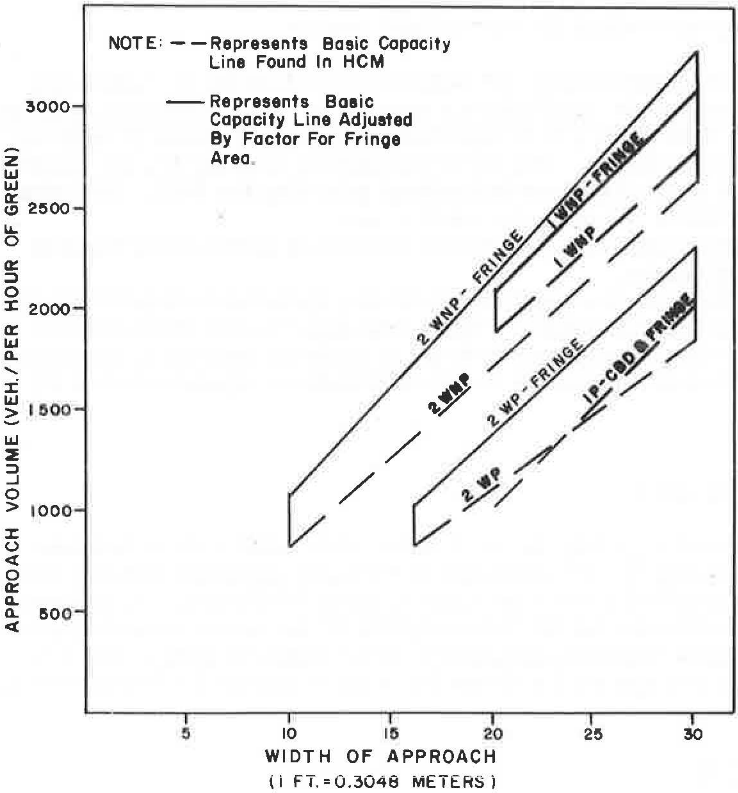
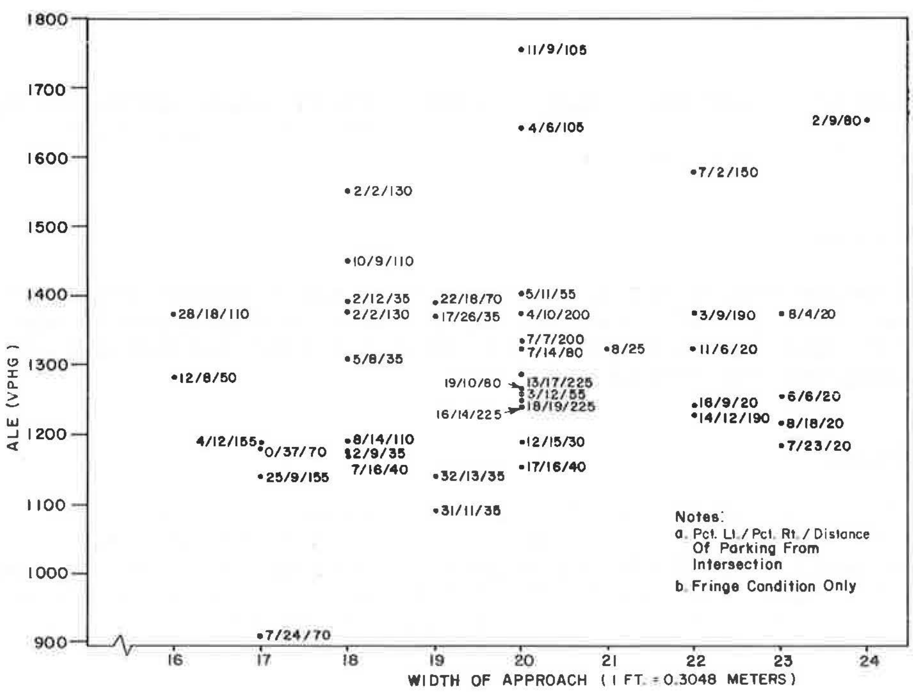


Figure 4. Parking conditions.



The impedance to traffic movement that is offered by parked vehicles is similar to that of a narrow street. But parked vehicles appear to have less effect at 200 ft (61 m) than at 100 ft (30.5 m).

A multiple linear regression analysis was made of the aforementioned variables to determine the effect of the distance of parking from the intersection.

RESULTS

Highway Capacity Manual

Error of Estimate

Mean and standard deviation percentage differences of the HCM estimates and ALE are as given in Table 3. The error of the unrevised HCM was expected to be negative, assuming that the correction factors in the HCM are accurate. The reason to expect a negative error is that the HCM uses an adjustment for PHF that is similar to the PHF itself; hence an adjustment that is less than 1.0 is made to the approach volume. The comparable volume for ALE has no adjustment for the peaking effect of traffic at the intersection approach.

The second set of errors listed in Table 3 is for the HCM estimate without an adjustment for PHF. Hence it should have a zero error with ALE, assuming that the correction factors in the HCM are accurate. Because the data used to develop the unrevised HCM estimate had a PHF average of approximately 0.85, the error for the HCM without PHF adjustment can be expected to be approximately 15 percent higher than the unrevised HCM method. However, the error percentage shown indicates that the capacity estimate for the HCM without PHF adjustment is from 20 to 25 percent higher than actual field conditions indicated. Moreover, the error as shown gives no indication of which parameters and to what extent their adjustments are inaccurate.

The third set of errors are those for revised HCM estimates with no adjustment for PHF. Adjustments can be made for the PHF at the discretion of the user with the understanding that they represent a subjective reduction in the intersection's ability to handle traffic on an hourly basis. In effect, we made no peak-hour adjustment if we were willing to let drivers wait on the approach. The effectiveness of the adjustments to the HCM factors is evident when the error estimates of revised HCM and HCM without PHF adjustments are compared. Further comparison can be made in Figure 5.

There is no conclusive evidence that adjustments we chose were the best ones to make. To more accurately test the effect and subsequent adjustments for some of the factors in the HCM, one would have to control the variation of a parameter at a single intersection approach. The ability to exert this control may never be within a researcher's power because 10 distinct parameters are used to vary the estimate of capacity in the HCM. Only 2 parameters could be tested in this study: parking and metropolitan area size.

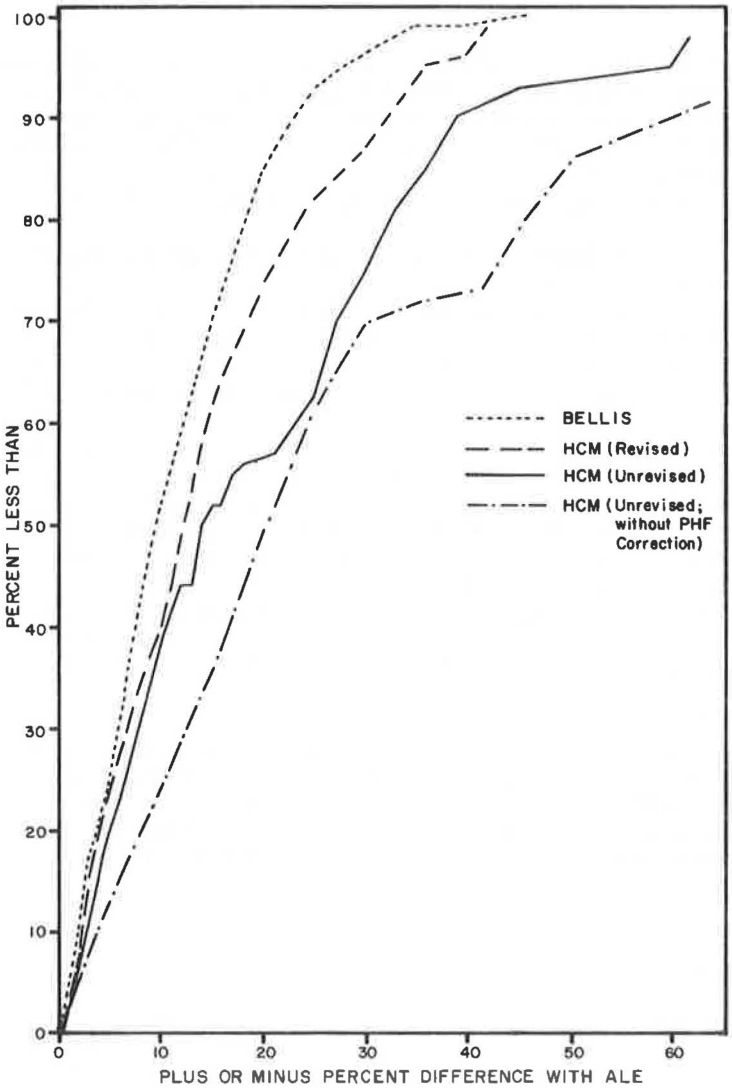
Distance of Parking to Intersection

We have defined as closely as possible those features common to an intersection in an attempt to determine the effect of parking on an intersection's approach. A multiple linear regression analysis of the data shown in Figure 4 showed that the use of the distance to parking from the stop line had no significant effect in a regression equation defining ALE. However, the previous reasoning that implied an improved ability of an approach to handle demand when parking was removed to 200 ft (61 m) [as opposed to 20 ft (6.1 m)] is more logical than the statistical results indicate. The results of the regression analysis highlight the need for a more controlled testing of this parameter.

Table 3. Average error of 1965 Highway Capacity Manual capacity estimates.

	2-Way, No Parking		2-Way, Parking	
Estimate Method	Error Percent	Standard Deviation	Error Percent	Standard Deviation
Unrevised HCM	+10	27	+7	24
HCM without PHF adjustment	+23	30	+22	25
Revised HCM	+4	24	+5	17

Figure 5. Cumulative frequency curves of capacity estimation errors.



Metropolitan Area Size Factor

Another comparison was made on the choice of any of 3 areas for the metropolitan area size. The error percentage of HCM versus ALE when these values are used is as follows:

Area	2-Way, No Parking (percent)	2-Way, Parking (percent)
Municipality	17	17
Municipality and surrounding area	23	22
Region	40	40

As might be expected, the difference in error percentage for the first 2 areas is approximately equal to the difference in factors. However, the error for the third area far exceeds the proportional difference of the factors. Essentially, the logic for using a metropolitan area size factor equivalent to population of the municipality and the surrounding area appears to be reason enough to overlook the small difference in error percentage.

Adjustment to Approach Volume Curves

The final step in the HCM analysis was the attempted derivation of a revised approach volume curve by using the values for ALE modified by the adjusted HCM parameters, which would thus allow a direct comparison to the HCM curves. A review of data available elsewhere (9, Tables 4 and 5) indicates the need for repositioning the basic curves relative to approach width. Table 4 in this report (9) has 1- and 2-lane data combined. For example, the first 7 fringe sites and the 9th fringe site were used as 1-lane approaches, and the 8th and 10th through 13th sites were used as 2-lane approaches. Within each of these groupings, the approach width increased from 14 ft (4.3 m) to 19 ft (5.8 m) for the 1-lane approaches and from 19 ft (5.8 m) to 26 ft (7.9 m) for the 2-lane approaches. The regression analyses grouped the data accordingly and were performed for each of the following groupings:

1. Two-way streets with parking for fringe areas only (40 samples);
2. Two-way streets with parking for all sites combined (56 samples);
3. Two-way streets with no parking for 1-lane approaches (12 samples);
4. Two-way streets with no parking for 2-lane approaches (8 samples); and
5. Two-way streets with no parking for all sites combined (20 samples).

The error percentage of the revised HCM method varied from a negative error for the streets with low widths to a positive error for streets with high widths. In effect, this would indicate a flattening of the basic approach volume curve. Figure 6 shows the results of this analysis against the background of the curves currently shown in the HCM.

The adjusted ALE curves for 1- and 2-lane 2-way streets with no parking yield reasonably high correlation coefficients. However, the curve for 1-lane streets shows a decrease in capacity for an increase in width. The curve for 2-lane streets also is questionable.

Extremes in the values for ALE for the higher and lower width streets account for the shape of the computed curves.

Inspection of ALE capacities as collected under field conditions (Tables 1 and 2) shows why the adjusted curves are questionable. Under constant physical and

Figure 6. Capacity curves.

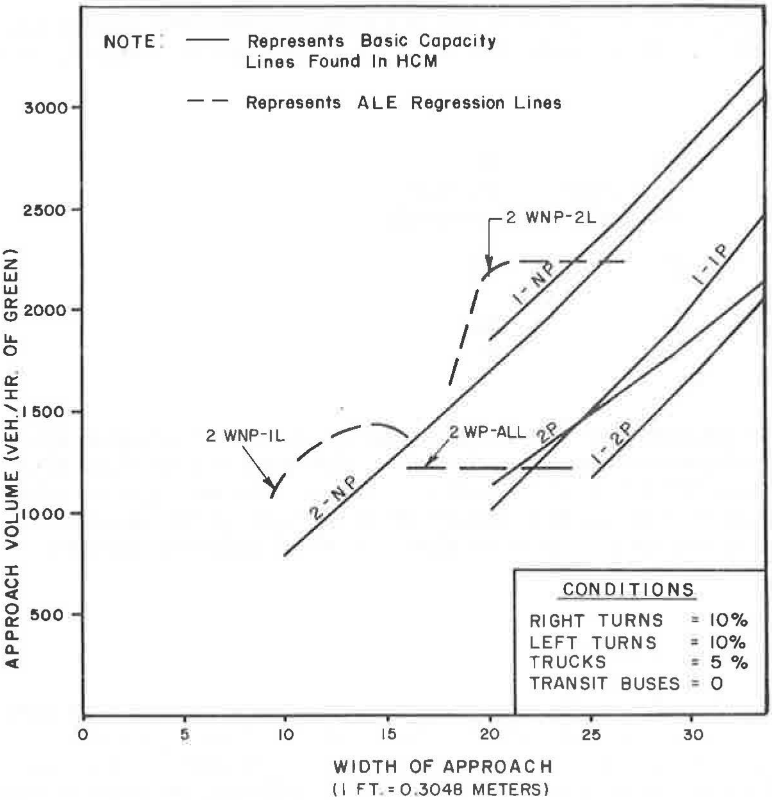
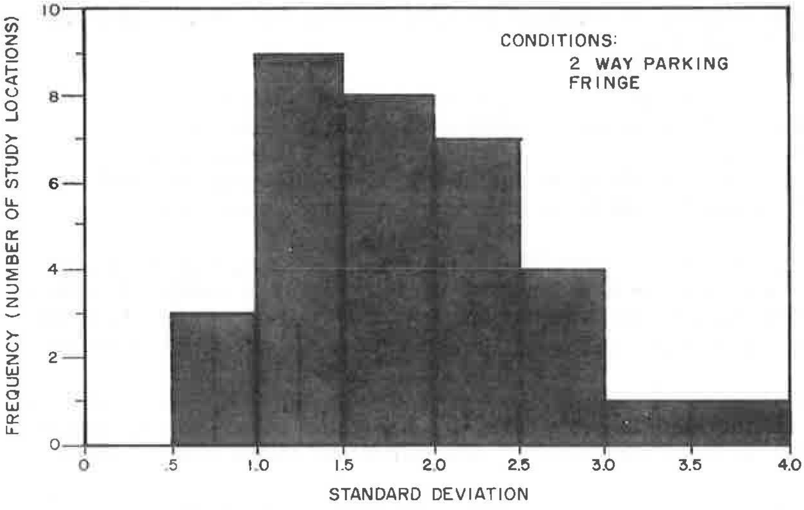


Figure 7. Frequency distribution of standard deviation of number of vehicles/loaded cycle.



environmental conditions, there is great variability in the actual capacity (as measured by ALE) for similar types of intersection approaches. There are several cases in which increased percentages of turns yield increased capacities. This appears to be contrary to the rationale behind the HCM turn correction factors, which holds that turns have a decreasing effect on capacity.

The variability found for the actual capacity of similar intersection approaches leads to the conclusion that capacity estimation, in its present state, can be subject to large inaccuracies. It is the opinion of the authors that these inaccuracies render the HCM useful for design estimates only. The capacity of specific locations should be determined by using intersection data and not the generalized information in the HCM.

Bellis Method

As defined by Reilly and Seifert (3) and Bellis (4), the Bellis method for estimating capacity does not consider street width and parking. It considers only the type of street and number of lanes. Although there are 4 types of approaches for Bellis curves, only the CBD (type 1) and those streets outside the CBD that allow both right and left turns (type 2) had sample sizes sufficient for consideration in this study. The error percentages of capacity estimate are as follows:

Type	Number of Samples	Error Percentage	Standard Deviation
1	10	-19	8
2	72	2	13

These errors are almost identical to those found by Reilly and Seifert (3). The resulting upward adjustment to the type 1 capacity curve would be sufficient to satisfy the discrepancy. Although the standard deviation of the error percentage for type 2 approaches is high (indicating the need for further refinement to the technique), the standard deviation is far less than that experienced with the HCM capacity estimates.

Data Collection

A very low number of intersections were used compared to the number that were studied. Hence an extremely costly and time-consuming effort would be required to extend the data collection effort in this study. Only 56 percent of all sites samples were used, and there would have to be substantial reasons to continue this study under the initial data collection format. A more productive approach may be found by varying parameters at individual sites.

Some of the reasons that data could not be used are as follows:

Reason	Percent
Zero load factor	13
Inaccurate	8
Lane use variation	5
High percentage of turns or trucks	5
Large green-phase variation	4
Miscellaneous	9

The variation of the number of vehicles/loaded cycle for any 1 intersection approach can be defined by the standard deviation of the number of vehicles/loaded cycle for that approach. Figure 7 shows the frequency distribution of the standard deviations for the intersections in the fringe-area 2-way street with parking category. As expected, a skewed distribution to the right results. There was absolutely no correlation of the standard deviation with the average number of vehicles/loaded cycle. Hence the distribution of the standard deviation, as shown in Figure 7, could result for most of the range of average loaded-cycle data (6.5 to 17.5 vehicles/loaded cycle). Inspection of the distribution only substantiates the variability of cycle-to-cycle activity that could result at an intersection.

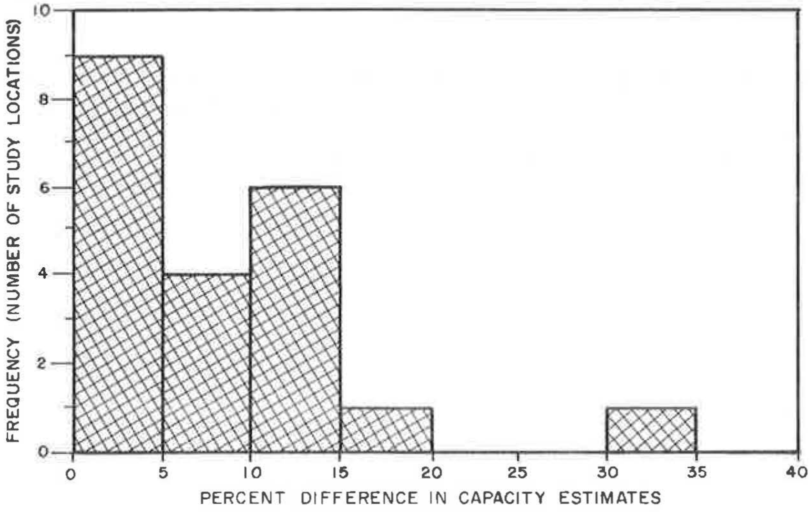
An indication of the repetitiveness of the field measurement of the actual capacity of an intersection approach, which is expressed as ALE, is shown in Figure 8. Eighteen intersections were sampled a second and third time. The percentage difference between repeat samples, as indicated by the frequency distribution of Figure 8, averaged 10 percent. Expressed in other terms, 90 percent of the repeated estimates of capacity (made from field measurements) were within 10 percent of the original estimate. The variation of field measurement of capacity for any 1 site can only be hypothesized, but the reasons may vary from differences in drivers through environmental and traffic changes.

SUMMARY AND CONCLUSIONS

The accuracy of the HCM in estimating capacity of approaches at 2-way signalized intersections was tested. In addition, revisions were made to 4 of the factors used in the HCM, and the accuracy of the HCM method was tested by using the revised factors. As a result, certain revisions to the HCM factors are suggested.

1. Reduce turn corrections for narrow approaches [less than 15 ft (4.6 m) for no parking areas and less than 20 ft (6.1 m) for parking areas] for up to 10 percent turns.
2. For estimating the population, use the population of the municipality plus the population of the surrounding municipalities in dense suburban areas.
3. Use factors for metropolitan area 2-way street locations that are consistent with the factors for 1-way streets.
4. Use a maximum correction factor of 1.0 for near-side bus stops.

Figure 8. Frequency distribution of percentage of difference in capacity estimates.



Twenty percent is the accepted error range. Results indicate that the unrevised HCM estimating method has errors in excess of approximately 20 percent for half of the study samples. The revised HCM method has errors in excess of approximately 20 percent for a quarter of the samples.

The large variation that was found to exist in the capacity of signalized intersections could not be satisfactorily explained even though certain parameter adjustments to the HCM resulted in dramatic reductions for error percentage estimates. We can only conclude that it is far more preferable to measure capacity in the field than it is to estimate from the HCM.

The sample data also were used to test the accuracy of the modified Bellis method of data collection, and it was found that an error in excess of approximately 20 percent existed for 15 percent of the sites.

Data at 150 sites were collected, but less than 60 percent of the sites had data that were considered useful. It is evident that continued efforts to extend this program by using the current methods of data collection would be extremely time-consuming.

ACKNOWLEDGMENT

This paper was prepared in cooperation with the Federal Highway Administration.

REFERENCES

1. Highway Capacity Manual. Bureau of Public Roads, U.S. Department of Commerce, 1950.
2. Highway Capacity Manual. HRB Special Rept. 87, 1965.
3. E. F. Reilly and J. Seifert. Capacity of Signalized Intersections. Highway Research Record 321, 1970, pp. 1-15.
4. W. R. Bellis. Capacity of Traffic Signals and Traffic Signal Timing. HRB Bulletin 271, 1960, pp. 45-67.
5. O. K. Norman. Variations in Flow at Intersections Related to Size of City, Type of Facility and Capacity Utilization. HRB Bulletin 352, 1962, pp. 55-99.
6. An Evaluation of the 1965 HCM Method of Computing Intersection Capacities. Missouri State Highway Commission, Study 68-2, Aug. 1969.
7. Y. B. Chang and D. S. Berry. Examination of Consistency in Signalized Intersection Capacity Charts of the Highway Capacity Manual. Highway Research Record 289, 1969, pp. 14-24.
8. A. D. May and D. Pratt. A Simulation Study of Load Factor at Signalized Intersections. Traffic Engineering, Feb. 1968.
9. E. Reilly, I. Dommasch, and M. Jagannath. Capacity of Signalized Intersections. Division of Research and Development, New Jersey Department of Transportation, 1974.