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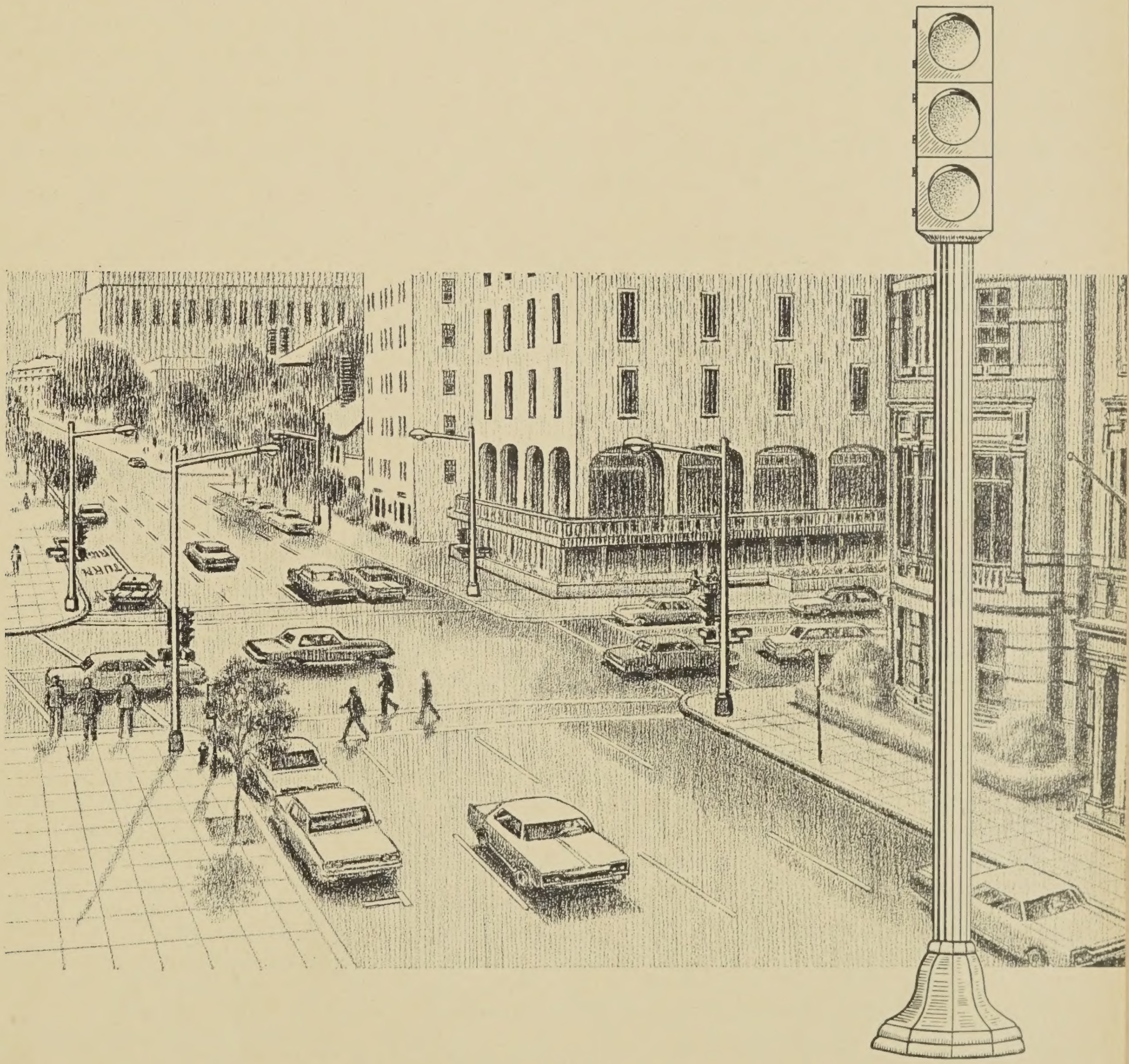

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SPECIAL ISSUE

Design capacity charts for signalized intersections

Second installment—continued from vol. 34, No. 9

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Standard Traffic Control Signs Chart (as defined in the Manua on Uniform Traffic Control Devices for Streets and Highways 22 x 34, 20 cents—100 for $15.00. 11 x 17, 10 cents—100 for $5.0

The Identification of Rock Types (revised edition, 1960). 20 cent

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Traffic Assignment and Distribution for Small Urban Area (1965). $1.00.

Traffic Assignment Manual (1964). $1.50.

Traffic Safety Services, Directory of National Organization (1963). 15 cents.

Transition Curves for Highways (1940). $1.75.

Capacity Analysis Techniques for Design of Signalized Intersections

Installment No. 2

Sponsored by the
OFFICE OF ENGINEERING AND OPERATIONS
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by [1] JACK E. LEISCH, Vice President and Chief Highway Engineer, DeLeuw, Cather & Co. of Canada Ltd.

PART 4—HIGH-TYPE FACILITIES AND INTERCHANGES

This is the second and final installment of an article in which procedures are presented for the graphic solution of capacity problems related to signalized intersections. The first installment was published in the August issue, vol. 34, No. 9, of PUBLIC ROADS.

The procedures are based on a set of charts consisting of 20 nomographs. Eighteen of the nomographs together with appropriate application procedures and sample problems were presented in the first installment. The other two nomographs and the remainder of the article are presented here.

The nomographic charts and procedures were devised by the author in 1950 to simplify the computational procedures of the 1950 Highway Capacity Manual. They were presented in PUBLIC ROADS in 1951 and were acclaimed by those concerned with intersection design. Since publication of the 1965 Highway Capacity Manual has provided a revised and comprehensive basis for capacity computations, the author in this article has again filled the need for a graphic procedure incorporating current knowledge. The original charts have been updated and new charts have been prepared to cover capacity procedures for which calculations previously required extensive application of judgment. The information presented provides a graphic procedure for the capacity analysis of most signalized street and highway intersections. Full discussion of the principles and procedures in the application of the charts in addition to sample problems have been included.

THE PROCEDURES AND CHARTS dealt with in previous parts of this article PUBLIC ROADS vol. 34, No. 9) are also applicable to high-type facilities, including intersections designed to above-minimum tandards that incorporate channelization. Sometimes such facilities accommodate relaively high-speed traffic characteristic of uburban and rural conditions. The at-grade amp terminals of diamond and parclo interchanges generally are forms of high-type intersections. Whereas the problem solutions previously covered consider only one or two approaches to illustrate basic procedures and uses of charts, part 4 deals with the entire intersection—all approaches and a complete olution. Included is a standard computaional form to facilitate analyses and a uggested format for a drawing or sketch howing the resulting geometric design, signal phasing, and a summary of volume-capacity elations.

Problem 35

The intersection indicated in figure 15 operates under congested conditions during peak periods, particularly between 5:15 and 6:15 p.m. It is to be reconstructed, not only to emove the present bottleneck but also to accommodate, at level of service C, the future traffic based on a 15-year projection. The north-south expressway at-grade, which has a design speed of 50 m.p.h., is to remain substantially the same. The east-west arterial, however, is to be improved basically to a 4-lane divided highway, using a design speed of 40 m.p.h., 12-foot lanes and a 16-foot median, with additional lanes, as required, at the major intersections. The percentages of trucks on the different approaches are N and S—6 percent, W—10 percent, and E—12 percent. A continuous right-turning movement is to be provided from W to S. Determine the geometrics for the improvement and the signal timing. Right-of-way is not a factor; moderate channelization is to be considered.

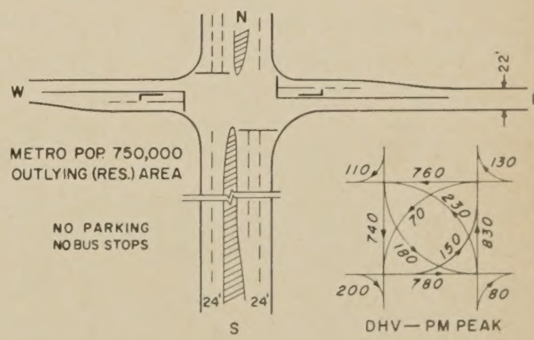

Figure 15.—Problem 35 illustrated.

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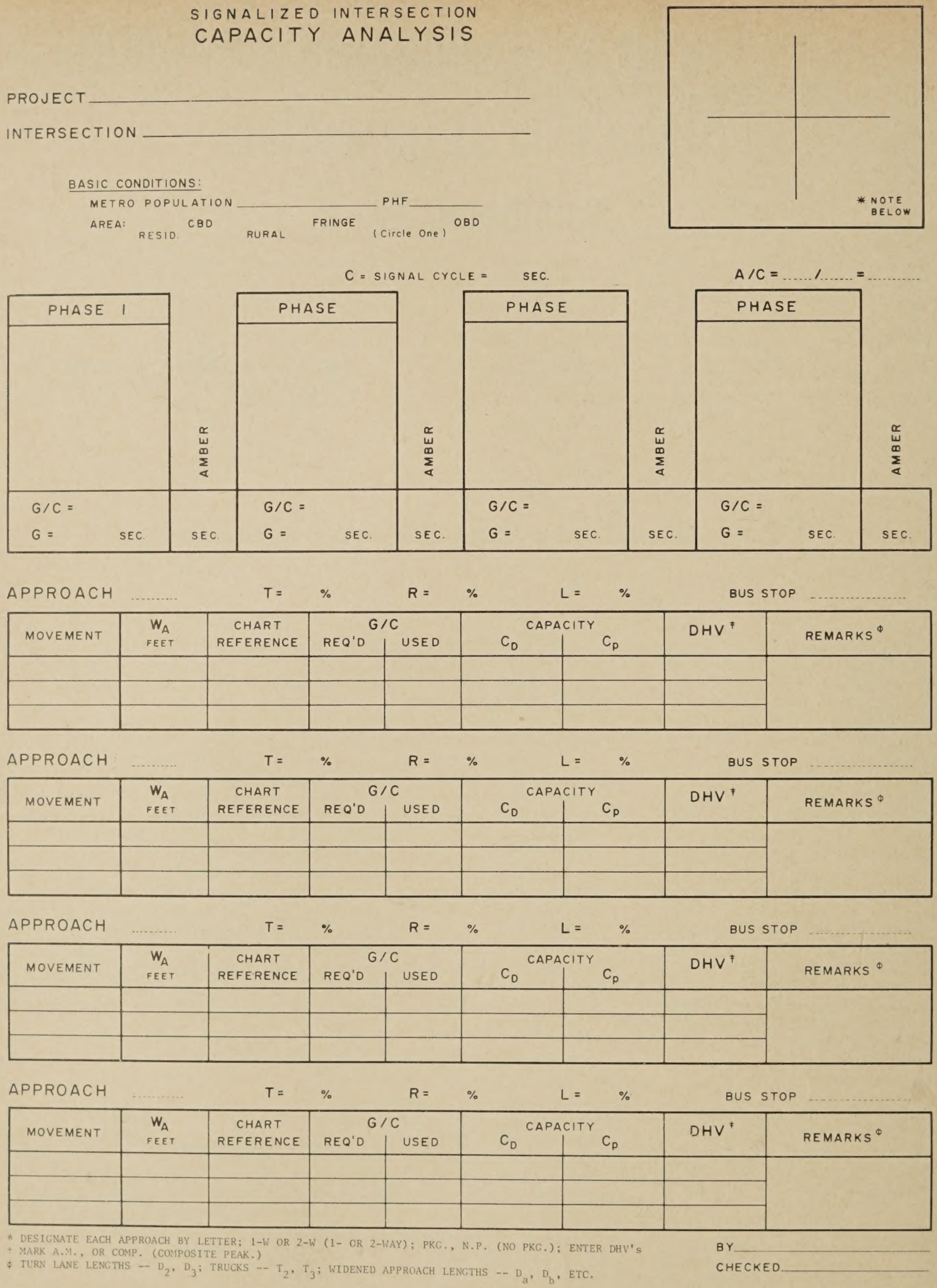
[1] Mr. Leisch was formerly Chief of Design Development Branch, Bureau of Public Roads. Mr Leisch acknowledges he assistance of DONALD W. LOUTZENHEISER, WILLIAM P. WALKER, and DONALD B. LEWIS of he Bureau of Public Roads who provided guidance during reparation of the material and reviewed the completed work. JOEL P. LEISCH and ARNE HAALAND of DeLeuw, Cather & Co. of Canada Limited also assisted in reparation of material and development of charts.



SIGNALIZED INTERSECTION
CAPACITY ANALYSIS

PROJECT ____________________

INTERSECTION ____________________

BASIC CONDITIONS:

METRO POPULATION ____________ PHF ________

AREA: CBD FRINGE OBD RESID. RURAL (Circle One)

C = SIGNAL CYCLE = SEC.

A/C = ... / ..... = ...

PHASE 1		PHASE		PHASE		PHASE	
	AMBER		AMBER		AMBER		AMBER
G/C = G = SEC.	SEC.	G/C = G = SEC.	SEC.	G/C = G = SEC.	SEC.	G/C = G = SEC.	SEC.

APPROACH .... T = % R = % L = % BUS STOP ....

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV†	REMARKS‡
			REQ'D	USED	C_D	C_p		

APPROACH .... T = % R = % L = % BUS STOP ....

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV†	REMARKS‡
			REQ'D	USED	C_D	C_p		

APPROACH .... T = % R = % L = % BUS STOP ....

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV†	REMARKS‡
			REQ'D	USED	C_D	C_p		

APPROACH .... T = % R = % L = % BUS STOP ....

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV†	REMARKS‡
			REQ'D	USED	C_D	C_p		

* DESIGNATE EACH APPROACH BY LETTER; 1-W OR 2-W (1- OR 2-WAY); PKG., N.P. (NO PKG.); ENTER DHV's
† MARK A.M., OR COMP. (COMPOSITE PEAK.)
‡ TURN LANE LENGTHS -- D_2, D_3; TRUCKS -- T_2, T_3; WIDENED APPROACH LENGTHS -- D_a, D_b, ETC.

BY ____________

CHECKED ____________

Figure 16.—Capacity analysis worksheet form.

olution: As a first step it is necessary to k for capacity of the left-turn on each rsection approach as discussed in part 3 er the heading *Check for Capacity of Left n.* A multi-phase signal control appears ly, for which a cycle length upwards of 80 nds is generally required. Using chart 3 with an assumed $C=80$ seconds, the gn capacity of the left-turn movement, if ating simultaneously with the opposing ugh movement, is $C_{D3}=70+$ on each ap ch; possible capacity is $C_{P3}=95$. Only the left turn E—S (70 v.p.h.) can be accommodated without a separate phase or advance green.

The opposing left turns on approach S and approach N are both relatively large and require a separate signal indication. This is a logical pattern for a third phase allowing both left-turning movements to operate simultaneously, each on a left arrow designation while all other traffic is stopped. Since the left-turning movement on approach W calls for a separate signal indication and the opposing left-turning movement on approach E does not, an advance green interval is logical and will be assumed in the preliminary analysis. On this basis, the signal phasing, with the third phase in two parts, is diagramed in figure 17.

The signal time required for moving through traffic on the expressway (phase 1) is controlled by approach S, which accommodates the larger of the two movements. Using in chart 4, $W_A=24$, $T=6\%$, $R=0\%$, $L=0\%$ (both right- and left-turning movements are on separate lanes), $MP=750{,}000$ population and $V=C_D=830$, the required G/C is 0.32.

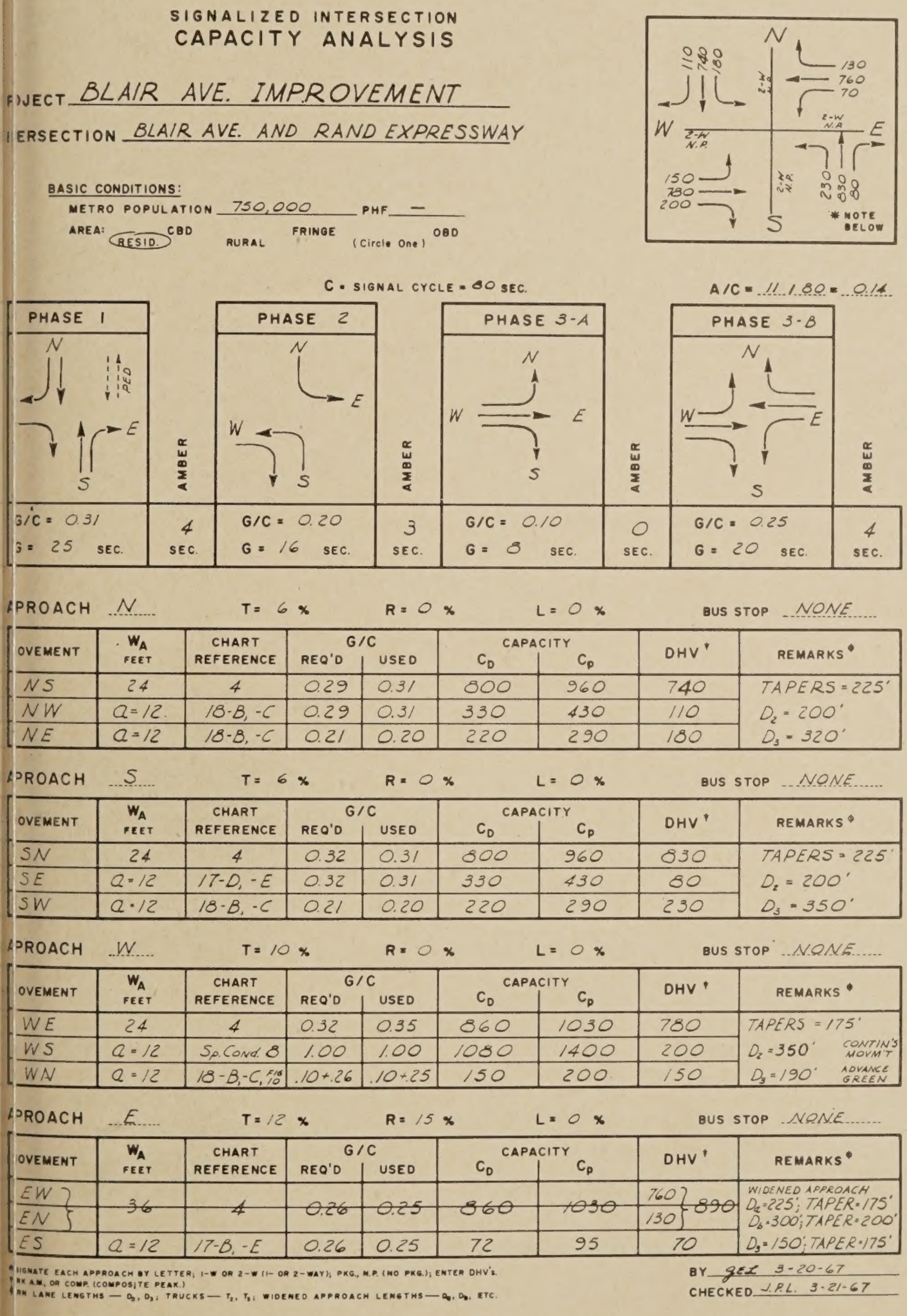
For the separate right-turn lane, on approaches S and N, using chart 17-D with $G/C=0.32$, $a=12$, $T_2=6\%$, and no pedestrian interference, the design capacity for each turning lane is found to be $C_{D2}=350$ v.p.h., which is in excess of the demand volumes. The left-turning volume of 230 v.p.h. on approach S is the controlling movement on phase 2. In chart 18-B, using $V=C_{D3}=230$ v.p.h., $T_2=6\%$, and $a=12$, the required $G'/C=0.21$.

To determine the minimum length of advance green required on approach W during phase 3, it is necessary first to determine the portion of the turning volume that can be accommodated at the end of the green period—on the amber—from chart 17-B; for $C=80$ seconds, it is 70 v.p.h. Volume to be accommodated by the advance green is 150—70=80 v.p.h. Enter the nomograph in figure 10 with a volume of 80 v.p.h., and using the condition of no pedestrians, $T_3=10\%$ and $C=80$, read $G_A=8$ seconds; $G_A/C=8/80=0.10$.

The three amber periods needed for the 3-phase control are selected to be two at 4 seconds following phases 1 and 3, and one at 3 seconds following phase 2. The portion of the cycle occupied by the amber periods is $(4+4+3)/80=0.14$. The portion of the cycle remaining for the balance of phase 3, and for handling the movement on approach E, is $1.00-(0.32+0.21+0.10+0.14)=0.23$.

Total G/C for approach W during phase 3 is $0.10+0.23=0.33$. The through volume that can be discharged from this approach on two lanes at design capacity, using chart 4 with $W_A=24$, $T=10\%$, $R=0\%$, $L=0\%$, $MP=750{,}000$ population, and $G/C=0.33$, is found to be $C_D=820$ v.p.h., while the demand volume is 780 v.p.h. A continuous right-turning movement is assumed on approach W with an added lane on the approach as well as on the exit. The design capacity, as discussed in part 3 under the heading *Right-Turning Movement—Continuous, Controlled by Yield Sign, or Permitted on Red After Stop* is $1{,}200\div(1+0.10)=1{,}080$ v.p.h. This is more than adequate since the demand volume is 200 v.p.h.

The G/C available for approach E, as previously discussed, is 0.23. Testing two lanes in chart 4 for the through-plus-right volume of $V=C_D=760+130=890$ v.p.h., $W_A=24$, $T=12\%$, $R=130/890=15\%$, $L=0\%$ and $MP=750{,}000$ population, reveals the need for G/C of 0.38. To overcome the deficiency a greater width should be provided. Assuming a widened approach through the intersection, and using



SIGNALIZED INTERSECTION
CAPACITY ANALYSIS

JECT BLAIR AVE. IMPROVEMENT
ERSECTION BLAIR AVE. AND RAND EXPRESSWAY

BASIC CONDITIONS:
METRO POPULATION 750,000 PHF —
AREA: CBD [✓ RESID.] RURAL FRINGE OBD (Circle One)

* NOTE BELOW

C = SIGNAL CYCLE = 80 SEC.
A/C = 11 / 80 = 0.14

PHASE 1	AMBER	PHASE 2	AMBER	PHASE 3-A	AMBER	PHASE 3-B	AMBER
G/C = 0.31 G = 25 SEC.	4 SEC.	G/C = 0.20 G = 16 SEC.	3 SEC.	G/C = 0.10 G = 8 SEC.	0 SEC.	G/C = 0.25 G = 20 SEC.	4 SEC.

PROACH N T= 6 % R= 0 % L= 0 % BUS STOP NONE

OVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_P	DHV†	REMARKS♦
NS	24	4	0.29	0.31	800	960	740	TAPERS = 225'
NW	a=12	18-B, -C	0.29	0.31	330	430	110	D_2 = 200'
NE	a=12	18-B, -C	0.21	0.20	220	290	180	D_3 = 320'

PROACH S T= 6 % R= 0 % L= 0 % BUS STOP NONE

OVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_P	DHV†	REMARKS♦
SN	24	4	0.32	0.31	800	960	830	TAPERS = 225'
SE	a=12	17-D, -E	0.32	0.31	330	430	80	D_2 = 200'
SW	a=12	18-B, -C	0.21	0.20	220	290	230	D_3 = 350'

PROACH W T= 10 % R= 0 % L= 0 % BUS STOP NONE

OVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_P	DHV†	REMARKS♦
WE	24	4	0.32	0.35	860	1030	780	TAPERS = 175'
WS	a=12	Sp. Cond. 8	1.00	1.00	1080	1400	200	D_2 = 350' CONTIN'S MOVM'T
WN	a=12	18-B,-C, FIG 10	.10+.26	.10+.25	150	200	150	D_3 = 190' ADVANCE GREEN

PROACH E T= 12 % R= 15 % L= 0 % BUS STOP NONE

OVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_P	DHV†	REMARKS♦
EW EN	~~36~~	~~4~~	~~0.26~~	~~0.25~~	~~860~~	~~1030~~	760 130 } 890	WIDENED APPROACH D_a=225'; TAPER=175' D_b=300'; TAPER=200'
ES	a=12	17-B, -E	0.26	0.25	72	95	70	D_3=150'; TAPER=175'

* IGNATE EACH APPROACH BY LETTER; 1-W OR 2-W (1- OR 2-WAY); PKG., N.P. (NO PKG.); ENTER DHV's.
† K AM, OR COMP. (COMPOSITE PEAK.)
♦ N LANE LENGTHS — D_2, D_3; TRUCKS — T_2, T_3; WIDENED APPROACH LENGTHS — D_a, D_b, ETC.

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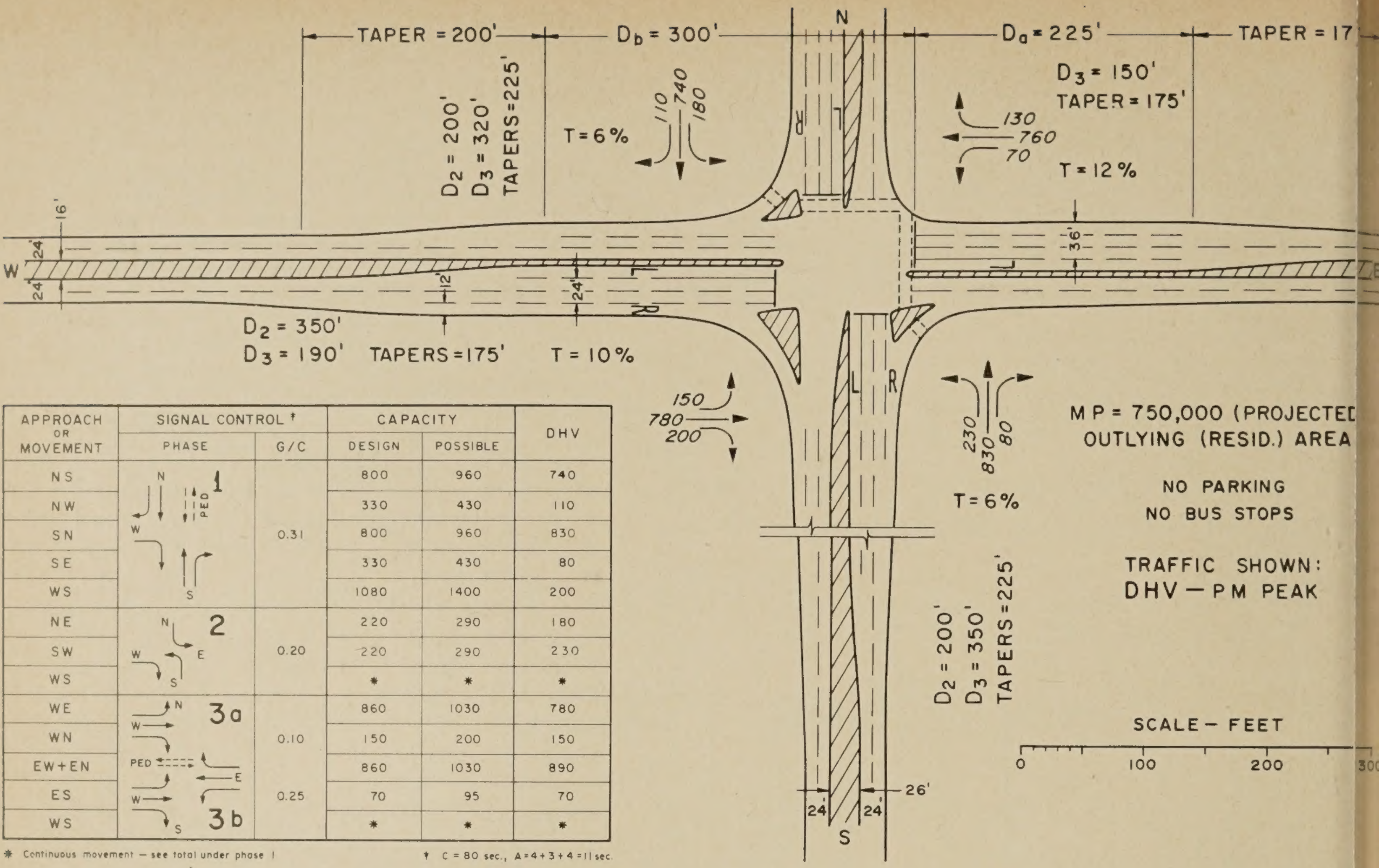
CHECKED J.P.L. 3-21-67

Figure 17.—Capacity analysis worksheet for problem 35.



APPROACH OR MOVEMENT	SIGNAL CONTROL †		CAPACITY		DHV
	PHASE	G/C	DESIGN	POSSIBLE	
N S	1	0.31	800	960	740
N W			330	430	110
S N			800	960	830
S E			330	430	80
W S			1080	1400	200
N E	2	0.20	220	290	180
S W			220	290	230
W S			*	*	*
W E	3a	0.10	860	1030	780
W N			150	200	150
EW+EN			860	1030	890
E S	3b	0.25	70	95	70
W S			*	*	*

* Continuous movement — see total under phase 1

† C = 80 sec., A=4+3+4=11 sec.

Figure 18.—Solution for problem 35.

in chart 4 W_A=36 and the other conditions noted above, find G/C=0.27. The 3-lane approach although somewhat deficient for level of service C operation is considered acceptable with a slight readjustment in the other phases. Lengths of widening, as discussed in part 3 under the heading *Widened Approaches*, are D_a=275 feet (minimum) preceded by 175-foot taper and D_b=300 feet followed by 200-foot taper. The required lengths of turning lanes are as follows:

Approach N.—Left-turn lane, D_3=320 feet (chart 18-C) is based on the premise that, because through traffic and left-turning traffic operate on separate phases, the length of left-turn lane must be sufficient to allow vehicles to accumulate in the lane without being blocked by stored vehicles in through lanes. The controlling value is the through traffic of 740/2=370 v.p.h. per lane storing on the approach, which stipulates a minimum length of 320 feet in chart 18-C. Right-turn lane, D_2=200 feet, is specified for deceleration from 50 m.p.h. (figure 9). Also, based on this speed, a taper length of 225 feet is indicated preceding the turning lanes.

Approach S.—Left-turn lane, D_3=350 feet (chart 18-C), is based on the minimum storage per lane of 830/2=415 v.p.h. in the through lanes to allow the left-turning vehicles to clear the end of the through traffic queue. Right-turn lane, D_2=200 feet, is based on deceleration from 50 m.p.h. In addition, a taper length of 225 feet is indicated for each lane.

Approach W.—Left-turn lane, D_3=190 feet (chart 18-C), is based on storage and is larger than the dimension indicated in figure 9 for deceleration from 40 m.p.h. The left turn does not operate on a signal phase separate from the through movement on the approach, and therefore there is no need to lengthen the left-turn lane to clear the end of through traffic storage. Since the right-turn lane is designated for continuous operation, it must be long enough to clear the through traffic queue for which D_2=350 feet. This is determined in chart 18-C on the basis of a through-volume storage per lane of 780/2=390 v.p.h. In addition, a taper length of 175 feet (figure 9) is indicated for each turning lane.

Approach E.—Left-turn lane, D_3=1 fe (figure 9), is based on deceleration fr 4 m.p.h., which is greater than the ngt required for storage in chart 18-C. A ap length of 175 feet is indicated.

A form that can be used as a ca city analysis worksheet is shown in figure 1 Th form, which can be duplicated for e i actual capacity problems, is design t facilitate the analysis of complete in rsec tions and to serve as a compact rec d c calculations. It can also be used as a com panion sheet to the solution format inc ate in figures 18, 22, and 26. For most interse ions the entire solution can be accomplis d o one copy of the form, which allows or signal phases and for 4 intersection appr che For analysis of more complex interse ion two or more forms can be used. If nec sary any number of trial solutions can be atte pte and the computations for the workable lan retained for the record to show the pr erre or selected plan.

The analysis for problem 35, alt oug covered step by step in preceding disc sion also presented on the calculation form in ure 17. The simplicity and compactness of analysis is well illustrated with all the eded information shown on one form. By owing the design capacity, possible capacity, d the *DHV* for each basic movement, a orough insight is gained as to the effective- ss of the solution. A design can rarely be hieved where each movement operates at ecisely the desired level of service. Some of controlling movements are set to operate design capacity, whereas other movements ult in operation where the demand volume either below or slightly above design pacity. Since this information is tabulated individual movements, it also allows for mparison and weighting of results between various movements. Thus, the analyst ble to make adjustments readily in geome- or signal timing to produce an effective erall solution and a balanced design. The alysis information is then transferred to the ution format shown in figure 18, which mpletely summarizes the results, including ometric requirements, and serves as a ndard document for preliminary or func- nal design.

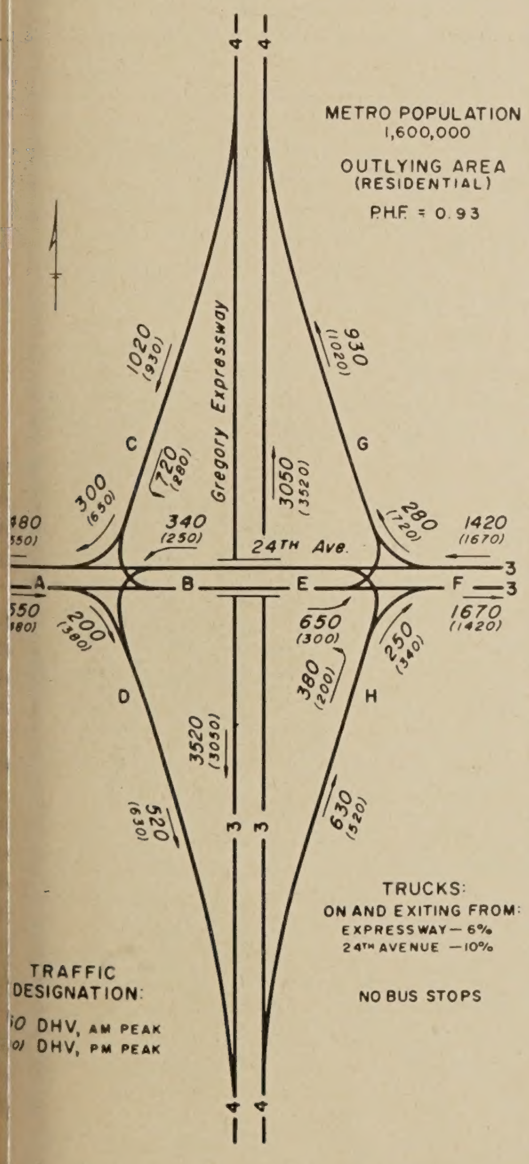
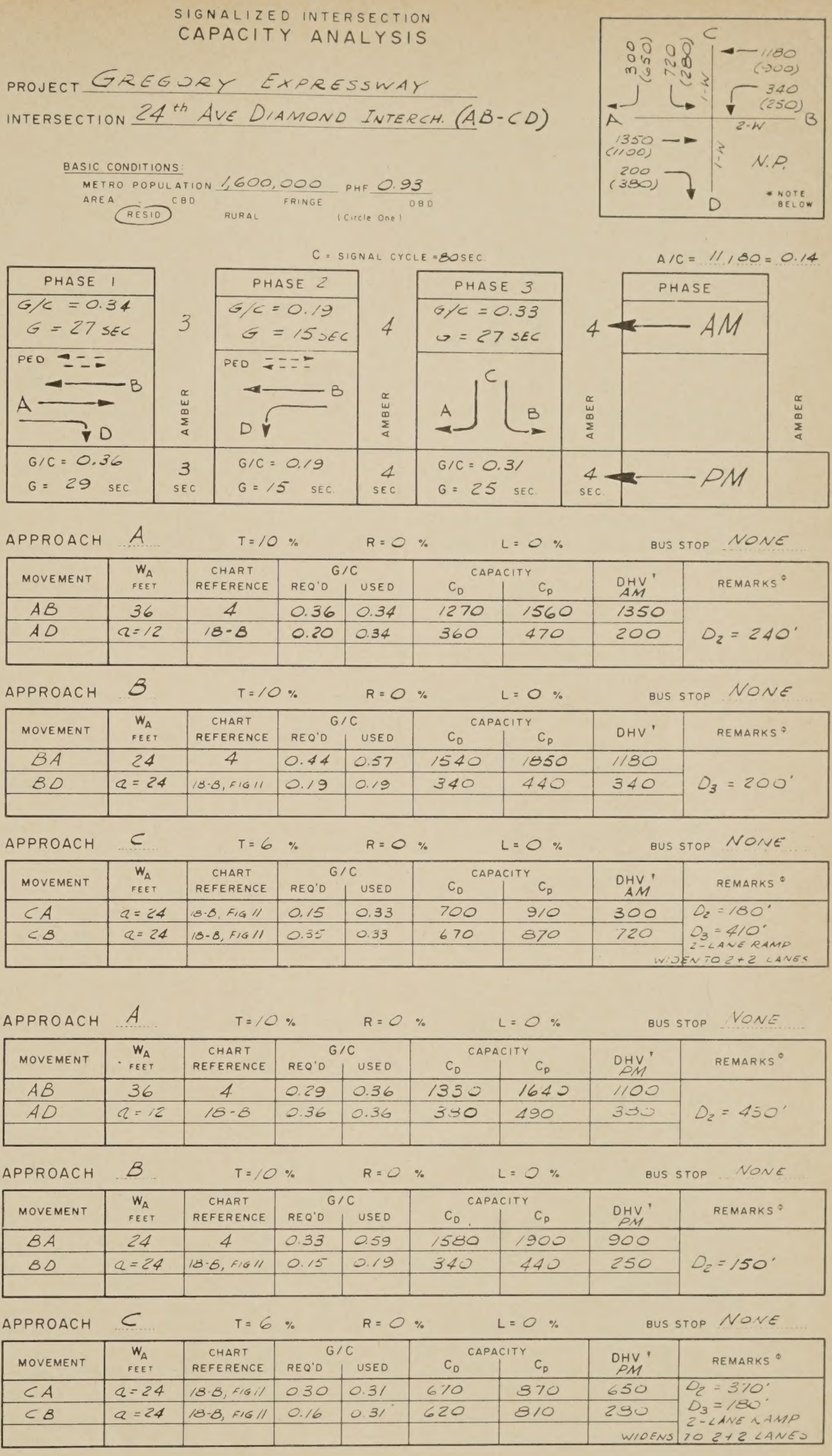


Figure 19.—Problem 36 illustrated.



SIGNALIZED INTERSECTION
CAPACITY ANALYSIS

PROJECT GREGORY EXPRESSWAY

INTERSECTION 24th AVE DIAMOND INTERCH. (AB-CD)

BASIC CONDITIONS:
METRO POPULATION 1,600,000 PHF 0.93
AREA CBD FRINGE OBD [✓ RESID] RURAL (Circle One)

C = SIGNAL CYCLE = 80 SEC.

A/C = 11/80 = 0.14

APPROACH A T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_p	DHV † AM	REMARKS °
AB	36	4	0.36	0.34	1270	1560	1350	D_2 = 240'
AD	a = 12	18-B	0.20	0.34	360	470	200	

APPROACH B T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_p	DHV †	REMARKS °
BA	24	4	0.44	0.57	1540	1850	1180	D_3 = 200'
BD	a = 24	18-B, FIG 11	0.19	0.19	340	440	340	

APPROACH C T = 6 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_p	DHV † AM	REMARKS °
CA	a = 24	18-B, FIG 11	0.15	0.33	700	910	300	D_2 = 180'
CB	a = 24	18-B, FIG 11	0.35	0.33	670	870	720	D_3 = 410' 2-LANE RAMP
							WIDEN	TO 2 + 2 LANES

APPROACH A T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_p	DHV † PM	REMARKS °
AB	36	4	0.29	0.36	1330	1640	1100	D_2 = 450'
AD	a = 12	18-B	0.36	0.36	380	490	330	

APPROACH B T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_p	DHV † PM	REMARKS °
BA	24	4	0.33	0.59	1580	1900	900	D_2 = 150'
BD	a = 24	18-B, FIG 11	0.15	0.19	340	440	250	

APPROACH C T = 6 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C REQ'D	G/C USED	CAPACITY C_D	CAPACITY C_p	DHV † PM	REMARKS °
CA	a = 24	18-B, FIG 11	0.30	0.31	670	870	650	D_2 = 370'
CB	a = 24	18-B, FIG 11	0.16	0.31	620	810	280	D_3 = 180' 2-LANE RAMP
							WIDENS	TO 2 + 2 LANES

Figure 20.—Capacity analysis worksheet for problem 36, intersection AB–CD.

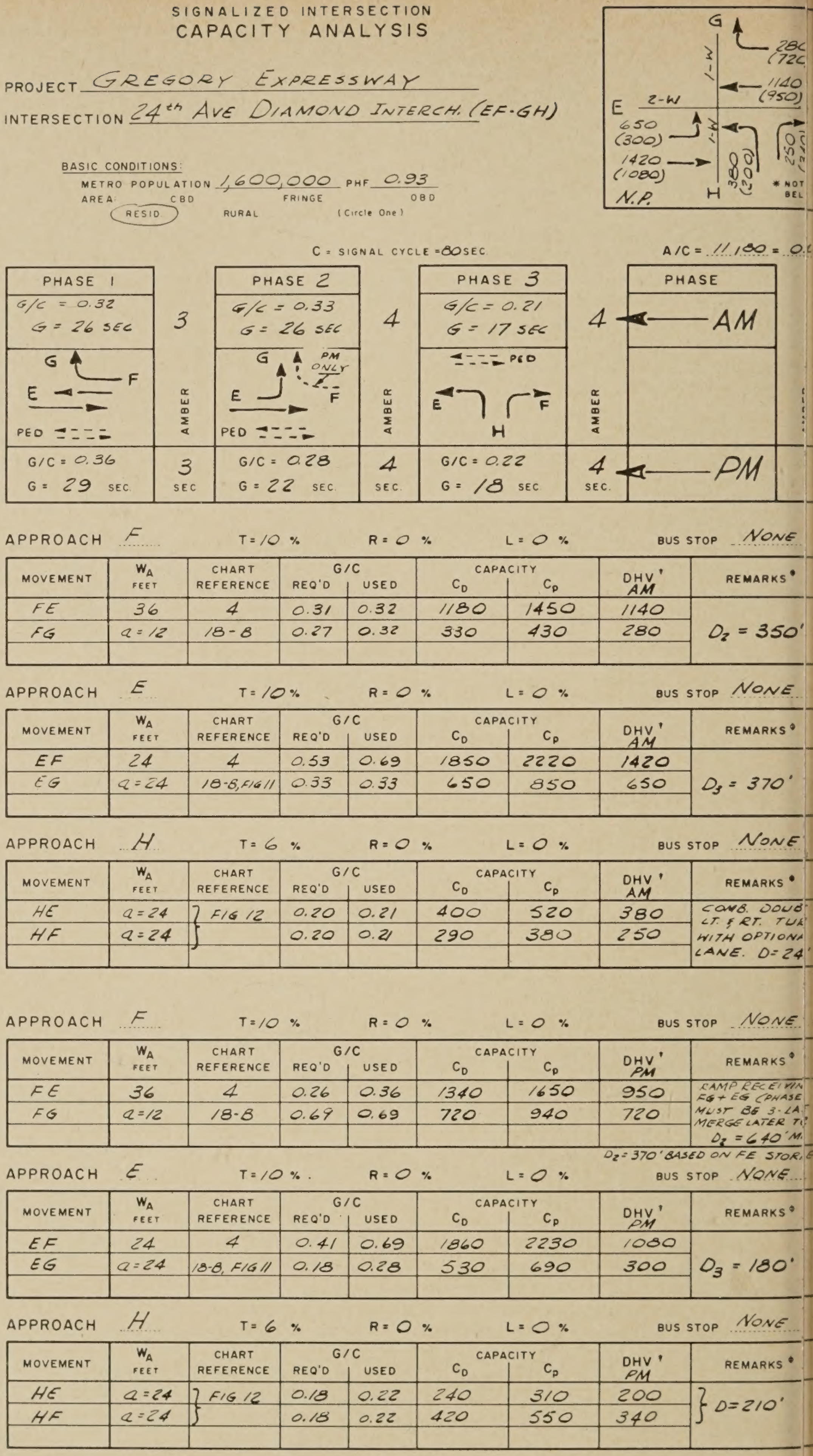
Problem 36

A diamond interchange is proposed at the crossing of a major street and an expressway in the outlying residential area of a city having a projected metropolitan population of 1.6 million. For the conditions indicated in figure 19, determine the essential geometric features of the cross street (24th Avenue) and the adjoining ramp terminals, including the number and arrangement of lanes, channelization, and signal phasing. Prepare a design sketch setting out the geometric requirements.

Solution: A detailed description of the procedural steps through the charts is not included for this problem. Instead, the solution is provided directly on the capacity analysis forms with primary references to charts 4 and 18. The results are tabulated on the worksheets in figures 20 and 21, covering intersections AB-CD and EF-GH, respectively. Both a.m. and p.m. peak-hour periods have been analyzed, and the different requirements for each are shown. The need for a 3-dial control system is apparent to allow for full efficiency and flexibility of operation to fit the characteristics and separate demands of the morning-, evening-, and off-peak periods.

An early step in the analysis of a complete intersection is the establishment of signal phasing. Sometimes there are several ways of phasing an intersection. Each way should be tested and the most efficient phasing established through preliminary use of the charts. After a phasing arrangement has been selected, the analysis is continued in a straightforward manner by determining the *G/C* required for each intersection approach based on the approach width, demand volume, and other pertinent conditions. The sum of the *G/C*'s, together with the amber periods divided by the cycle time, *A/C*, should be equal to or less than 1.00. If the *G/C*'s total less than 1.00, each *G/C* is adjusted upward by inspection or in proportion to demand on the approaches to the required total. If the *G/C*'s total more than 1.00, the design capacity or the service volume for a given level of service has been exceeded, and it may be necessary to re-analyze some of the approaches by increasing the width or changing some other condition in order to reduce the *G/C* total to approximately 1.00.

It is not always feasible to have each individual movement accommodated precisely at design capacity; this kind of balance is practically impossible. Some movements will operate at a volume below the available design capacity; other movements may operate at a volume exceeding the design capacity. Although an attempt is made to avoid the latter situation, a slight excess of demand volume over design capacity, that is, a nominal lowering of the selected level of service, is frequently acceptable as illustrated in movement AB for the a.m. peak shown in figure 20. Here the required *G/C* of 0.36 was adjusted downward to 0.34 to achieve a balance in the total *G/C;* otherwise, it would have been necessary to increase the approach from 3 to 4 lanes.



SIGNALIZED INTERSECTION
CAPACITY ANALYSIS

PROJECT GREGORY EXPRESSWAY

INTERSECTION 24th AVE DIAMOND INTERCH. (EF-GH)

BASIC CONDITIONS:

METRO POPULATION 1,600,000 PHF 0.93

AREA: CBD FRINGE OBD [✓ RESID.] RURAL (Circle One)

C = SIGNAL CYCLE = 80 SEC

A/C = 11/80 = 0.

PHASE 1		PHASE 2		PHASE 3		PHASE
G/C = 0.32 G = 26 SEC	3	G/C = 0.33 G = 26 SEC	4	G/C = 0.21 G = 17 SEC	4	← AM
	AMBER		AMBER		AMBER	
G/C = 0.36 G = 29 SEC.	3 SEC	G/C = 0.28 G = 22 SEC.	4 SEC.	G/C = 0.22 G = 18 SEC.	4 SEC.	← PM

APPROACH F T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV AM	REMARKS
			REQ'D	USED	C_D	C_P		
FE	36	4	0.31	0.32	1180	1450	1140	D_2 = 350'
FG	a = 12	18-8	0.27	0.32	330	430	280	

APPROACH E T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV AM	REMARKS
			REQ'D	USED	C_D	C_P		
EF	24	4	0.53	0.69	1850	2220	1420	D_3 = 370'
EG	a = 24	18-8, FIG 11	0.33	0.33	650	850	650	

APPROACH H T = 6 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV AM	REMARKS
			REQ'D	USED	C_D	C_P		
HE	a = 24	FIG 12	0.20	0.21	400	520	380	COMB. DOUB LT. & RT. TUR WITH OPTIONA LANE. D = 24
HF	a = 24		0.20	0.21	290	380	250	

APPROACH F T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV PM	REMARKS
			REQ'D	USED	C_D	C_P		
FE	36	4	0.26	0.36	1340	1650	950	RAMP RECEIVIN FG + EG (PHASE MUST BE 3-LA MERGE LATER T D_2 = 640' M
FG	a = 12	18-8	0.69	0.69	720	940	720	

D_2 = 370' BASED ON FE STORAGE

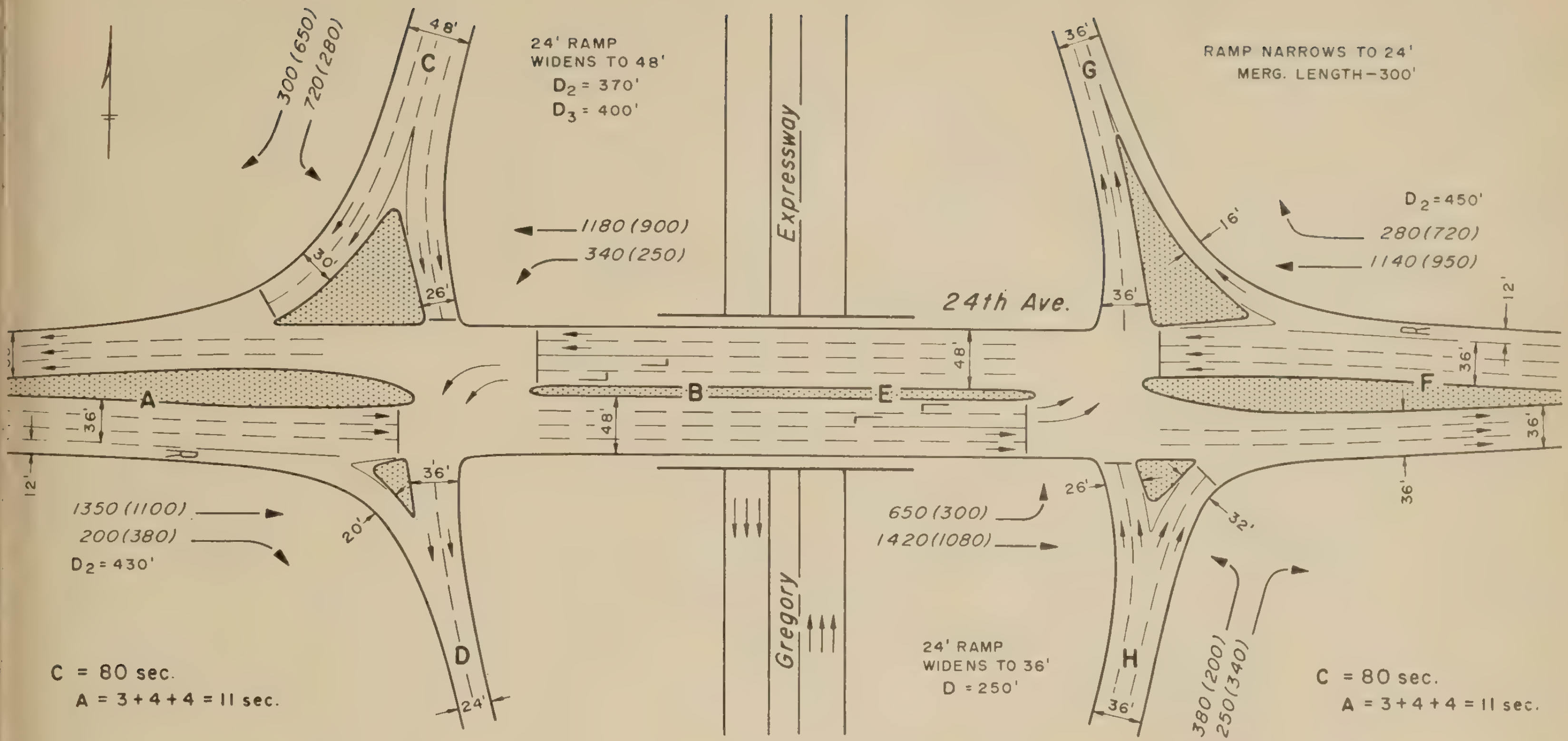
APPROACH E T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV PM	REMARKS
			REQ'D	USED	C_D	C_P		
EF	24	4	0.41	0.69	1860	2230	1080	D_3 = 180'
EG	a = 24	18-8, FIG 11	0.18	0.28	530	690	300	

APPROACH H T = 6 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV PM	REMARKS
			REQ'D	USED	C_D	C_P		
HE	a = 24	FIG 12	0.18	0.22	240	310	200	D = 210'
HF	a = 24		0.18	0.22	420	550	340	

Figure 21.—Capacity anlaysis worksheet for problem 36, intersection EF-GH.



INTERSECTION AB-CD — AM PEAK

PPROACH OR OVEMENT	SIGNAL CONTROL		CAPACITY		DHV
	PHASE	G/C	DESIGN	POSSIBLE	
AB	① B A D	0.34	1270	1560	1350
AD			360	470	200
BA	② A B D	0.19	1540	1850	1180
BD			340	440	340
CA	③ C A B	0.33	700	910	300
CB			670	870	720

INTERSECTION DE-FG — AM PEAK

APPROACH OR MOVEMENT	SIGNAL CONTROL		CAPACITY		DHV
	PHASE	G/C	DESIGN	POSSIBLE	
FE	① G F E	0.32	1180	1450	1140
FG			330	430	280
EF	② G E F	0.33	1850	2220	1420
EG			650	850	650
HE	③ E F H	0.21	400	520	380
HF			290	380	250

INTERSECTION AB-CD — PM PEAK

AB	① B A D	0.36	1330	1640	1100
AD			380	490	380
BA	② A B D	0.19	1580	1900	900
BD			340	440	250
CA	③ C A B	0.31	670	870	650
CB			620	810	280

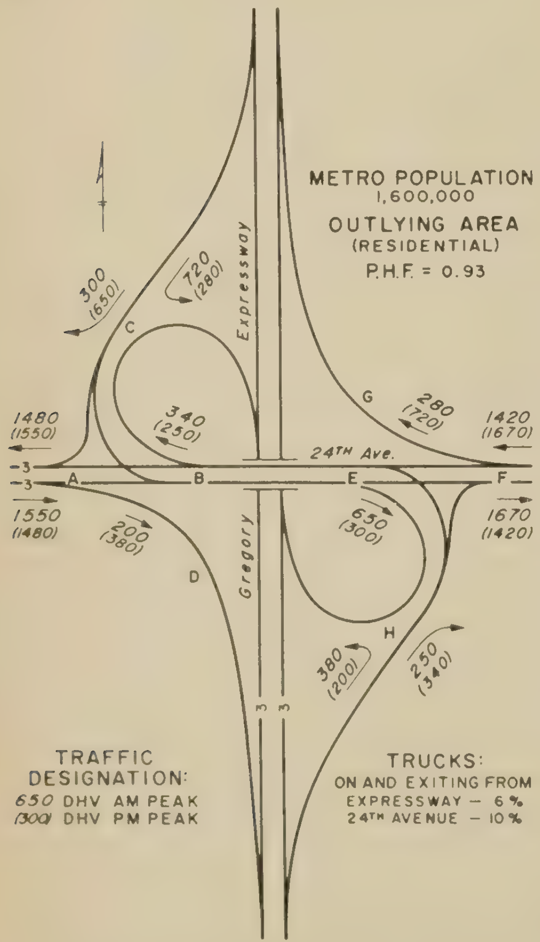
INTERSECTION DE-FG — PM PEAK

FE	① G F E	0.36	1340	1650	950
FG ✱			720	940	720
EF	② G F E	0.28	1860	2230	1080
EG			530	690	300
FG ✱			✱	✱	✱
HE	③ E F H	0.22	240	310	200
HF			420	550	340

✱ Moves during phases 1 and 2 (G/C=0·69); total shown under phase 1

Figure 22.—Solution for problem 36.

The solution, showing the design requirements, is indicated in figure 22. The tabulations below the geometric layout are part of the suggested format for summarizing the analysis. Both a.m. and p.m. peaks are considered, and the selected signal phasing and a comparison for each movement of the *DHV* with design capacity and possible capacity are shown. The other information tabulated on the worksheets of figures 20 and 21—such as the number, arrangement, and lengths of lanes—is reflected in the design sketch of figure 22. Several features developed in this design are characteristic of diamond interchanges in urban areas. The cross street widens within the interchange to accommodate left-turning vehicles. In urban areas, the 2-abreast left-turn design on the cross street is sometimes required, frequently for one and occasionally for both left-turning movements. The 4-lane approach at C divides into a 2-lane right-turning movement and a 2-lane left-turning movement to handle the indicated volumes. The ramp proper widens from a 2-lane width at the expressway exit to a 4-lane section at C. Lengths called for on the widened portion, D_2 and D_3, are indicated on the plan. The requirement on approach II is a 3-lane section, separating into two 2-lane turning movements with the center lane serving as an optional lane. Exit G is designed for 3 lanes to allow the 2-lane movement EG to merge with the relatively large movement FG during phase 2 in the evening peak. The ramp then narrows to 2 lanes before entering the expressway.

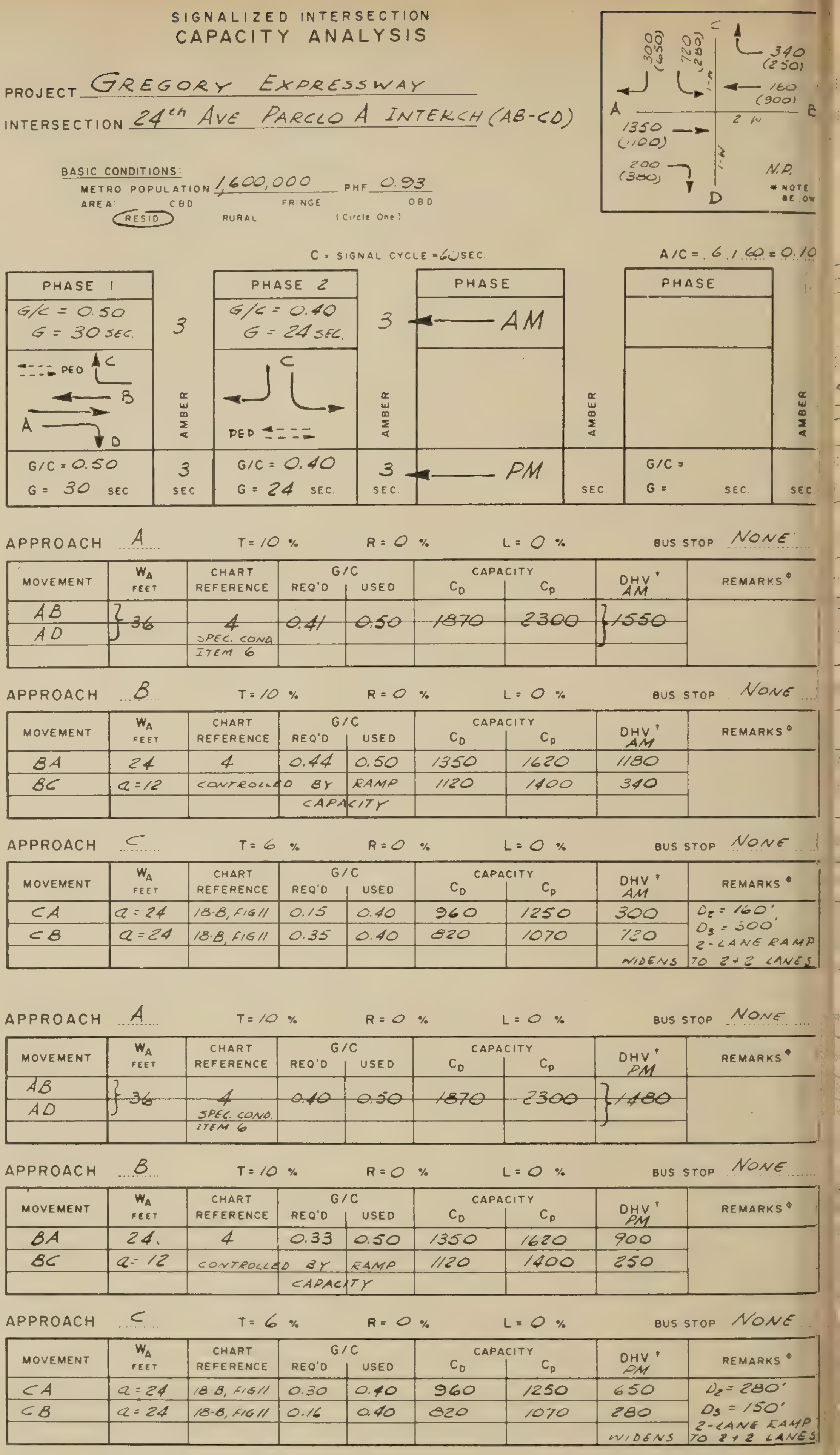


METRO POPULATION
1,600,000
OUTLYING AREA
(RESIDENTIAL)
P.H.F. = 0.93

TRAFFIC
DESIGNATION:
650 DHV AM PEAK
(300) DHV PM PEAK

TRUCKS:
ON AND EXITING FROM
EXPRESSWAY — 6 %
24TH AVENUE — 10 %

Figure 23.—Problem 37 illustrated.



SIGNALIZED INTERSECTION
CAPACITY ANALYSIS

PROJECT GREGORY EXPRESSWAY

INTERSECTION 24th AVE PARCLO A INTERCH (AB-CD)

BASIC CONDITIONS:
METRO POPULATION 1,600,000 PHF 0.93
AREA: CBD FRINGE OBD [✓ RESID] RURAL (Circle One)

C = SIGNAL CYCLE = 60 SEC.

A/C = 6 / 60 = 0.10

PHASE 1		PHASE 2		PHASE		PHASE	
G/C = 0.50 G = 30 SEC.	3	G/C = 0.40 G = 24 SEC.	3 ← AM				
	AMBER		AMBER		AMBER		AMBER
G/C = 0.50 G = 30 SEC	3 SEC	G/C = 0.40 G = 24 SEC.	3 ← PM SEC.		SEC.	G/C = G = SEC.	SEC.

APPROACH A T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV [†] AM	REMARKS [*]
			REQ'D	USED	C_D	C_p		
AB	~~36~~	~~4~~	~~0.41~~	~~0.50~~	~~1870~~	~~2300~~	~~1550~~	
AD		SPEC. COND.						
		ITEM 6						

APPROACH B T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV [†] AM	REMARKS [*]
			REQ'D	USED	C_D	C_p		
BA	24	4	0.44	0.50	1350	1620	1180	
BC	a = 12	CONTROLLED	BY	RAMP	1120	1400	340	
			CAPACITY					

APPROACH C T = 6 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV [†] AM	REMARKS [*]
			REQ'D	USED	C_D	C_p		
CA	a = 24	18-B, FIG 11	0.15	0.40	960	1250	300	D_2 = 160',
CB	a = 24	18-B, FIG 11	0.35	0.40	820	1070	720	D_3 = 300' 2-LANE RAMP
							WIDENS	TO 2+2 LANES

APPROACH A T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV [†] PM	REMARKS [*]
			REQ'D	USED	C_D	C_p		
AB	~~36~~	~~4~~	~~0.40~~	~~0.50~~	~~1870~~	~~2300~~	~~1480~~	
AD		SPEC. COND.						
		ITEM 6						

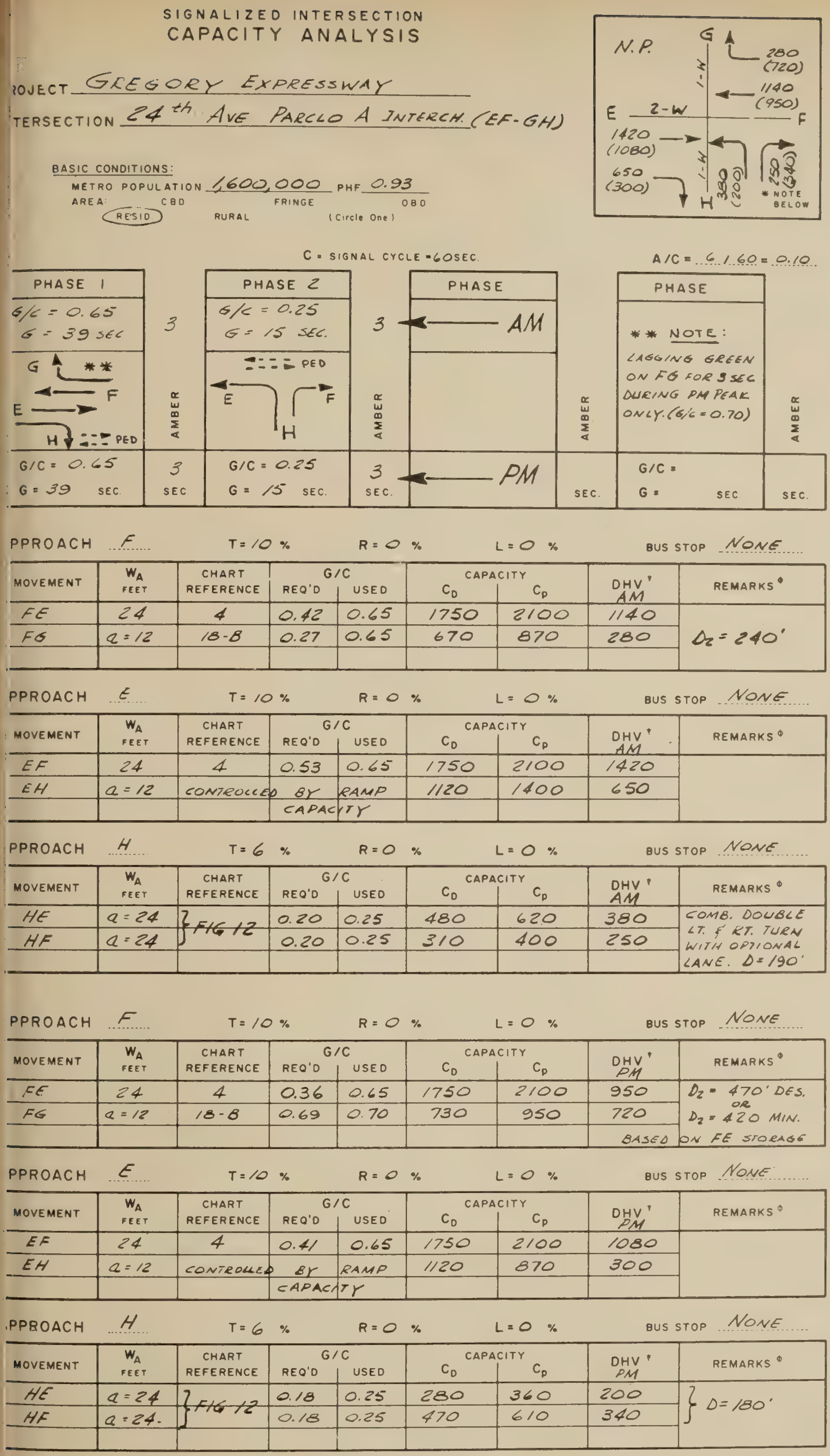
APPROACH B T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV [†] PM	REMARKS [*]
			REQ'D	USED	C_D	C_p		
BA	24.	4	0.33	0.50	1350	1620	900	
BC	a = 12	CONTROLLED	BY	RAMP	1120	1400	250	
			CAPACITY					

APPROACH C T = 6 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV [†] PM	REMARKS [*]
			REQ'D	USED	C_D	C_p		
CA	a = 24	18-B, FIG 11	0.30	0.40	960	1250	650	D_2 = 280'
CB	a = 24	18-B, FIG 11	0.16	0.40	820	1070	280	D_3 = 150' 2-LANE RAMP
							WIDENS	TO 2+2 LANES

Figure 24.—Capacity analysis worksheet for problem 37, intersection AB–CD.



SIGNALIZED INTERSECTION
CAPACITY ANALYSIS

ROJECT GREGORY EXPRESSWAY
TERSECTION 24th AVE PARCLO A INTERCH. (EF-GH)

BASIC CONDITIONS:
METRO POPULATION 1,600,000 PHF 0.93
AREA: CBD FRINGE OBD
[✓ RESID.] RURAL (Circle One)

C = SIGNAL CYCLE = 60 SEC.
A/C = 6 / 60 = 0.10

PHASE 1		PHASE 2		PHASE		PHASE	
G/C = 0.65 G = 39 SEC	3	G/C = 0.25 G = 15 SEC.	3	← AM		** NOTE: LAGGING GREEN ON FG FOR 3 SEC DURING PM PEAK ONLY. (G/C = 0.70)	
	AMBER		AMBER		AMBER		AMBER
G/C = 0.65 G = 39 SEC.	3 SEC.	G/C = 0.25 G = 15 SEC.	3 SEC.	← PM	SEC.	G/C = G = SEC	SEC.

PPROACH F T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV † AM	REMARKS ◊
			REQ'D	USED	C_D	C_P		
FE	24	4	0.42	0.65	1750	2100	1140	D_2 = 240'
FG	a = 12	18-8	0.27	0.65	670	870	280	

PPROACH E T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV † AM	REMARKS ◊
			REQ'D	USED	C_D	C_P		
EF	24	4	0.53	0.65	1750	2100	1420	
EH	a = 12	CONTROLLED	BY	RAMP	1120	1400	650	
			CAPACITY					

PPROACH H T = 6 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV † AM	REMARKS ◊
			REQ'D	USED	C_D	C_P		
HE	a = 24	FIG 12	0.20	0.25	480	620	380	COMB. DOUBLE LT. & RT. TURN WITH OPTIONAL LANE. D = 190'
HF	a = 24		0.20	0.25	310	400	250	

PPROACH F T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV † PM	REMARKS ◊
			REQ'D	USED	C_D	C_P		
FE	24	4	0.36	0.65	1750	2100	950	D_2 = 470' DES. OR D_2 = 420 MIN.
FG	a = 12	18-8	0.69	0.70	730	950	720	
							BASED	ON FE STORAGE

PPROACH E T = 10 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV † PM	REMARKS ◊
			REQ'D	USED	C_D	C_P		
EF	24	4	0.41	0.65	1750	2100	1080	
EH	a = 12	CONTROLLED	BY	RAMP	1120	870	300	
			CAPACITY					

PPROACH H T = 6 % R = 0 % L = 0 % BUS STOP NONE

MOVEMENT	W_A FEET	CHART REFERENCE	G/C		CAPACITY		DHV † PM	REMARKS ◊
			REQ'D	USED	C_D	C_P		
HE	a = 24	FIG 12	0.18	0.25	280	360	200	D = 180'
HF	a = 24.		0.18	0.25	470	610	340	

Figure 25.—Capacity anlysis worksheet for problem 37, intersection EF–GH.

The capacity analysis, using the 3-phase control at intersection AB–CD and at intersection EF–GH, provides the basis for the geometric design of the interchange along 24th Avenue. A more refined and complete analysis of signalization, including the use of time-space diagrams and overlap intervals to provide maximum degree of coordination between the two intersections and progression of movements, also can be an important aspect of design. Usually, however, this is not essential in establishing the basic geometry of the intersection. Sometimes a nominal increase in capacity is achieved through such refinement; but, if not accounted for initially, it places the design on the safe side.

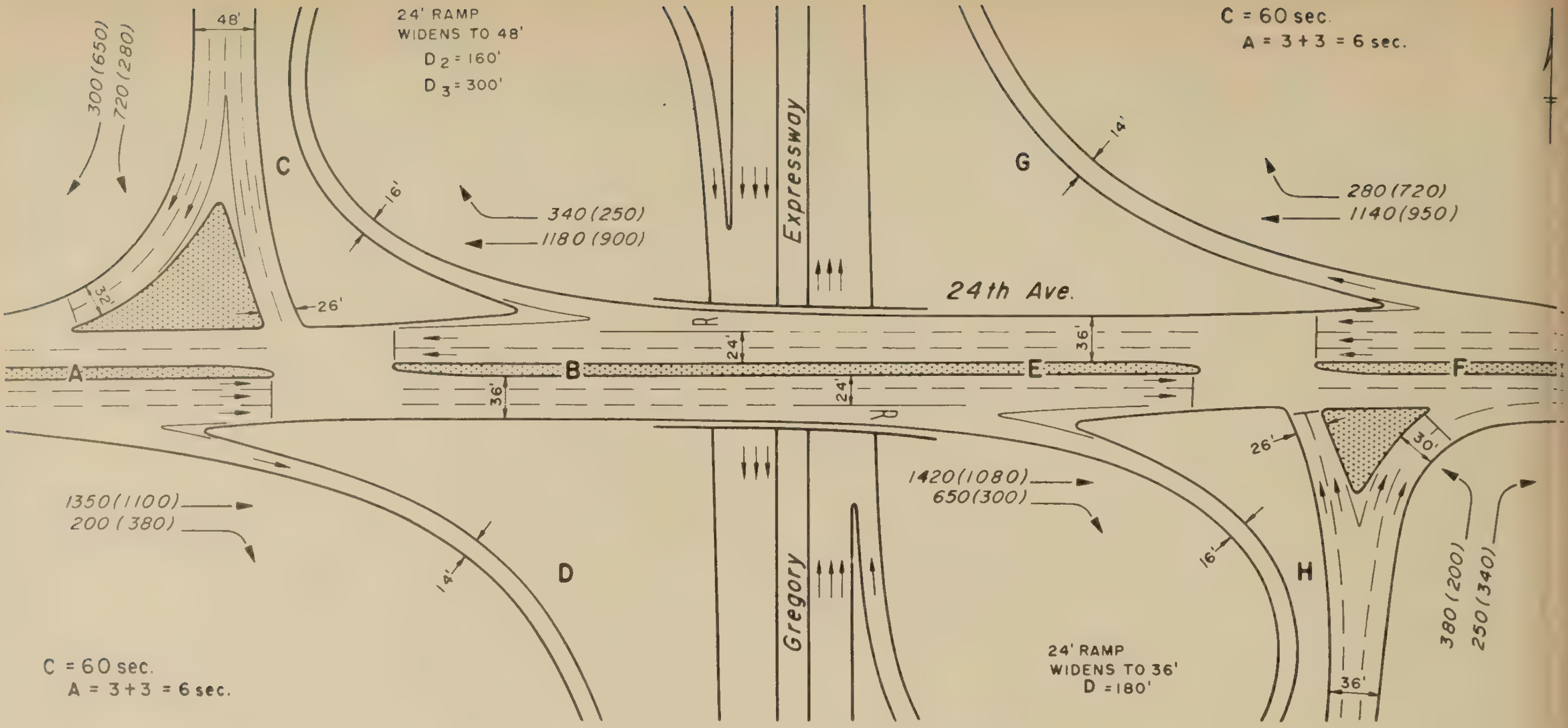
Problem 37

For the basic conditions described in problem 36, a parclo-A interchange of the form shown in figure 23 is also to be considered at the same location. As before, determine the essential geometric features of the cross street and the adjoining ramp terminals, including the number and arrangement of lanes, channelization, and signal phasing. Prepare a design sketch setting forth the geometric requirements.

Solution: The analysis and procedure in the solution are much the same as in the previous problem. An important initial step in the analysis is the determination of signal phasing. For a parclo-A a simple 2-phase control at each intersection is all that is required. Complete analysis for intersections AB–CD and EF–GH for both a.m. and p.m. peaks are detailed on the worksheets of figures 24 and 25. The solution, including the geometric layout, signal timing, and summary of volume-capacity relations, is shown in figure 26.

Basically, the parclo-A requires no widening of the cross street through the interchange. Moreover, the space occupied by the approaches to the interchange is equivalent to the normal street width. The designs for the movements exiting from the cross street differ significantly from the diamond interchange; however, the designs for the entering ramp terminals, approaches C and H, are essentially the same as on the diamond interchange. In this example, the parclo-A requires not only a lesser number of lanes than the diamond to handle the same traffic, but operates at an overall higher level of service; that is, for the majority of the movements there is a greater difference between capacity and *DHV*.

To achieve a more meaningful comparison of the two alternative plans with regard to capacity potential, a *design capacity index* can be employed. This measure of performance or overall ability of the intersection to handle traffic is the ratio of the sum of all traffic entering the intersection, during a given period of time, to the sum of all approach design capacities handling this traffic. In brief, it is the composite V/C_D, representing the a.m. peak, the p.m. peak, or a combination of the two. For example, the design capacity index, V/C_D, for intersection AB–CD during



INTERSECTION AB-CD — AM PEAK

APPROACH OR MOVEMENT	SIGNAL CONTROL		CAPACITY		DHV
	PHASE	G/C	DESIGN	POSSIBLE	
	① C	0.50			
AB+AD	PED B		1870	2300	1550
BA	A		1350	1620	1180
BC	D		1120	1400	340
CA	② C	0.40	960	1250	300
CB	A B		820	1070	720
	PED				

INTERSECTION EF-GH — AM PEAK

APPROACH OR MOVEMENT	SIGNAL CONTROL		CAPACITY		DHV
	PHASE	G/C	DESIGN	POSSIBLE	
FE	① G	0.65	1750	2100	1140
FG	F		670	870	280
EF	E		1750	2100	1420
EH	H PED		1120	1400	650
HE	② PED	0.25	480	620	380
HF	E H F		310	400	250

INTERSECTION AB-CD — PM PEAK

	① C	0.50			
AB+AD	PED B		1870	2300	1480
BA	A		1350	1620	900
BC	D		1120	1400	250
CA	② C	0.40	960	1250	650
CB	A B		820	1070	280
	PED				

INTERSECTION EF-GH — PM PEAK

FE	① G	0.65	1750	2100	950
FG *	F		730	950	720
EF	E		1750	2100	1080
EH	H PED		1120	870	300
HE	② PED	0.25	280	360	200
HF	E H F		470	610	340

* FG has 3-sec. lagging green during PM peak only, yielding G/C = 0.70

Figure 26.—Solution for problem 37.

the a.m. peak is: on the diamond interchange, 4,090/4,880 = 0.84; on the parclo-A interchange. 4,090/6,020 = 0.68. The indices indicate that, as a whole, the diamond is operating at 84 percent of design capacity, and the parclo-A at 68 percent of design capacity. Comparison of the two operating percentages in itself is not fully indicative of conditions. It is also necessary to consider the number of individual movements or vehicles operating at V/C_D larger than 1.00. For the diamond interchange, movements AB and CB are in this category; but on the parclo-A interchange, all movements are well below the ratio of 1.00.

Another more detailed way of evaluating and comparing volume-capacity relations on alternative designs is by determining des capacity indices along with levels of serv for individual movements. The following t ulation, compiled from the summary tables figures 22 and 26, allows for a compariso the a.m. peak of intersection AB–CD on diamond with the a.m. peak of intersect AB–CD on the parclo-A.

Diamond Interchange

Movement	V	C_D	V/C_D	Level of Service
AB	1,350	1,270	1.06	D
AD	200	360	0.56	A
BA	1,180	1,540	0.77	A
BD	340	340	1.00	C
CA	300	700	0.43	A
CB	720	670	1.07	D
Design Capacity Index__	4,090 ÷	4,880	= 0.84	A–D

Parclo-A Interchange

Movement	V	C_D	V/C_D	Level of Service
AB+AD	1,550	1,870	0.83	A
BA	1,180	1,350	0.87	A
BC	340	1,120	0.30	A
CA	300	860	0.35	A
CB	720	820	0.88	A
Design Capacity Index__	4,090 ÷	6,020	= 0.68	A

The levels of service shown in the tabulations were determined by comparing the V/C_D ratios with the f factors in tables 3 and 5. A thorough insight is gained with regard to operation and capacity potential of the two designs. Note the superiority of the parclo-A interchange when the levels of service of individual movements and the design capacity indices are compared. The operation of a complete intersection cannot be rated with a single level of service, unless all component movements of the intersection operate at one given level. Thus, as shown above, the intersection on the diamond is rated as a range—level of service A–D, with a design capacity index of 0.84. The intersection on the parclo-A is rated—level of service A with a design capacity index of 0.68.

PART 5—OVERALL INTERSECTION CAPACITY

AS PART of planning and preliminary design processes, a quick, approximate determination of capacities is often needed. The problem usually resolves itself into one of two conditions: (1) where the approach volumes and street widths are known, the adequacy of the capacity of the intersection must be determined; or (2) where the approach volumes and the width of one street are known, the width of the intersecting street must be determined. The need for analysis may pertain to an individual intersection, or may extend to a route with a series of intersections, or possibly to a whole system of streets in a given sector of a city. Charts 19 and 20 were devised for this purpose; they combine the necessary information for both of the intersecting streets on one chart and give results in terms of overall capacity. Each chart takes into account jointly, for average conditions, the intersection of any two facilities, regardless of 1-way or 2-way operation, type of area, and parking regulation. The left half of the chart is used for the approach on one street and the right half for the approach on the other or intersecting street. A line projected between the inner sides of the two halves of the chart determines, at the intersection of the y-y axis and related metropolitan sizes, the adequacy of the street intersection.

The two parts of charts 19 and 20 are identical except for the reverse plotting. The arrangement of each part is similar to that of charts 1 and 2, but the G/C ratio in charts 19 and 20 is made the outer scale and the volume is shown as the lower series of curves. The G/C ratio on the side scales is the proportion of time required on the one approach for operation at design capacity. Assuming that 10 percent of the cycle time is being used in amber periods, design capacity is obtained when the total of two green intervals is 90 percent of the cycle (the sum of the two G/C values $=0.90$). The 1.00 point on the y-y axis is located so that a straight line between any two G/C values passes through the 1.00 point when their sum is 0.90. The scale values above and below the 1.00 point on the y-y axis show the proportion by which the sum of the G/C values is deficient or in excess of the design capacity condition.

The scale on the axis also gives V/C_D, the ratio of approach volume to design capacity, combined for the two approaches. Thus, when the combined approach volumes equal the combined design capacities, the ratio is 1.00 (level of service C operation). Points on the scale below 1.00 indicate operation at superior levels of service, B or A. Points above 1.00 indicate operation at less favorable levels of service, D, E, and F. Possible capacity, level E, is the value on the y-y axis corresponding to the average f value for the two approaches as found in table C on charts 19 and 20. Also, any reading on the axis can be compared with the average values for the two approaches in tables 3 and 4 to find the level of service at which the intersection as a whole is operating. The y-y axis is representative of conditions in metropolitan areas of 250,000 population. To allow for adjustment of results to other metropolitan sizes, bar scales parallel to the y-y axis are included.

Charts 19 and 20 are intended for preliminary design and general evaluation of operation and capacity of intersections, including analyses of a series of intersections and street systems. The charts incorporate numerous specific conditions and several average conditions. Specific conditions accounted for are approach width; 1-way or 2-way operation; parking regulation; area of city, such as *CBD*, fringe, etc.; approach volume, G/C; and metropolitan area population. Average conditions built into the charts assume 5 percent trucks, 10 percent right turns, 10 percent left turns, and no bus stops. Allowance of 10 percent total for amber periods is incorporated in the charts as a constant. Under normal circumstances the deviation from these average conditions is not significant. Moreover, those variables that generally have a pronounced effect on capacity allow for adjustment in the charts. Hence, the results produced are reasonably correct for regular intersections.

Charts 19 and 20 also may be adapted to other than regular intersections for planning and preliminary design, as follows:

(1) Approaches with separate left-turn lane, not requiring separate signal indication: Deduct 10 percent of the approach volume or 100 v.p.h., whichever is smaller, and use the width of approach exclusive of the separate left-turn lane.

(2) Approaches with separate left-turn lane, requiring separate signal indication: Deduct left-turn volume from approach volume. Use the width of approach exclusive of the separate left-turn lane. Allow an additional G/C of 0.10 for left-turning volumes of 120 to 140 v.p.h., and an additional $G/C=$ (v.p.h. turning left)$\div$1,000 for larger volumes. Thus, for a left-turning volume of 200 v.p.h., the additional G/C would equal 0.20. The procedure in the chart for applying the additional G/C is demonstrated in problem 40 and figure 28(1).

(3) Intercepted approaches at T or Y intersections: The capacities of intercepted approaches are lower than on the approaches

of normal (4-leg) intersections, as discussed in part 3 under the heading *T and Y Intersections*. The overall adjustment, indicated therein, for the angle of turn of the predominant movement may be applied to the solution in charts 20 and 21. For angles of turn in the vicinity of 90 degrees, capacities or service volumes on intercepted approaches are approximately 0.80 of the capacities or service volumes on 4-leg intersection approaches for the same width and traffic conditions. Thus, if the end product in chart 19 or 21 is the approach (service) volume for an intercepted approach, the result should be multiplied by 0.80. If the end product is the V/C_D ratio, the G/C indicated for the intercepted approach should be divided by 0.80, and the adjusted G/C should then be used to complete the solution.

The various applications of charts 19 and 20 are demonstrated in the following problems.

Problem 38

In the *CBD* of a 2 million population metropolitan area, a 1-way street (approach A) 42 feet wide with parking on both sides intersects a 2-way street (approach B) 66 feet wide without parking. Conditions are assumed to be average. Determine whether the intersection capacity is adequate when the peak-hour volume in one direction on approach A is 900 v.p.h. and on approach B 1,280 v.p.h.

Solution: For approach A, enter chart 19 at upper left with $W_A=42$, proceed right to the curve for 1-way street with parking on both sides in the *CBD*, then down to an approach volume of 900 v.p.h. and to the right where a $G/C=0.41$ is intersected. For approach B, enter chart at extreme right with $W_A=66/2=33$, proceed left to the curve for 2-way street without parking in the *CBD*, then down to an approach volume of 1,280 v.p.h., and to the left where a $G/C=0.56$ is intersected. Find the intersection point on the y-y axis by drawing a straight line between the two G/C values. Project horizontally to the left, intersecting the *MP* scale for over 1 million population; read $V/C_D=0.90$.

Because the result falls below the level of service C line (ratio 1.00), operation is superior to level of service C; that is, the demand volume is below design capacity. To find the required G/C at design capacity for approach A and approach B, for the indicated city size, to handle the volume of 900 and 1,280 v.p.h., respectively, the G/C values previously found should be divided by the adjustment factor shown in the chart along the top of the *MP* scales (see footnote under left part of chart). Thus, for approach A the required $G/C=0.41/1.20=0.34$, and for approach B the required $G/C=0.56/1.20=0.47$. If it is desired to adjust the G/C values proportionally to acheive balanced operation, the required G/C values should be divided by the V/C_D ratio or $G/C=0.34/0.90=0.38$ for approach A and $G/C=0.47/0.90=0.52$ for approach B; that is, including 10 percent of the cycle for amber, the total$=0.38+0.52+0.10=1.00$.

Problem 39

In the *OBD* of a 750,000 population metropolitan area, a 2-way street (approach A) 86 feet wide with parking intersects a 1-way street (approach B), 47 feet wide with parking on one side. Conditions are assumed to be average. The *DHV* on approach A is 1,200 v.p.h. and on approach B it is 2,200 v.p.h. Determine the following:

(1) Level of service at which the intersection would operate.

(2) The extent to which traffic can be increased on approach A—keeping approach B constant—to produce possible capacity operation on the intersection as a whole.

(3) The extent to which traffic can be increased uniformly in solution (1) to produce possible capacity operation on the intersection as a whole; what would be the signal timing?

(4) The required width of approach B for operation at design capacity, if parking on approach B is removed and all other conditions remain the same; what would be the signal timing?

Solution: The solutions for the four parts of this problem are illustrated by the schematics in figure 27, which show the various ways in which charts 19 and 20 can be used.

Part 1.—To find the level of service, first the V/C_D ratio must be found in chart 20. The procedure is demonstrated in figure 27(1). For approach A, course *a-b-c-d* is followed, producing on the left G/C scale an intercept of 0.44; for approach B, course *e-f-g-h* is followed, producing on the right G/C scale an intercept of 0.61; points *d* and *h* are connected by a straight line intersecting the y-y axis at point *i*; a horizontal projection from *i* to point *j* on the *MP* scale for 750,000 population yields the result $V/C_D=1.06$. Because this ratio is larger than 1.00, the demand volume exceeds design capacity or level C service volume. Demand volume, however, is well within possible capacity (level E) limitations, for which the V/C_D ratio would be 1.25, the average f value for the two approaches determined in table C (chart 20). To find the specific level of service at which the intersection is operating, it is necessary to consult tables 3 and 4. The composite f values for the two approaches, representing various levels of service, are the averages for the 43-foot approach on a 2-way street with parking and for the 47-foot approach on a 1-way street with parking on one side. These are level A, 0.87; level B, 0.90; level C, 1.00; level D, 1.15; and level E, 1.25. The V/C_D ratio of 1.06 found in chart 20 for this intersection falls between 1.00 and 1.15, the limiting values of levels C and D. The intersection, therefore, operates at level D during peak hours.

Part 2.—To find the extent to which traffic may be increased on approach A to correspond to possible capacity, the composite f value for approaches A and B of 1.25, as found in part 1, must be used in chart 20. The chart is entered by locating a point at 1.25 on the V/C_D scale for $MP=750{,}000$. This is point k as shown in the schematic of figure 27(2). Proceed to the right horizontally from k to intercept point l on y-y axis. Enter chart at the upper right for approach B, following a before course *e-f-g-h*. From *h* project a straight line through *l* to point *m* at the intersectio with the left G/C scale. Proceed horizontall to the left from *m* to the intersection point on the previously established course *a-b-c* fo approach A. Read at intersection point *n* a approach A volume of 1,730 v.p.h.

Part 3.—To find the extent to which traffi may be increased on both approaches uniformly to obtain possible capacity operation the chart is entered with $V/C_D=1.25$ as i part 2, establishing points *k* and *l*. As shown i the schematic of figure 27(3), draw line *p* through point *l* parallel to line *dh*, set in th solution of part 1. Project a horizontal line t the left from point *p* to intersect point *r* o course *a-b-c* situated before; read a volume o 1,470 v.p.h. on approach A. Project a horizontal line to the right from point *q* to intersect point *s* on the previously set course *e-f-g* read a volume of 2,500 v.p.h. on approach B The G/C values of 0.54 and 0.70 at points and *q* pertain to *MP* base of 250,000 and t

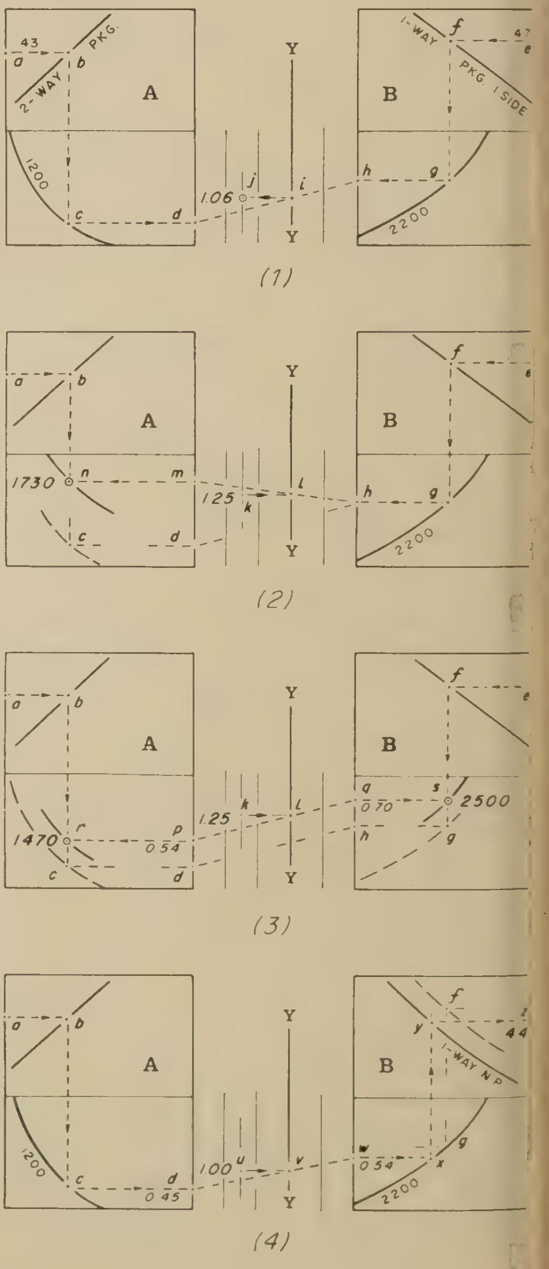


Figure 27.—Chart solutions for problem 3

TABLE C — RATIO OF POSSIBLE CAPACITY TO DESIGN CAPACITY

STREET TYPE	PARKING CONDITIONS	FACTOR f, when W_A (in feet) is: —								
		10	15	20	25	30	35	40	50	60
TWO WAY	No Parking	1.20	1.20	1.20	1.20	1.21	1.23	1.25	1.27	1.30
	With Parking	–	–	1.10	1.14	1.18	1.21	1.25	1.31	1.34
ONE WAY	No Parking	–	–	1.15	1.13	1.12	1.12	1.13	1.15	1.17
	Parking One Side	–	–	1.10	1.13	1.16	1.18	1.20	1.25	1.30
	Parking Both Sides	–	–	–	1.25	1.25	1.25	1.27	1.32	1.37

EXAMPLE

Given

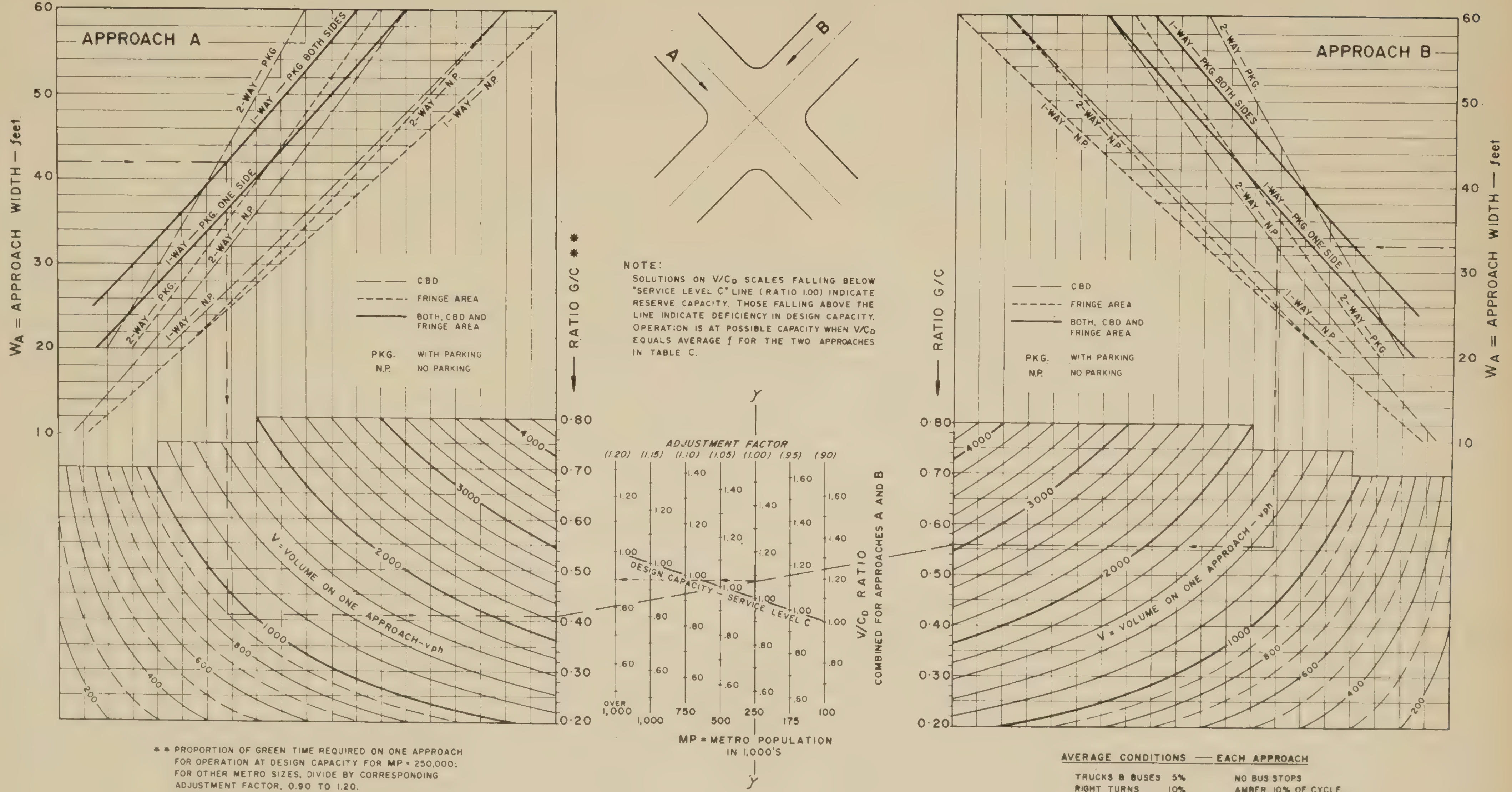
MP = 2,000,000, CBD.

APPROACH A:
One-way street
Parking both sides
W_A = 42'
DHV = 900 vph

APPROACH B:
Two-way street
No parking
W_A = 33'
DHV = 1280 vph

Solution

V/C_D = 0.90
Operation superior to service level C; i.e. demand volume below design capacity.



NOTE:
SOLUTIONS ON V/C_D SCALES FALLING BELOW "SERVICE LEVEL C" LINE (RATIO 1.00) INDICATE RESERVE CAPACITY. THOSE FALLING ABOVE THE LINE INDICATE DEFICIENCY IN DESIGN CAPACITY. OPERATION IS AT POSSIBLE CAPACITY WHEN V/C_D EQUALS AVERAGE f FOR THE TWO APPROACHES IN TABLE C.

** PROPORTION OF GREEN TIME REQUIRED ON ONE APPROACH FOR OPERATION AT DESIGN CAPACITY FOR MP = 250,000; FOR OTHER METRO SIZES, DIVIDE BY CORRESPONDING ADJUSTMENT FACTOR, 0.90 TO 1.20.

AVERAGE CONDITIONS — EACH APPROACH

TRUCKS & BUSES	5%	NO BUS STOPS
RIGHT TURNS	10%	AMBER, 10% OF CYCLE
LEFT TURNS	10%	

DESIGN CAPACITY OF SIGNALIZED INTERSECTIONS

OVER-ALL INTERSECTION CAPACITY — AVERAGE URBAN CONDITIONS
C.B.D. AND FRINGE AREA

CHART 19

19
C.B.D.
FRNG.

the volumes if handled at design capacity. These values, however, can be used proportionately to establish the signal timing for possible capacity operation, as follows: approach A, $G/C=0.54/(0.54+0.70)=0.39$; approach B, $G/C=0.70/(0.54+0.70)=0.51$. The sum of the G/C's checks the requirement of 0.90 for 2-phase control, allowing for 0.10 for amber periods.

Part 4.—Here the required solution is for the width of approach B when the approach A width and the intersecting volumes are given. The procedure through the chart is continuously from left to right, using a design capacity setting on the y-y axis. The steps are diagramed in the schematic of figure 27(4). Enter chart at upper left with $W_A=43$ feet for a 2-way street with parking and approach volume of 1,200 v.p.h. This is shown by course *a-b-c-d*, intercepting $G/C=0.45$ at *d*. Locate point *u* on a reading of 1.00 on the V/C_D scale for $MP=750{,}000$, and project horizontally to the right to intersect point *v* on the y-y axis. Draw line *dw* through point *v* intercepting a value of 0.54 on the right G/C scale. Proceed horizontally from *w* to *x*, turning on $V=2{,}200$. Continue vertically to 1-way, no parking curve and turn on point *y*. Then proceed to the right and read $W_A=44$ feet at point *z*. Actual signal timing is: for approach A, $G/C=0.45/1.10=0.41$; and for approach B, $G/C=0.54/1.10=0.49$.

Problem 40

In the *CBD* of a metropolitan area having a population of 1 million, a 2-way, 40-foot street intersects a 2-way 56-foot street. There is no parking on either street. The latter uses the center 12-foot lane for opposing left turns, while the remaining 22-foot approach accommodates through-plus-right movements. The critical approach, A, on the 40-foot street carries a traffic volume of 650 v.p.h. The critical approach, B, on the 56-foot street accommodates 800 v.p.h. of which 200 v.p.h. use the exclusive left-turn lane on a separate signal indication. Other conditions are assumed to be average. Determine the adequacy of the intersection and signal timing.

Solution: Although a heavy left-turning movement is to be accommodated, chart 19 can be used by assuming an additional average G/C of 0.20 for the third signal phase. For approach A enter chart on left with $W_A=$ 20 feet and, using 2-way, no parking curve and $V=650$, intercept an initial G/C of 0.47 as shown by course *a-b-c-d* in figure 28(1). For approach B enter chart on right with $W_A=$ 22 and, using 2-way, no parking curve and $V=800$, intercept an initial G/C of 0.51, course *e-f-g-h*. Adjusted initial G/C for approach B is $0.51+0.20=0.71$, as indicated by a vertical shift from *h* to *i*. Connect the two G/C's, 0.47 and 0.71, by a straight line *di*. From the intersection point, *j*, on the y-y axis, project a line horizontally to the left to intercept the V/C_D scale for MP of 1 million population; at point *k* read $V/C_D=$ 1.12. In table 3, find *f* values for approaches A and B combined, as follows: level C, 1.00; level D, 1.14; level E (possible capacity), 1.20. The intersection, therefore, can accommodate the indicated volumes at level of service D. The required G/C's for operation at level of service D are determined by adjusting the initial G/C values for metropolitan size and for V/C_D ratio; that is, the initial G/C for each phase, in this case, is divided by 1.15 and by 1.12. For approach A, $G/C=0.47/(1.15\times1.12)=0.36$; for approach B, through-plus-right movement, $G/C=0.51/(1.15\times1.12)=0.39$; and for approach B, left-turning movement, $G/C=0.20/(1.15\times1.12)=0.15$. Allowing 10 percent of the cycle for amber, the sum $(0.36+0.39+0.15+0.10)$ totals 1.00.

Problem 41

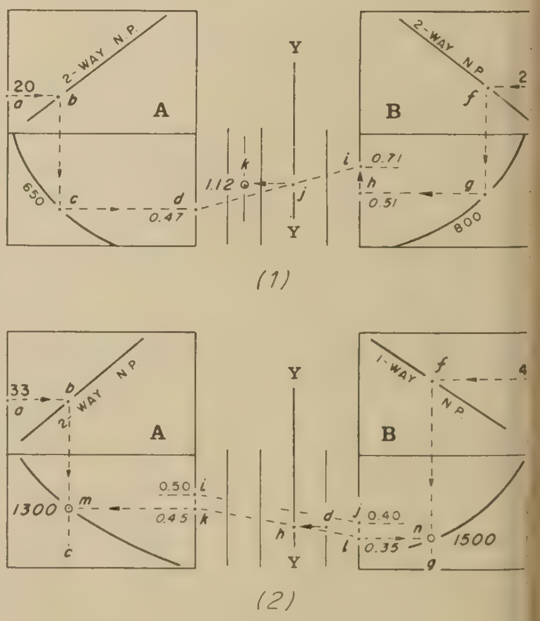
A 66-foot, 2-way street intersects a 42-foot 1-way street in the residential section of a metropolitan area of 100,000 population. There is no parking on either street. Conditions are assumed to be average. If 50 percent of the cycle is to be devoted to green on the 66-foot street and 40 percent of the cycle on the 42-foot street, what volumes can be accommodated on each facility at design capacity and at possible capacity?

Solution: For approach A, enter chart 20 with $W_A=33$ and turning on the 2-way, no parking curve, project downward through the approach volume curves, as indicated by course *a-b-c* in the schematic of figure 28(2). For approach B, enter chart with $W_A=42$ and turning on the 1-way, no parking curve, project downward through the approach volume curves, as shown by course *e-f-g*. Locate point *d* at a reading of 1.00 on the V/C_D scale for MP of 100,000 population. Project to the left horizontally intercepting the y-y axis at point *h*. Through *h* draw line *kl* parallel to line *ij* (where line *ij* connects $G/C=0.50$ on the left scale and $G/C=0.40$ on the right scale, the signal split as per problem statement). From point *k* project horizontally to the intersection point *m* on line *bc* previously established; read $V=1{,}300$ v.p.h. on approach A. From point *l* project horizontally to the intersection point *n* on line *fg* previously established; read $V=1{,}500$ v.p.h. on approach B. Dividing the intercepted G/C values of 0.45 at point *k* and 0.35 at point *l* by the MP adjustment factor of 0.90, yields the required G/C values of 0.50 and 0.40 on approaches A and B. The approach volumes which the intersection can handle at possible capacity are the volumes found above corresponding to design capacity multiplied by the *f* factor in table C of chart 20. Possible capacity: approach A, $1{,}300\times1.22=1{,}600$ v.p.h.; approach B, $1{,}500\times1.13=1{,}700$ v.p.h.

Problem 42

In the *CBD* of a metropolitan area of ½ million population, Main Avenue, a 2-way arterial, is to be improved from a 62-foot street with parking to a facility with two 34-foot traveled ways, without parking, and a 14-foot median including separate left-turn lanes. The existing conditions as well as the proposed improvements of Main Avenue, together with a series of five intersections, are shown in the upper part of figure 29. The peak-hour traffic projected for the improvement is indicated at the critical approache on the plan. As part of the planning proces and preliminary design of a street improvement program, determine first the adequacy of the intersections with Main Avenue improved and cross streets unaltered. Then, a a second step, determine the improvement that are also required on the cross streets t provide operation at level of service C. Typ of operation and parking condition on eac cross street is to be retained. Generally widening is to be kept to a minimum; however approximate limits to which the streets ma be widened curb-to-curb, if required, are 20th and 21st Streets, 44 feet; 22d and 24t Streets, 50 feet; and 23d Street, 68 feet. T save space, the latter may be an odd numbe of lanes with the center lane at the intersection reserved for left turns.

Solution: The analysis, using chart 19, fo the condition where Main Avenue is improve to two 34-foot traveled ways and a 14-foo median with left-turn lanes, while the cros streets remain unaltered, is shown in the lef part of the tabulation in figure 29. Futur traffic, representative of the p.m. peak, i applied to the plan. Although average cond tions are assumed in this type of analysi adjustment in approach volumes should b made where turns take place on separate lane In such instances, the deduction should be o the order of 10 percent of the approach volum or 100 v.p.h., whichever is smaller. A dedu tion of 100 v.p.h. has been applied generall as shown in the tabulation, on Main Avenu approaches at 21st, 22d and 24th Streets. A 23d Street, the left-turning movement in th northwest quadrant is sufficiently heavy t require a separate signal indication. The lef



(1)

(2)

Figure 28.—Chart solutions for problen 40 and 41.

STREET TYPE	PARKING CONDITIONS	FACTOR f, when W_A (in feet) is: —								
		10	15	20	25	30	35	40	50	60
TWO WAY	No Parking	1.20	1.20	1.20	1.20	1.21	1.23	1.25	1.27	1.30
	With Parking	–	–	1.10	1.14	1.18	1.21	1.25	1.31	1.34
ONE WAY	No Parking	–	–	1.15	1.13	1.12	1.12	1.13	1.15	1.17
	Parking One Side	–	–	1.10	1.13	1.16	1.18	1.20	1.25	1.30
	Parking Both Sides	–	–	–	1.25	1.25	1.25	1.27	1.32	1.37

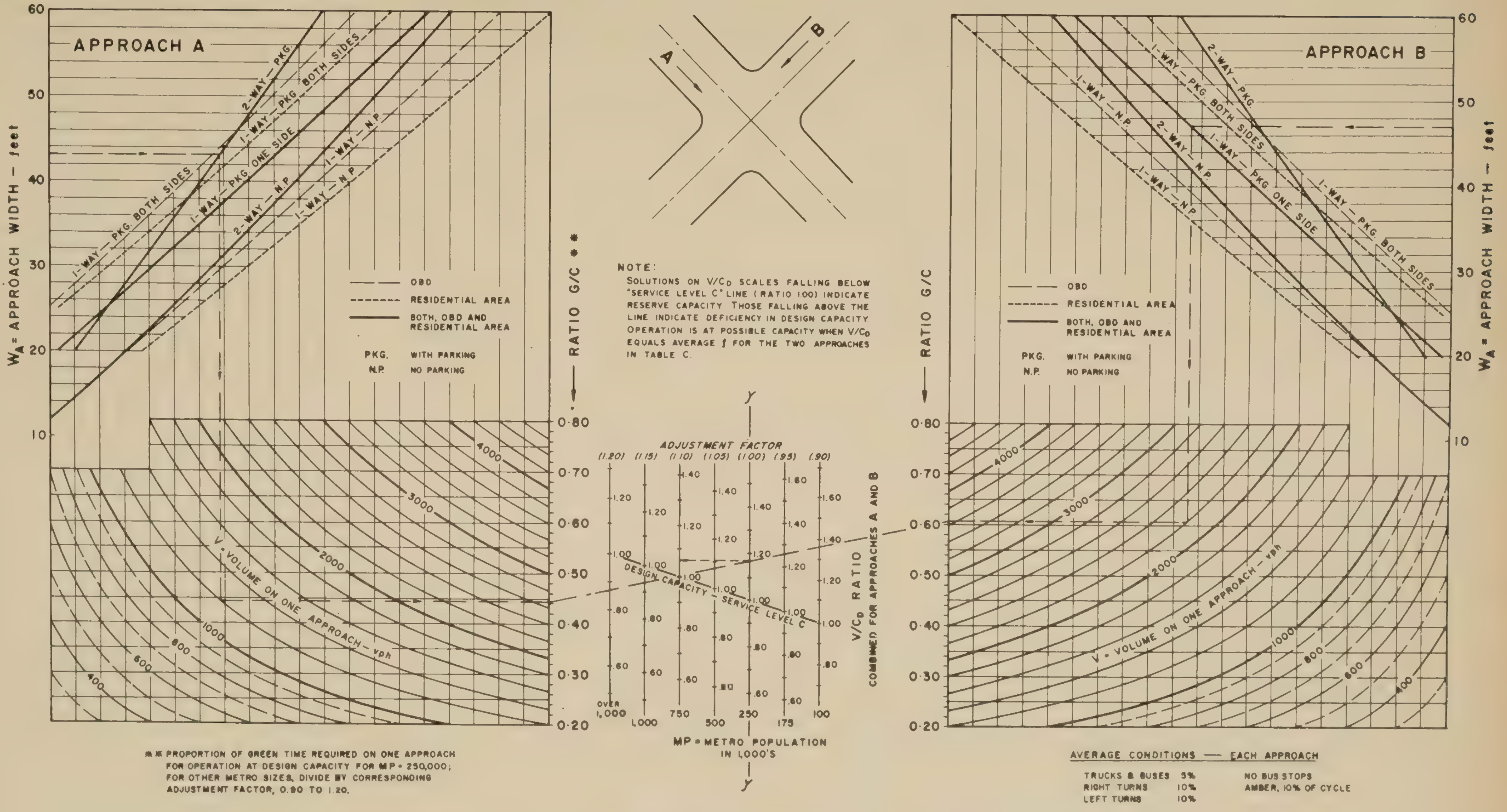
MP = 750,000, O.B.D.

APPROACH A:
Two-way
With parking
W_A = 43'
DHV = 1200 vph

APPROACH B:
One-way
Parking one side
W_A = 47'
DHV = 2200 vph

V/C_D = 1.06

Operation inferior to service level C; i.e., demand volume exceeds design capacity, but well within possible capacity for which the ratio would be 1.25 (average f for the two approaches in Table C).



NOTE:
SOLUTIONS ON V/C_D SCALES FALLING BELOW "SERVICE LEVEL C" LINE (RATIO 1.00) INDICATE RESERVE CAPACITY. THOSE FALLING ABOVE THE LINE INDICATE DEFICIENCY IN DESIGN CAPACITY. OPERATION IS AT POSSIBLE CAPACITY WHEN V/C_D EQUALS AVERAGE f FOR THE TWO APPROACHES IN TABLE C.

** PROPORTION OF GREEN TIME REQUIRED ON ONE APPROACH FOR OPERATION AT DESIGN CAPACITY FOR MP = 250,000; FOR OTHER METRO SIZES, DIVIDE BY CORRESPONDING ADJUSTMENT FACTOR, 0.90 TO 1.20.

AVERAGE CONDITIONS — EACH APPROACH

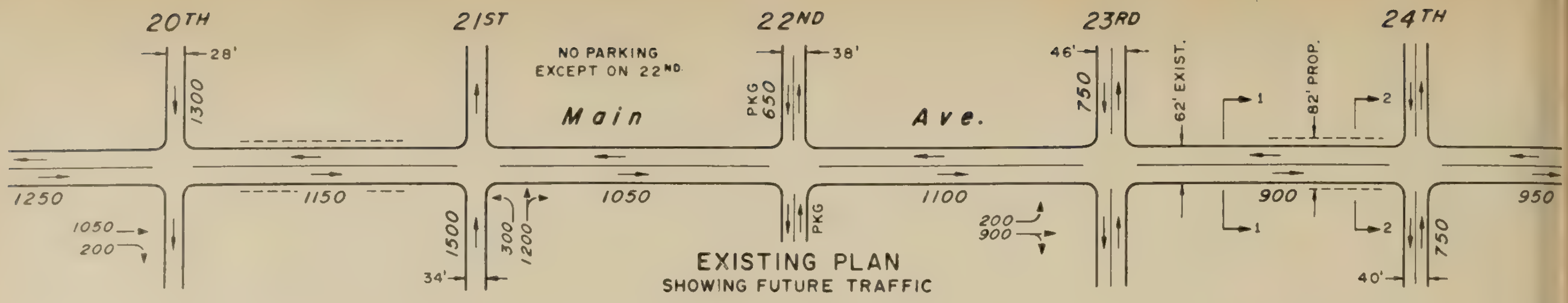
TRUCKS & BUSES	5%	NO BUS STOPS
RIGHT TURNS	10%	AMBER, 10% OF CYCLE
LEFT TURNS	10%	

DESIGN CAPACITY OF SIGNALIZED INTERSECTIONS

OVER-ALL INTERSECTION CAPACITY — AVERAGE URBAN CONDITIONS
O.B.D. AND RESIDENTIAL AREA

CHART 20

20
O.B.D.
RES.



CAPACITY ANALYSIS FOR WIDENED MAIN AVENUE

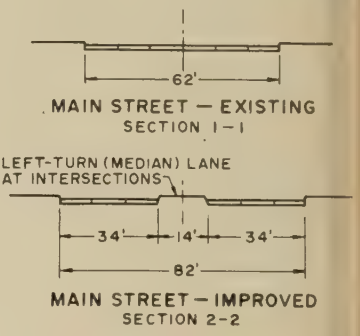
CROSS STREETS — EXISTING							CROSS STREETS — IMPROVED	
CROSS STREET		W_A feet	DHV — vph ONE DIRECTION		V/C_D**	f	W_A — APPROACH WIDTH — feet FOR LEVEL OF SERVICE C	
LOCATION	TYPE		MAIN *	CROSS ST.			REQUIRED	SELECTED
20TH	1-WAY, NP	28	1250	1300	1·17	1·17	39	44 (44)
21ST	1-WAY, NP	34	1050	1500	1·07	1·17	40	44 (44)
22ND	2-WAY, PKG	19	950	650	1·14	1·16	25	25 (50)
23RD	2-WAY, NP	23	900 ɸ	750 †	1·12	1·21	25	24 (60) ♀
24TH	2-WAY, NP	20	800	750	0·93	1·21	18	20 (40)

* LEFT-TURN MOVEMENT ON SEPARATE LANE REMOVED: 200 vph AT 23RD ST ; 100 vph AT 21ST, 22ND AND 24TH STS.
ɸ APPROACH REQUIRES THIRD PHASE (ASSUMED G/C = 0·20) FOR LEFT TURN.
† 650 ON IMPROVED CROSS STREET, ALLOWING FOR 100 vph ON SEPARATE LEFT-TURN LANE.
♀ 24+12+24 ; CENTER LANE FOR LEFT TURNS.
** ANALYSIS BASED ON W_A = 34' ON MAIN AVE. WITH LEFT-TURN LANES.

METRO POPULATION — 500,00
LOCATION — CBD

TRAFFIC SHOWN:
DHV — PM PEAK

AVERAGE CONDITIONS ASSUMED EXCEF
FOR TURNING MOVEMENTS AT:
20TH-21ST ST. COUPLE, SW QUA
AND AT 23RD ST., NW QUA



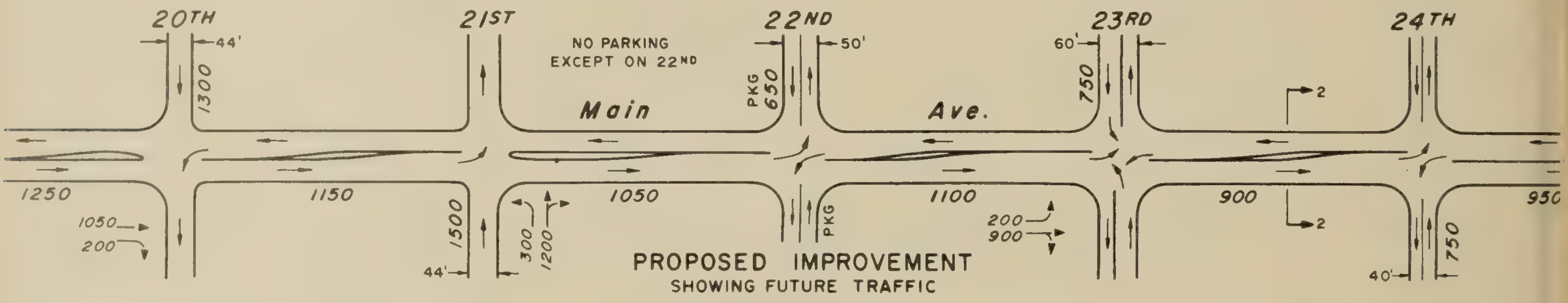


Figure 29.—Problem 42 illustrated.

turning volume of 200 v.p.h. is deducted from the approach volume and an additional G/C of 0.20 is assumed in the solution of chart 19.

With the information listed in the first five columns of the tabulation in figure 29, the V/C_D values were found readily in chart 19 and recorded in the sixth column. In the seventh column, the possible capacity ratios, or f factors, were obtained for the same intersections from table C in chart 19. All V/C_D ratios exceed 1.00, indicating that design capacity would be surpassed, except at 24th Street. Comparison of V/C_D values with the f factors clearly indicates the degree of overloading beyond level of service C. Intersections at 20th and 22d Streets would operate at approximately the possible capacity, and intersections at 21st and 23d Streets would operate at an intermediate level between design and possible capacities. The cross streets at these intersections require improvement along with Main Avenue to accommodate the future traffic. The intersection at 24th Street, on the other hand, shows a V/C_D ratio of less than 1.00, indicating that no widening on the cross street is required.

The proposed cross-street improvemen are shown in the last two columns of t tabulation and in the lower plan of figure The required widths of cross streets w taken directly from chart 19, using the i dicated volumes, a 34-foot approach on M Avenue, and a design capacity control. T selected widths are rounded values predicat on lane widths of 11 feet or more, within t indicated limits of permissible maximu widening. Twenty-fourth Street was l unaltered because of available capaci reserve.

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IN THIS ISSUE

Capacity Analysis Techniques for Design of Signalized Intersections

Installment No. 2

ERRATA

I he first installment of this article, published in the August 1967 is e of PUBLIC ROADS, *A Journal of Highway Research*, vol. 34, N 9, an error has been noted in charts 3 through 15. In the last line of he note at the top of each of these charts, please change *item 5* to ead *page 198*. Also, in chart 10, under example, Pkg *left* side sh ld read Pkg *right* side.

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