Analysis of the Proposed Use of Delay-Based Levels of Service at Signalized Intersections

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Stopped delay calculations were made for many combinations of cycle length, ratio of effective green time to cycle length (*g/C* ratio), and quality of signal progression, to aid in the following: identifying the relationships between computed delay and volume-to-capacity (*v/c*) ratio for lane groups at signalized intersections; determining how to solve for *v/c* ratio and service flow rate when the desired level-of-service (LOS) delay value is known; examining methods for using the delay-based LOSs in intersection design, both geometrics and signal timing. Sensitivity analyses reveal that many combinations of long cycle lengths, low *g/C* ratios, and adverse progression result in such high delays that LOS levels of A, B, and C are unattainable, even at low *v/c* ratios. Computer-generated tabulations are proposed to aid in solving for *v/c* ratios and maximum flow rates associated with desired delay-based LOSs.

In the new Highway Capacity Manual (HCM), use of computed average stopped delay for determining the level of service (LOS) at signalized intersections is specified *(1)*. In the process of the refinement of the methodology for inclusion in the new HCM, several issues were raised. Among these were the following:

- What role, if any, should the volume-to-capacity (*v/c*) ratio have in the process?
- What are the appropriate average delay ranges to use in defining LOS?
- How readily can the method be employed in intersection design when the analyst seeks a direct indication of the maximum service volume flow rate for a given condition and stated LOS?

For the purpose of examining these issues, a preliminary investigation of the LOS module is described in this paper. First, basic tabulations developed for this analysis are introduced and explained. Second, the results are presented as a series of sensitivity analyses, with significant attributes highlighted. This is followed by a series of observations on the results. The paper concludes with some suggestions on design applications.

BASIC TABULATIONS

Basic tabulations were prepared by computing stopped delay for different combinations of cycle length, ratios of effective green time to cycle length (*g/C* ratios), and categories of signal progression. Eleven combinations of cycle length and *g/C* ratios were used, as follows:

Cycle Length (sec)	*g/C Ratio*
60	0.3, 0.5, 0.6, 0.7
90	0.2, 0.5, 0.7
120	0.2, 0.4, 0.5, 0.6

The calculations were made for a typical intersection approach with two through lanes, saturation flow of 3,200 vehicles per hour of green time (vphg), and pretimed signal control.

Stopped delay for random arrivals was calculated by using Equation 9-18 of the HCM. The results were then multiplied by adjustment factors for quality of signal progression, as given in Table 9-13 of the HCM. Equation 9-18 is as follows *(1)*:

$$d = 0.38C\ \{(1 - g/C)^2/[1 - g/C(x)]\} + 173x^2\ \{(x - 1) + [(x - 1)^2 + (16x/c)]^{1/2}\}$$

where

- d = average stopped delay for a lane group (sec/veh) for random arrivals;
- C = cycle length (sec);
- g/C = green ratio for the lane group; the ratio of effective green to cycle length;
- x = v/c ratio for the lane group;
- v = flow rate (vph); and
- c = capacity of the lane group (vph).

Progression adjustment factors are given in Table 9-13 of the HCM for five qualities of progression (QP1 to QP5). These factors vary from 1.85 for very adverse progression (QP1) to 0.40 for excellent progression (QP5). These adjustment factors also vary somewhat with *v/c* ratio and by type of traffic control signal, as indicated by the data in Table 9-13 of the HCM.

The tables in Appendix A of this paper were created by using an IBM personal computer and the Lotus 1-2-3 spreadsheet. The spreadsheet was created by using the table lookup functions that are a part of the Lotus 1-2-3 package. The initial tabulation (given in the tops of Tables A-1 to A-11) of delays for various combinations of *v/c* and quality of progression was developed, as noted previously, by using Equation 9-18 of the HCM *(1)*. The tabulations of maximum service volume and *v/c* for various levels of delay and quality of progression (given in the bottoms of Tables A-1 to A-11) were created by looking up

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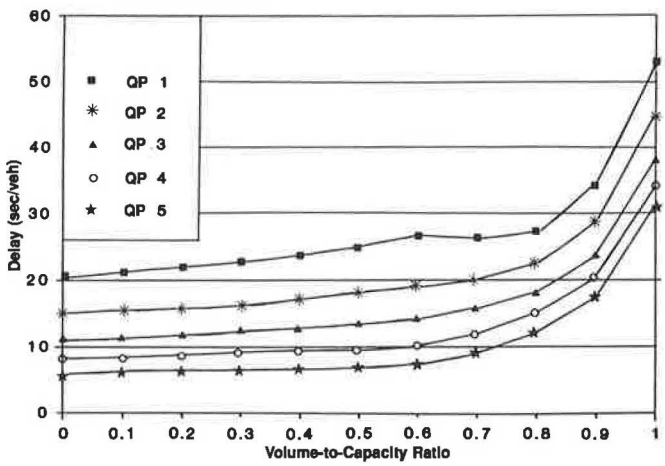

FIGURE 1 Delay versus *v/c* ratio [*c* = 60 sec, *g/C* = 0.3, and *s* = 3,200 vph (two lanes)].

the values in the initial tabulation and interpolating to arrive at the exact figures.

Two tables were created for each combination of cycle length and *v/c* ratio and placed on a single sheet, as indicated by the data in Table A-1 of Appendix A. The top table provides a tabulation of average stopped delay, for each quality of progression (1 through 5) for *v/c* ratios between 0 and 1 in increments of 0.1. The table includes a listing of both the uniform delay (U.D.) and random delay (R.D.) elements of Equation 9-18, as well as the flow rate associated with the *v/c* ratio. The lower table is a tabulation of maximum service volume *(sv)* flow rates and *v/c* ratios up to 1.0 associated with 5-sec increments of delay from 5 to 60 sec per vehicle. Columns are included for each quality of progression. Blank cells in the tables result either for delay levels that are unattainable, or for which *v/c* is greater than 1.0.

Basic attributes of the delay equation are evident, as shown graphically in Figure 1. There is a minimum level of average stopped delay associated with the cycle length, quality of progression, and *g/C* ratio, below which one cannot go as volume approaches zero. As a result, the *v/c* ratio has little influence on average stopped delay at *v/c* levels below 0.6 or 0.7. It is at levels above this that delay increases rapidly. Delays at *v/c* values of 1.10 are much higher than delay at *v/c* of 1.0, as indicated by the data in Table A-4.

Figure 1 shows that the effect of quality of progression on average stopped delay can be significant. The extrapolation of progression adjustment factors that was made in creating Table 9-13 of the HCM highlights a small area of concern in some areas of computation. There are some cases in which the decrease in the progression adjustment factor that results when *v/c* increases above 0.6 more than offsets the associated increase in delay. As a result, computed delay may decrease as *v/c* increases above 0.60. A case in point is the tabulation for 120-sec cycle length at *g/C* of 0.4 with Quality of Progression 1 (QP1). Computed average stopped delays for *v/c* values of 0.7 and 0.8 are lower than those computed on either side. This discontinuity is not likely to be a problem at other levels of quality of progression because the increments for the other progression adjustment factors are much less than for QP1. Some modification of Table 9-13 of the HCM is needed *(1)*.

SENSITIVITY ANALYSIS (SATURATION FLOW = 3,200 VPHG)

Table 1 gives, for three cycle lengths and several *g/C* ratios, the *v/c* ratios associated with each of nine delay values as com-

TABLE 1 EFFECTS OF CYCLE LENGTH AND *g/C* ON *v/C* VALUES FOR AVERAGE STOPPED DELAY

CYCLE		CAPACITY	AVERAGE STOPPED DELAY, SEC/VEH								
LENGTH	G/C	VPH	5	10	15	20	25	30	35	40	45
60 Sec	.70	2240	.72	.90	.95	.99	>1	>1	>1	>1	>1
	.60	1920	.40	.83	.92	.96	>1	>1	>1	>1	>1
	.50	1600	-	.71	.88	.93	.97	>1	>1	>1	>1
	.30	960	-	-	.65	.84	.91	.94	.98	>1	>1
90 Sec	.70	2240	.51	.84	.92	.96	>1	>1	>1	>1	>1
	.50	1600	-	.28	.74	.88	.93	.97	>1	>1	>1
	.20	640	-	-	-	-	.51	.77	.86	.91	.94
120 Sec	.60	1920	-	.43	.77	.89	.93	.97	>1	>1	>1
	.50	1600	-	-	.46	.76	.88	.93	.96	1.0	>1
	.40	1280	-	-	-	.43	.74	.86	.92	.95	.99
	.20	640	-	-	-	-	-	.13	.63	.80	.87

Note: For Quality of Progression 3 (random approach) using adjustment factors from Table 9-13 *(1)* and saturation flow = 3,200 vphg.

puted for Quality of Progression 3 (QP3). These data were obtained from the tables in Appendix A. It is apparent from the data in Table 1 that short cycle lengths and high *g/C* ratios are associated with low delays, even at high *v/c* ratios. For this type of signal timing, an LOS A delay range of 0 to 5 sec/veh is suitable and was adopted for Table 9-1 of the HCM. The data in Table 1 also indicate that, conversely, some long cycle lengths and low *g/C* ratios result in such high delays that the lower delay levels associated with certain high levels of service such as LOS A, B, and C are not attainable. This could influence use of shorter cycle lengths.

Tables 2, 3, and 4 present additional results for each of five qualities of signal progression for different combinations of cycle length and *g/C* ratios. It is apparent that quality of progression is a major factor in affecting *v/c* ratios and the resulting *sv*'s that can be accommodated at each LOS delay range.

Table 4 gives a summary of the effects of using longer cycle lengths and shorter *g/C* ratios such as those used in multiphase signal timing. The data in this table indicate that with a timing plan with a 120-sec cycle, *g/C* of 0.20, and random arrivals (QP3), the *v/c* value must not exceed 0.13 in order to keep the stopped delay below 30 sec/veh. However, if *g/C* is increased to 0.40, with the same 120-sec cycle and QP3, it is possible to attain a *v/c* ratio of 0.86 and still not exceed a delay of 30 sec/veh.

In Table 5, the use of data from Tables 2 and 3 in comparing *v/c* values and *sv*'s for different quality of progression values is explored further. In Case 1, a change from QP1 to QP5 results in a large increase in *sv* for an LOS A delay value of 5.0 sec/veh (from 739 to 1,859 vph). In Case 3, (90-sec cycle and *g/C* of 0.50), a change from QP3 to QP5 results in only a moderate increase in *sv* (from 1,184 to 1,424) when using the LOS B delay criterion of 15 sec/veh.

OBSERVATIONS

Role of *v/c*

Some continue to suggest that *v/c* be used in lieu of average stopped delay as the basis for LOS. The Transportation Research Board Committee on Highway Capacity and Quality of Service continues to stand firm in its use of stopped delay as the measure for LOS. The analysis in this paper demonstrates one value of using the delay measure. Long cycle lengths and low *g/C* values have relatively high levels of delay associated with relatively low *v/c* values. Use of *v/c* for defining LOS could easily result in excessive and costly delays, which are already a matter for concern in some jurisdictions currently using long cycle lengths. The use of average delay as the LOS

TABLE 2 EFFECTS OF *g/C* ON *v/C* VALUES BY LEVEL OF DELAY FOR 60-SEC CYCLE LENGTH AND SATURATION FLOW = 3,200 VPHG

		AVERAGE STOPPED DELAY, SEC/VEH								
G/C	QUALITY OF PROGRESS	5	10	15	20	25	30	35	40	45
.70	1	.33	.82	.91	.94	.97	1.0	>1	>1	>1
	2	.57	.86	.93	.96	1.0	>1	>1	>1	>1
c=2240	3	.72	.90	.95	.99	>1	>1	>1	>1	>1
	4	.79	.92	.96	>1	>1	>1	>1	>1	>1
	5	.83	.93	.98	>1	>1	>1	>1	>1	>1
.60	1	-	.50	.84	.91	.94	.97	>1	>1	>1
	2	-	.76	.90	.93	.98	>1	>1	>1	>1
c=1920	3	.40	.83	.92	.96	>1	>1	>1	>1	>1
	4	.64	.88	.94	.98	>1	>1	>1	>1	>1
	5	.75	.91	.95	1.0	>1	>1	>1	>1	>1
.50	1	-	-	.54	.85	.91	.94	.97	>1	>1
	2	-	.43	.82	.91	.94	.97	>1	>1	>1
c=1600	3	-	.71	.88	.93	.97	>1	>1	>1	>1
	4	.34	.81	.91	.97	>1	>1	>1	>1	>1
	5	.63	.86	.93	>1	>1	>1	>1	>1	>1
.30	1	-	-	-	-	.50	.84	.91	.93	.96
	2	-	-	-	.68	.85	.91	.94	.97	1.0
c=960	3	-	-	.65	.84	.91	.94	.98	>1	>1
	4	-	.54	.80	.90	.93	.97	>1	>1	>1
	5	-	.72	.85	.92	.95	.99	>1	>1	>1

TABLE 3 EFFECTS OF *g/C* ON *v/C* VALUES BY LEVEL OF DELAY FOR 90-SEC CYCLE LENGTH AND SATURATION FLOW = 3,200 VPHG

G/C	QUALITY OF PROGRESS	AVERAGE STOPPED DELAY, SEC/VEH								
		5	10	15	20	25	30	35	40	45
.70	1	-	.57	.84	.91	.94	.97	>1	>1	>1
	2	.24	.78	.90	.94	.97	>1	>1	>1	>1
c=2240	3	.51	.84	.92	.96	>1	>1	>1	>1	>1
	4	.68	.88	.94	.98	>1	>1	>1	>1	>1
	5	.76	.91	.95	1.0	>1	>1	>1	>1	>1
.50	1	-	-	-	.40	.81	.90	.93	.95	.98
	2	-	-	.44	.80	.90	.93	.96	1.0	>1
c=1600	3	-	.28	.74	.88	.93	.97	>1	>1	>1
	4	-	.65	.84	.92	.95	.99	>1	>1	>1
	5	.19	.76	.89	.93	.97	>1	>1	>1	>1
.20	1	-	-	-	-	-	-	-	-	.44
	2	-	-	-	-	-	.07	.59	.83	.89
c=640	3	-	-	-	-	.51	.77	.86	.91	.94
	4	-	-	-	.65	.79	.86	.91	.94	.97
	5	-	-	.64	.78	.85	.91	.94	.97	>1

TABLE 4 EFFECTS OF *g/C* ON *v/C* VALUES BY LEVEL OF DELAY FOR 120-SEC CYCLE LENGTH AND SATURATION FLOW = 3,200 VPHG

G/C	QUALITY OF PROGRESS	AVERAGE STOPPED DELAY, SEC/VEH								
		5	10	15	20	25	30	35	40	45
.60	1	-	-	.16	.52	.82	.90	.93	.96	.99
	2	-	.02	.54	.81	.90	.94	.97	1.0	>1
c=1920	3	-	.43	.77	.89	.93	.97	>1	>1	>1
	4	-	.68	.84	.92	.96	1.0	>1	>1	>1
	5	.37	.78	.89	.94	.98	>1	>1	>1	>1
.50	1	-	-	-	-	.31	.56	.85	.91	.94
	2	-	-	-	.44	.76	.88	.92	.95	.99
c=1600	3	-	-	.46	.76	.88	.93	.96	1.0	>1
	4	-	.35	.72	.85	.92	.96	.99	>1	>1
	5	-	.65	.82	.90	.94	.98	>1	>1	>1
.40	1	-	-	-	-	-	-	.32	.56	.88
	2	-	-	-	-	.28	.61	.84	.91	.94
c=1280	3	-	-	-	.43	.74	.86	.92	.95	.99
	4	-	-	.50	.74	.85	.92	.95	.99	>1
	5	-	.32	.72	.83	.91	.94	.98	>1	>1
.20	1	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	.07	.53
c=640	3	-	-	-	-	-	.13	.63	.80	.87
	4	-	-	-	-	.61	.74	.83	.90	.93
	5	-	-	-	.65	.77	.84	.90	.93	.96

TABLE 5 EXAMPLES: EFFECTS OF IMPROVING QUALITY OF PROGRESSION ON v/C RATIOS AND SERVICE VOLUMES

CASE NO.	CYCLE LENGTH	G/C	AVERAGE STOPPED DELAY, Sec/veh	QUALITY OF PROGRESSION	v/c	SERVICE VOLUME
1	60	.70	5	QP_1	.33	739
				QP_5	.83	1859
2	90	.50	10	QP_3	.28	448
				QP_5	.76	1217
3	90	.50	15	QP_3	.74	1184
				QP_5	.89	1424

Note: The source of the data is Tables 2 and 3.

criterion should encourage selection of the shortest cycle lengths possible.

However, given the sensitivity of delay to high *v/c* ratios, the designer should be discouraged from designing to relatively high *v/c* ratios even though they can be associated with delays approximating LOS C with the criteria currently proposed. This would be in order to create a supplementary factor of safety. To accomplish this, it may be desirable to add guidelines that specify *v/c* ratios as a supplement to the delay criteria for LOS in the design range. Suggested for trial are the following:

LOS	*v/c Not to Exceed*
A	0.85
B	0.90
C	0.93

Using such supplementary criteria will avoid the situation in which a designer, needing to service high demands, will select high *v/c* values that are possible at some LOS delay ranges. Use of such high *v/c* ratios could readily result in excessive delays when small increases in volume occur that exceed assumed design volumes.

Delay Criteria for LOS

The tabulations in this paper have already been useful to the Committee on Highway Capacity and Quality of Service in finalizing the delay criteria used for LOS in Table 9-1 of Chapter 9 of the HCM, Level-of-Service Criteria for Signalized Intersections.

Design Applications

There are a variety of situations for which analyses of a signalized intersection may take place. The majority may be classified into three types:

- Operational analysis,
- Intersection design or redesign, and
- Signal control design or redesign.

An operational analysis has as its objective the determination of LOS for a stated set of geometric, traffic, and signal timing conditions. The intersection design or redesign classification involves arriving at an optimum set of geometric and control design parameters for a given set of traffic conditions and desired LOS. The signal control design or redesign classification is similar to the preceding one, except that geometric conditions are essentially taken as a given and traffic signal control parameters are determined for a desired LOS.

In addition to the three major cases noted, there is present within each class the implicit objective of finding the maximum *v/c* and *sv* associated with a specific LOS.

The steps involved in applying the proposed methodology to determine maximum *v/c* and *sv*'s associated with a desired LOS delay value are shown in Figures 9-14*a*, 9-14*b*, and 9-14*c* of the HCM. Figure 2 in this paper (identical to Figure 9-14*a* of HCM) shows the steps to follow when the geometric configuration, the signal timing, and the desired LOS delay value are known, and the *v/c* ratio and maximum *sv*'s are the unknowns. In this case, the delay tabulation is quickly generated, as presented in the upper part of Table A-1. The lower part of Table A-1 gives the *v/c* and *sv* values associated with desired LOS delay values.

Sample calculation 6 of the HCM is an example of use of the computer in generating data for Step 6 of Figure 9-14*a*. Inputs are geometrics (two through lanes), cycle length (90 sec), *g/C* ratio (0.50), and a desired LOS of B (maximum delay of 15 sec/veh). The computer generates the output given in Table A-6 (also shown in the HCM as Figure 9-36). The data in the lower part of the table indicates that for a LOS delay of 15.0 sec/veh and QP3 (random arrivals), the maximum *v/c* ratio is 0.74 and the maximum service flow rate is 1,183 vph.

When the geometrics or the signal timing are the unknown elements, as in Figures 9-14*b* and 9-14*c* of the HCM, alternative procedures are needed. The generation of tables by computer permits the analyst to quickly identify the ranges of geometric and/or signal design that will accommodate the given *sv*'s at the desired LOS delay value.

Tables of this type may be prepared in a variety of formats. The appropriate one is to be determined in the context of the overall automated package. The ability to generate a tabulation of this type facilitates the performance of sensitivity analyses by the analyst. In the context of a comprehensive applications package, this type of computation might be most effectively employed in a built-in optimization process in which the computation for alternative phasing arrangements might be performed by the computer, which then prints out the results, identifying an optimum configuration according to a specified objective function. This would further reduce the number of data entry steps required of the analyst. The analyst would retain the flexibility to choose from the nonoptimum alternatives if constraints are present that dictate such an action.

Using delay as the criterion for level of service will undoubtedly affect procedures for selecting cycle length and the phasing for isolated signals. Tables of the type displayed in this paper may be helpful in preliminary analyses of alternative designs and signal timing plans. Because short-cycle, two-phase signals produce the lowest delays, there may be a shift toward use of two-phase signals and toward alternative methods for providing for left turns. There also may be more

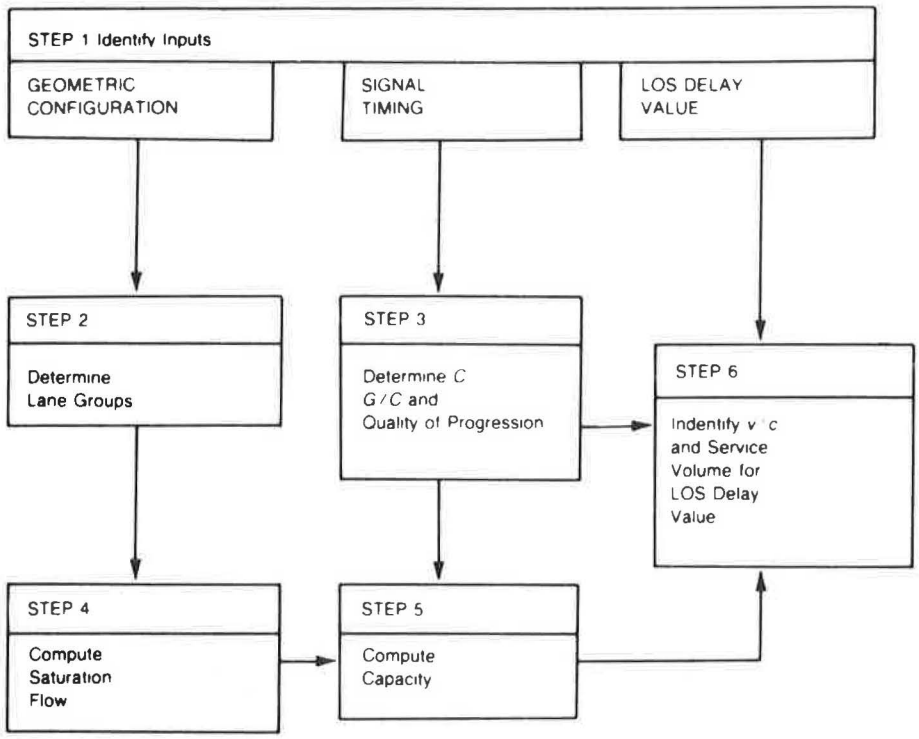

FIGURE 2 Determining *v/c* ratios and service flow rates.

effort devoted to attaining a higher quality of progression in order to increase service volumes and reduce delay.

REFERENCE

1. Signalized Intersections. In *Special Report 209: Highway Capacity Manual*, TRB, National Research Council, Washington, D.C., 1985, Chapter 9.

Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.

APPENDIX A

Basic Tabulations

Table	Cycle Length	g/C
A-1	60	0.3
A-2	60	0.5
A-3	60	0.6
A-4	60	0.7
A-5	90	0.2
A-6	90	0.5
A-7	90	0.7
A-8	120	0.2
A-9	120	0.4
A-10	120	0.5
A-11	120	0.6

AVERAGE STOPPED DELAY FOR:

TABLE A-1

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 60
G/C= 0.3
CAPACITY 960

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	11.17	0.00	0	20.67	15.08	11.17	8.04	5.92
0.1	11.52	.00	96	21.31	15.55	11.52	8.29	6.11
0.2	11.89	0.01	192	22.01	16.06	11.90	8.57	6.31
0.3	12.28	0.06	288	22.81	16.65	12.33	8.88	6.54
0.4	12.70	0.15	384	23.77	17.35	12.85	9.25	6.81
0.5	13.14	0.36	480	24.98	18.23	13.50	9.72	7.16
0.6	13.62	0.77	576	26.62	19.43	14.39	10.36	7.63
0.7	14.14	1.60	672	26.44	20.15	15.74	12.12	9.44
0.8	14.70	3.43	768	27.19	22.11	18.13	14.86	12.14
0.9	15.30	8.14	864	34.00	28.14	23.45	20.16	17.59
1	15.96	22.33	960	53.61	45.19	38.29	34.46	31.40
1.1	16.67	56.17	1056	101.98	85.95	72.84	65.56	59.73

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QP=1 MAX SV	V/C	QP=2 *MAX SV	V/C	QP=3 *MAX SV	V/C	QP=4 *MAX SV	V/C	QP=5 *MAX SV	V/C
A	5										
	10							522	0.54	692	0.72
B	15					619	0.65	770	0.80	818	0.85
	20			652	0.68	802	0.84	861	0.90	881	0.92
C	25	481	0.50	814	0.85	874	0.91	896	0.93	916	0.95
	30	808	0.84	874	0.91	906	0.94	930	0.97	950	0.99
	35	869	0.91	903	0.94	939	0.98				
D	40	893	0.93	931	0.97						
	45	918	0.96	959	1.00						
	50	942	0.98								
	55										
E	60										

AVERAGE STOPPED DELAY FOR:

TABLE A-2

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 60
G/C= 0.5
CAPACITY 1600

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	5.70	0.00	0	10.55	7.70	5.70	4.10	3.02
0.1	6.00	.00	160	11.10	8.10	6.00	4.32	3.18
0.2	6.33	0.01	320	11.73	8.56	6.34	4.57	3.36
0.3	6.71	0.03	480	12.47	9.10	6.74	4.85	3.57
0.4	7.13	0.09	640	13.35	9.74	7.22	5.20	3.83
0.5	7.60	0.22	800	14.46	10.55	7.82	5.63	4.14
0.6	8.14	0.46	960	15.92	11.62	8.61	6.20	4.56
0.7	8.77	0.97	1120	16.36	12.47	9.74	7.50	5.84
0.8	9.50	2.11	1280	17.42	14.17	11.61	9.52	7.78
0.9	10.36	5.30	1440	22.72	18.80	15.67	13.47	11.75
1	11.40	17.30	1600	40.18	33.87	28.70	25.83	23.53
1.1	12.67	51.27	1760	89.51	75.44	63.93	57.54	52.43

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QP=1 MAX SV	QP=1 V/C	QP=2 MAX SV	QP=2 V/C	QP=3 MAX SV	QP=3 V/C	QP=4 MAX SV	QP=4 V/C	QP=5 MAX SV	QP=5 V/C
A	5							549	0.34	1015	0.63
	10			691	0.43	1142	0.71	1299	0.81	1369	0.86
B	15	859	0.54	1309	0.82	1414	0.88	1460	0.91	1484	0.93
	20	1358	0.85	1453	0.91	1493	0.93	1525	0.95	1552	0.97
C	25	1461	0.91	1506	0.94	1555	0.97	1589	0.99		
	30	1507	0.94	1559	0.97						
	35	1553	0.97								
D	40	1598	1.00								
	45										
	50										
	55										
E	60										

AVERAGE STOPPED DELAY FOR:

TABLE A-4

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 60
G/C= 0.7
CAPACITY 2240

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	2.05	0.00	0	3.80	2.77	2.05	1.48	1.09
0.1	2.21	.00	224	4.08	2.98	2.21	1.59	1.17
0.2	2.39	0.01	448	4.43	3.23	2.39	1.72	1.27
0.3	2.60	0.02	672	4.85	3.54	2.62	1.89	1.39
0.4	2.85	0.07	896	5.39	3.94	2.92	2.10	1.55
0.5	3.16	0.15	1120	6.13	4.47	3.31	2.38	1.75
0.6	3.54	0.33	1344	7.16	5.22	3.87	2.79	2.05
0.7	4.02	0.70	1568	7.93	6.04	4.72	3.63	2.83
0.8	4.66	1.53	1792	9.29	7.55	6.19	5.08	4.15
0.9	5.55	3.95	2016	13.77	11.39	9.49	8.16	7.12
1	6.84	14.62	2240	30.05	25.32	21.46	19.32	17.60
1.1	8.92	48.91	2464	80.96	68.24	57.83	52.04	47.42

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QP=1 MAX SV	QP=1 V/C	QP=2 MAX SV	QP=2 V/C	QP=3 MAX SV	QP=3 V/C	QP=4 MAX SV	QP=4 V/C	QP=5 MAX SV	QP=5 V/C
A	5	734	0.33	1278	0.57	1611	0.72	1780	0.79	1856	0.83
	10	1828	0.82	1935	0.86	2025	0.90	2053	0.92	2078	0.93
B	15	2033	0.91	2074	0.93	2119	0.95	2153	0.96	2184	0.98
	20	2102	0.94	2154	0.96	2213	0.99				
C	25	2171	0.97	2235	1.00						
	30	2239	1.00								
	35										
D	40										
	45										
	50										
	55										
E	60										

AVERAGE STOPPED DELAY FOR:

TABLE A-3

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 60
G/C= 0.6
CAPACITY 1920

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	3.65	0.00	0	6.75	4.92	3.65	2.63	1.93
0.1	3.88	.00	192	7.18	5.24	3.88	2.79	2.06
0.2	4.15	0.01	384	7.68	5.61	4.15	2.99	2.20
0.3	4.45	0.03	576	8.28	6.04	4.48	3.22	2.37
0.4	4.80	0.08	768	9.02	6.58	4.88	3.51	2.58
0.5	5.21	0.18	960	9.97	7.28	5.39	3.88	2.86
0.6	5.70	0.39	1152	11.26	8.22	6.09	4.38	3.23
0.7	6.29	0.81	1344	11.93	9.09	7.10	5.47	4.26
0.8	7.02	1.77	1536	13.18	10.72	8.79	7.21	5.89
0.9	7.93	4.52	1728	18.06	14.95	12.45	10.71	9.34
1	9.12	15.79	1920	34.88	29.40	24.91	22.42	20.43
1.1	10.73	49.91	2112	84.90	71.56	60.64	54.58	49.73

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QP=1 MAX SV	QP=1 V/C	QP=2 MAX SV	QP=2 V/C	QP=3 MAX SV	QP=3 V/C	QP=4 MAX SV	QP=4 V/C	QP=5 MAX SV	QP=5 V/C
A	5			46	0.02	814	0.42	1261	0.66	1431	0.75
	10	964	0.50	1451	0.76	1599	0.83	1689	0.88	1739	0.91
B	15	1608	0.84	1729	0.90	1767	0.92	1798	0.94	1826	0.95
	20	1750	0.91	1795	0.93	1844	0.96	1880	0.98	1913	1.00
C	25	1807	0.94	1962	0.97						
	30	1864	0.97								
	35										
D	40										
	45										
	50										
	55										
E	60										

AVERAGE STOPPED DELAY FOR:

TABLE A-5

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 90
G/C= 0.2
CAPACITY 640

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	21.89	0.00	0	40.49	29.55	21.89	15.76	11.60
0.1	22.33	.00	64	41.32	30.16	22.34	16.08	11.84
0.2	22.80	0.02	128	42.22	30.81	22.82	16.43	12.10
0.3	23.29	0.08	192	43.23	31.55	23.37	16.83	12.39
0.4	23.79	0.23	256	44.44	32.43	24.02	17.29	12.73
0.5	24.32	0.53	320	45.98	33.55	24.85	17.89	13.17
0.6	24.87	1.14	384	48.13	35.12	26.01	18.73	13.79
0.7	25.45	2.36	448	46.73	35.60	27.81	21.42	16.69
0.8	26.06	4.98	512	46.55	37.86	31.03	25.45	20.79
0.9	26.69	11.25	576	55.02	45.53	37.94	32.63	28.46
1	27.36	27.35	640	76.60	64.56	54.71	49.24	44.87
1.1	28.06	61.47	704	125.34	105.65	89.53	80.58	73.42

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QP=1 MAX SV	QP=1 V/C	QP=2 MAX SV	QP=2 V/C	QP=3 MAX SV	QP=3 V/C	QP=4 MAX SV	QP=4 V/C	QP=5 MAX SV	QP=5 V/C
A	5										
	10										
B	15									411	0.64
	20							414	0.65	500	0.78
C	25					328	0.51	505	0.79	547	0.85
	30			48	0.07	491	0.77	553	0.86	582	0.91
	35			379	0.59	549	0.86	585	0.91	602	0.94
D	40			530	0.83	584	0.91	604	0.94	621	0.97
	45	279	0.44	572	0.89	603	0.94	624	0.97		
	50	538	0.84	591	0.92	622	0.97				
	55	576	0.90	608	0.95						
E	60	591	0.92	625	0.98						

AVERAGE STOPPED DELAY FOR:

TABLE A-6

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 90
G/C= 0.5
CAPACITY 1600

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	8.55	0.00	0	15.82	11.54	8.55	6.16	4.53
0.1	9.00	.00	160	16.65	12.15	9.00	6.48	4.77
0.2	9.50	0.01	320	17.59	12.84	9.51	6.85	5.04
0.3	10.06	0.03	480	18.67	13.62	10.09	7.27	5.35
0.4	10.69	0.09	640	19.94	14.55	10.78	7.76	5.71
0.5	11.40	0.22	800	21.49	15.68	11.62	8.36	6.16
0.6	12.21	0.46	960	23.45	17.11	12.68	9.13	6.72
0.7	13.15	0.97	1120	23.73	18.08	14.12	10.88	8.47
0.8	14.25	2.11	1280	24.55	19.96	16.36	13.42	10.96
0.9	15.55	5.30	1440	30.23	25.02	20.85	17.93	15.64
1	17.10	17.30	1600	48.16	40.59	34.40	30.96	28.21
1.1	19.00	51.27	1760	98.37	82.92	70.27	63.24	57.62

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QUALITY OF PROGRESSION QP=1 MAX SV	V/C	QP=2 MAX SV	V/C	QP=3 MAX SV	V/C	QP=4 MAX SV	V/C	QP=5 MAX SV	V/C
A	5									296	0.19
	10					455	0.28	1040	0.65	1218	0.76
B	15			703	0.44	1183	0.74	1336	0.84	1418	0.89
	20	646	0.40	1281	0.80	1410	0.88	1465	0.92	1496	0.93
C	25	1293	0.81	1439	0.90	1489	0.93	1527	0.95	1559	0.97
	30	1434	0.90	1491	0.93	1548	0.97	1588	0.99		
	35	1483	0.93	1543	0.96						
D	40	1527	0.95	1594	1.00						
	45	1572	0.98								
	50										
	55										
E	60										

AVERAGE STOPPED DELAY FOR:

TABLE A-8

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 120
G/C= 0.2
CAPACITY 640

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	29.18	0.00	0	53.99	39.40	29.18	21.01	15.47
0.1	29.78	.00	64	55.10	40.21	29.78	21.44	15.78
0.2	30.40	0.02	128	56.28	41.07	30.42	21.90	16.12
0.3	31.05	0.08	192	57.59	42.03	31.13	22.41	16.50
0.4	31.72	0.23	256	59.11	43.13	31.95	23.00	16.93
0.5	32.43	0.53	320	60.98	44.50	32.96	23.73	17.47
0.6	33.16	1.14	384	63.46	46.31	34.31	24.70	18.18
0.7	33.93	2.36	448	60.98	46.46	36.30	27.95	21.78
0.8	34.74	4.98	512	59.58	48.46	39.72	32.57	26.61
0.9	35.59	11.25	576	67.92	56.21	46.84	40.28	35.13
1	36.48	27.35	640	89.37	75.32	63.83	57.45	52.34
1.1	37.42	61.47	704	138.44	116.68	98.88	89.00	81.09

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QUALITY OF PROGRESSION QP=1 MAX SV	V/C	QP=2 MAX SV	V/C	QP=3 MAX SV	V/C	QP=4 MAX SV	V/C	QP=5 MAX SV	V/C
A	5										
	10										
B	15										
	20									416	0.65
C	25							390	0.61	491	0.77
	30					86	0.13	476	0.74	537	0.84
	35					406	0.63	532	0.83	575	0.90
D	40			48	0.07	515	0.80	574	0.90	594	0.93
	45			338	0.53	559	0.87	594	0.93	613	0.96
	50			525	0.82	588	0.92	612	0.96	631	0.99
	55	58	0.09	566	0.88	607	0.95	631	0.99		
E	60	287	0.45	589	0.92	626	0.98				

AVERAGE STOPPED DELAY FOR:

TABLE A-7

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 90
G/C= 0.7
CAPACITY= 2240

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	3.08	0.00	0	5.69	4.16	3.08	2.22	1.63
0.1	3.31	.00	224	6.12	4.47	3.31	2.38	1.75
0.2	3.58	0.01	448	6.63	4.84	3.59	2.58	1.90
0.3	3.90	0.02	672	7.25	5.29	3.92	2.82	2.08
0.4	4.28	0.07	896	8.03	5.86	4.34	3.13	2.30
0.5	4.74	0.15	1120	9.05	6.60	4.89	3.52	2.59
0.6	5.31	0.33	1344	10.43	7.61	5.64	4.06	2.99
0.7	6.04	0.70	1568	11.31	8.62	6.73	5.18	4.04
0.8	7.00	1.53	1792	12.79	10.40	8.52	6.99	5.71
0.9	8.32	3.95	2016	17.79	14.72	12.27	10.55	9.20
1	10.26	14.62	2240	34.83	29.36	24.88	22.39	20.40
1.1	13.38	48.91	2464	87.20	73.50	62.29	56.06	51.08

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QUALITY OF PROGRESSION QP=1 MAX SV	V/C	QP=2 MAX SV	V/C	QP=3 MAX SV	V/C	QP=4 MAX SV	V/C	QP=5 MAX SV	V/C
A	5			527	0.24	1153	0.51	1531	0.68	1697	0.76
	10	1274	0.57	1742	0.78	1880	0.84	1981	0.88	2032	0.91
B	15	1891	0.84	2020	0.90	2065	0.92	2100	0.94	2132	0.95
	20	2045	0.91	2097	0.94	2153	0.96	2195	0.98	2232	1.00
C	25	2111	0.94	2173	0.97						
	30	2176	0.97								
	35										
D	40										
	45										
	50										
	55										
E	60										

AVERAGE STOPPED DELAY FOR:

TABLE A-9

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 120
G/C= 0.4
CAPACITY 1280

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	16.42	0.00	0	30.37	22.16	16.42	11.82	8.70
0.1	17.10	.00	128	31.64	23.09	17.10	12.31	9.06
0.2	17.84	0.01	256	33.03	24.10	17.85	12.86	9.46
0.3	18.65	0.04	384	34.59	25.24	18.70	13.46	9.91
0.4	19.54	0.11	512	36.37	26.54	19.66	14.15	10.42
0.5	20.52	0.27	640	38.46	28.06	20.79	14.97	11.02
0.6	21.60	0.58	768	41.03	29.94	22.18	15.97	11.75
0.7	22.80	1.21	896	40.33	30.73	24.01	18.49	14.40
0.8	24.14	2.61	1024	40.13	32.64	26.75	21.94	17.93
0.9	25.65	6.41	1152	46.49	38.48	32.06	27.58	24.05
1	27.36	19.34	1280	65.38	55.11	46.70	42.03	38.30
1.1	29.31	53.19	1408	115.51	97.36	82.51	74.26	67.66

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QUALITY OF PROGRESSION QP=1 MAX SV	V/C	QP=2 MAX SV	V/C	QP=3 MAX SV	V/C	QP=4 MAX SV	V/C	QP=5 MAX SV	V/C
A	5										
	10									407	0.32
B	15							644	0.50	918	0.72
	20					551	0.43	952	0.74	1067	0.83
C	25			357	0.28	942	0.74	1094	0.85	1161	0.91
	30			778	0.61	1102	0.86	1173	0.92	1205	0.94
	35	414	0.32	1076	0.84	1178	0.92	1218	0.95	1250	0.98
D	40	717	0.56	1164	0.91	1221	0.95	1262	0.99		
	45	1122	0.88	1202	0.94	1265	0.99				
	50	1176	0.92	1241	0.97						
	55	1210	0.95	1279	1.00						
E	60	1244	0.97								

AVERAGE STOPPED DELAY FOR:

TABLE A-10

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 120
G/C= 0.5
CAPACITY 1600

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	11.40	0.00	0	21.09	15.39	11.40	8.21	6.04
0.1	12.00	.00	160	22.20	16.20	12.00	8.64	6.36
0.2	12.67	0.01	320	23.45	17.11	12.68	9.13	6.72
0.3	13.41	0.03	480	24.87	18.15	13.45	9.68	7.13
0.4	14.25	0.09	640	26.53	19.36	14.34	10.33	7.60
0.5	15.20	0.22	800	28.52	20.81	15.42	11.10	8.17
0.6	16.29	0.46	960	30.98	22.61	16.75	12.06	8.88
0.7	17.54	0.97	1120	31.09	23.69	18.51	14.25	11.11
0.8	19.00	2.11	1280	31.67	25.76	21.11	17.31	14.15
0.9	20.73	5.30	1440	37.74	31.24	26.03	22.39	19.52
1	22.80	17.30	1600	56.14	47.32	40.10	36.09	32.88
1.1	25.33	51.27	1760	107.24	90.39	76.60	68.94	62.81

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QP=1 MAX SV	V/C	QP=2 MAX SV	V/C	QP=3 MAX SV	V/C	QP=4 MAX SV	V/C	QP=5 MAX SV	V/C
A	5				ERR	ERR					
	10				ERR	ERR		559	0.35	1041	0.65
B	15				ERR	738	0.46	1159	0.72	1305	0.82
	20			710	0.44	1212	0.76	1365	0.85	1446	0.90
C	25	492	0.31	1221	0.76	1406	0.88	1471	0.92	1506	0.94
	30	896	0.56	1404	0.88	1485	0.93	1529	0.96	1565	0.98
	35	1368	0.85	1477	0.92	1542	0.96	1587	0.99		
D	40	1460	0.91	1527	0.95	1599	1.00		ERR		
	45	1503	0.94	1577	0.99				ERR		
	50	1547	0.97						ERR		
	55	1590	0.99						ERR		
E	60	ERR	ERR						ERR		

AVERAGE STOPPED DELAY FOR:

TABLE A-11

SIGNAL TYPE= PRETIMED
SAT FLOW= 3200
CYCLE= 120
G/C= 0.6
CAPACITY 1920

V/C	U.D.	R.D.	FLOW RATE	QUALITY OF PROGRESSION 1	2	3	4	5
0	7.30	0.00	0	13.50	9.85	7.30	5.25	3.87
0.1	7.76	.00	192	14.36	10.48	7.76	5.59	4.11
0.2	8.29	0.01	384	15.35	11.20	8.30	5.97	4.40
0.3	8.90	0.03	576	16.51	12.05	8.93	6.43	4.73
0.4	9.60	0.08	768	17.90	13.06	9.68	6.97	5.13
0.5	10.42	0.18	960	19.61	14.31	10.60	7.63	5.62
0.6	11.40	0.39	1152	21.80	15.91	11.79	8.49	6.25
0.7	12.58	0.81	1344	22.50	17.14	13.39	10.31	8.03
0.8	14.03	1.77	1536	23.71	19.28	15.81	12.96	10.59
0.9	15.86	4.52	1728	29.56	24.46	20.39	17.53	15.29
1	18.24	15.79	1920	47.65	40.16	34.03	30.63	27.91
1.1	21.46	49.91	2112	99.92	84.22	71.37	64.24	58.53

SERVICE VOLUME AND VOLUME/CAPACITY RATIO

LOS	MAXIMUM STOPPED DELAY	QP=1 MAX SV	V/C	QP=2 MAX SV	V/C	QP=3 MAX SV	V/C	QP=4 MAX SV	V/C	QP=5 MAX SV	V/C
A	5									706	0.37
	10			46	0.02	835	0.43	1311	0.68	1492	0.78
B	15	316	0.16	1043	0.54	1472	0.77	1622	0.84	1716	0.89
	20	994	0.52	1563	0.81	1712	0.89	1764	0.92	1800	0.94
C	25	1578	0.82	1735	0.90	1793	0.93	1837	0.96	1876	0.98
	30	1733	0.90	1796	0.94	1863	0.97	1911	1.00		
	35	1786	0.93	1857	0.97						
D	40	1839	0.96	1918	1.00						
	45	1892	0.99								
	50										
	55										
E	60										

Saturation Flows of Exclusive Double Left-Turn Lanes

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The objectives of this study were to develop estimates of the saturation flows of exclusive double left-turn lanes, and to investigate the physical and operating characteristics of the intersection that may affect left-turn saturation flows. The results are based on observations of 3,458 completed left turns from exclusive double left-turn lanes on 14 intersection approaches in Austin, College Station, and Houston, Texas. Based on the results of this study and a review of the data from a limited number of related studies, an average double left-turn saturation flow rate of approximately 1,600 vehicles per hour of green per lane would appear to be a reasonable value for most planning applications. This flow rate can be assumed to be achieved for the third vehicle in the queue and beyond. Also, this flow rate appears to be applicable for mixed traffic conditions in which heavy vehicles constitute as much as 3 to 5 percent of the left-turn traffic volume.

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The continuing emphasis on obtaining a more efficient utilization of the existing urban street infrastructure suggests that applications of the double left-turn lane concept will become increasingly widespread. Reliable estimates of double left-turn saturation flows have several important applications in traffic