TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-84/49+258-3F		

4. Title and Subtitle	5. Report Date
PROCEDURAL GUIDE FOR LEFT-TURN ANALYSIS	November 1983
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Randy B. Machemehl and Ann M. Mechler	Research Report 258-3F
9. Performing Organization Name and Address	10. Work Unit No.
Center for Transportation Research The University of Texas at Austin Austin, Texas 78712-1075	11. Contract or Grant No. Research Study 3-18-80-258
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation; Transportation Planning Division P. O. Box 5051 Austin, Texas 78763	Final
	14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration. Research Study Title: "Warrants for Left-Turn Lanes and Signal Phases (Actuated Controllers)"

16. Abstract

Procedures for calculating intersection left-turn capacities and determining left-turn bay and protected phase requirements were developed in Report 258-1 of Study 3-18-80-258, "Guidelines for Left-Turn Treatments." In addition, Report 258-2 developed guidelines for choosing left-turn phase sequence patterns. The procedures and guidelines from the two reports are synthesized and presented in a stepwise format. A series of example problems is included to illustrate the procedures and facilitate usage.

17. Key Words	18. Distribution Statement
left-turn phase, left-turn bay, signal timing, capacity	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	90	

Form DOT F 1700.7 (8-69)

PROCEDURAL GUIDE FOR LEFT-TURN ANALYSIS

by

Randy B. Machemehl
Ann M. Mechler

Research Report No. 258-3F

Warrants for Left-Turn Lanes and Signal Phases (Actuated Controllers)

Research Project 3-18-80-258-3F

conducted for

Texas
State Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

November 1983

PREFACE

Research results presented in this document represent extensions of work originally done by Dr. Han-Jei Lin and presented within Center for Transportation Research Report 258-1. Dr. Lin's original work was carefully guided by Drs Clyde Lee and Robert Herman who were co-principal investigators of this research study. Mr. Rick Denney served as the contact representative of the State Department of Highways and Public Transportation throughout the study efforts.

The authors wish to express their thanks to these individuals and attribute to them any positive impacts of these research findings. The authors also wish to thank Mrs. Candace Gloyd for her patient efforts in providing this research report.

SUMMARY

Procedures for calculating intersection left-turn capacities and determining left-turn bay and protected phase requirements were developed in Report 258-1 of study 3-18-80-258 "Guidelines for Left-Turn Treatments." In addition, report 258-2 developed guidelines for choosing left-turn phase sequence patterns. The procedures and guidelines from the two reports are synthesized and presented in a stepwise format. A series of example problems are included to illustrate the procedures and facilitate usage.

Key Words: Left-Turn Phase, Left-Turn Bay, Signal Timing, Capacity

IMPLEMENTATION STATEMENT

The procedural guidelines and example problem solutions contained within this document should provide practicing engineers with an easily utilized source of information regarding potential left-turn treatments within signalized intersections. In order to facilitate ease of usage, both the procedures and examples have been arranged according to typically encountered situations or cases. Rationale for procedures and virtually all background development have been deleted for brevity. Users are strongly urged to familiarize themselves with Center for Transportation Research Reports 258-1 and 258-2 which describe the development of these procedures before using the procedural guides.

TABLE OF CONTENTS

LIST OF VARIABLES

C = cycle length, seconds

f_c = allowable utilization factor of the conflict area with an adequate length of bay

$\tilde{f}_c$ = allowable utilization factor of the conflict area with no bay

f_T = left-turn capacity correction factor for trucks and buses

G = sum of green and yellow phases, seconds

h = discharging headway, seconds

L_B = required length of left-turn bay, ft

L_m = maximum left-turn queue length, veh

N = number of opposing lanes Q_o is carried on

P_c = percentage of the opposing straight through traffic that is in the heaviest volume lane, decimal

p_T = percentage of trucks in the left-turn traffic flow, decimal

Q_c = effective capacity of the conflict area with an adequate length of bay, vphg

$\tilde{Q}_c$ = effective capacity of the conflict area with no bay, vphg

Q_L = left-turn capacity with an adequate length of bay, no separate left-turn phase, and assuming no trucks or buses, vph

Q_L^* = left-turn capacity with an adequate length of bay and no separate left-turn phase, vph

$\tilde{Q}_L$ = left-turn capacity with no left-turn bay, no separate left-turn phase, and assuming no left-turn vehicles in the opposing approach and no trucks or buses, vph

$\hat{Q}_L$ = left-turn capacity with no left-turn bay, no separate left-turn phase, and assuming no trucks or buses, vph

$\hat{Q}_L^*$ = left-turn capacity with no left-turn bay and no separate left-turn phase, vph

Q_o = opposing traffic volume, vph. Q_o is the sum of the opposing right-turning and straight through traffic volumes.

Q'_o = opposing traffic volume that must be converted in order to use Figures 2-7 through 2-9, vph

Q_w = warranted left-turn volume for a separate left-turn phase without correction for trucks and buses, vph

Q^*_w = warranted left-turn volume for a separate left-turn phase, vph

$\hat{Q}^*_w$ = warranted left-turn volume for a left-turn bay, vph

$\overline{V}_L$ = left-turn volume in the approach under consideration, vph

$\overline{V}_T$ = through volume in the median lane of the approach under consideration, vph. $\overline{V}_T$ includes right-turn vehicles if N = 1.

w_c = length of bay a passenger car will occupy, ft

w_T = length of bay a bus or truck will occupy, ft

CHAPTER 1. INTRODUCTION

Research results of study 3-18-80-258 "Guidelines for Left-Turn Treatments" have been reported in two interim reports. These reports numbered 258-1 and 258-2 presented procedures for capacity analyses, conditions for installation of protected left-turn phases and guidelines for choosing protected left-turn phase sequence patterns.

Stepwise procedural guides have been synthesized from these research findings. These guides are presented as Chapter 2 of this document along with a series of example problem solutions which are presented as Chapter 3. Tables and figures originally developed for Research Report 258-1 have also been included in chapter 2 in order to facilitate usage.

CHAPTER 2. PROCEDURAL GUIDELINES

The following discussion provides procedural guidelines for left-turn capacity analyses, guidelines for protected left-turn phase utilization, and general guidance for signal timing where protected left-turns are used. Complete documentation of procedure development is contained within Center for Transportation Research Reports 258-1 and 258-2. Users are directed to these sources for answers to questions regarding development of procedures, and all users are urged to review these documents before attempting use of these techniques.

Information is presented in an outline format in which specific cases are described by case numbers. The table of contents of this document provides an easy means of locating specific topics. Several alternative computational methods are provided for each case. Users may choose any method, although precision of results will vary due to errors inherent in linear interpolation of tabular information or graphical interpretation of certain figures.

Case I - Determination of left-turn maximum flow rate (capacity) if a turn bay of adequate length is provided but there is no separate left-turn signal phase.

1. Two methods can be used to determine the left-turn capacity, Q_L, assuming no trucks or buses on either approach. Correction for trucks and buses is included in item three.

   METHOD I

   Q_L can be found from Table 2-1 if Q_o, G/C and N are known.

TABLE 2-1. THE UNPROTECTED LEFT-TURN CAPACITY FOR SIGNALIZED INTERSECTIONS HAVING ADEQUATE LENGTH OF BAY WITHOUT A SEPARATE LEFT-TURN PHASE (CYCLE LENGTH = 60 SEC)

	Opposing Approach Volume, vph						
	200	300	400	500	600	800	1000
G/C = 0.3							
N = 1	135	71	60	-	-	-	-
N = 2	177	126	92	60	60	60	-
N = 3	189	143	114	83	72	60	60
G/C = 0.4							
N = 1	223	159	94	62	-	-	-
N = 2	270	219	168	134	84	60	60
N = 3	282	236	191	162	118	95	73
G/C = 0.5							
N = 1	317	252	183	121	80	-	-
N = 2	353	316	256	218	175	97	63
N = 3	375	330	284	239	210	142	119
G/C = 0.6							
N = 1	400	335	270	206	142	76	-
N = 2	457	406	355	303	252	183	109
N = 3	468	423	377	332	286	229	166
G/C = 0.7							
N = 1	487	422	358	294	229	135	-
N = 2	550	499	448	397	346	261	156
N = 3	561	516	470	425	380	307	213

N = number of opposing lanes

Not corrected for trucks or buses

Q_o, the opposing traffic volume, is the sum of the opposing right-turning and through traffic volumes (left-turning vehicles are excluded).

N is the number of opposing lanes upon which Q_o is carried but excludes left-turn bays or lanes. The ratio G/C represents the percentage of the cycle in which the approach under consideration does not have a red phase. Thus, G includes green and yellow time.

METHOD II - (from Fig 2-1 through Fig 2-5)

The appropriate Figure 2-1 through 2-5 is selected based upon the G/C ratio as defined in METHOD I. Q_L can be determined from the plot of Q_L versus Q_o for various values of N where these quantities are defined as in METHOD I.

2. Q_L does not require correction for left-turning vehicles in the opposing approach because with a bay condition on both approaches the opposing left-turn vehicles do not interact with those on the approach of concern.

3. The capacity Q_L must be corrected for the effect of trucks and buses as follows:

$$Q^*_L = f_T Q_L \qquad (2\text{-}1)$$

The left-turn capacity correction factor, f_T, is dependent on the percentages of trucks and buses on the approach under consideration and the opposing approach. Figure 2-6 is a plot of f_T versus the percentage of trucks and buses in the left-turn traffic (on the approach under consideration) for various percentages of opposing trucks and buses.

Case II - Determination of left-turn maximum flow rate (capacity) if no left-turn bays or lanes and no separate protected left-turn signal phase are provided.

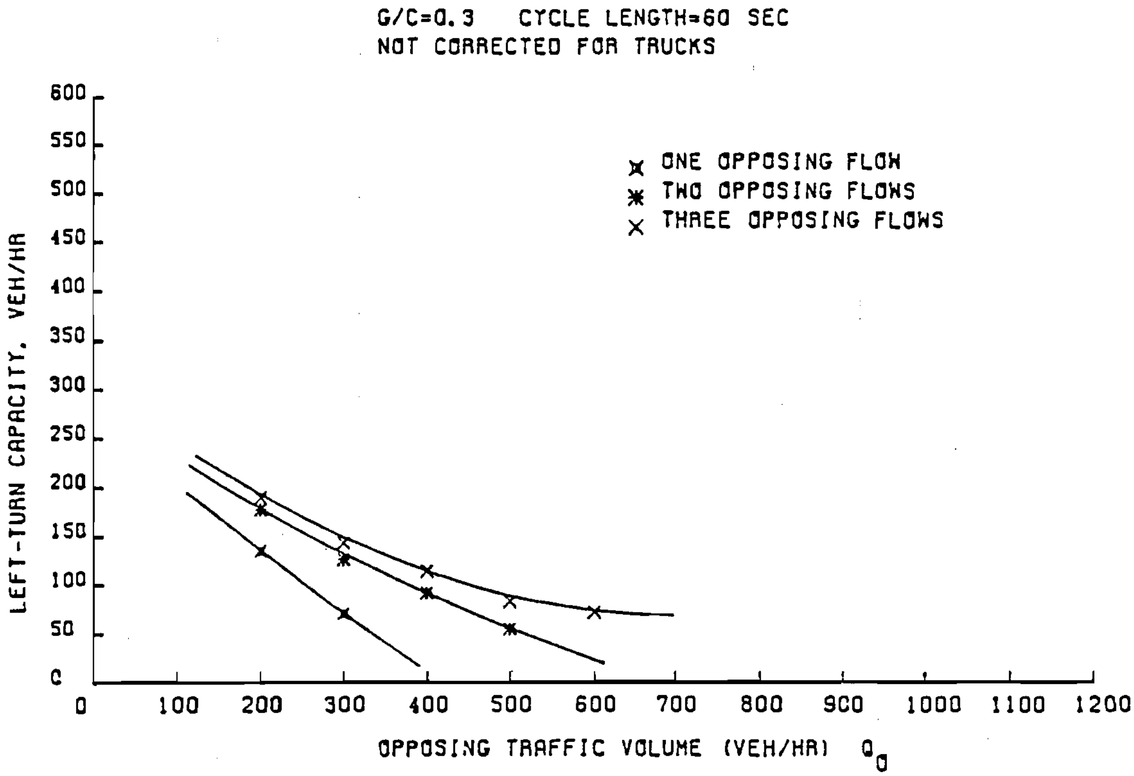


Figure 2-1. Left-turn capacity at signalized intersections having adequate length of bay for G/C = 0.3 and C = 60 sec.

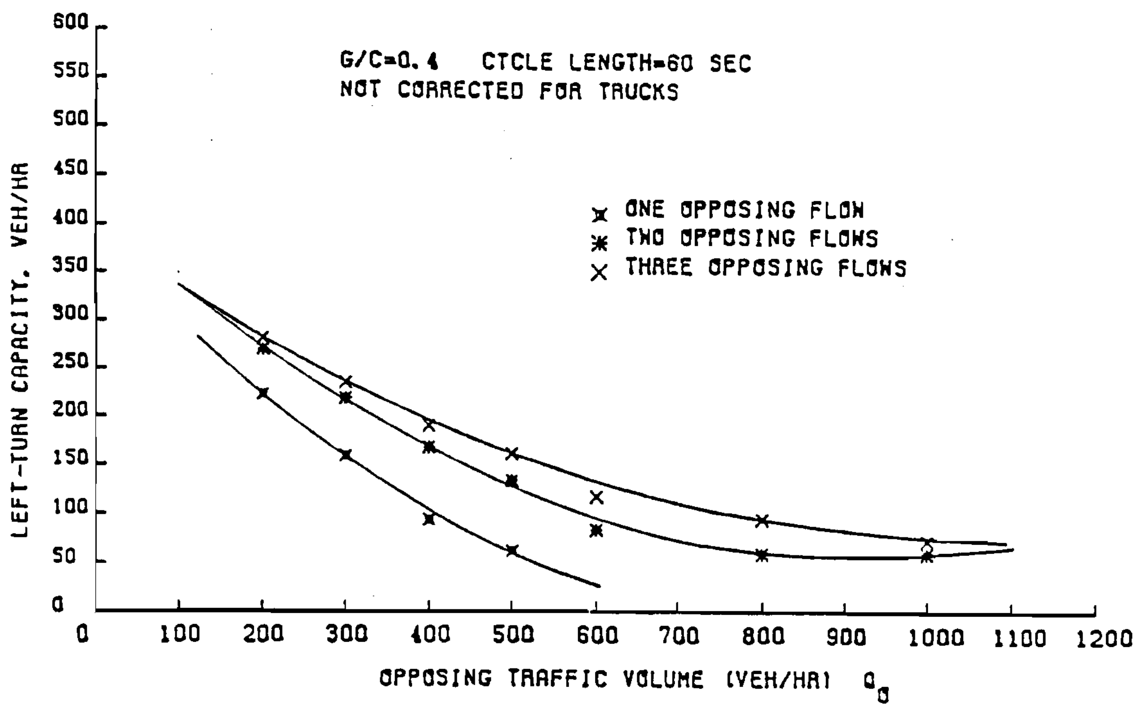


Figure 2-2. Left-turn capacity at signalized intersections having adequate length of bay for G/C = 0.4 and C = 60 sec.

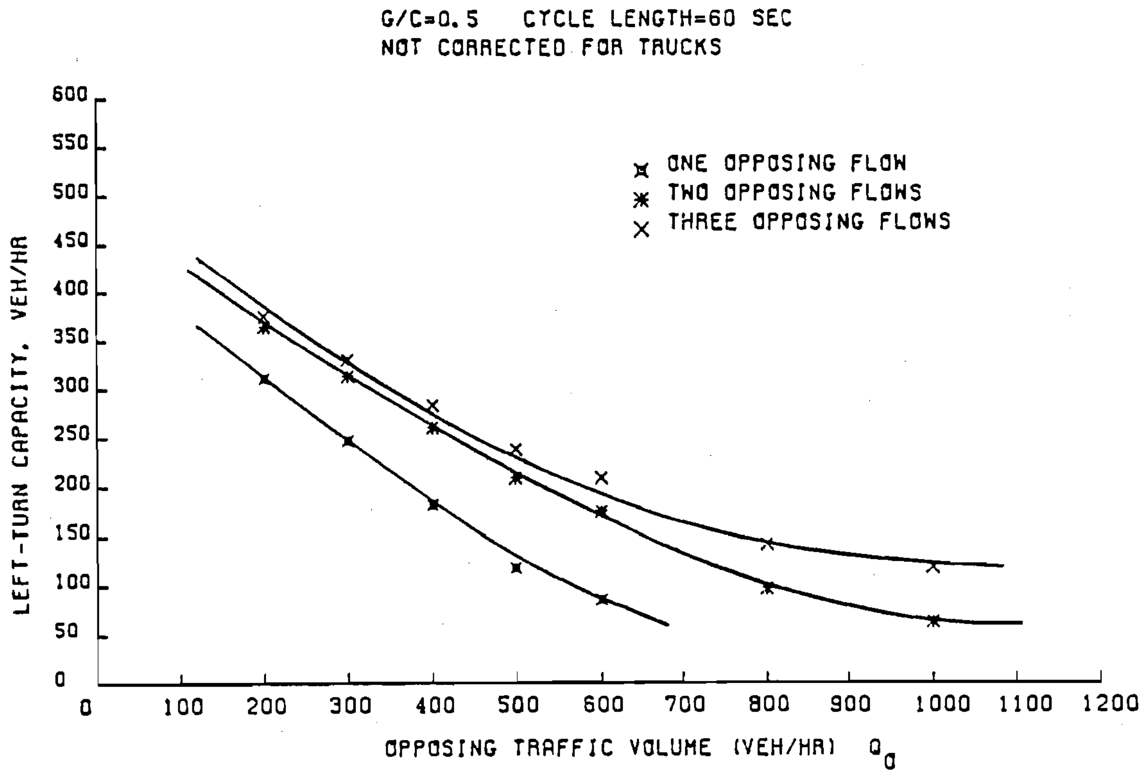


Figure 2-3. Left-turn capacity at signalized intersections having adequate length of bay for G/C = 0.5 and C = 60 sec.

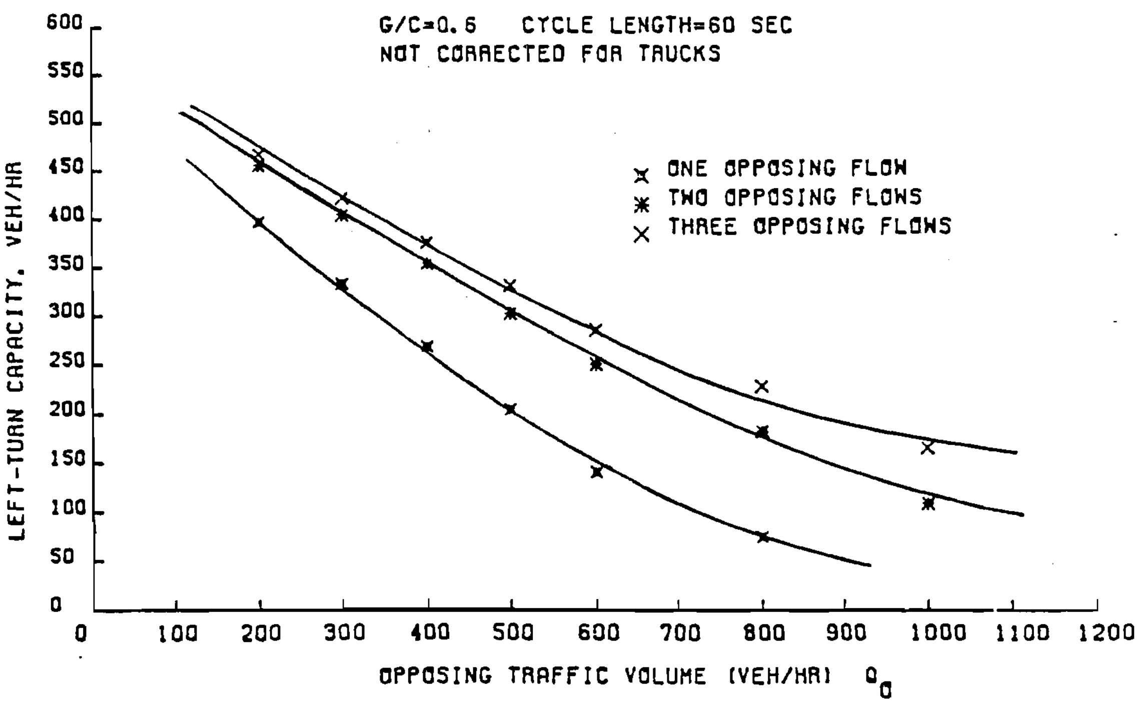


Figure 2-4. Left-turn capacity at signalized intersections having adequate length of bay for G/C = 0.6 and C = 60 sec.

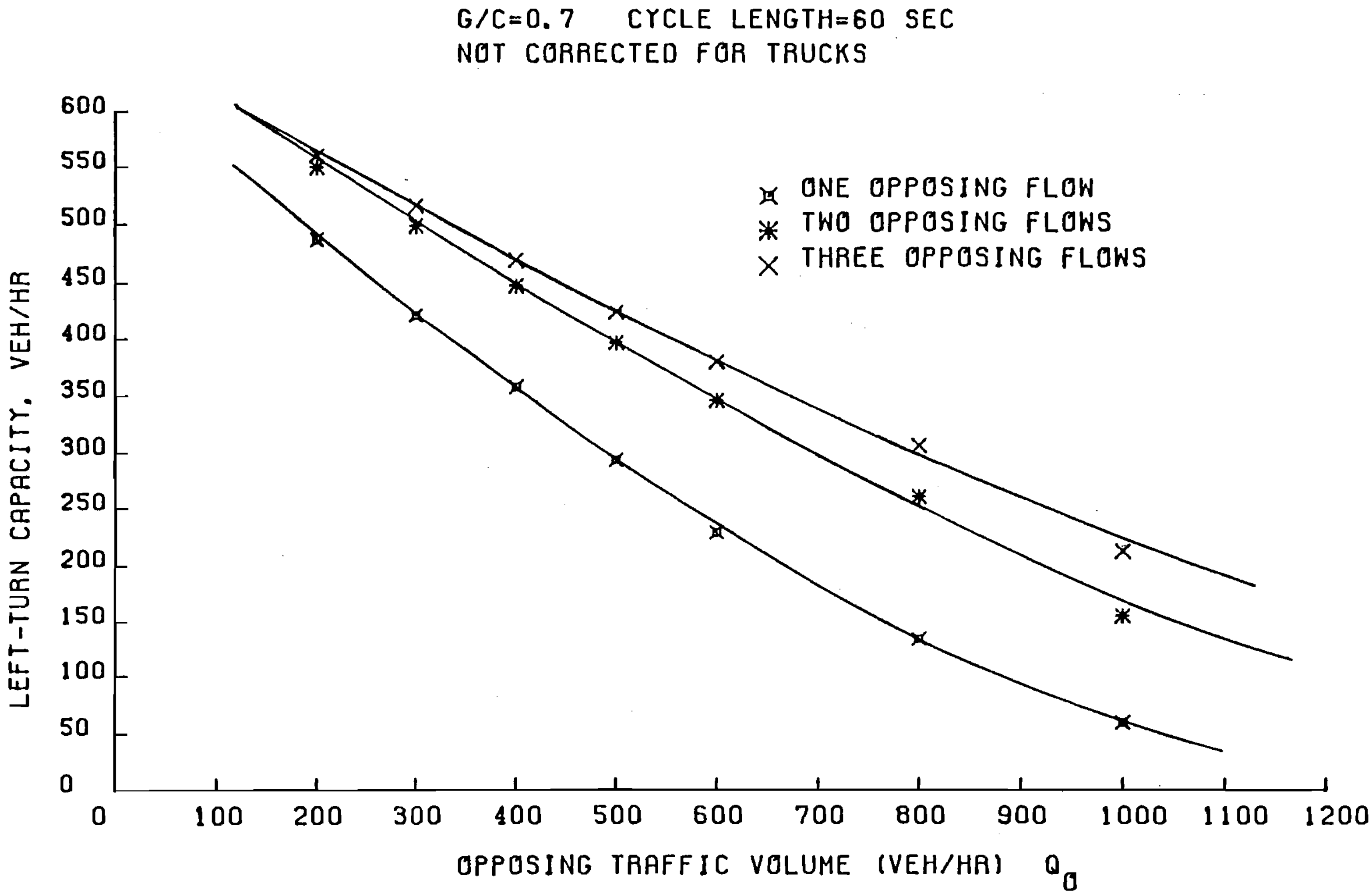


Figure 2-5. Left-turn capacity at signalized intersections having adequate length of bay for G/C = 0.7 and C = 60 sec.

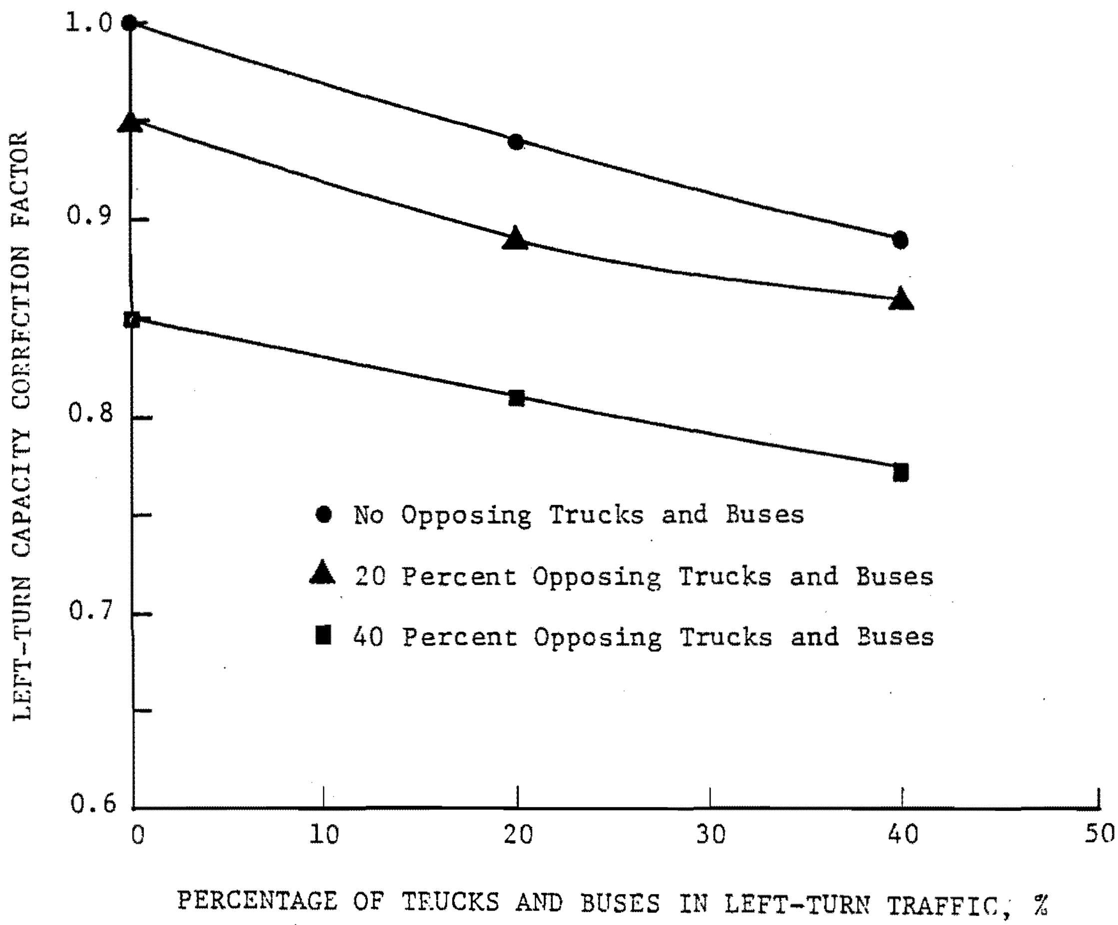


Figure 2-6. Factors for adjusting left-turn capacity for different combinations of opposing and left-turn truck percentages.

1. Two methods can be used to determine the left-turn capacity, $\tilde{Q}_L$, assuming no left-turn vehicles in the opposing approach and no trucks or buses.

METHOD I - by equation

$$\tilde{Q}_L = 0.5(-b + \sqrt{b^2 - 4c}) \qquad (2\text{-}2)$$

where

$$b = \overline{V}_T - Q_L$$

$$c = \overline{V}_T Q_L [(h\overline{V}_T)/(3600(G/C)) - 1]$$

Variables are defined as:

Q_L = left-turn capacity when there is a bay but no separate phase; not adjusted for trucks and buses

$\overline{V}_T$ = through volume in the median lane of the approach under consideration

h = discharging headway, found to be 2.6 seconds in the TEXAS Model

METHOD II - from Tables 2-2 through 2-6

The appropriate Table 2-2 through 2-6 is selected based on the G/C ratio. Ratios from 0.3 to 0.7 are provided. Interpolation between tables may be done for other G/C values. As previously mentioned, G represents the green plus yellow time.

Once the appropriate table is selected, the left-turn capacity, Q_L, can be found directly if $\overline{V}_T$, N, and Q_o are known. $\overline{V}_T$ is defined in METHOD I of this section, Q_o is the sum of the opposing straight through and right-turning volumes, and N is the number of opposing through lanes.

All of the tables are for 60 second cycle lengths. Since the cycle split has a much greater effect on capacity than

TABLE 2-2. LEFT-TURN CAPACITY FOR SIGNALIZED INTERSECTIONS WITHOUT A SEPARATE LEFT-TURN PHASE OR BAY

Through Traffic On Median Lane, vph	Number of Opposing Lanes (N)	Opposing Approach Volume, vph						
		200	300	400	500	600	800	1000
100	N = 1	120	60	31	-	-	-	-
	N = 2	161	112	79	46	31	16	-
	N = 3	172	128	101	71	61	41	26
200	N = 1	90	43	21	-	-	-	-
	N = 2	125	83	57	32	21	11	-
	N = 3	134	97	74	51	43	28	18
300	N = 1	52	23	12	-	-	-	-
	N = 2	75	48	32	17	11	6	-
	N = 3	82	56	42	28	24	15	10

G/C = 0.3 C = 60 sec
Not corrected for trucks or buses

TABLE 2-3. LEFT-TURN CAPACITY FOR SIGNALIZED INTERSECTIONS WITHOUT A SEPARATE LEFT-TURN PHASE OR BAY

Through Traffic On Median Lane, vph	Number of Opposing Lanes (N)	Opposing Approach Volume, vph						
		200	300	400	500	600	800	1000
100	N = 1	210	147	85	55	-	-	-
	N = 2	257	206	156	123	75	44	28
	N = 3	268	223	179	151	108	86	65
200	N = 1	181	123	69	44	-	-	-
	N = 2	224	177	132	102	61	35	22
	N = 3	235	193	152	126	89	70	52
300	N = 1	141	93	51	32	-	-	-
	N = 2	179	138	100	76	44	25	16
	N = 3	188	151	116	96	66	51	38
400	N = 1	92	59	31	19	-	-	-
	N = 2	120	90	63	47	27	15	10
	N = 3	127	100	75	61	41	32	23

G/C = 0.4 C = 60 sec
Not corrected for trucks or buses

TABLE 2-4. LEFT-TURN CAPACITY FOR SIGNALIZED INTERSECTIONS WITHOUT A SEPARATE LEFT-TURN PHASE OR BAY

Through Traffic On Median Lane, vph	Number of Opposing Lanes (N)	Opposing Approach Volume, vph						
		200	300	400	500	600	800	1000
100	N = 1	300	236	173	110	79	-	-
	N = 2	352	301	251	200	167	89	57
	N = 3	363	318	273	228	200	133	111
200	N = 1	273	212	152	95	68	-	-
	N = 2	323	274	226	178	147	76	48
	N = 3	334	291	247	205	178	116	96
300	N = 1	235	180	127	77	55	-	-
	N = 2	282	237	192	149	122	62	39
	N = 3	293	252	212	173	150	95	78
400	N = 1	189	141	98	59	41	-	-
	N = 2	230	190	152	116	94	47	29
	N = 3	239	203	169	136	116	73	59
500	N = 1	134	98	66	39	27	-	-
	N = 2	167	135	106	79	63	31	19
	N = 3	174	145	118	93	79	49	39

G/C = 0.5   C = 60 sec
Not corrected for trucks or buses

TABLE 2-5. LEFT-TURN CAPACITY FOR SIGNALIZED INTERSECTIONS WITHOUT A SEPARATE LEFT-TURN PHASE OR BAY

Through Traffic On Median Lane, vph	Number of Opposing Lanes (N)	Opposing Approach Volume, vph						
		200	300	400	500	600	800	1000
100	N = 1	389	325	261	198	134	70	-
	N = 2	447	396	345	294	243	175	103
	N = 3	458	413	368	322	277	220	158
200	N = 1	365	302	241	180	120	62	-
	N = 2	421	372	322	273	224	159	91
	N = 3	433	388	344	300	256	201	143
300	N = 1	330	271	213	157	104	52	-
	N = 2	385	337	289	243	197	138	78
	N = 3	395	353	310	269	228	177	123
400	N = 1	287	233	181	131	85	43	-
	N = 2	338	293	249	207	167	115	64
	N = 3	348	308	269	230	193	148	102
500	N = 1	236	188	144	103	66	33	-
	N = 2	281	241	203	166	132	90	49
	N = 3	290	254	219	186	155	117	80
600	N = 1	176	138	104	73	47	23	-
	N = 2	213	180	150	121	95	64	35
	N = 3	221	191	163	137	112	84	56

G/C = 0.6 C = 60 sec Not corrected for trucks or buses

TABLE 2-6. LEFT-TURN CAPACITY FOR SIGNALIZED INTERSECTIONS WITHOUT A SEPARATE LEFT-TURN PHASE OR BAY

Through Traffic On Median Lane, vph	Number of Opposing Lanes (N)	Opposing Approach Volume, vph						
		200	300	400	500	600	800	1000
100	N = 1	478	414	350	286	222	129	-
	N = 2	541	490	439	388	337	254	149
	N = 3	552	507	462	417	371	299	205
200	N = 1	456	393	330	268	206	117	-
	N = 2	518	468	418	368	318	236	137
	N = 3	530	485	440	396	351	280	190
300	N = 1	424	363	303	244	186	104	-
	N = 2	485	436	387	339	291	214	121
	N = 3	496	452	409	366	323	255	171
400	N = 1	384	326	270	215	162	89	-
	N = 2	442	395	349	304	259	188	105
	N = 3	453	411	370	329	289	226	149
500	N = 1	337	283	232	183	136	74	-
	N = 2	391	347	304	262	222	159	87
	N = 3	401	361	323	285	249	192	125
600	N = 1	282	234	190	148	109	59	-
	N = 2	330	291	253	216	181	128	69
	N = 3	339	304	269	236	204	156	100

G/C = 0.7 C = 60 sec Not corrected for trucks or buses the cycle length, the tables can be used for most moderate (<100 seconds) cycle lengths. This procedure should not be used for long cycle lengths.

2. Since $\tilde{Q}_L$ does not account for the effect of left-turning vehicles in the opposing approach, a correction must be made as follows.

$$\hat{Q}_L = \tilde{Q}_L - aQ_o \tag{2-3}$$

where

$$a = 0.317(P_c - 1/N) \tag{2-4}$$

P_c = percentage of the opposing through traffic that is in the heaviest volume lanes

N = number of opposing lanes.

3. Correction for trucks and buses must be made as follows.

$$\hat{Q}^*_L = f_T \hat{Q}_L \tag{2-5}$$

The left-turn capacity correction factor, f_T, can be found using Fig 2-6.

Case III - Determination of the left-turn demand which will require a separate left-turn bay.

1. The left-turn capacity for no bay, no phase conditions, $\hat{Q}^*_L$ is computed using the procedures of Case II.

2. The product Q_o (C/G) is computed where Q_o is the sum of the opposing straight and right-turn maneuvers. The term C/G is the inverse of the G/C ratio, and G is the sum of the green and yellow intervals.

3. Tables 2-7 through 2-9 are utilized to determine $\tilde{f}_c$ and Q_c using Q_o C/G and the through volume in the median lane of the approach under consideration, $\bar{V}_T$. The

TABLE 2-7. VALUES OF $\tilde{e}_L$, $\tilde{e}_o$, $\tilde{Q}_c$, AND $\tilde{f}_c$ FOR SINGLE OPPOSING FLOW

Opposing Volume Q_o, vph	Through Volume In Median Lane, vph	$\tilde{e}_L$	$\tilde{e}_o$	$\tilde{Q}_c$	$\tilde{f}_c$
$0 < Q_oC/G < 1000$	100	1.6	0.634	855	0.84 - 0.87
	200	1.7	0.593	820	0.84 - 0.87
	300	1.9	0.526	680	0.84 - 0.87
	400	2.2	0.455	560	0.84 - 0.87
$0 < Q_oC/G < 800$	500	2.9	0.340	415	0.84 - 0.87
$1000 < Q_oC/G < 1350$	100	3.2	0.310	530	0.79 - 0.82
	200	3.7	0.270	460	0.79 - 0.82
	300	4.5	0.220	375	0.79 - 0.82
	400	5.6	0.180	300	0.79 - 0.82
$800 < Q_oC/G < 1350$	500	4.0	0.250	295	0.79 - 0.82

TABLE 2-8. VALUES OF $\tilde{e}_L$, $\tilde{e}_o$, $\tilde{Q}_c$, AND $\tilde{f}_c$ FOR TWO OPPOSING FLOWS

Opposing Volume Q_o, vph	Through Volume In Median Lane, vph	$\tilde{e}_L$	$\tilde{e}_o$	$\tilde{Q}_c$	$\tilde{f}_c$
$0 < Q_oC/G < 1000$	100	2.0	0.507	910	0.86 - 0.92
	200	2.1	0.483	840	0.86 - 0.92
	300	2.3	0.443	740	0.86 - 0.92
	400	2.6	0.380	615	0.86 - 0.92
$0 < Q_oC/G < 800$	500	3.3	0.305	455	0.86 - 0.92
$1000 < Q_oC/G < 1600$	100	2.7	0.370	770	0.82 - 0.87
	200	2.9	0.340	695	0.82 - 0.87
	300	3.4	0.290	590	0.82 - 0.87
	400	4.4	0.230	465	0.82 - 0.87
$800 < Q_oC/G < 1600$	500	5.3	0.188	365	0.82 - 0.87
$1600 < Q_oC/G < 2000$	100	6.3	0.160	435	0.79 - 0.84
	200	7.1	0.140	375	0.79 - 0.84
	300	8.7	0.115	310	0.79 - 0.84
	400	11.1	0.090	240	0.79 - 0.84
	500	16.7	0.06	160	0.79 - 0.84

TABLE 2-9. VALUES OF $\tilde{e}_L$, $\tilde{e}_o$, $\tilde{Q}_c$, and $\tilde{f}_c$ FOR THREE OPPOSING FLOWS

Opposing Volume Q_o, vph	Through Volume In Median Lane, vph	$\tilde{e}_L$	$\tilde{e}_o$	$\tilde{Q}_c$	$\tilde{f}_c$
$0 < Q_oC/G < 1000$	100	2.2	0.450	910	0.91 - 0.96
	200	2.3	0.430	840	0.91 - 0.96
	300	2.5	0.400	745	0.91 - 0.96
	400	2.9	0.343	615	0.91 - 0.96
$0 < Q_oC/G < 800$	500	3.6	0.280	460	0.91 - 0.96
$1000 < Q_oC/G < 1600$	100	3.2	0.317	775	0.88 - 0.94
	200	3.4	0.297	705	0.88 - 0.94
	300	3.9	0.260	605	0.88 - 0.94
	400	4.8	0.210	485	0.88 - 0.94
$800 < Q_oC/G < 1600$	500	5.8	0.173	375	0.88 - 0.94
$1600 < Q_oC/G < 2000$	100	9.1	0.110	445	0.72 - 0.84
	200	10.0	0.100	395	0.72 - 0.84
	300	11.1	0.090	335	0.72 - 0.84
	400	14.3	0.070	260	0.72 - 0.84
	500	20.0	0.050	105	0.72 - 0.84

correct table is determined by N, the number of lanes of opposing flow, excluding any left-turn bay.

4. Equation 2-6 is used to calculate the "warrant" volume, $\hat{Q}^*_w$.

$$\hat{Q}^*_w = \hat{Q}^*_L - (1 - \tilde{f}_c)\tilde{Q}_c (G/C) \qquad (2\text{-}6)$$

If the "warranted" volume, $\hat{Q}^*_w$, is less than the actual left-turn volume, $\bar{V}_L$, a left-turn bay is needed.

Case IV - Determination of the required left-turn bay length.

The steps to determine the required bay length, L_B, are as follows:

1. The maximum left-turn queue length, L_m, is determined from Fig 2-7 through Fig 2-9.

   All figures are based upon a G/C ratio of 0.5. If the actual G/C ratio is not 0.5, the opposing traffic volume, Q'_o, must be converted using Eq 2-6 before using the figures.

$$Q_o = Q'_o/(2(G/C)) \qquad (2\text{-}7)$$

   With a known Q_o and left-turn volume, V_L, the maximum queue length can be found.

   The correct figure is selected according to the number of through lanes of traffic on the approach of concern. For example, if two lanes of through traffic are on the approach, Fig 2-8, four-by-four intersections, would be used even if the crosstreet were not four lanes wide.

2. The required length of bay, L_B, is calculated from Equation 2-8.

$$L_B = w_T p_T L_m + w_c (1 - p_T) L_m \qquad (2\text{-}8)$$

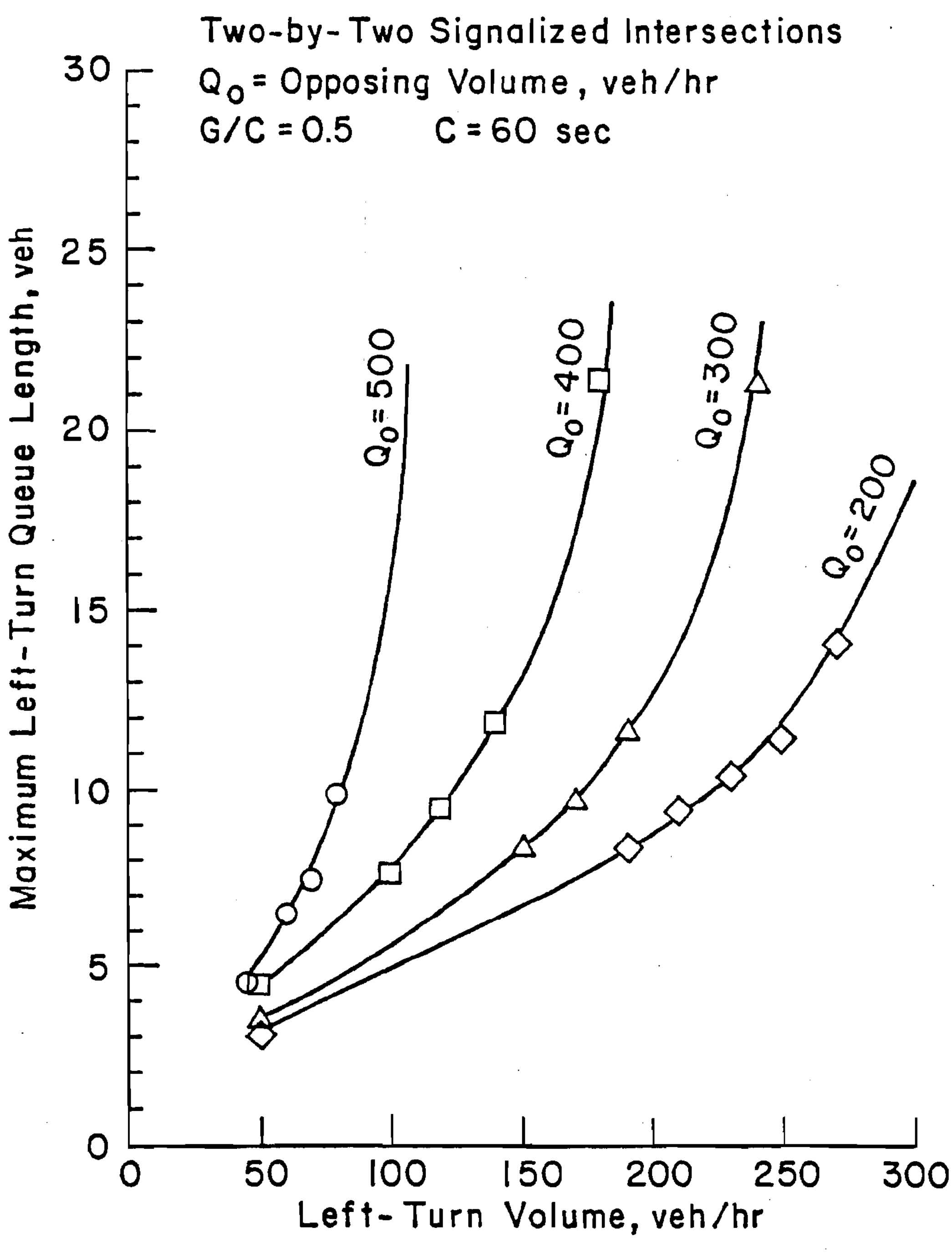


Figure 2-7. The maximum number of left-turn vehicles stored in the bay under various traffic conditions at two-by-two signalized intersections.

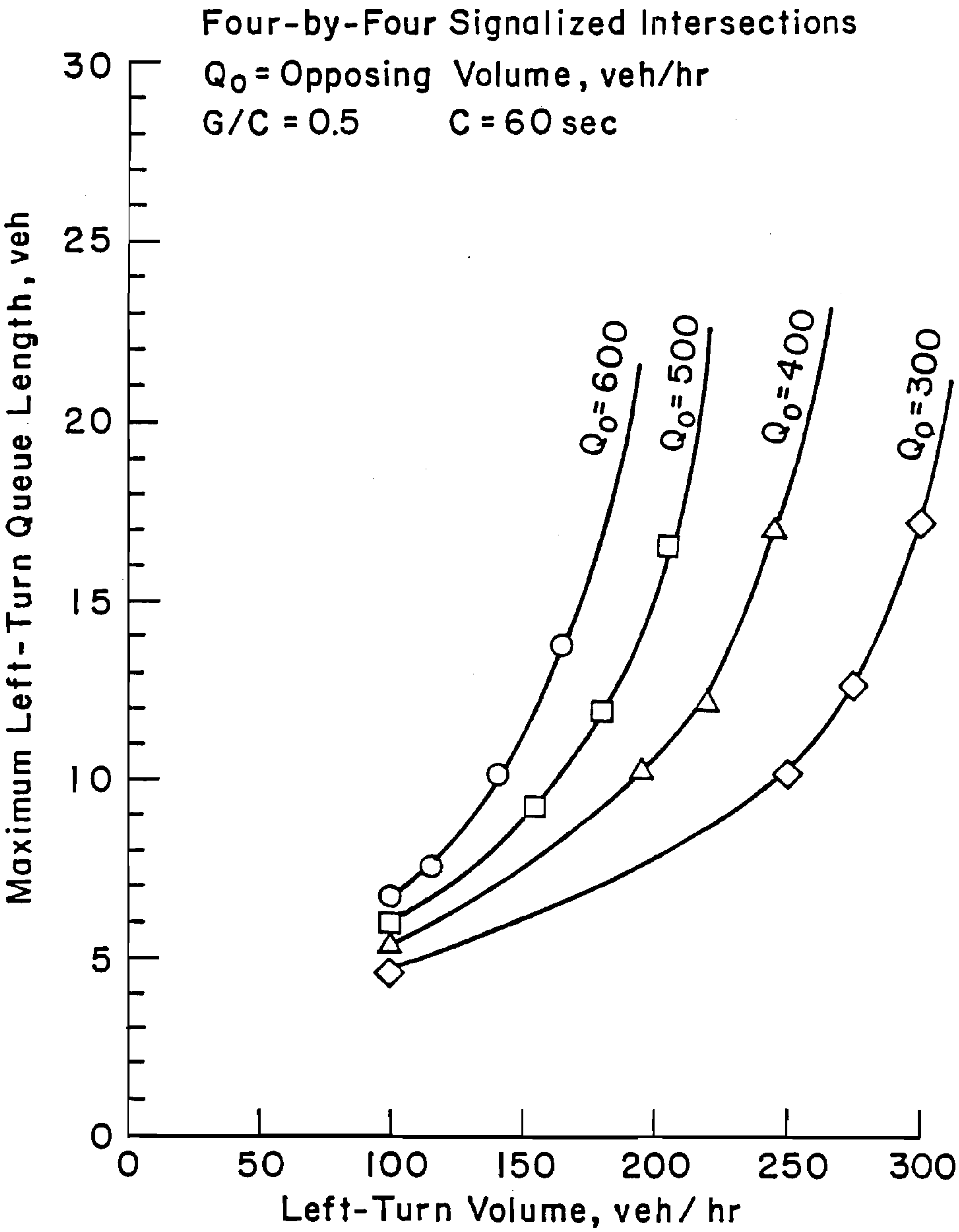


Figure 2-8. The maximum number of left-turn vehicles stored in the bay under various traffic conditions at four-by-four signalized intersections.

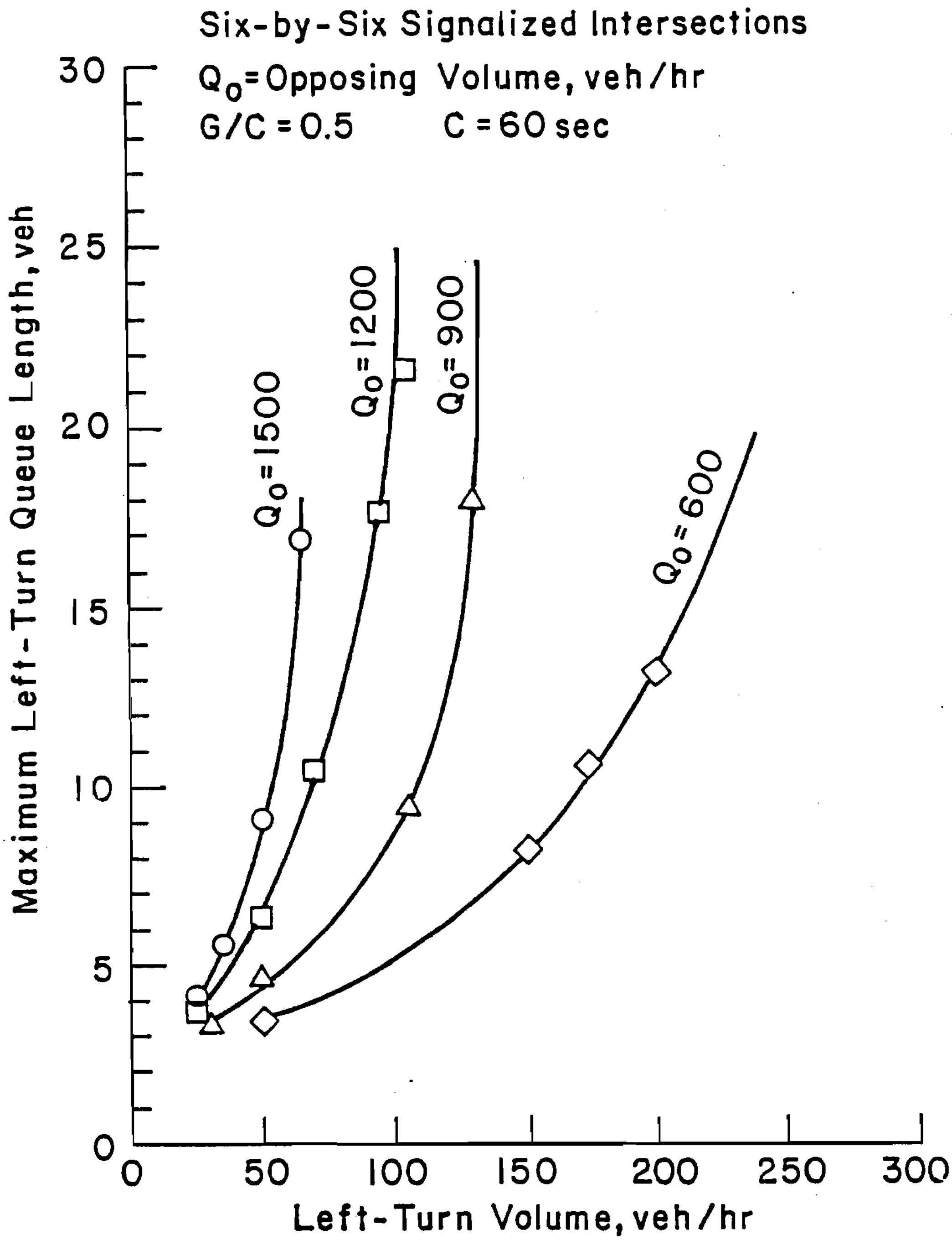


Figure 2-9. The maximum number of left-turn vehicles stored in the bay under various traffic conditions at six-by-six signalized intersections.

where

w_T = ft of bay length a bus or truck will occupy, assumed

w_c = ft of bay length a passenger car will occupy, assumed

p_T = percentage of trucks in the left-turn traffic flow (decimal)

Case V - Determination of the need for a protected left-turn signal phase.

The need for a separate left-turn phase can be determined by three methods.

METHOD I - From Fig 2-10 through Fig 2-12

Figures 2-10 through 2-12 are decision charts for deciding whether to implement a separate left-turn phase at signalized intersections with G/C ratios of 0.4 to 0.6 when there are no trucks and buses in the traffic. The correct decision can be taken directly from the chart if the left-turn traffic volume, V_L, and the opposing traffic volume excluding left-turning vehicles, Q_o, are known. If the intersecting point for the two values is to the right of the appropriate intersection geometry curve, a left-turn phase is recommended.

METHOD II - from Table 2-10

1. The product of Q_o (C/G) is computed where Q_o is the sum of the opposing straight through and right-turning vehicles, and G is the sum of the green and yellow phase lengths.

2. With Q_o, Q_o C/G, and the number of opposing lanes, N, the correct equation for the critical left-turn volume, Q_w, can be located in Table 2-10. The basic left-turn demand Q_w which will justify a separate signal phase must be computed.

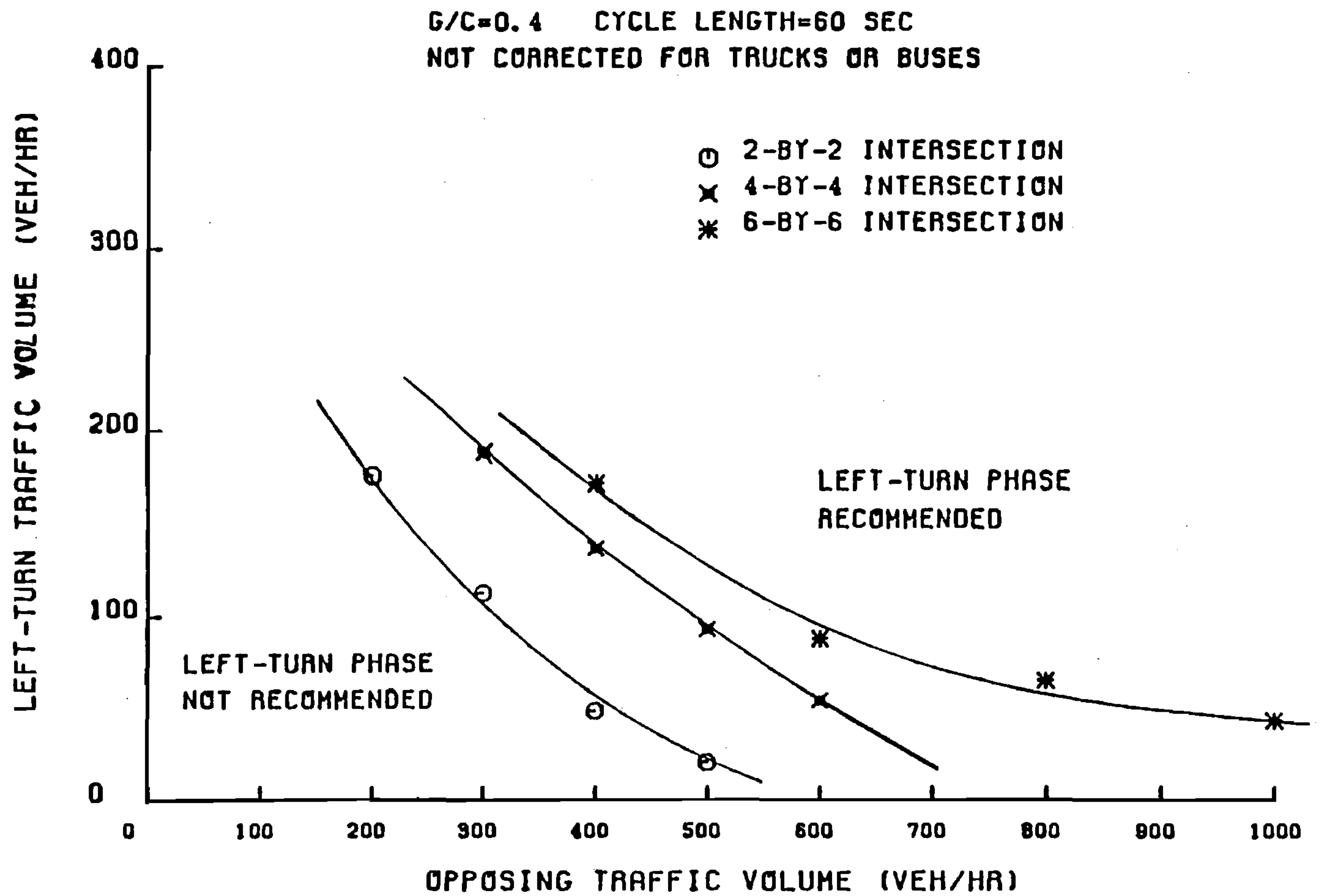


Figure 2-10. Decision chart for implementing a separate left-turn phase at signalized intersections with G/C = 0.4 and C = 60 sec.

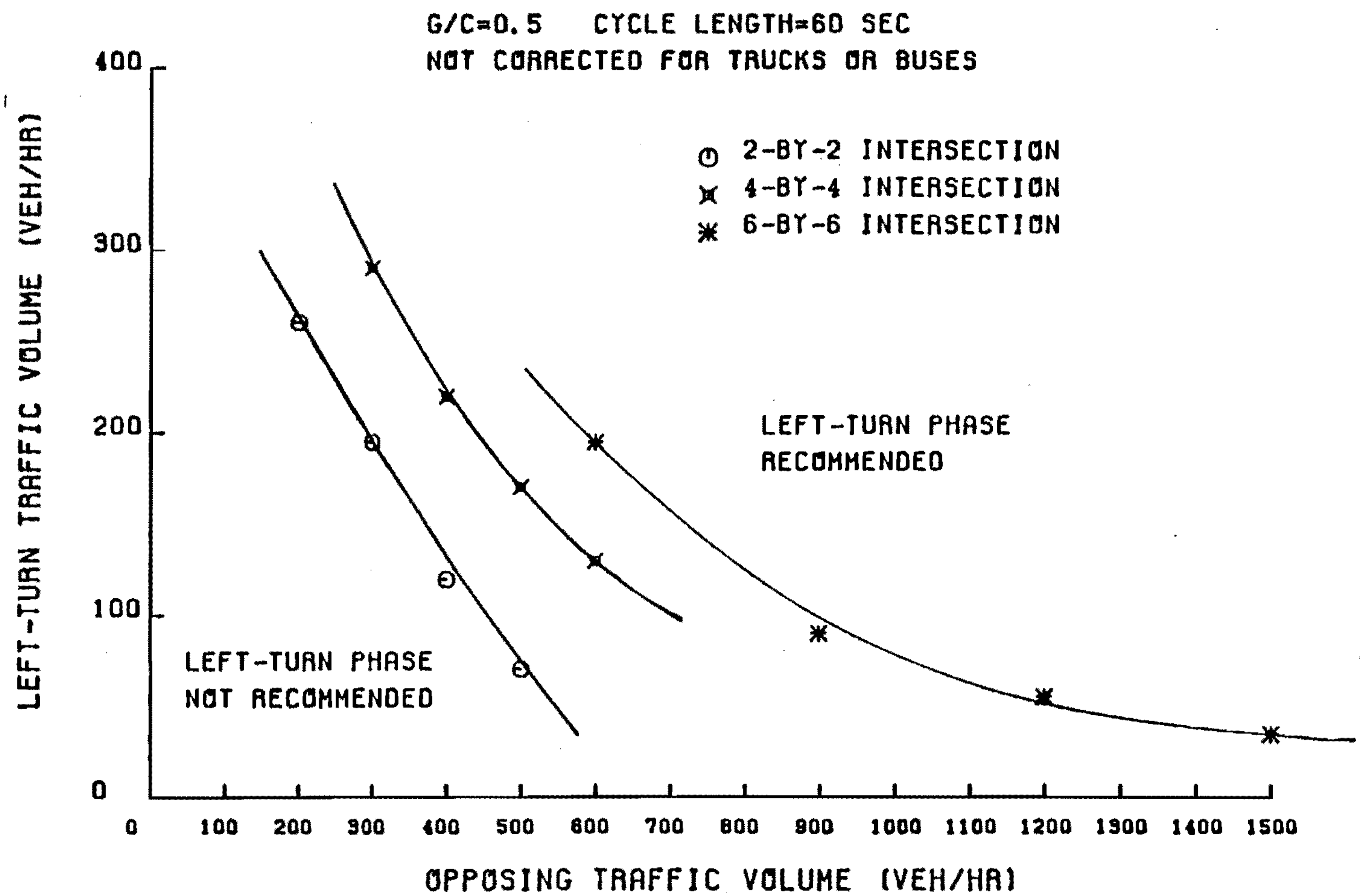


Figure 2-11. Decision chart for implementing a separate left-turn phase at signalized intersections with G/C = 0.5 and C = 60 sec.

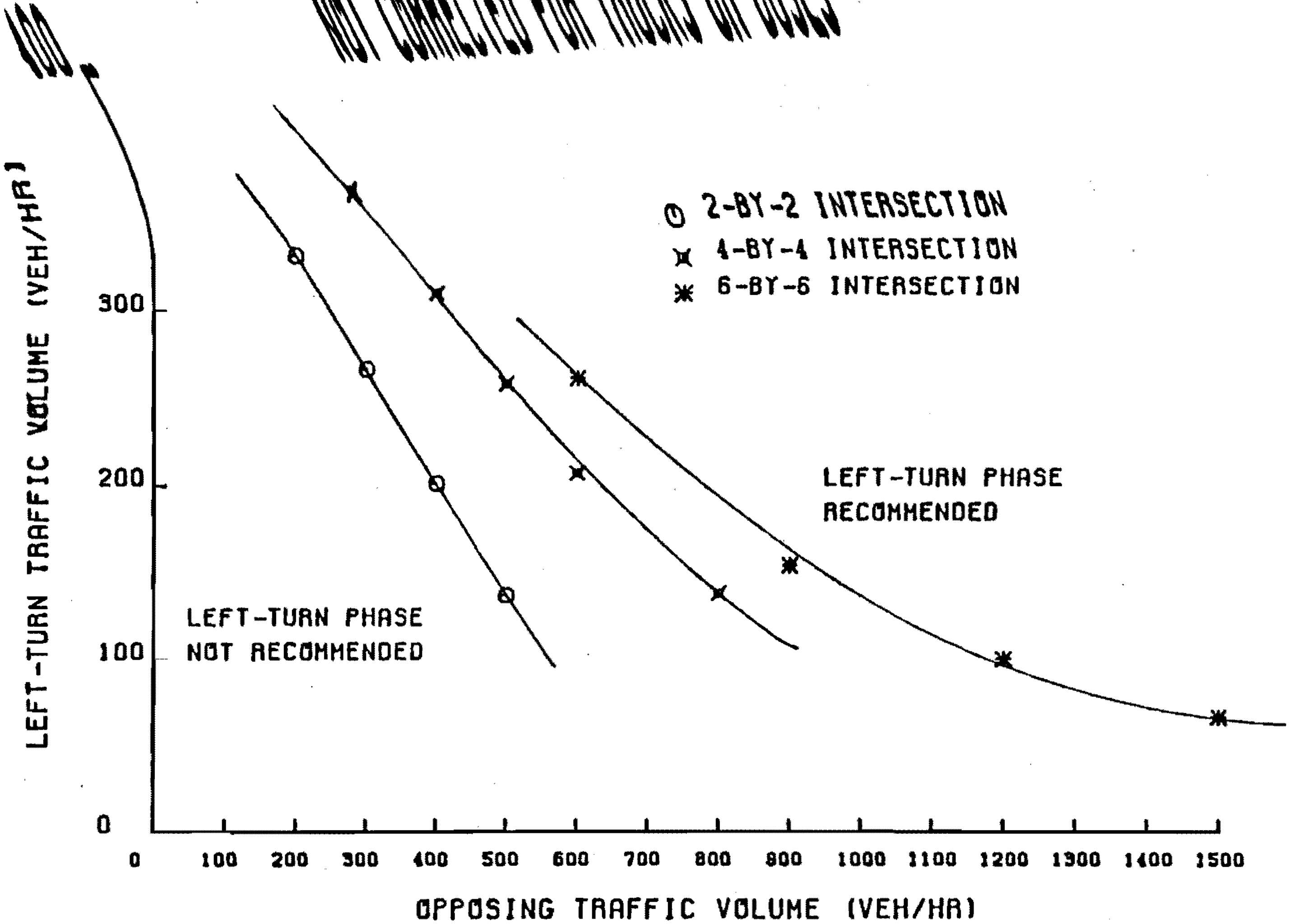


Figure 2-12. Decision chart for implementing a separate left-turn phase at signalized intersections with G/C = 0.6 and C = 60 sec.

TABLE 2-10. RECOMMENDED LEFT-TURN WARRANTS FOR A SEPARATE LEFT-TURN PHASE UNDER DIFFERENT LEVELS OF OPPOSING VOLUMES AND NUMBER OF OPPOSING LANES

Number Of Opposing Lanes	Opposing Volume Q_o, vph	Critical Left-turn Volume Q_w, vph
One	$0 < Q_o C/G < 1000$	$765 (G/C) - 0.634Q_o$
	$1000 < Q_o C/G < 1350$	$485 (G/C) - 0.348Q_o$
Two	$0 < Q_o C/G < 1000$	$855(G/C) - 0.500Q_o$
	$1000 < Q_o C/G < 1350$	$680(G/C) - 0.353Q_o$
	$1350 < Q_o C/G < 2000$	$390(G/C) - 0.167Q_o$
Three	$0 < Q_o C/G < 1000$	$895(G/C) - 0.448Q_o$
	$1000 < Q_o C/G < 1350$	$735(G/C) - 0.297Q_o$
	$1350 < Q_o C/G < 2400$	$390(G/C) - 0.112Q_o$

3. The basic left-turn demand Q_w must be corrected for the effect of trucks and buses as follows.

$$Q^*_w = f_T Q_w \qquad (2\text{-}9)$$

f_T can be determined from Fig 2-6.

Since the equations of Table 2-10 do not account for trucks and buses, this correction induces a small amount of error, so METHOD III may be a better solution when the decision is by a very narrow margin.

4. If the actual left-turn volume, V_L, is greater than Q^*_w, a separate left-turn phase is needed.

METHOD III - by equation

1. The maximum left-turn flow rate (capacity) is computed as described in Case I or II depending upon whether a left-turn bay is present. If a bay is present this quantity is termed Q^*_L, and if not it is termed Q_L.

2. The product Q_o (C/G) as described in METHOD II is computed as in item one METHOD II of this case.

3. Using Table 2-11 the effective capacity of the conflict area, Q_c, and the allowable utilization factor of the conflict area, f_c are determined. The number of opposing lanes, N, does not include the opposing bay.

4. The left-turn demand which will justify a separate signal phase is computed using Q^*_w, Eq 2-10.

$$Q^*_w = Q^*_L - M \qquad (2\text{-}10)$$

TABLE 2-11. VALUES OF e_L, e_o, AND Q_c FOR DIFFERENT OPPOSING VOLUMES AND NUMBER OF OPPOSING LANES

with bay

Number of Opposing Lanes	Opposing Volume Q_o, vph	Equivalence Factor		Effective Capacity of the Conflict Area Q_c, vpgh	Allowable Utilization Factor f_c
		e_L	e_o		
One	$0 < Q_oC/G < 1000$	1.6	0.634	879	0.84 - 0.87
	$1000 < Q_oC/G < 1350$	2.9	0.348	590	0.79 - 0.82
Two	$0 < Q_oC/G < 1000$	2.0	0.500	930	0.86 - 0.92
	$1000 < Q_oc/G < 1350$	2.8	0.353	780	0.82 - 0.87
	$1350 < Q_oC/G < 2000$	6.0	0.167	465	0.79 - 0.84
Three	$0 < Q_oC/G < 1000$	2.2	0.448	930	0.91 - 0.96
	$1000 < Q_oC/G < 1350$	3.4	0.297	780	0.88 - 0.94
	$1350 < Q_oC/G < 2400$	8.9	0.112	465	0.72 - 0.84

where

$$M = (1 - f_c)Q_c(G/C)$$

5. If the actual left-turn volume, $\overline{V}_L$, is greater than Q^*_w, a separate left-turn phase is needed.

CASE VI - Determination of required phase and cycle lengths under dual or split left turn sequence patterns. (Procedures can be applied with minor modification to protected only or protected/permissive sequence patterns. The procedures are developed for "single" intersections, and the requirements of an interconnected system may override those of a single location.)

Dual Left-Turn Phasing

1. Using Figure 2-13 calculate the duration of the through movement green phase using the critical lane volume for the street and a first estimate of cycle length.

2. a. Using Figure 2-14 determine the left-turn hourly volume that can be processed during the through movement green using the phase length calculated in step one plus the yellow clearance interval for the phase.

   b. Calculate the hourly left-turn capacity if one left-turn per cycle is made during the yellow phase.

   Left turns per hour = (1 vehicle/cycle length) * 3600 sec/hr

   Select the largest value of a. or b.

3. Subtract the volume of permissive turns found in step two from the demand to get the protected left-turn demand volume. Calculate the length of the protected left-turn phase using Figure 2-13.

4. Repeat steps one through three for the other street. Add clearance intervals to the green phase to determine cycle length.

5. Repeat the above steps with a new estimated cycle length until the resulting cycle length is within five seconds of the estimate.

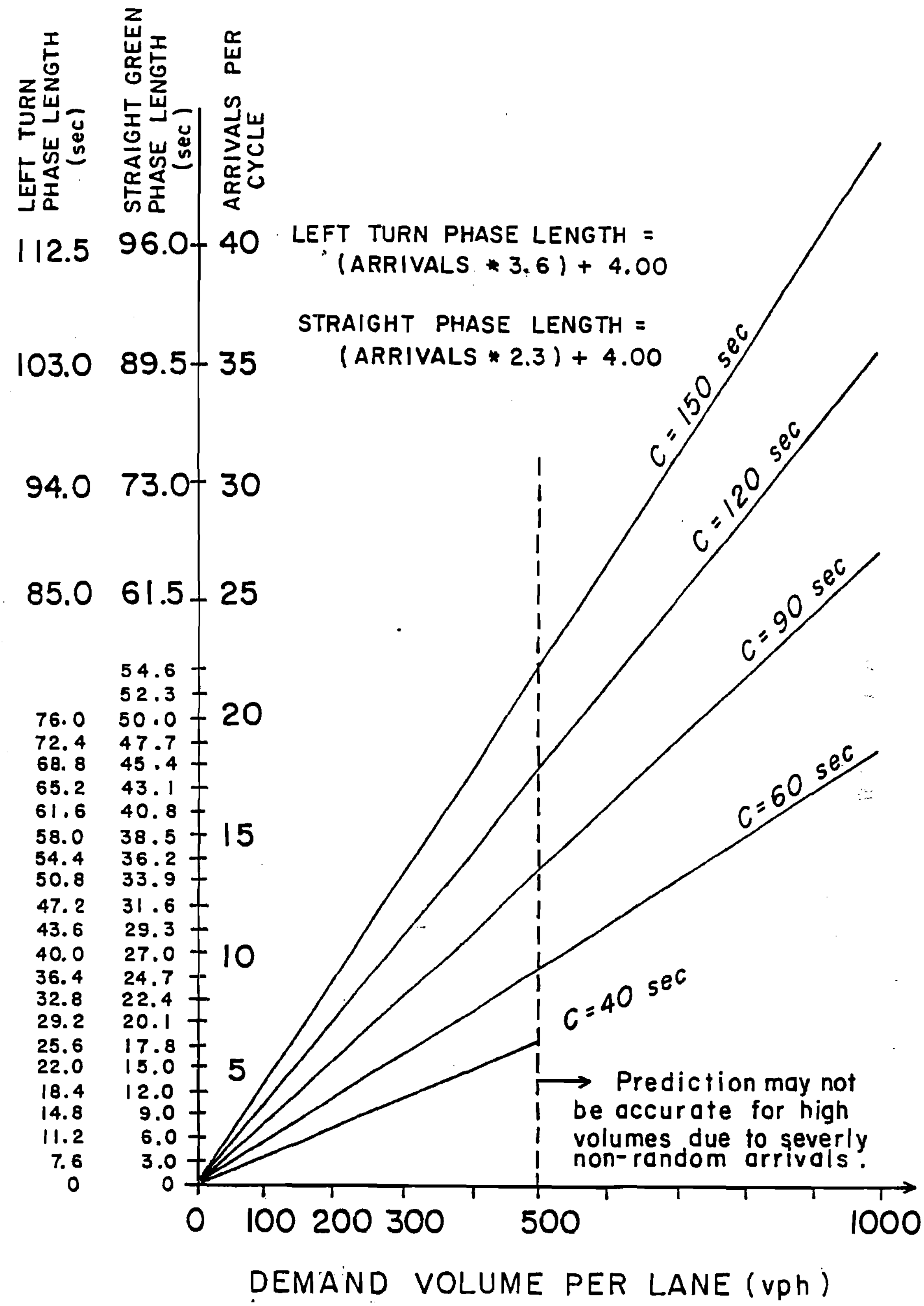


Figure 2-13. Phase lengths.

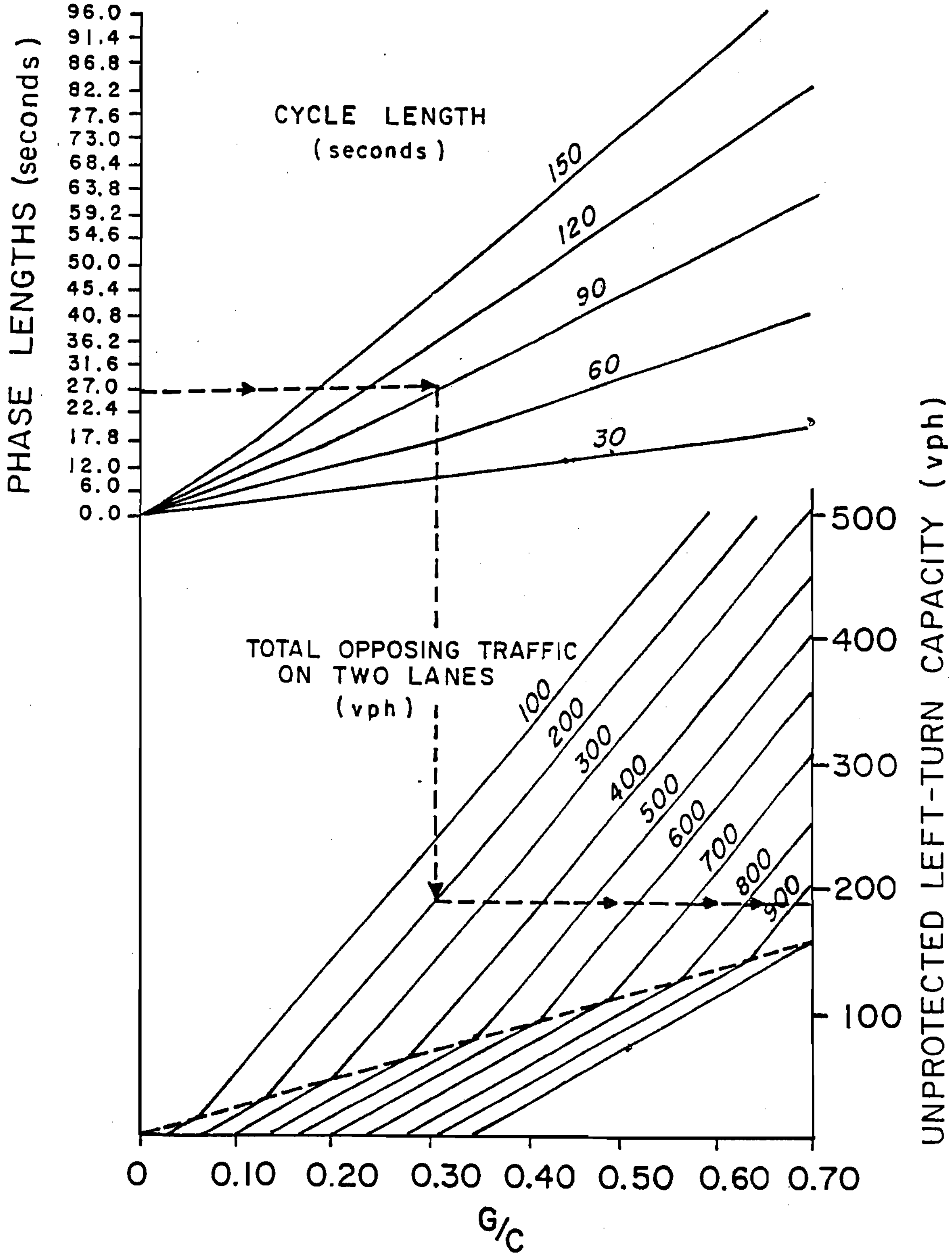
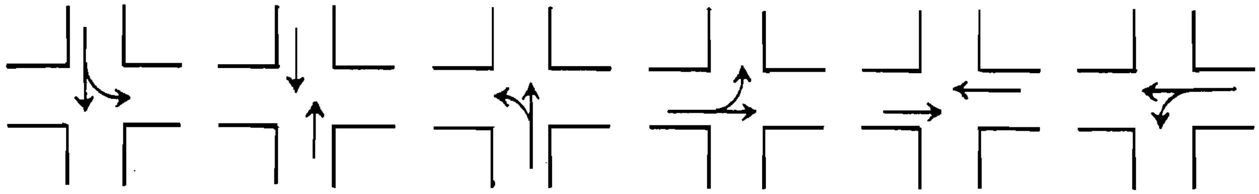


Figure 2-14. Left-turn capacity during permissive phases.

Phase Numbers:



1A 2A 3A 1B 2B 3B

Several procedures can be used to develop a single timing plan for split phasing. The basic concepts behind these procedures are the same. Graphical computational aids presented in the previous section as Figs 2-13 and 2-14 may be utilized for this case.

If protected only left-turn phasing is to be used, and left turns are the critical maneuvers on both approaches, phase two should be eliminated. Enough processing time should be provided for left-turn as well as through vehicles during the green phase for each approach.

Where permissive turns are allowed, phases one and three should be designed to process the protected left-turn demand volume. Any additional time required to process the through traffic should be provided in phase two. This allows left-turn vehicles on both approaches to utilize the intersection for permissive left-turn maneuvers, and the protected left-turn demand volumes and phase lengths can be reduced. However, use of permissive turning with split phasing may increase driver confusion and safety concerns. Phase two may also require adjustments to maintain enough processing time for through vehicles.

CASE VII - Selection of Left-Turn Phase Sequence Pattern

The decision chart (Table 2-12) is intended to provide prospective users with a convenient mechanism for choosing among possible sequence patterns. The sequence patterns are illustrated in Fig 2-15. Recommended choices are based upon an assumed desire to minimize vehicular delay. Protected only left-turn phasing is recommended where approach speeds exceed 45 mph or other traffic or geometric characteristics are indicative of safety problems which might develop from permissive left-turning.

TABLE 2-12. PHASE SEQUENCE DECISION CHART

Traffic Arrangement	With Permissive Left Turns		Protected Only
	Actuated Control	Pretimed Control	
The critical left-turn and through movement demands are on the same approach. On only one approach, the left-turn demand requires more processing time than the through movement	Split[1]	Split[1]	Split[1]
The critical left-turn and through movement demands are on the same approach of the street. On both approaches or on neither approach, the left-turn demand requires more processing time than the through movement	Dual Lag[1]	Dual Lag[1]	Split[1]
All other cases	Dual Lag[1]	Dual Lead[1]	Dual Lead[1] or Dual Lag[1]

[1] See Figure 2-15 for illustrations of phase sequences

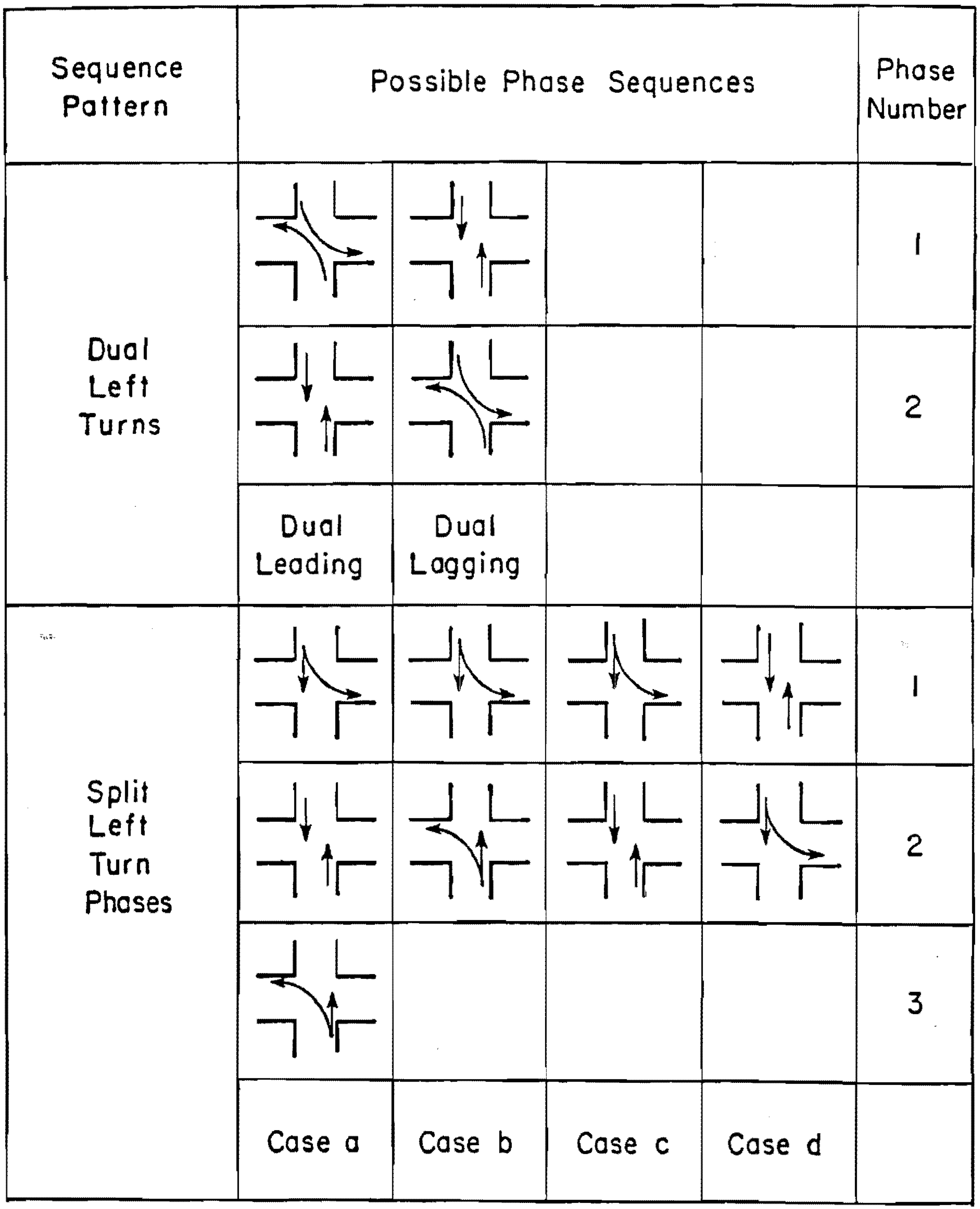


Figure 2-15. Basic left-turn phase arrangements.

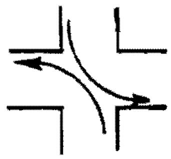
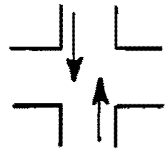
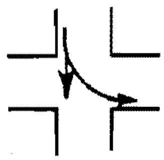
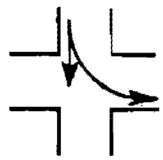
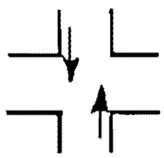
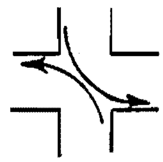
Sequence Pattern	Possible Phase Sequences		Phase Number
Composite Left Turns			1
			2
			3
	Case a Composite	Case b Composite	

Figure 2-15. (Continued).

CHAPTER 3. EXAMPLE PROBLEM SOLUTIONS

A series of example problem solutions have been prepared to illustrate applications of the procedures presented in Chapter 2. Example problems are identified by case numbers which correspond to the procedure numbers utilized in the previous chapter. Multiple examples are presented for several cases in order to illustrate the various situations which may occur.

CASE I - Determination of maximum separated left-turn flow rate (capacity) with no turn bay and no protected signal phase.

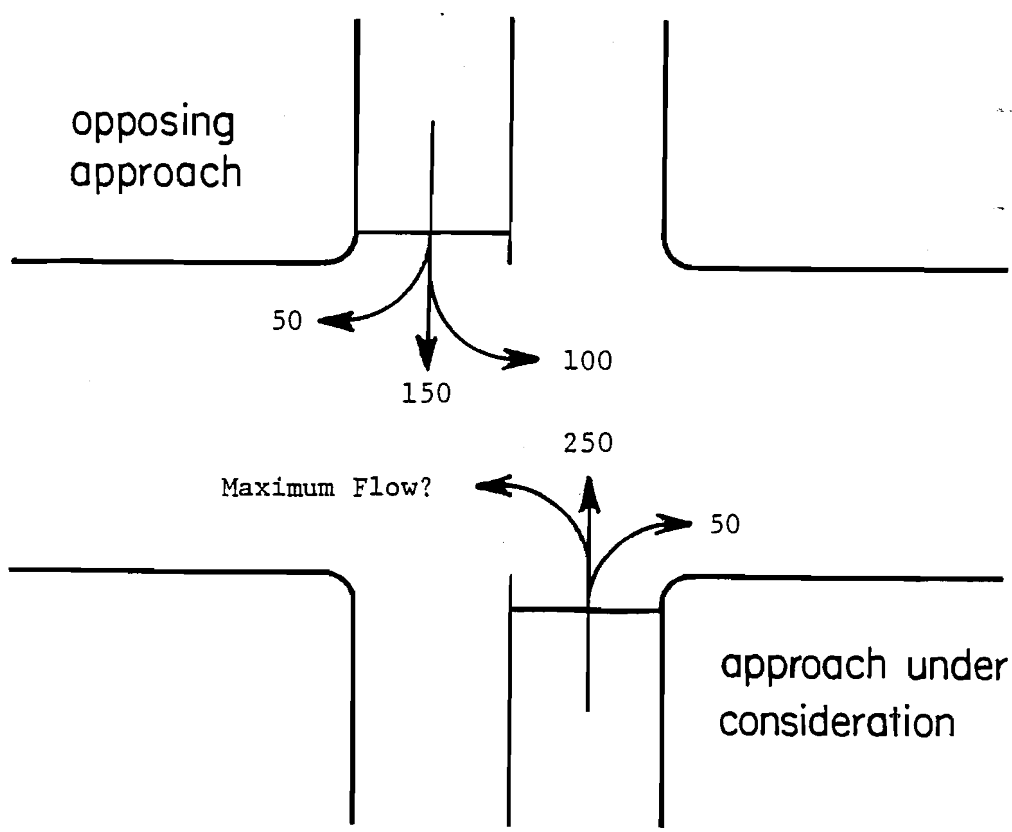


Figure 3-1. Plan view of intersection.

Problem:

GIVEN CONDITIONS:

One lane approach without left-turn bay

Two phase signal timing

$C = 60$ sec

$G/C = 0.40$

15 percent trucks in opposing traffic

20 percent trucks in approach under consideration

Volumes as shown

DETERMINE:

(a) Find the left-turn capacity with no turn bay and no protected signal phase assuming no left-turn vehicles in the opposing approach, $\tilde{Q}_L$.

Solution:

METHOD I

From Table 2-1 for

$G/C = 0.4,\ N = 1,\ Q_o = 200 \qquad Q_L = 223$ vph

or

from Fig 2-2, $Q_L = 220$ vph

$\bar{V}_T = 250 \text{ vph} + 50 \text{ vph} = 300 \text{ vph}$

$b = \bar{V}_T - Q_L = 300 - 220 \text{ vph} = 80 \text{ vph}$

$c = \bar{V}_T Q_L [(h\bar{V}_T)/(3600(G/C)) - 1]$

$= 300 \text{ vph}(220 \text{ vph})[(2.6 \text{ sec/veh}(300 \text{ vph}))/$

$(3600 \text{ sec/hr}(0.40)) - 1]$

$= -30{,}250(\text{vph})^2$

From Eq 2-2

$$\tilde{Q}_L = 0.5(-b + \sqrt{b^2 - 4c})$$

$$= 0.5(-80 \text{ vph} + \sqrt{(80 \text{ vph})^2 - 4(-30{,}250 \text{ vph}^2)})$$

$$= 138 \text{ vph}$$

METHOD II

From Table 2-3 for

$\bar{V}_T = 300$ vph, $N = 1$, $Q_o = 200 \rightarrow \tilde{Q}_L = 141$ vph

then $\tilde{Q}_L = 140$ vph

(b) Correct the left-turn capacity for the effect of left-turning vehicles in the opposing approach ($\hat{Q}_L$).

P_c = percentage of opposing traffic in the heaviest volume opposing lane, decimal

= 1.00

From equation 2-4

$$a = 0.317(P_c - 1/N) = 0.317(1.00 - 1/1) = 0$$

From equation 2-3

$$\hat{Q}_L = \tilde{Q}_L - aQ_o$$

$$= 140 \text{ vph} - 0\,(200 \text{ vph}) = 140 \text{ vph}$$

(c) Correct the left-turn capacity for the effect of trucks and buses $\hat{Q}^*_L$.

From Fig 2-6, $f_T = 0.90$

and from equation 2-5

$$\hat{Q}^*_L = f_T \hat{Q}_L = 0.90(140 \text{ vph}) = 126 \text{ vph}$$

where $\hat{Q}^*_L$ is the maximum unprotected flow rate for left turns with all appropriate corrections applied.

CASE II - Determination of maximum unprotected left turn flow rate (capacity) with no protected signal phase but adequate turn bay.

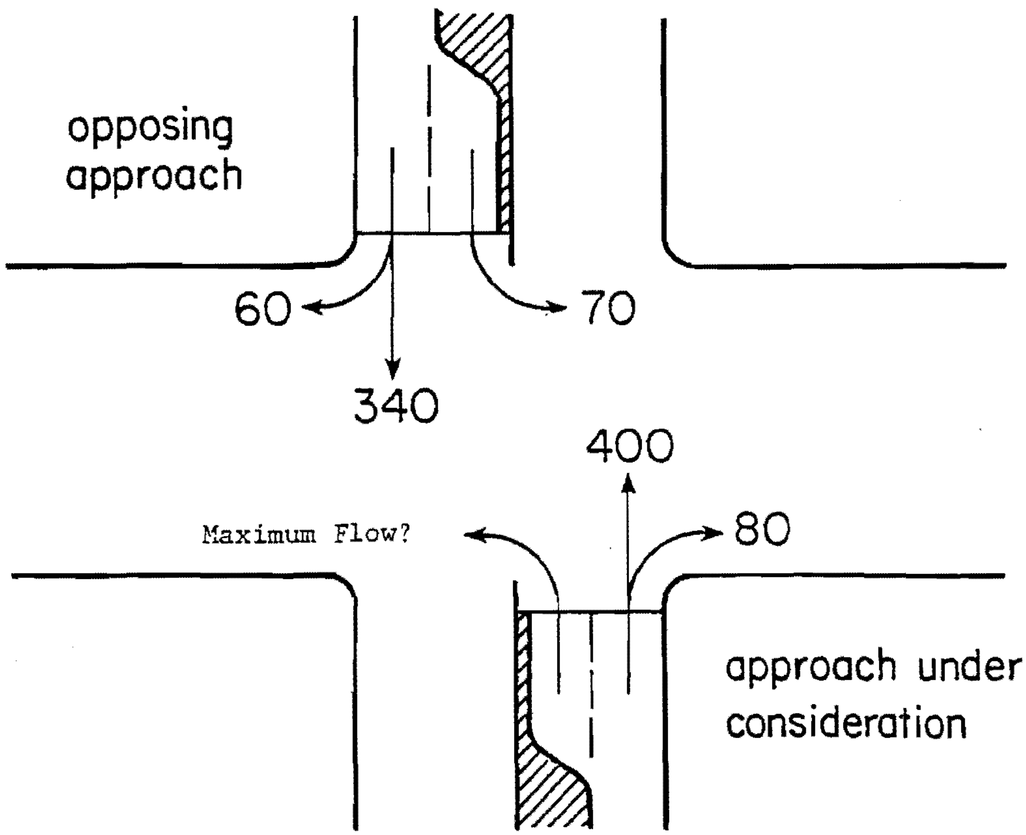


Figure 3-2. Plan view of intersection.

Problem:

GIVEN CONDITIONS:

One-lane approach with an adequate length of left-turn bay

Two-phase signal timing

C = 60 sec

G/C = 0.5

20 percent trucks in the opposing approach and the approach under consideration

Volumes as shown

DETERMINE:

What is the maximum unprotected flow rate for the left turn movement which is assumed to have an adequate turn bay?

Solution:

(a) Calculate the left-turn capacity Q_L for adequate bay, no protected signal phase uncorrected for trucks and buses.

From Table 2-1 for

Q_o = 400 vph, G/C = 0.5, N = 1 → Q_L = 183 vph

or from Fig 2-3, Q_L = 180 vph

(b) Compute Q^*_L by correcting Q_L for the effects of trucks and buses.

From Fig 2-6, f_T = 0.89

(20 percent trucks and buses in opposing approach and approach under consideration)

From Eq 2-1

$$Q^*_L = f_T Q_L = 0.89 \text{ (183 vph)} = 163 \text{ vph}$$

CASE III AND IV - Example 1, Determination of the need for a separate left-turn bay and required bay length.

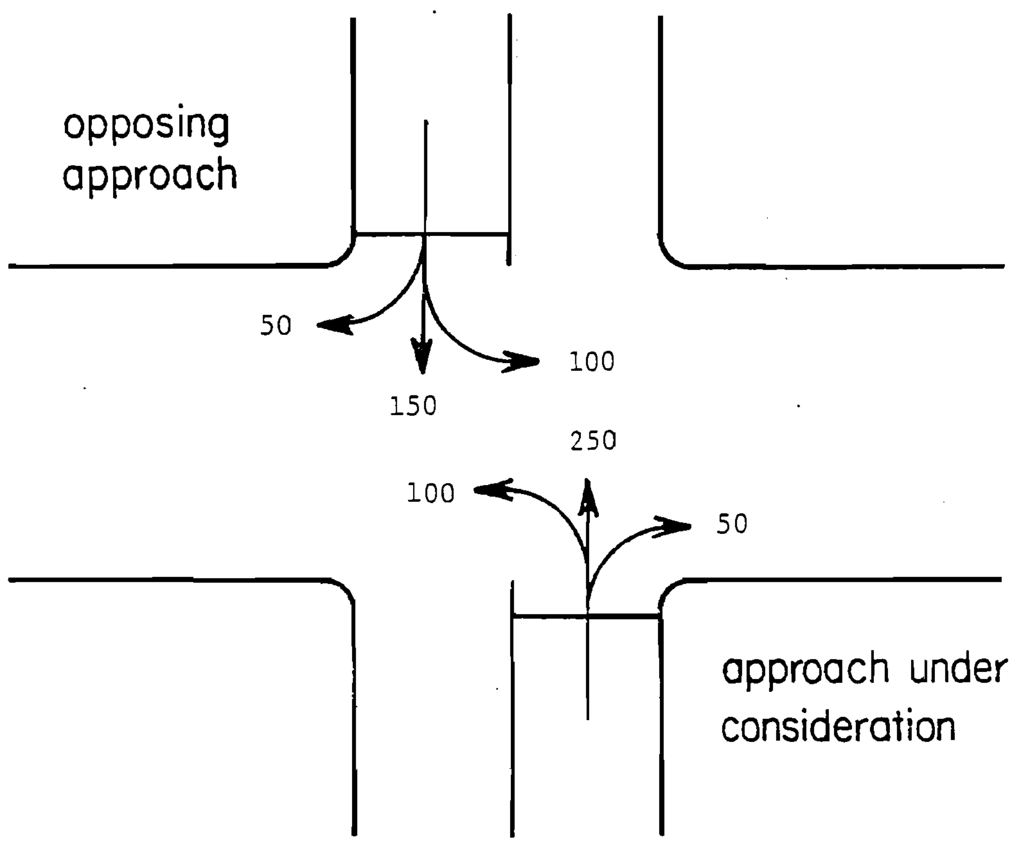


Figure 3-3. Plan view of intersection.

Problem:

GIVEN CONDITIONS;

One lane approach without a left-turn bay

Two phase signal timing

C = 60 sec

G/C = 0.40

15 percent trucks in the opposing traffic

20 percent trucks in the approach under consideration

Volumes as shown

DETERMINE:

(a) Is a left-turn bay needed for the approach under consideration?

(b) How long should the bay be if it is needed?

Solution

(a) Calculate $\hat{Q}^*_L$, the left-turn capacity with no bay, no phase conditions.

1. Find the left-turn capacity assuming no left-turn vehicles in the opposing approach, $\tilde{Q}_L$.

METHOD I

From Table 2-1 for

$G/C = 0.4,\ N = 1,\ Q_o = 200, \rightarrow Q_L = 223 \text{ vph}$

or from Fig 2-2, $Q_L = 220$ vph

$$\bar{V}_T = 250 \text{ vph} + 50 \text{ vph} = 300 \text{ vph}$$

$$b = \bar{V}_T - Q_L = 300 \text{ vph} - 220 \text{ vph} = 80 \text{ vph}$$

$$c = \bar{V}_T Q_L [(h\bar{V}_T)/(3600(G/C)) - 1]$$

$$= 300 \text{ vph}(220 \text{ vph}) [(2.6 \text{ sec/veh}(300 \text{ vph}))/(3600 \text{ sec/hr}(0.40)) - 1]$$

$$= -30{,}250 \text{ (vph)}^2$$

From Eq 2-2

$$Q_L = 0.5(-b + \sqrt{b^2 - 4c})$$

$$= 0.5(-80 \text{ vph} + \sqrt{(80 \text{ vph})^2 - 4(-30{,}250 \text{ vph}^2)})$$

$$= 138 \text{ vph}$$

METHOD II

From Table 2-3, for

$\bar{V}_T = 300$ vph, $N = 1$, $Q_o = 200$ vph, $\rightarrow$ $\tilde{Q}_L = 141$ vph

Use $\tilde{Q}_L = 140$ vph

2. Correct the left-turn capacity for the effect of left-turning vehicles in the opposing approach. Calculate $\hat{Q}_L$.

P_c = percentage of opposing traffic in the heaviest volume opposing lane, decimal

= 1.00

From Eq 2-4

$$a = 0.317(P_c - 1/N) = 0.317(1.00 - 1/1) = 0$$

From Eq 2-3

$$\hat{Q}_L = \tilde{Q}_L - aQ_o$$

$$= 140 \text{ vph} - 0(200 \text{ vph}) = 140 \text{ vph}$$

3. Correct the left-turn capacity for the effect of trucks and buses. Calculate $\hat{Q}^*_L$.

From Fig 2-6, $f_T = 0.90$

From Eq 2-5

$$\hat{Q}^*_L = f_T \hat{Q}_L = 0.90(140 \text{ vph}) = 126 \text{ vph}$$

(c) Find $\tilde{f}_c$, $\tilde{Q}_c$.

From Table 2-7

$N = 1$, Q_o C/G = 500, $\bar{V}_T = 300$, $\rightarrow$ $\tilde{f}_c = 0.87$ and $\tilde{Q}_c = 680$ vph

(d) Calculate the warrant volume, $\hat{Q}^*_w$.

From Eq 2-6

$$\hat{Q}^*_w = \hat{Q}^*_L - (1 - \tilde{f}_c)\tilde{Q}_c\,(G/C)$$

$$= 126 \text{ vph} - (1 - 0.87)(680 \text{ vph})(0.40)$$

$$= 91 \text{ vph}$$

(e) $\overline{V}_L = 100 \text{ vph} > \hat{Q}^*_w = 91 \text{ vph}$

a left-turn bay is needed

(f) Determine the required bay length, L_B.

1. Determine the maximum queue length, L_m.

From Eq 2-7

$$Q_o = Q'_o/(2(G/C)) = 200 \text{ vph}/(2(0.40)) = 250 \text{ vph}$$

From Fig 2-7 for

$$Q_o = 250 \text{ vph},\ V_L = 100 \text{ vph},\ \rightarrow\ L_m = 5 \text{ veh}$$

2. Calculate L_B

From Eq 2-8

$$L_B = w_T\,p_T\,L_m + w_c\,(1 - p_T)L_m$$

Assuming $w_T = 45$ ft, $w_c = 25$ ft, and $p_T = 0.20$

$$L_B = (45)(0.20)(5) + (25)(1 - 0.20)(5)$$

$$= 145 \text{ ft}$$

Use 150 ft length of bay.

CASES III AND IV - Example 2, Determination of the need for separate left-turn bay and required bay length.

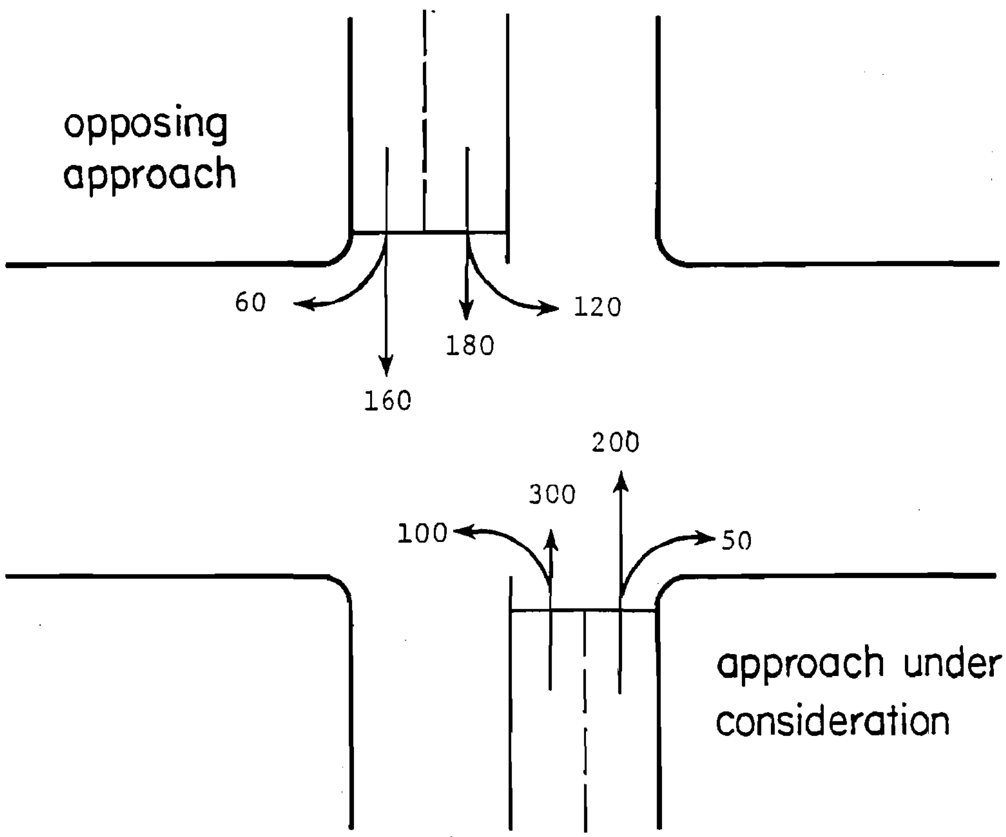


Figure 3-4. Plan view of intersection.

Problem A:

GIVEN CONDITIONS:

Two lane approach without a left-turn bay

Two phase signal timing

C = 60 sec

G/C = 0.5

20 percent trucks in the opposing approach

20 percent trucks in the approach under consideration

Volumes as shown

DETERMINE:

(a) Is a left-turn bay needed for the approach under consideration?

(b) How long should the bay be if it is needed?

<u>Solution</u>:

(a) Calculate the left-turn capacity with no bay, no phase conditions, $\hat{Q}^*_L$.

1. Find the left-turn capacity assuming no left-turning vehicles in the opposing approach, $\tilde{Q}_L$.

METHOD I

From Table 2-1 for

$G/C = 0.4$, $N = 2$, $Q_o = 60 + 160 + 180 = 400$ vph, $\rightarrow$ $Q_L = 256$ vph

or from Fig 2-3, $Q_L = 260$ vph

$\overline{V}_T = 300$ vph

$b = \overline{V}_T - Q_L = 300 \text{ vph} - 256 \text{ vph} = 44 \text{ vph}$

$c = \overline{V}_T Q_L \left[(h\overline{V}_T)/(3600(G/C)) - 1\right]$

$= 300 \text{ vph}(256 \text{ vph})\left[(2.6 \text{ sec/veh}(300 \text{ vph}))/(3600 \text{ sec/hr}(0.5)) - 1\right] = -43{,}520(\text{vph})^2$

From Eq 2-2

$$\tilde{Q}_L = 0.5(-b + \sqrt{b^2 - 4c})$$

$$= 0.5(-44 \text{ vph} + \sqrt{(44 \text{ vph})^2 - 4(-43{,}520 \text{ vph}^2)})$$

$$= 188 \text{ vph}$$

METHOD II

From Table 2-4, for

$\overline{V}_T$ = 300 vph, N = 2, Q_o = 400 vph, → $\tilde{Q}_L$ = 192 vph

Use $\tilde{Q}_L$ = 190 vph

2. Correct the left-turn capacity for the effect of left-turning vehicles in the opposing approach. Find, $\hat{Q}_L$.

P_c = percentage of opposing traffic in the heaviest volume opposing lane, decimal

= (60 + 160)/400 = 0.55

From Eq 2-4

$a = 0.317(P_c - 1/N) = 0.317(0.55 - 1/2) = 0.0159$

From Eq 2-3

$\hat{Q}_L = \tilde{Q}_L - aQ_o$

= 190 vph - 0.0159(400 vph) = 184 vph

3. Correct the left-turn capacity for the effect of trucks and buses. Find $\hat{Q}^*_L$.

From Fig 2-6, f_T = 0.89

From Eq 2-5

$\hat{Q}^*_L = f_T \hat{Q}_L$ = 0.89(184 vph) = 163 vph

(b) Calculate Q_o C/G.

Q_o C/G = 400 vph(1/0.5) = 800 vph

(c) Find $\tilde{f}_c$, $\tilde{Q}_c$

From Table 2-8, for

$N = 2$, $Q_o C/G = 800$, $V_T = 300$, $\rightarrow$ $\tilde{f}_c = 0.92$ and $\tilde{Q}_c = 740$ vph

(d) Calculate the warrant volume, $\hat{Q}^*_w$.

From Eq 2-6

$$\hat{Q}^*_w = \hat{Q}^*_L - (1 - \tilde{f}_c)\tilde{Q}_c (G/C)$$
$$= 163 \text{ vph} - (1 - 0.92)(740 \text{ vph})(0.5) = 133 \text{ vph}$$

(e) $\overline{V}_L = 100 \text{ vph} < \hat{Q}^*_w = 133 \text{ vph}$

No left-turn bay is needed.

CASES III AND IV - Example 2, Determination of the need for separate left-turn bay and required bay length.

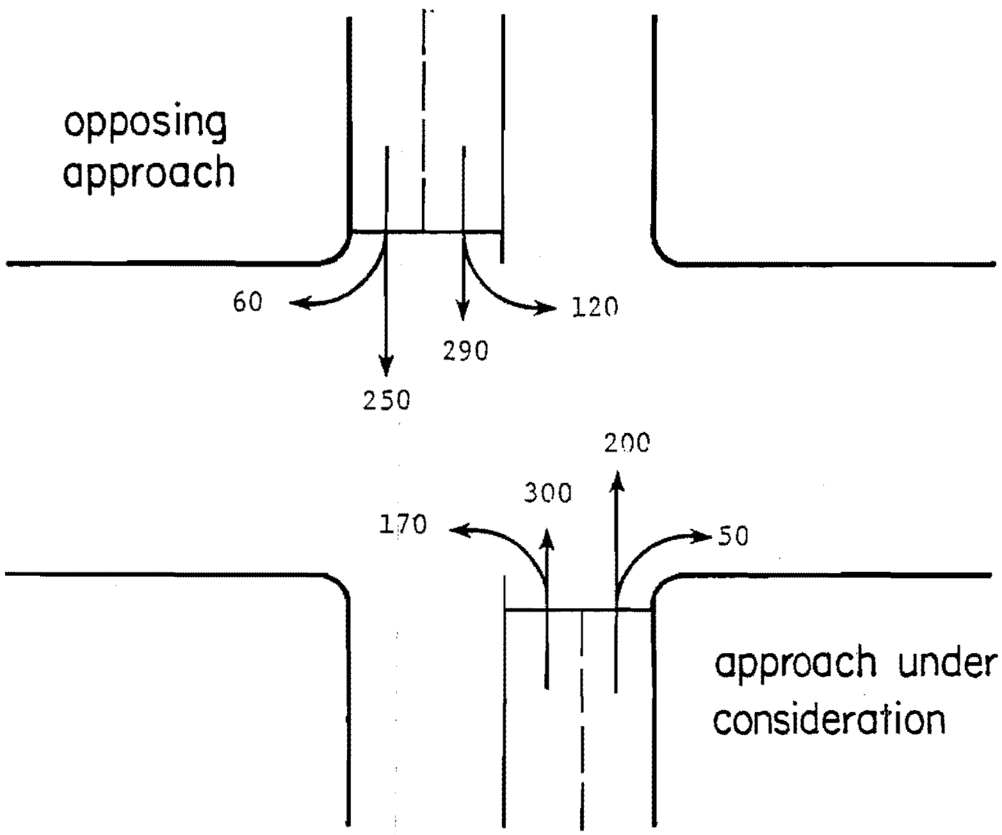


Figure 3-5. Plan view of intersection.

Problem B:

GIVEN CONDITIONS:

Two lane approach without a left-turn bay

Two phase signal timing

C = 80

G/C = 0.6

20 percent trucks in the opposing approach

20 percent trucks in the approach under consideration

Volumes as shown

DETERMINE:

(a) Is a left-turn bay needed for the approach under consideration?

(b) How long should the bay be if it is needed?

Solution:

(a) Solve for $\hat{Q}^*_L$.

1. Find $\tilde{Q}_L$.

METHOD I

From Table 2-1, for

$G/C = 0.6$, $N = 2$, $Q_o = 60 + 290 + 250 = 600$ vph $\rightarrow$ $Q_L = 252$ vph

or from Fig 2-4, $Q_L = 250$ vph

$\bar{V}_T = 300$ vph

$$b = \bar{V}_T - Q_L = 300 \text{ vph} - 252 \text{ vph} = 48 \text{ vph}$$

$$c = \bar{V}_T Q_L [(h\bar{V}_T)/(3600(G/C)) - 1]$$

$$= 300 \text{ vph}(252 \text{ vph})[(2.6 \text{ sec/veh}(300 \text{ vph}))/(3600 \text{ sec/hr}(0.60)) - 1] = -48{,}300 \text{ (vph)}^2$$

From Eq 2-2

$$\tilde{Q}_L = 0.5(-b + \sqrt{b^2 - 4c})$$

$$= 0.5(-48 \text{ vph} + \sqrt{(48 \text{ vph})^2 - 4(-48{,}300 \text{ vph}^2)}) = 197 \text{ vph}$$

METHOD II

From Table 2-5, for

$\bar{V}_T = 300$ vph, $N = 2$, $Q_o = 600$ vph, $\rightarrow$ $\tilde{Q}_L = 197$ vph

2. Find $\hat{Q}_L$.

$P_c = (60 + 290)/600 = 0.58$

From Eq 2-4

$a = 0.317(P_c - 1/N) = 0.317(0.58 - 1/2) = 0.0254$

From Eq 2-3

$\hat{Q}_L = \tilde{Q}_L - aQ_o$

$= 197 \text{ vph} - 0.254(600 \text{ vph}) = 182 \text{ vph}$

3. Find $\hat{Q}^*_L$.

From Fig 2-6, $f_T = 0.89$

From Eq 2-5

$\hat{Q}^*_L = f_T \hat{Q}_L = 0.89(18 \text{ vph}) = 162 \text{ vph}$

Note: $\hat{Q}^*_L$ is almost the same in Problem A as in Problem B because the increase in cycle split compensated for the increase in opposing traffic.

(b) Calculate $Q_o C/G$

$Q_o C/G = 600 \text{ vph}(1/0.60) = 1000 \text{ vph}$

(c) Find $\tilde{f}_c$, $\tilde{Q}_c$

From Table 2-8

$N = 2$, $Q_o C/G = 1000$ vph, $\overline{V}_T = 300$ vph, $\rightarrow$ $\tilde{f}_c = 0.87$ and $\tilde{Q}_c = 590$ vph

(d) Calculate $\hat{Q}^*_w$.

From Eq 2-6

$$\hat{Q}^*_w = \hat{Q}^*_L - (1 - \tilde{f}_c)\tilde{Q}_c (G/C)$$

$$= 162 \text{ vph} - (1 - .87)(590 \text{ vph})(0.60) = 116 \text{ vph}$$

(e) $V_L = 170 > \hat{Q}^*_w = 116$ vph

A left-turn bay is needed.

(f) Determine the required bay length, L_B.

1. Determine the maximum queue length, L_m.

   From Eq 2-7

   $$Q_o = Q'_o/(2(G/C)) = 600 \text{ vph}/(2(0.6)) = 500 \text{ vph}$$

   From Fig 2-8, for

   $Q_o = 500$ vph, $\overline{V}_L = 170$ vph, $\rightarrow$ $L_m = 10$ veh

2. Calculate L_B.

   From Eq 2-8

   $$L_B = w_T p_T L_m + w_c (1 - p_T)L_m$$

   Assuming $w_T = 45$ ft, $w_c = 25$ ft, and $p_T = 0.20$

   $$L_B = 45(0.2)(10) + 25(1 - 0.2)10$$

   $$= 290 \text{ ft}$$

   Use 290 ft or 300 ft length of bay.

CASES III AND IV - Example 3, Determination of the need for separate left-turn bay and required bay length.

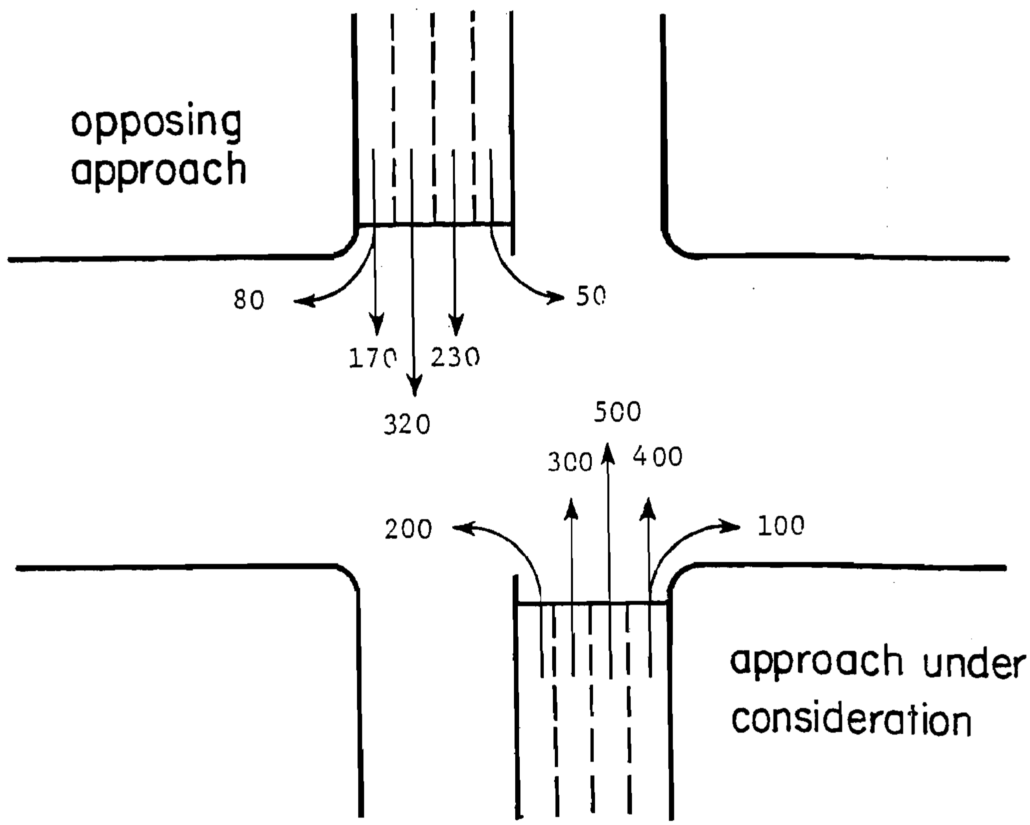


Figure 3-6. Plan view of intersection.

Problem:

GIVEN CONDITIONS:

Three lane approach without a left-turn bay

Two phase signal timing

C = 80 sec

G/C = 0.70

10 percent trucks in the opposing approach

0 percent trucks in the approach under consideration

Volumes as shown

DETERMINE:

(a) Is a left-turn bay needed for the approach under consideration?

(b) How long should the bay be if it is needed?

Solution:

(a) Calculate the left-turn capacity with no bay, no phase conditions, $\hat{Q}^*_L$.

1. Find the left-turn capacity assuming no left-turning vehicles in the opposing approach, $\tilde{Q}_L$.

METHOD I

From Table 2-1, for

$G/C = 0.7,\ N = 3,\ Q_o = 80 + 170 + 320 + 230 = 800$ vph

$\rightarrow Q_L = 307$ vph

$\bar{V}_T = 300$ vph

$b = V_T - Q_L = 300 \text{ vph} - 307 \text{ vph} = -7 \text{ vph}$

$c = \bar{V}_T Q_L [(h\bar{V}_T)/(3600(G/C)) - 1]$

$= 300 \text{ vph}(307 \text{ vph}) [(2.6 \text{ sec/veh}(300 \text{ vph}))/(3600 \text{ sec/hr}(0.7)) - 1] = -63{,}590 \text{ (vph)}^2$

From Eq 2-2

$\tilde{Q}_L = 0.5(-b + \sqrt{b^2 - 4c})$

$= 0.5(-(-7) + \sqrt{7^2 - 4(-63{,}590)}) = 256$ vph

METHOD II

From Table 2-6, for

$\bar{V}_T = 300$ vph, $N = 3$, $Q_o = 800$ vph $\rightarrow \tilde{Q}_L = 255$ vph

2. Correct the left-turn capacity for the effect of left-turning vehicles in the opposing approach. Find $\hat{Q}$.

   P_c = percentage of opposing traffic in the heaviest volume opposing lane, decimal.

   = 320 vph/800 vph = 0.40

   From Eq 2-4

   $a = 0.317(P_c - 1/N) = 0.317(0.40 - 1/3) = 0.0211$

   From Eq 2-3

   $\hat{Q}_L = \tilde{Q}_L - aQ_o$

   $= 255 \text{ vph} - 0.0211(800 \text{ vph}) = 238 \text{ vph}$

3. Correct the left-turn capacity for the effect of trucks and buses. Find $\hat{Q}^*_L$.

   From Fig 2-6, $f_T = 0.97$

   From Eq 2-5

   $\hat{Q}^*_L = f_T \hat{Q}_L = 0.97(238 \text{ vph}) = 231 \text{ vph}$

(b) Calculate $Q_o C/G$.

   $Q_o C/G = 800 \text{ vph}(1/0.70) = 1140 \text{ vph}$

(c) Find $\tilde{f}_c$, $\tilde{Q}_c$

   From Table 2-9

   $N = 3$, $Q_o C/G = 1000$ vph, $\overline{V}_T = 300$ vph → $\tilde{f}_c = 0.94$ and $\tilde{Q}_c = 605$ vph

(d) Calculate the warrant volume, $\hat{Q}^*_w$.

   From Eq 2-6

$$\hat{Q}^*_w = \hat{Q}^*_L - (1 - \tilde{f}_c)(\tilde{Q}_c)(G/C)$$

$$= 231 \text{ vph} - (1 - 0.94)(605 \text{ vph})(0.7) = 206 \text{ vph}$$

(e) $\overline{V}_L = 200 \text{ vph} \approx \hat{Q}^*_w = 206 \text{ vph}$

Although a left-turn bay is not actually warranted, the engineer may choose to use a bay since this procedure only approximates the left-turn capacity.

(f) Determine the required bay length, L_B.

1. Determine the maximum queue length, L_m.

From Eq 2-7

$$Q_o = Q'_o/(2(G/C)) = 800 \text{ vph}/(2(0.7)) = 571 \text{ vph}$$

From Fig 2-9

$$Q_o = 570 \text{ vph}, \overline{V}_L = 200 \text{ vph}, \rightarrow L_m = 9 \text{ veh}$$

2. Calculate L_B.

From Eq 2-8

$$L_B = w_T p_T L_m + w_c (1 - p_T) L_m$$

Assuming $w_T = 45$ ft, $w_c = 25$ ft, and $p_T = 0$

$$L_B = 0 + 25(1 - 0)9 = 225 \text{ ft}$$

CASE V - Example 1, Determination of Requirement for Protected Left-Turn Signal Phase.

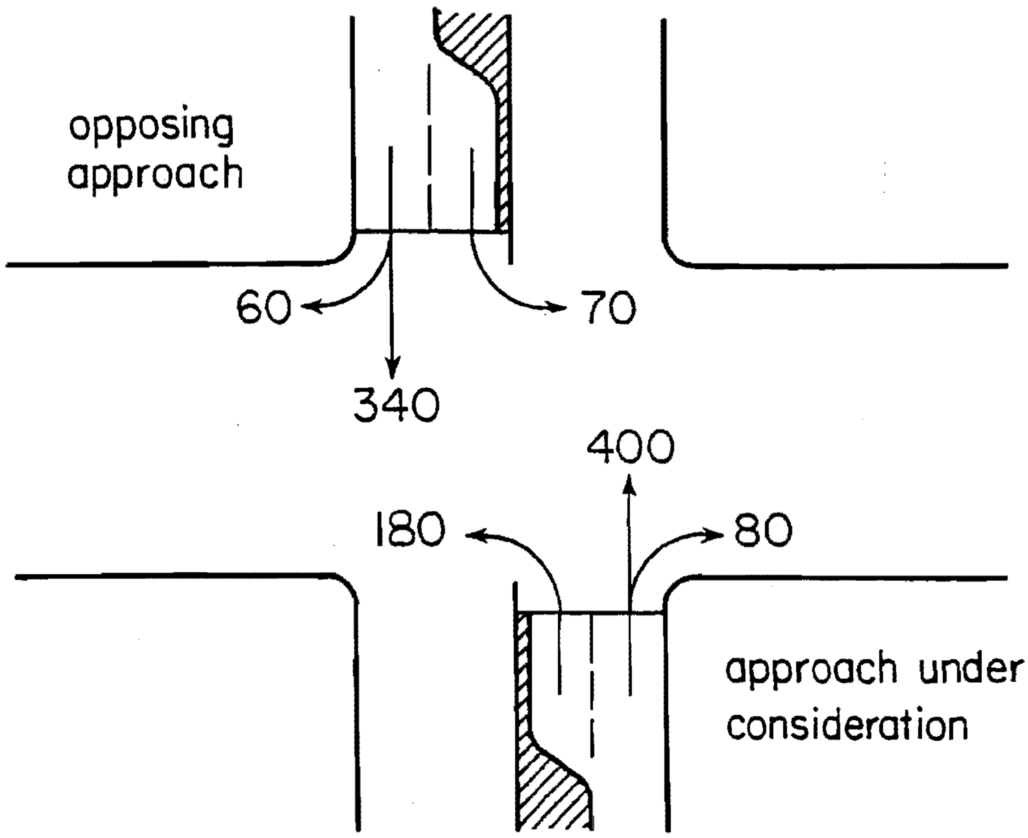


Figure 3-7. Plan view of intersection.

Problem:

GIVEN CONDITIONS:

One-lane approach with an adequate length of bay

Two-phase signal timing

C = 60 sec

G/C = 0.5

20 percent trucks in the opposing approach and the approach under consideration

Volumes as shown

DETERMINE:

(a) Is a separate left-turn phase justified for the approach under consideration?

Solution:

METHOD I

From Fig 2-11, for

$Q_o = 60 + 340 = 400$ vph, $\overline{V}_L = 180$ vph, 2-by-2 intersection,

a left-turn phase is recommended even without considering trucks and buses.

METHOD II

1. Calculate $Q_o C/G$.

$Q_o C/G = 400 \text{ vph}(1/0.50) = 800$ vph

2. From Table 2-10, for

$N = 1$, $Q_o C/G = 800$ vph, $\rightarrow$ $Q_w = 765(G/C) - 0.634Q_o$

$= 765(0.5) - 0.634(400)$

$= 129$ vph

3. Determine f_T.

From Fig 2-6, $f_T = 0.89$

4. Correct Q_w for the effects of trucks and buses, Q^*_w.

From Eq 2-9

$Q^*_w = f_T Q_w = 0.89(129 \text{ vph}) = 115$ vph

5. Since $\overline{V}_L = 180$ vph > $Q^*_w = 115$ vph, a left turn phase is recommended.

METHOD III

1. Calculate the left-turn capacity for adequate bay, no phase conditions, Q^*_L.

   From Table 2-1, for

   Q_o = 400 vph, G/C = 0.5, N = 1, → Q_L = 183 vph

   or from Fig 2-3, Q_L = 180 vph

   From Fig 2-6, f_T = 0.89

   From Eq 2-1

   $Q^*_L = f_T Q_L = 0.89(183 \text{ vph}) = 163 \text{ vph}$

2. Calculate Q_o C/G.

   Q_o C/G = 800 vph

3. Determine f_c and Q_c.

   From Table 2-11, for

   N = 1, Q_o C/G = 800 vph, → Q_c = 879 vph and f_c = 0.87

4. Calculate the warrant volume, Q^*_w.

   From Eq 2-10

   $Q^*_w = Q^*_L - (1 - f_c)Q_c\,(G/C)$

   $= 163 \text{ vph} - (1 - 0.87)(879 \text{ vph})(0.5) = 106 \text{ vph}$

5. Since $\overline{V}_L = 180 > Q^*_w = 106$ vph, a left-turn phase is recommended.

Note that METHOD III gives a lower volume for the left-turn phase warrant. METHOD III should always be used if METHOD I or II indicate a questionable decision because it adjusts for trucks and buses most accurately. In many cases, however, the easier methods (I and II) are acceptable.

CASE V - Example 2, Determination of requirements for protected left-turn signal phase.

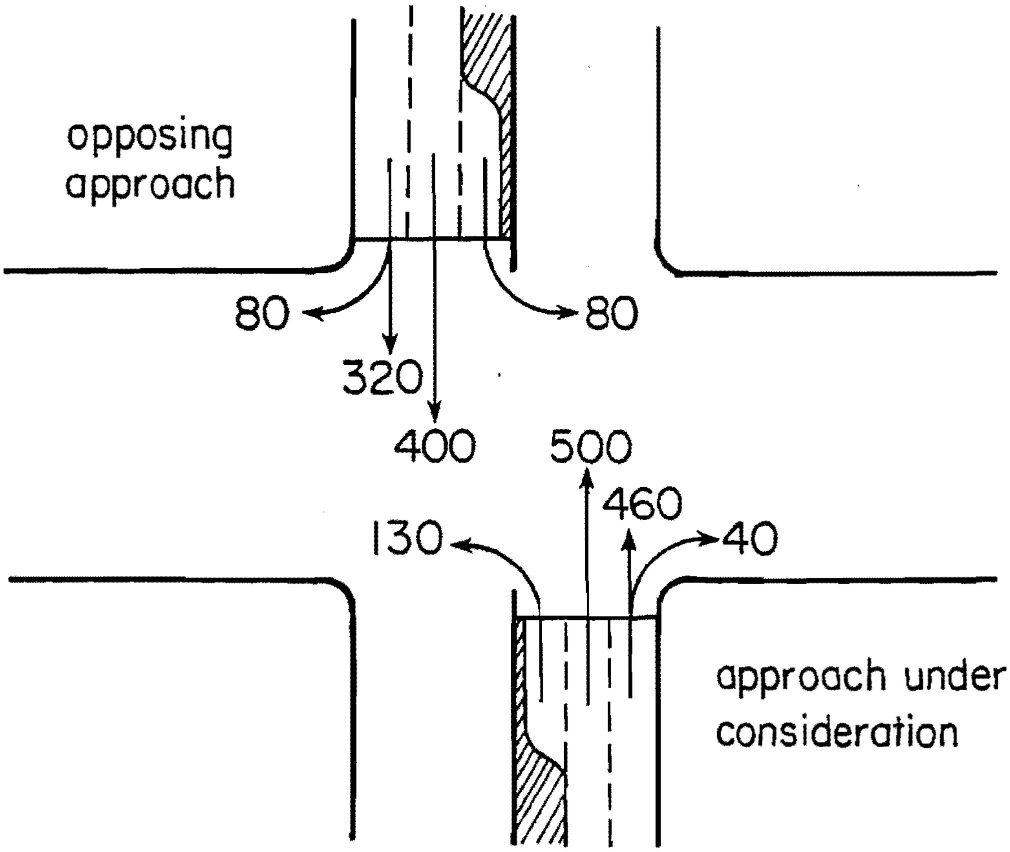


Figure 3-8. Plan view of intersection.

Problem A:

GIVEN CONDITIONS:

Two lane approach with an adequate length of bay

Two-phase signal timing

C = 60 sec

G/C = 0.6

No trucks or buses

Volumes as shown

DETERMINE:

(a) Is a separate left-turn phase justified for the approach under consideration?

Solution:

METHOD I

From Fig 2-12, for

Q_o = 80 + 320 + 400 = 800 vph, $\overline{V}_L$ = 130 vph, 4-by-4 intersection,
Left-turn phase not recommended. The point of intersection is very close to the decision line, so METHOD III should be used for a more accurate decision.

METHOD II

1. Calculate Q_o C/G

   Q_o C/G = 800 vph(1/0.60) = 1333 vph

2. From Table 2-10, for

   N = 2, Q_o C/G = 1333 vph, → Q_w = 679(G/C) - 0.353Q_o

   = 679(0.6) - 0.353(800)

   = 125 vph

3. Since $\overline{V}_L$ = 130 vph > Q_w = 125 vph, a left-turn phase is recommended. Since the margin is only 5 vph, a decision not to implement a separate phase would be acceptable.

METHOD III

1. Calculate the left-turn capacity for adequate bay, no phase conditions, Q_L.

   From Table 2-1, for

   Q_o = 800 vph, G/C = 0.6, N = 2, → Q_L = 183 vph

   or From Fig 2-4, Q_L = 190 vph

2. Calculate $Q_o C/G$.

$Q_o C/G = 1333$ vph

3. Determine f_c and Q_c.

From Table 2-11, for

$N = 2$, $Q_o C/G = 1333$ vph, $\rightarrow Q_c = 780$ vph and $f_c = 0.87$

4. Calculate the warrant volume, Q_w.

From Eq 2-10

$$Q_w = Q_L - (1 - f_c)Q_c (G/C)$$

$$= 183 \text{ vph} - (1 - 0.87)(780 \text{ vph})(0.6) = 122 \text{ vph}$$

5. Since $\overline{V}_L = 130$ vph $> Q_w = 122$ vph, a left-turn phase is recommended. As mentioned in METHOD II, the decision is up to the engineer because $\overline{V}_L$ and Q_w are almost equal. Q_w is based on an estimate of the left-turn capacity and should be treated as a guideline only.

Problem B

GIVEN CONDITIONS:

Two lane approach with an adequate length of bay

Two-phase signal timing

C = 60 sec

G/C = 0.6

20 percent trucks in the approach under consideration

10 percent trucks in the opposing approach

Volumes as shown in Fig 3-8

DETERMINE:

(a) Is a separate left-turn phase justified for the approach under consideration?

Solution:

METHOD I

From Problem A, the decision based on Figure 6-4 is questionable. With the adjustment for trucks not included in METHOD I, METHOD III should be used.

METHOD III

1. Steps 1 through 3 are the same as in Problem A - METHOD III.

2. From Fig 2-6, $f_T = 0.92$

   From Eq 2-1

   $Q^*_L = f_T Q_L = 0.92(183 \text{ vph}) = 168 \text{ vph}$

3. Calculate the warrant volume, Q^*_w.

   From Eq 2-10

   $Q^*_w = Q^*_L - (1 - f_c)Q_c (G/C)$

   $= 168 \text{ vph} - (1 - 0.87)(780 \text{ vph})(0.6) = 107 \text{ vph}$

4. Since $\overline{V}_L = 130$ vph > 107 vph, a separate left-turn phase is recommended.

CASE V - Example 3, Determination of requirements for protected left-turn signal phase.

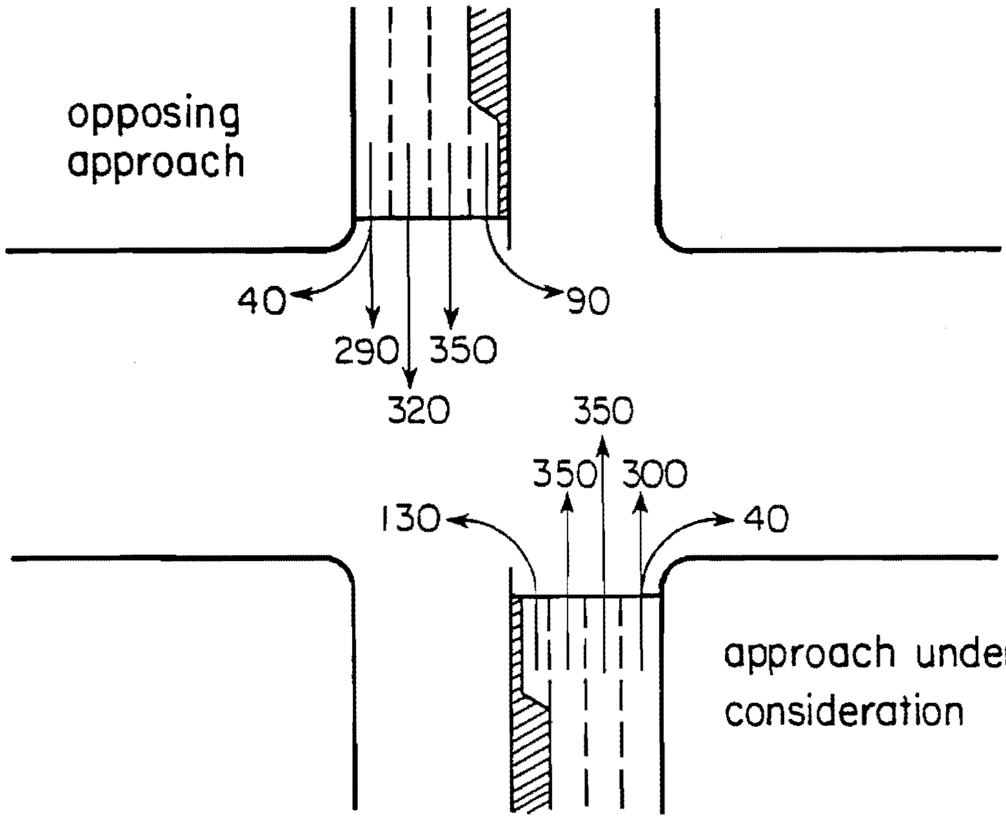


Figure 3-9. Plan view of intersection.

Problem:

GIVEN CONDITIONS:

Three lane approach with an adequate length of bay

Two-phase signal timing

C = 90 sec

G/C = 0.6

20 percent trucks and buses in the opposing approach and the approach under consideration

DETERMINE:

(a) Is a separate left-turn phase needed for the approach under consideration?

Solution:

METHOD I

From Fig 2-12, for

Q_o = 40 + 290 + 320 + 350 = 1000 vph, $\overline{V}_L$ = 130 vph,
6-by-6 intersection

A left-turn phase is recommended even without adjustments for trucks and buses.

METHOD II

1. Calculate $Q_o\,C/G$

   $Q_o\,C/G$ = 1000 vph(1/0.60) = 1667 vph

2. From Table 2-10, for

   N = 3, $Q_o\,C/G$ = 1667, $Q_w = 391(G/C) - 0.112Q_o$

   $= 391(0.60) - 0.112(1000)$

   $= 123$ vph

3. Adjust Q_w for trucks and buses.

   From Fig 2-6, f_T = 0.89

   From Eq 2-9

   $Q^*_w = f_T Q_w$ = 0.8 (123 vph) = 109 vph

4. Since $\overline{V}_L$ = 130 vph > Q^*_w = 109 vph, a left-turn phase is recommended.

METHOD III

1. Calculate the left-turn capacity for adequate bay, no phase conditions, Q^*_L.

   From Table 2-1, for

   Q_o = 1000 vph, G/C = 0.6, N = 3, → Q_L = 166 vph

   From Fig 2-6, f_T = 0.89

   From Eq 2-1

   $Q^*_L = f_T Q_L$ = 0.89(166 vph) = 148 vph

2. Calculate Q_o C/G.

   Q_o C/G = 1667 vph

3. Determine f_c and Q_c.

   From Table 2-11, for

   N = 3, Q_o C/G = 1667 vph, → Q_c = 465 vph and f_c = 0.84

4. Calculate the warrant volume, Q^*_w.

   From Eq 2-10

   $Q^*_w = Q^*_L - (1 - f_c)Q_c(G/C)$

   = 148 vph - (1 - 0.84)(465 vph)(0.60) = 103 vph

5. Since $\overline{V}_L$ = 130 vph > Q^*_w = 103 vph, a left-turn phase is recommended.

CASE VI - Example 1, Determination of phase and cycle duration.

GIVEN CONDITIONS:

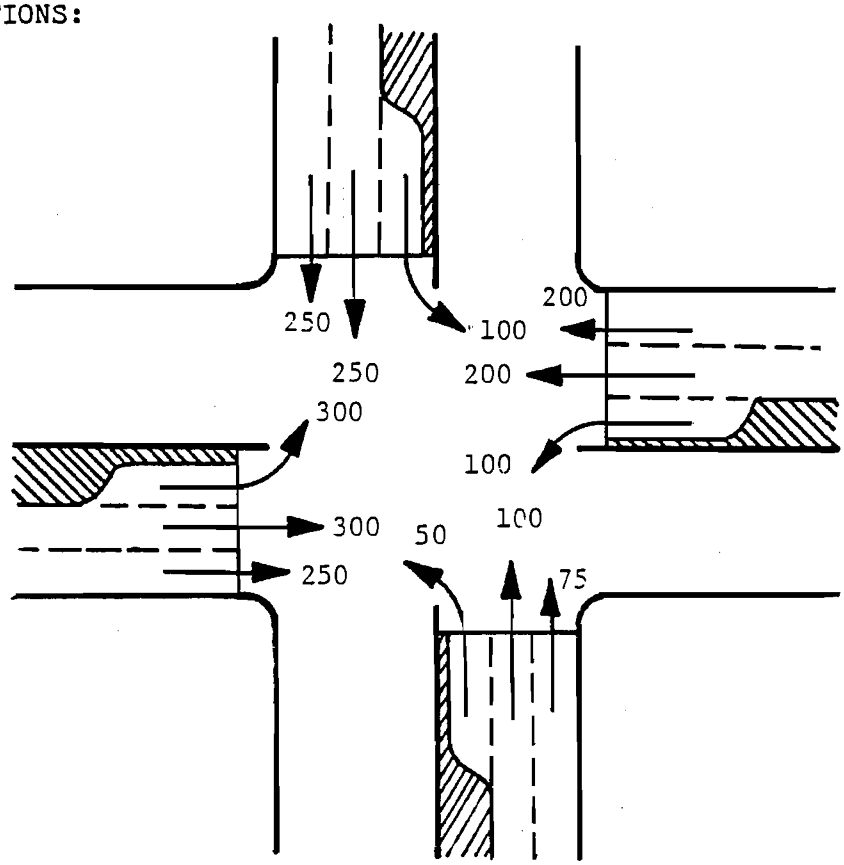


Figure 3-10. Plan view of intersection.

Problem:

Develop a signal timing plan for the intersection if dual lead phasing with permissive left turns is to be used. Use 3 sec clearance intervals.

Solution:

The solution outlined below is summarized in Tables 3-1 and 3-2.

1. Assume C = 150 sec. The critical through lane volume for the north-south street = 250 vph. Find the length of the through movement green phase.

   From Fig 2-13, for

   Vol = 250 vph, C = 150 sec, → G_{thru} = 32 sec

TABLE 3-1. EXAMPLE 1 - SIGNALIZATION (SIGNAL TIMING ESTIMATE FOR ASSUMED C = 150 SEC)

Step			Street A		Street B	
			SB	NB	EB	WB
1		Critical lane volume for street (vph)	250		300	
		Through movement green, from Fig 2-13 (sec)	32		36	
2	a	Left-turn capacity of through movement green, from Fig 2-14 (vph)	130	30	60	40
	b	Left-turn capacity in yellow - one veh/cycle (vph)	24	24	24	24
	c	Capacity for permissive left-turns, largest of 2a and 2b (vph)	130	30	60	40
3		Protected left-turn demand volume (vph)	0	20	240	60
		Critical protected left-turn	20		240	
		Protected left-turn phase length, from Fig 2-13 (sec)	8		44	
4		Clearance intervals (sec)	6		6	
		Cycle length (sec)	132			

TABLE 3-2. EXAMPLE 1 - SIGNALIZATION (SIGNAL TIMING ESTIMATE FOR ASSUMED C = 90 SEC)

Step			Street A		Street B	
			SB	NB	EB	WB
1		Critical lane volume for street (vph)	250		300	
		Through movement green, from Fig 2-13 (sec)	20		25	
2	a	Left-turn capacity of through movement green, from Fig 2-14 (vph)	150	35	90	50
	b	Left-turn capacity in yellow = one veh/cycle (vph)	40	40	40	40
	c	Capacity for permissive left-turns, largest of 2a and 2b (vph)	150	40	90	50
3		Protected left-turn demand volume (vph)	0	10	210	50
		Critical protected left-turn demand volume (vph)	10		210	
		Protected left-turn phase length, from Fig 2-13 (sec)	8		26	
4		Clearance interval (sec)	6		6	
		Cycle length (sec)	91			

2. (a) Determine the left-turn capacity of the through movement green for each approach.

   From Fig 2-14, for

   Phase = 32 + 3 = 35 sec, C = 150 sec, $Vol_{opp.}$ = 175 vph

   → Permissive Green $Capacity_{SB}$ = 130 vph

   Phase = 35 sec, C = 150 sec, $Vol_{opp.}$ = 500 vph

   Permissive Green $Capacity_{NB}$ = 30 vph

   (b) Determine the hourly left-turn capacity if one left-turn per cycle is made during the yellow.

   (1 veh/cycle) * 3600 sec/hr = 1/150(3600) = 24 vph

   (c) Since the capacities in (a) are larger than 24 vph, the values found in (a) are the permissive left-turn capacities.

3. Find the protected left turn demand volumes.

   Protected $Demand_{SB}$ = 100 - 130 < 0 vph

   Protected $Demand_{NB}$ = 50 - 30 = 20 vph

   The critical protected demand volume = 20 vph

   Determine the length of the left-turn phase.

   From Fig 2-13, for

   Vol = 20 vph, C = 150 sec, → G_{left} = 8 sec

4. Table 3-1 summarizes the steps for the east-west street.

   G_{thru} = 36 sec

   G_{left} = 44 sec

   Calculate the cycle length.

$$C = (G_{\text{thru NS}}) + (G_{\text{thru EW}}) + (G_{\text{left NS}}) + (G_{\text{left EW}}) + \Sigma\,\text{yellow}$$

$$= 32 + 36 + 8 + 44 + 12$$

$$= 132 \text{ sec}$$

5. Since C is smaller than the assumed value, the procedure must be repeated with a smaller value.

   Table 3-2 summarizes the procedure for an assumed cycle length of 90 sec.

   Figure 3-11 illustrates the resulting phasing scheme.

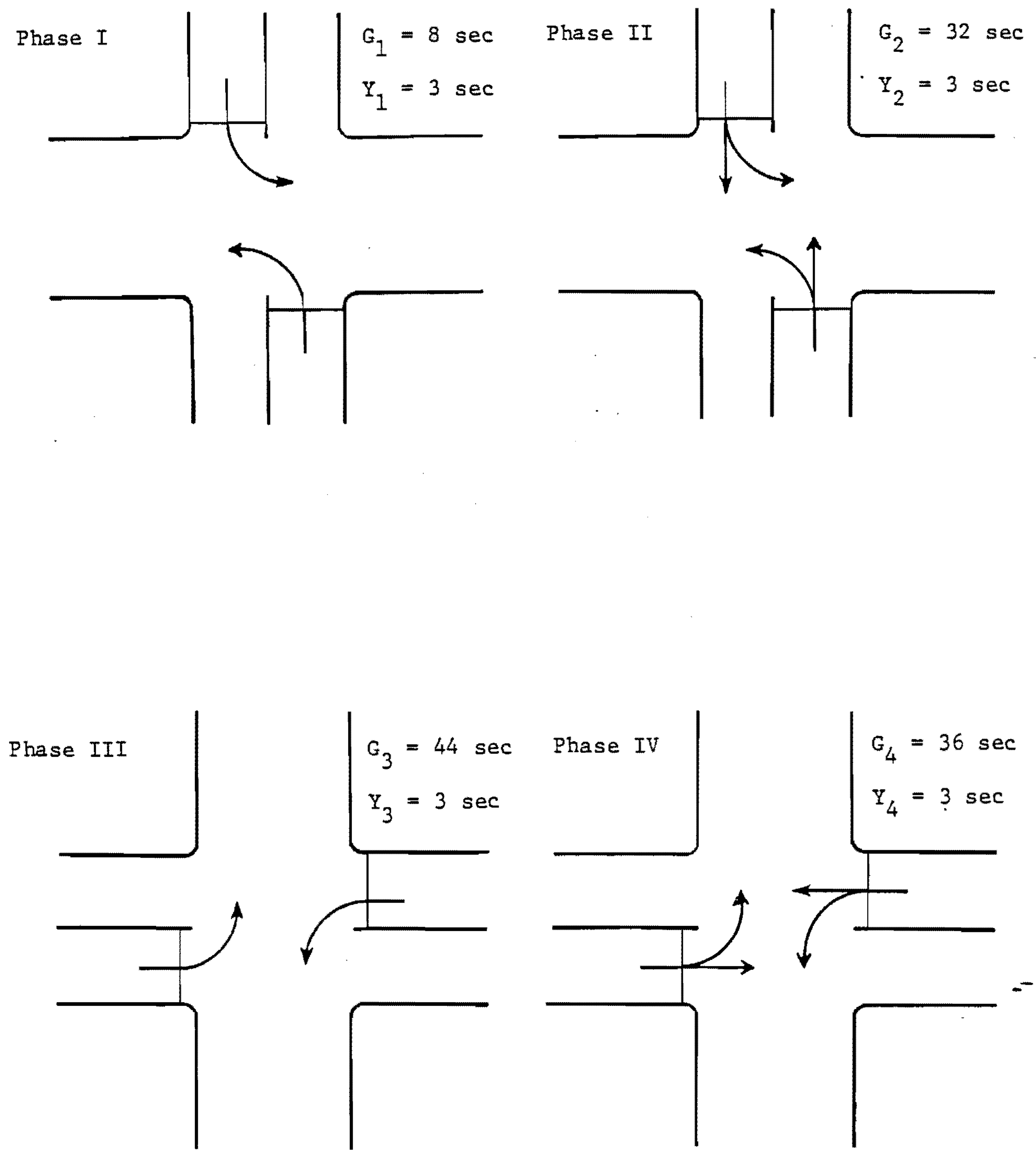


Figure 3-11. Phasing scheme for CASE VI - Example 1.

CASE VI - Example 2, Determination of phase and cycle duration.

GIVEN CONDITIONS:

Volumes as shown in Fig 3-10

Problem:

Develop a signal timing plan for the intersection if split phasing with permissive left turns is to be used. Use 3 sec clearance intervals.

Solution:

1. Assume C = 90 sec. The critical through lane volume for the north-south street = 250 vph. Develop an initial estimate of the through movement green phase (2A).

   From Fig 2-13, for

   Vol = 250 vph, C = 90 sec, → G_{2A} = 20 sec

2. Compute the permissive left-turn capacity for each approach using the initial estimate of phase 2A.

   From Fig 2-14, for

   Phase = $G_{2A} + Y_{2A}$ = 20 + 3 = 23 sec, C = 90 sec,
   $Vol_{opp.}$ = 175 vph, → Permissive Green $Capacity_{SB}$ = 145 vph

   Phase = 23 sec, C = 90 sec, $Vol_{opp.}$ = 500 vph,
   → Permissive Green $Capacity_{NB}$ = 40 vph

   Check the permissive capacity to see if it is less than one vehicle per cycle during the yellow.

   One vehicle per cycle = (1 veh/90 sec)3600 sec/hr

   = 40 vph

3. Determine the protected left-turn demand that must be serviced by phases 1A and 3A.

   Protective Demand = Demand - Permissive Capacity

   Protective $Demand_{1A}$ = 100 vph - 145 vph < 0 vph

Protective $Demand_{3A}$ = 50 vph - 40 vph = 10 vph

Determine the duration of the phases. Phase 1A is not required.

From Fig 2-13, for

Vol = 10 vph, C = 90 vph, → G_{3A} = 8 sec

4. Determine the amount of the critical lane through volume that is serviced by phase 3A.

   Since the southbound approach has the critical through traffic, and phase 3A only services the northbound vehicles, phase 2A does not need to be adjusted.

5. Repeat steps 1-5 for the east-west street.

   (a) Critical through lane volume = 300 vph

   From Fig 2-13, for

   Vol = 300 vph, C = 90 sec, → G_{2B} = 25 sec

   (b) From Fig 2-14, for

   Phase = G_{2B} + Y_{2B} = 25 + 3 = 28 sec, C = 90 sec,
   $Vol_{opp.}$ = 400 vph, → Permissive Green $Capacity_{EB}$ = 105 vph

   Phase = 28 sec, C = 90, $Vol_{opp.}$ = 550 → Permissive Green $Capacity_{WB}$ = 60 vph

   (c) Protective $Demand_{1B}$ = 300 vph - 105 vph = 195 vph

   Protective $Demand_{3B}$ = 100 vph - 60 vph = 40 vph

   From Fig 2-13, for

   Vol = 195 vph, C = 90 sec, → G_{1B} = 26 sec

   Vol = 40 vph, C = 90 sec, → G_{3B} = 11 sec

   (d) Determine the amount of critical lane through volume that is serviced by phases 1B and 3B.

From Fig 2-13, for

Phase = G_{1B} = 26 sec, C = 90 sec, → Vol_{1B} = 340 vph

Phase = 11 sec, C = 90 sec, → Vol_{3B} = 115 vph

Reduce the critical lane volume by the appropriate volume to determine the new critical through lane volume for the street.

EB, 300 vph - 340 vph < 0 vph

WB, 200 vph - 115 vph = 85 vph

(e) Determine the required duration of phase 2B, using the new critical through lane volume.

From Fig 2-13, for

Vol = 85 vph, C = 90 sec, → G_{2B} = 9 sec

(f) Repeat from step 5B.

From Fig 2-14, for

Phase = G_{2B} + Y_{2B} = 9 + 3 = 12 sec, C = 90 sec,
$Vol_{opp.}$ = 400 vph, → Permissive Green $Capacity_{EB}$ = 0 vph

Phase = 12 sec, C = 90 sec, $Vol_{opp.}$ = 550 vph,
→ Permissive Green $Capacity_{WB}$ = 0 vph

Use permssive green capacity = one veh/cycle
= 40 vph for both approaches

(g) Protective $Demand_{1B}$ = 300 - 40 = 260 vph

Protective $Demand_{3B}$ = 100 - 40 = 60 vph

From Fig 2-13, for

Vol = 260 vph, C = 90 sec, → G'_{1B} = 33 sec

Vol = 60 vph, C = 90 sec, → G'_{3B} = 11 sec

(h) From Fig 2-13, for

Phase G'_{1B} = 33 sec, C = 90 sec, → Vol_{1B} = 450 vph

Phase = G'_{3B} = 11 sec, C = 90 sec, → Vol_{3B} = 115 vph

EB Crit lane = 300 - 450 < 0 vph

WB Crit lane = 200 - 115 = 85 vph

(i) The critical through lane volume to be processed in phase 2B is the same as in step 5d.

Since G_{2B} did not change, do not iterate again.

6. Add the phases to determine the cycle length.

$C = \Sigma G + \Sigma Y$

$= 20 + 0 + 8 + 9 + 33 + 11 + 15 = 96$ sec

7. Since 96 is close to the estimated 90 sec cycle length, it is not necessary to repeat the procedure.

Figure 3-12 illustrates the resulting phasing scheme.

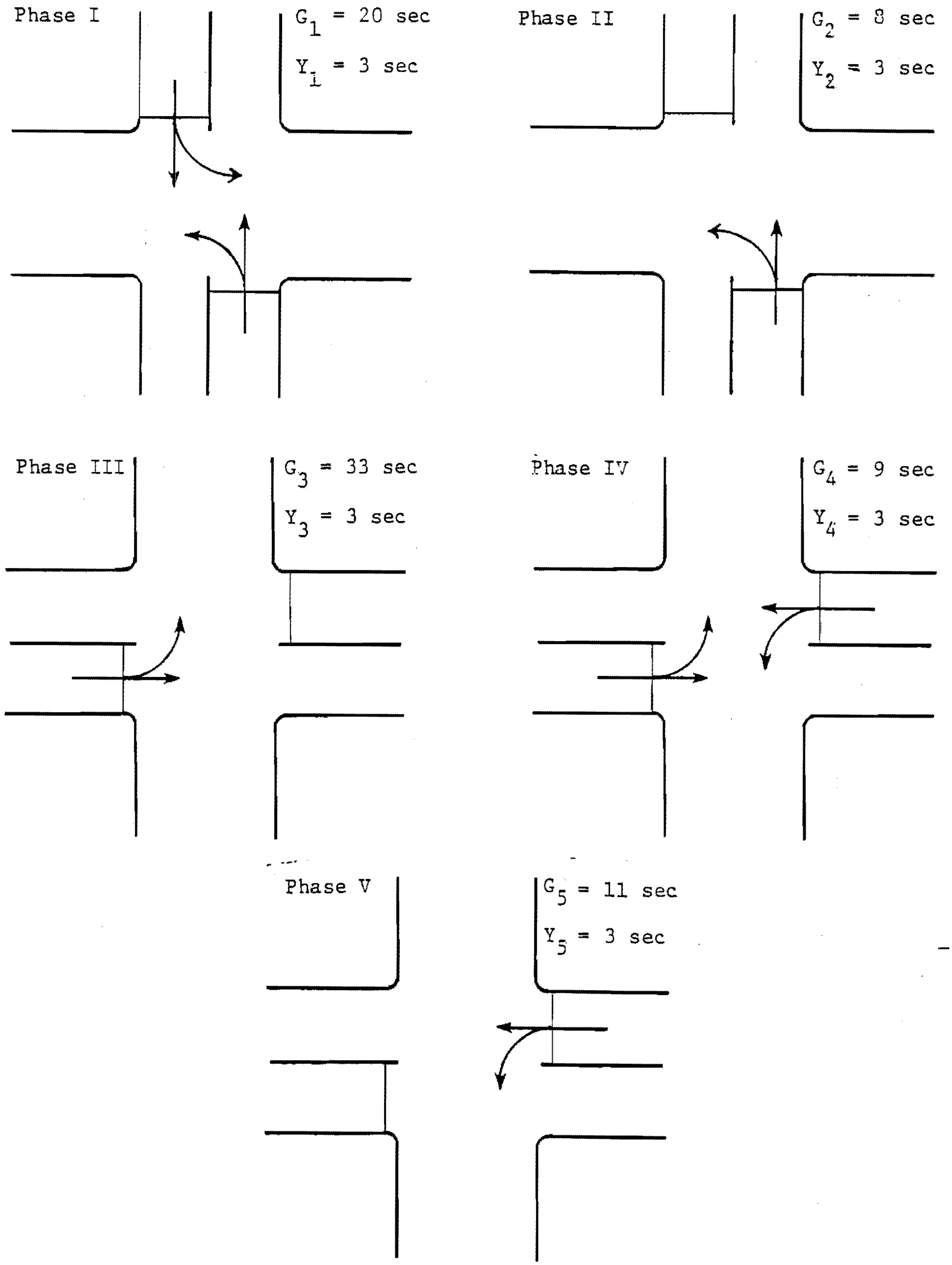


Figure 3-12. Phasing scheme for CASE VI - Example 2.

REFERENCES

1. Machemehl, R.B., and H.J. Lin, "Guidelines for Left-Turn Lanes and Signal Phases," Compendium of Technical Papers, Institute of Transportation Engineers, Washington, D.C., August 1982.

2. Lin, H.J., and R.B. Machemehl, "A Developmental Study of Implementation Guidelines for Left-Turn Treatments," A paper presented to the 62nd Annual Meeting of the Transportation Research Board, Washington, D.C., January 1983, currently in press.

3. Lin, H.J., R.B. Machemehl, C.E. Lee, and R. Herman, "Guidelines for use of Left-Turn Lanes and Signal Phases," Research Report 258-1, Center for Transportation Research, The University of Texas at Austin, February 1983.

4. Lee, C.E., et al, "The TEXAS Model for Intersection Traffic," Research Report 184-1, Center for Highway Research, The University of Texas at Austin, July 1977.

5. Lee, F.P., et al, "Vehicle Emissions at Intersections," Research Report 250-1, Center for Transportation Research, The University of Texas at Austin, August 1983.

6. "Left-Turn phase Design in Florida," Florida Section ITE, ITE Journal, Institute of Transportation Engineers, Washington, D.C., September 1982.

7. "A Study of Clearance Intervals, Flashing Operations, and Left-Turn Phasing at Traffic Signals," Volume 4, Federal Highway Administration, Report No. FHWA-RD-78-49, Washington, D.C., May 1980.

8. Machemehl, R.B. and A.M. Mechler, "Comparative Analysis of Left-Turn Phase Sequencing," Center for Transportation Research Report No. 258-2, Center for Transportation Research, The University of Texas at Austin, November 1983.

9. C.S. Wu, et al, "Detector Configuration and Location at Signalized Intersections," Center for Transportation Report No. 259-1F, Center for Transportation Research, The University of Texas at Austin, June 1981.

10. Messer, C.J., D.B. Fambro, and D.A. Andersen, "A Study of the Effects of Design and Operational Performance of Signal Systems - Final Report," Research Report 203-2F, Texas Transportation Institute, August 1975.

11. Agent, Kenneth R., "An Evaluation of permissive Left-Turn Phasing," Research Report 519, Division of Research, Kentucky Department of Transportation, April 1979.