Using Volume-to-Capacity Ratios to Supplement Delay as Criteria for Levels of Service at Traffic Signals

DONALD S. BERRY

The feasibility of using volume-to-capacity (v/c) ratios to supplement stopped delay for determining levels of service (LOS) at traffic signals when operating at near-capacity conditions is examined. Results indicate that the supplemental v/c criteria would be applicable in identifying LOS B, C, D, and E for many combinations of signal timing. Timing plans using the shorter cycle lengths and the longer green-to-cycle length (g/C) ratios benefitted the most because use of stopped delay criteria alone for those cases frequently requires that v/c exceed 1.00 in order to attain a delay value associated with LOS B, C, D, and E. Use of delay Equation 9-18 of the 1985 *Highway Capacity Manual* should be avoided when there is an overflow queue at the beginning of the 15-min analysis period, or when duration of overflow queueing lasts for more than 15 min.

The 1985 *Highway Capacity Manual (1)* uses stopped delay as the only criterion for identifying the levels of service (LOS) for lane groups at signalized intersections. Stopped delay is computed by Equation 9-18 of the manual, with adjustments also made for quality of signal progression, as obtained from Table 9–13 of the manual.

Stopped delay is quite an effective criterion for LOS for uncongested conditions because higher LOS are assigned to approaches with low delay due to their short cycle lengths, large green-to-cycle length (g/C) ratios, and favorable signal progression. Use of v/c for LOS criteria would have assigned the same LOS at low v/c ratios regardless of whether stopped delay was 5 or 50 sec per vehicle. For congested conditions, when v/c ratios approach or exceed 1.0, the use of computed stopped delay alone in identifying levels of service may be inappropriate.

Given in Table 1 are examples of delay–v/c relationships that indicate that very high v/c ratios are required in many cases in order to attain delay values specified for LOS C, D, and E of the manual. For example, in the case of a 60-sec cycle, g/C of 0.70, and random arrivals, v/c must equal or exceed 1.03 in order to produce an average delay of 25 sec per vehicle (LOS C). If there were excellent signal progression, the v/c ratio needed would be even higher than 1.03.

The high v/c ratios given in Table 1 for LOS C, D, and E are somewhat disconcerting because operation for 15 min or more at volumes exceeding capacity does not appear to be a desirable practice.

These high v/c ratios are obtained by using Equation 9-18 from the 1985 manual. This equation is based on use of the peak 15-min rate of flow. With this 15-min duration of overflow queueing, some lane groups with short cycle lengths and high v/c ratios may be able to operate for the 15 min without causing excessive delay. If the v/c ratio of 1.03 were to persist for a second, a third, and a fourth 15-min period, the delay would of course become quite high because of the growing overflow queue.

TABLE 1 VALUES OF v/c NEEDED FOR LOS C, D, AND E DELAYS FOR DIFFERENT CYCLE LENGTHS AND g/C VALUES

		Values of v/c Needed to Attain LOS Delays[a]		
g/C	Red *R* (sec)	For LOS C (25 sec)	For LOS D (40 sec)	For LOS E (60 sec)
For Cycles of 60 sec				
0.7	18	1.02	1.07	1.11
0.6	24	1.00	1.06	1.10
0.5	30	0.97	1.04	1.08
0.3	42	0.91	1.01	1.06
For Cycles of 90 sec				
0.7	27	1.00	1.05	1.09
0.5	45	0.93	1.03	1.06
0.2	72	0.51	0.91	1.03
For Cycles of 120 sec				
0.6	48	0.93	1.02	1.07
0.5	60	0.88	1.00	1.05
0.4	72	0.74	0.95	1.02
0.2	96	0	0.80	0.98

[a]Computations made using Equation 9-18 of the *Highway Capacity Manual*, with $S = 3{,}200$ vphg and quality of progression 3.

Equation 9-18 seems to give reasonable estimates of overflow stopped delay when v/c is less than 1.0, which covers the vast majority of the cases in which Chapter 9 of the 1985 manual is used. However, the equation has not been validated for v/c greater than 1.0, and will frequently give misleading results for the following cases:

1. When duration of overflow delay is more than 15 min,
2. When an overflow queue exists at the beginning of the 15-min analysis period,
3. When surges of arrival volumes result in highly variable cycle-by-cycle arrival volumes, and
4. When v/c values are being determined for conditions with considerable overflow delay and the input volumes for computing v/c ratios are based on discharge volumes only.

The need for computing overflow delay can be minimized by use of v/c criteria to supplement delay criteria whenever v/c

Department of Civil Engineering, Northwestern University, Evanston, Ill. 60201. Currently at 2520 Park Place, Evanston, Ill. 60201.

TABLE 2 PROPOSED LOS CRITERIA FOR SIGNALIZED INTERSECTIONS

LOS	Stopped Delay (sec)	Ratio of v/c
A	≤ 5	≤ 0.90
B	5.0–15	≤ 0.90
C	15.1–25	≤ 0.93
D	25.1–40	≤ 0.95
E	40.1–60	≤ 1.0
F	≥ 60	≥ 1.0

approaches or exceeds 1.0. By using a dual delay–v/c system as criteria for LOS, the need for specifying v/c ratios higher than 1.0 in order to attain LOS B, C, D, or E can be avoided.

The feasibility of LOS criteria that use stopped delay supplemented by ceilings on v/c ratios for each LOS is explored. Alternative methods for computing overflow delay when v/c exceeds 1.0 are also suggested.

EVALUATING v/c–DELAY CRITERIA

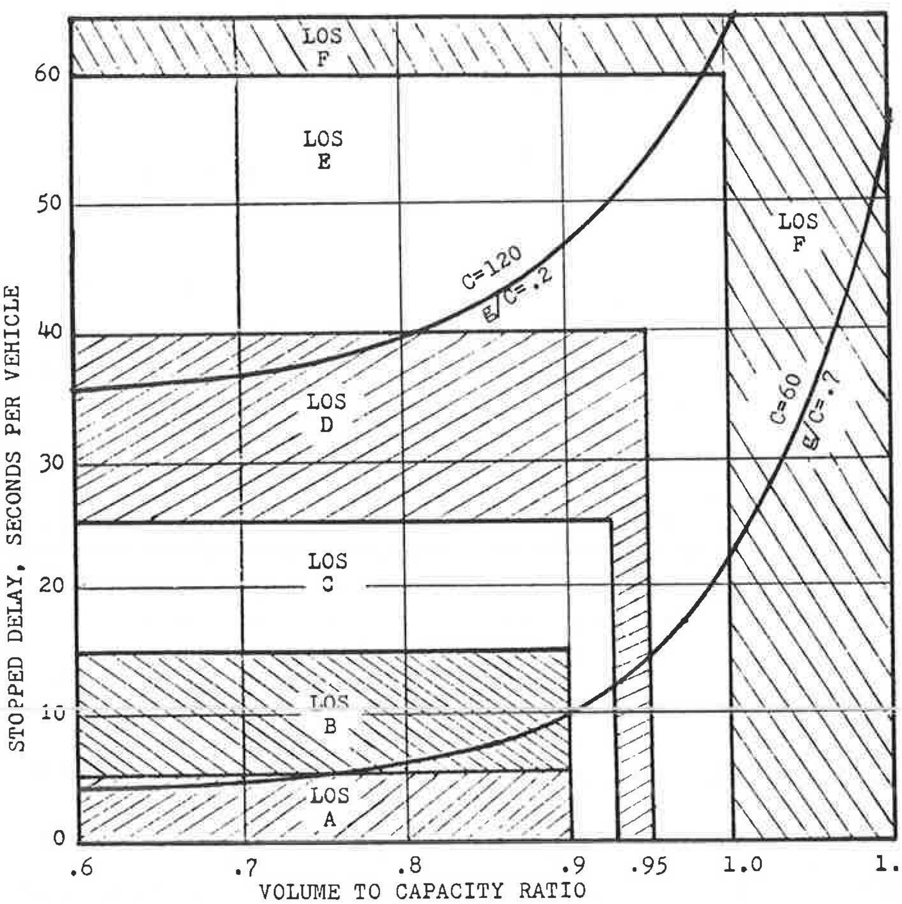
The feasibility of using both stopped delay and v/c ratios as criteria for LOS has been evaluated by making computations of stopped delay for 132 combinations of cycle lengths, g/C ratios, qualities of signal progression and arrival volumes. Most of the computations are based on a saturation flow of 3,200 vehicles per hour of green such as that used for a lane group of two through lanes.

The criteria for determining levels of service are given in Table 2. The values of stopped delay are specified in Table 9-1 of the 1985 manual. Also shown are supplementary v/c ratios, which are proposed in this paper for controlling LOS when v/c values approach or exceed 1.0.

The application of these dual delay–v/c criteria to two examples is graphically shown in Figure 1. In each of the two cases, stopped delay has been computed by Equation 9-18 of the 1985 manual. For the example in the lower part of Figure 1, which represents a 60-sec cycle and g/C of 0.70, LOS C is controlled by v/c of 0.93. Stopped delay does not reach the delay criterion value of 25 sec per vehicle until v/c is 1.03. Similarly, LOS D is controlled by v/c = 0.95 because stopped delay does not reach 40 sec per vehicle until v/c is 1.07. In contrast, for the upper curve, which represents a 120-sec cycle and g/C of 0.2, LOS D and E are controlled by the stopped delay criteria.

Results of the computations for all 132 cases are given in Tables 3–5. The cases when stopped delay governs levels of service are marked with a superscript *a* as are those cases when v/c controls the levels of service.

Given in Table 3 are results for 60-sec cycles, the 48 combinations of g/C ratios, qualities of signal progression, and four LOS. As would be expected, stopped delay controls the LOS



Note: s = 3,200 vphg: random arrivals.

FIGURE 1 Two examples of use of both v/c and delay as criteria for LOS.

TABLE 3 USING BOTH v/c AND DELAY AS CRITERIA FOR LOS: 60-SEC CYCLES

	QP1		QP3		QP5	
g/C	v/c	*d*	v/c	*d*	v/c	*d*
LOS A[a], *d* ≤ 5 sec, v/c ≤ 0.90						
0.3	0	5[a]	0	5[a]	0	5[a]
0.5	0	5[a]	0	5[a]	0.63	5[a]
0.6	0	5[a]	0.42	5[a]	0.75	5[a]
0.7	0.33	5[a]	0.72	5[a]	0.83	5[a]
LOS B[a], *d* ≤ 15 sec, v/c ≤ 0.90						
0.3	0	15[a]	0.65	15[a]	0.85	15[a]
0.5	0.54	15[a]	0.88	15[a]	0.90[a]	11.7
0.6	0.84	15[a]	0.90[a]	11.7	0.90[a]	9.3
0.7	0.90[a]	13.8	0.90[a]	9.5	0.90[a]	7.1
LOS C[a], *d* ≤ 25 sec, v/c ≤ 0.93						
0.3	0.50	25[a]	0.91	25[a]	0.93[a]	21.6
0.5	0.91	25[a]	0.93[a]	20	0.93[a]	15.0
0.6	0.93[a]	23	0.93[a]	16	0.93[a]	11.4
0.7	0.93[a]	20	0.93[a]	12	0.93[a]	10.1
LOS D[a], *d* ≤ 40 sec, v/c ≤ 0.95						
0.3	0.93	40[a]	0.95[a]	29	0.95[a]	21
0.5	0.95[a]	31	0.95[a]	22	0.95[a]	17
0.6	0.95[a]	24	0.95[a]	17	0.95[a]	13
0.7	0.95[a]	21	0.95[a]	14	0.95[a]	11

NOTE: Saturation flow = 3,200 vphg.
[a]LOS is controlled by these values.

for all LOS A cases. For LOS B, six of the 12 cases have LOS controlled by stopped delay, while the v/c ratio of 0.90 controls for the other six cases. For LOS C and D, only four of the 24 cases have LOS controlled by delay. The other 20 cases have LOS controlled by v/c criteria.

For the 36 cases with 90-sec cycles, given in Table 4, delay controls LOS for all LOS A cases and for seven of the nine LOS B cases. The LOS A delay value of 5 sec per vehicle is not attainable in six of the nine LOS A cases. Delay controls levels of service in five of the nine LOS C cases and for three of the nine LOS D cases.

TABLE 4 v/c AND DELAY USED AS CRITERIA FOR LOS: 90-SEC CYCLES

	QP1		QP3		QP5	
g/C	v/c	*d*	v/c	*d*	v/c	*d*
LOS A[a], *d* ≤ 5 sec, v/c ≤ 0.90						
0.2	0	5[a]	0	5[a]	0	5[a]
0.5	0	5[a]	0	5[a]	0.19	5[a]
0.7	0	5[a]	0.51	5[a]	0.76	5[a]
LOS B[a], *d* ≤ 15 sec, v/c ≤ 0.90						
0.2	0	15[a]	0	15[a]	0.64	15[a]
0.5	0	15[a]	0.74	15[a]	0.89	15[a]
0.7	0.81	15[a]	0.90[a]	12.3	0.90[a]	9.2
LOS C[a], *d* ≤ 25 sec, v/c ≤ 0.93						
0.2	0	25[a]	0.51	25[a]	0.85	25[a]
0.5	0.81	25[a]	0.92	25[a]	0.93[a]	20
0.7	0.93[a]	24	0.93[a]	15	0.93[a]	12
LOS D[a], *d* ≤ 40 sec, v/c ≤ 0.95						
0.2	0	40[a]	0.91	40[a]	0.95[a]	36
0.5	0.95[a]	40[a]	0.95[a]	26.8	0.95[a]	22
0.7	0.95[a]	26	0.95[a]	18	0.95[a]	15

NOTE: Saturation flow = 3,200 vphg.
[a]LOS is controlled by these values.

TABLE 5 v/c AND DELAY USED AS CRITERIA FOR LOS: 120-SEC CYCLES

	QP1		QP3		QP5	
g/C	v/c	*d*	v/c	*d*	v/c	*d*
LOS A[a], *d* ≤ 5 sec, v/c ≤ 0.90						
0.2	0	5[a]	0	5[a]	0	5[a]
0.4	0	5[a]	0	5[a]	0	5[a]
0.5	0	5[a]	0	5[a]	0	5[a]
0.6	0	5[a]	0	5[a]	0.37	5[a]
LOS B[a], *d* ≤ 15 sec, v/c ≤ 0.90						
0.2	0	15[a]	0	15[a]	0	15[a]
0.4	0	15[a]	0	15[a]	0.72	15[a]
0.5	0	15[a]	0.46	15[a]	0.82	15[a]
0.6	0.16	15[a]	0.77	15[a]	0.89	15[a]
LOS C[a], *d* ≤ 25 sec, v/c ≤ 0.93						
0.2	0	25[a]	0	25[a]	0.77	25[a]
0.4	0	25[a]	0.74	25[a]	0.91	25[a]
0.5	0.31	25[a]	0.88	25[a]	0.93[a]	24
0.6	0.82	25[a]	0.93	25[a]	0.93[a]	19
LOS D[a], *d* ≤ 40 sec, v/c ≤ 0.95						
0.2	0	40[a]	0.80	40[a]	0.93	40[a]
0.4	0.56	40[a]	0.95[a]	40[a]	0.95[a]	31
0.5	0.91	40[a]	0.95[a]	33	0.95[a]	26
0.6	0.95[a]	39	0.95[a]	27	0.95[a]	21

NOTE: Saturation flow = 3,200 vphg.
[a]LOS is controlled by these values.

For the 48 cases with a cycle length of 120 sec, given in Table 5, there are 21 cases with zero v/c because delay is too high to attain the specified LOS delay value. Delay controls LOS for all LOS A and B cases, as well as for 10 of the 12 LOS C cases, and for 6 of 12 LOS D cases.

Given in Table 6 are the results of calculations of stopped delay for v/c = 1.0 to compare results for saturation flow of 3,200 vphg with those using a saturation flow of 1,600 vphg. Delays are 18 to 25 percent higher when using the lower saturation flows. If a saturation flow higher than 3,200 vphg had been used, computed delays would be lower than those shown for 3,200 vphg. The formula used to compute delay for v/c = 1.0 is shown at the bottom of Table 6, and was derived from Equation 9-18 of the 1985 manual.

Table 6 can also be used to identify cases where v/c ratios govern in selecting LOS E. There are only nine cases with delays of over 60 sec per vehicle; these nine would have LOS E determined by delay. The other 39 cases would have LOS controlled by v/c of 1.0.

When using stopped delay and v/c for LOS criteria for signalized intersections, signal progression adjustment factors may be needed only in those cases controlled by LOS delay criteria. These generally are the cases in which v/c is below 0.90, 0.93, or 0.95, depending on whether it is LOS A, B, C, or D. When v/c is larger than these values, and v/c controls LOS, the delay computations would be needed only when they are

TABLE 6 AVERAGE STOPPED DELAY WHEN v/c = 1.0

Cycle (sec)	Saturation Flow (vphg)	g/C	R	Delay by Arrival Type[a]		
				Type 1	Type 3	Type 5
60	3,200	0.3	42	53.6	38.3	31.8
60	3,200	0.5	30	40.2	28.7	23.8
60	3,200	0.6	24	34.9	24.9	20.7
60	3,200	0.7	18	30.0	21.4	17.8
60	1,600	0.3	42	66.6	47.6	39.5
60	1,600	0.5	30	50.1	35.8	30.8
60	1,600	0.6	24	44.0	31.4	26.1
60	1,600	0.7	18	38.5	27.5	22.8
120	3,200	0.2	96	89.2	63.7	52.8
120	3,200	0.4	72	65.4	46.7	38.8
120	3,200	0.5	60	56.1	40.1	33.3
120	3,200	0.6	48	47.6	34.0	28.2
120	1,600	0.2	96	105.1	75.1	62.3
120	1,600	0.4	72	76.6	54.7	45.4
120	1,600	0.5	60	66.1	47.2	39.2
120	1,600	0.6	48	56.7	40.5	33.6

[a]Computed by

$$d = [0.38R + 692/(c)^{**}0.5]PF \quad (1)$$

where

d = stopped delay in seconds per vehicle,
R = $c - g$,
c = capacity in vehicles per hour, and
PF = progression factor.

desired to supplement the v/c criteria. For example, in Table 3, with a 60-sec cycle and g/C of 0.60, the v/c criterion of 0.93 controls LOS C, but delay can vary from 11.4 to 23 sec per vehicle because of changes in the quality of progression. The drop in delay with improved progression can be cited, but it would not change the LOS, which is controlled by the v/c of 0.93.

Many combinations of the longer cycle lengths, low g/C values, and poor progression produce delay values that are too high to attain LOS A, B, or C even at v/c values of zero. Conversely, many combinations of short cycle lengths, high g/C ratios, and good progression can attain high LOS values of A and B even at high v/c ratios. In the latter cases, LOS would be governed by the controlling v/c ratios in Table 2.

Use of the dual v/c–delay criteria for LOS at signals should simplify use of Chapter 9 of the *Highway Capacity Manual* because delay would not need to be computed for any lane group where v/c values are higher than the values of 0.90, 0.93, and 0.95 as specified in Table 2. Also, there would be less need to worry about the accuracy of quality of progression adjustment factors for cases with v/c above 0.95.

In a paper submitted to the TRB Committee on Highway Capacity in July 1984 *(2)*, results of delay computations for a wide range of cycle lengths, g/C ratios, and qualities of signal progression were tabulated. One of the tables is included in the *Highway Capacity Manual* as Figure 9-36. These tables formed the basis for some of those included in this paper. The 1984 paper also suggested use of v/c ratios for supplementing delay as criteria for LOS at signalized intersections. The following were suggested for trial use:

- LOS A—v/c not to exceed 0.85,
- LOS B—v/c not to exceed 0.90, and
- LOS C—v/c not to exceed 0.93.

The exact v/c values to use as criteria for LOS A, B, C, D, or E could perhaps be higher or lower than the values shown in Table 2. When v/c values are close to 1.0, the variations in cycle-by-cycle arrival volumes increase the probability of cycle overloading. The adverse effects of temporary reductions in capacity because of weather, slow-moving or stalled vehicles, or other incidents are also greater when v/c is close to 1.0. Cycle overloading affects the quality of signal progression and degrades the service experienced by motorists. The lower the v/c ratio, the higher the LOS, as shown in Table 2 and Figure 1. These v/c LOS criteria can be adjusted somewhat, but it is important that they all be 1.00 or below.

Application of the dual criteria for LOS (v/c and stopped delay) may result in different LOS for two separate intersection approaches that have the same computed delay. For example, both may have computed delays of 18 sec per vehicle, but one has v/c = 0.95 and the other a v/c = 0.80. Using Table 2 criteria, one would be assigned LOS C and the other LOS D because of differences in v/c ratios. If stopped delay had been the only criterion, both would be assigned LOS C.

The new nomographic charts in *Capacity Analysis Techniques for Signalized Intersections*, by Jack E. Leisch, use both stopped delay and limiting v/c values as criteria for LOS *(3)*.

COMPUTING OVERFLOW DELAY

Alternative methods for computing or estimating overflow delay should be considered in refining the procedures of Chapter 9 of the 1985 *Highway Capacity Manual*. Some suggestions are made here.

Formulae are available that take into account the duration of the overloading. These include an Australian formula *(4)*, and a Canadian formula *(5)*. The formulae should be evaluated to determine their applicability to Chapter 9. These formulae compute total delay rather than stopped delay.

A promising method for obtaining arrival volumes and for determining overflow delay for existing conditions is to use discharge volumes and overflow queue counts made for each cycle in the analysis period. The formula for computing overflow delay, d_2, is based on Australian delay formulae 6.3 and 6.4 *(4)*, and is given as follows:

$$d_2 = N_O/1.3c \quad (1)$$

where

d_2 = the overflow stopped delay for the time period of 15 min or longer, in seconds per vehicle;
N_o = the average length of the overflow queues for all cycles in the analysis period; and
c = the capacity of the lane group in vehicles per second.

Use of Equation 1 may be the most accurate method for computing overflow delay because the equation takes into

TABLE 7 OVERFLOW DELAY FOR THREE 15-MIN PERIODS

Time Period	Vehicle Arrivals: Vehicles per Second	Vehicle Arrivals: Total 15 min	Vehicle Output 15 min	v/c	Overflow Queue N_o	Overflow Delay: Using N_o	Overflow Delay: Using *Highway Capacity Manual* Equation 9-18
First 15 min	0.53	477	450	1.06	13.5	20.8	30.1
Second 15 min	0.50	450	450	1.00	27.0	41.5	16.3
Third 15 min	0.47	423	450	94	13.5	20.8	8.5

NOTE: $c = 0.50$ vehicle/sec. Uniform arrivals in each 15-min period.

account the possible existence of an overflow queue at the beginning of the analysis period. It also takes into account the variability of cycle-by-cycle arrival patterns (see Berry *6*).

Before using Equation 1, it is necessary to make cycle-by-cycle counts of discharge volumes, and counts of the lengths of the overflow queues at the end of each yellow interval. Arrival volumes then can be determined for each cycle. A selection is then made of the 15-min period with the highest arrival volume. The average overflow queue, N_o, is determined for this 15-min period and is used in Equation 1 to calculate overflow delay, d_2. Similarly, overflow delay can be calculated for a second, a third, and subsequent 15-min analysis periods.

When an approach is loaded and v/c may exceed 1.0, cycle-by-cycle counting of discharge volumes and overflow queues is also needed for determining arrival volumes for use in Equation 9-18 of the manual. If only discharge volumes are used as volume inputs for Equation 9-18, v/c can never exceed 1.0. Thus, cycle-by-cycle counting is also needed for providing inputs for delay Equation 9-18 whenever the approach is at or above capacity (see *6* for details on cycle-by-cycle counting).

When the duration of overflow delay exceeds 15 min, the maximum 15-min delay may not occur in the first 15-min period, during which the rate of arrivals is the highest. An example with an overflow delay duration of 45 min is shown in Table 7 and Figure 2. The highest arrival rate occurs in the first 15 min. However, the maximum overflow delay occurs in the second 15-min period, when the arrival rate is equal to the discharge rate, and there is an overflow queue of 27 vehicles at the beginning of that 15-min period. The average overflow queue for the second 15 min is 27 vehicles, which yields an overflow delay of 41.5 sec of stopped delay per vehicle. If delay Equation 9-18 had been used to compute overflow delay, d_2, the result would be only 16.3 sec per vehicle for this 15-min period, as given in Table 7.

Three other questionable features of Equation 9-18 that undoubtedly affect its usefulness at v/c > 1.0 are as follows:

1. Delay computed by the first term of Equation 9-18 continues to increase as v/c exceeds 1.0, whereas it probably should not increase above the value computed for v/c = 1.0.
2. The ratio for converting total delay to stopped delay of 1.3 was derived empirically from data for v/c < 1.0, and probably is not applicable for v/c values exceeding 1.0.
3. The effects on delay of the quality of progression is not known for v/c values above 1.0.

Use of total delay rather than stopped delay is another alternative to consider because most computer simulation pro-

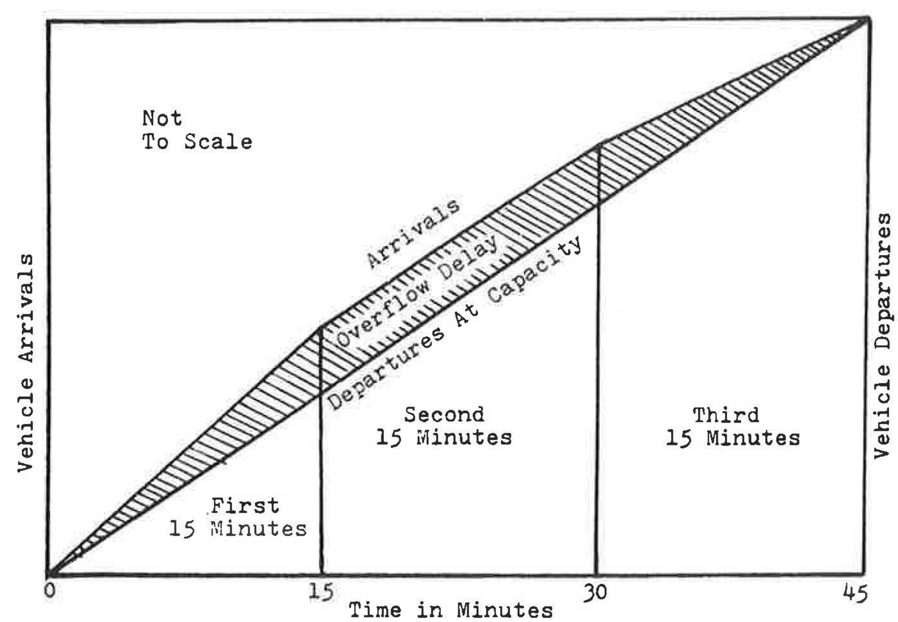


FIGURE 2 Arrivals and departures under loaded conditions as given in Table 7.

grams for determining delay yield total delay rather than stopped delay. A useful field-study procedure for measuring total delay is the time-in-queue delay procedure reported by Buehler et al. *(7)* and Weber *(8)*. This procedure can also yield lengths of overflow queues on a cycle-by-cycle basis for use in equations such as the following for computing total delay when v/c exceeds 1.0:

$$d_t = R/2 + N_O/c \quad (2)$$

where

d_t = total delay for random arrivals in seconds per vehicle,
R = $C - g$,
N_o = the average length of the overflow queues for all cycles in the analysis period, and
c = capacity in vehicles per second.

The ongoing NCHRP research project on relationships between delay and quality of signal progression should provide some helpful data for evaluating alternative procedures for determining delay for Chapter 9 of the *Highway Capacity Manual.*

RECOMMENDATIONS

Stopped delay criteria for levels of service at signalized intersections should be supplemented by use of limiting v/c ratios such as those set forth in Table 2. The exact values to use may need further study.

Alternative methods for predicting overflow delay should be considered for refining the procedures of Chapter 9 of the 1985 *Highway Capacity Manual.* For existing oversaturated intersections, measurements or estimates of average lengths of overflow queues are useful in determining overflow delay.

REFERENCES

1. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985, 516 pp.
2. D. S. Berry and R. C. Pfefer. Analysis of the Proposed Delay-Based Levels of Service at Signalized Intersections. In *Transportation Research Record 1091*, TRB, National Research Council, Washington, D.C., 1986, pp. 78–86.
3. J. E. Leisch. *Capacity Analysis Techniques for Signalized Intersections.* Institute of Transportation Engineers, Washington, D.C., 1986.
4. R. Akcelik. Traffic Signals: Capacity and Timing Analysis. In *ARR 123*, Australian Road Research Board, Victoria, 1981.
5. S. Teply, ed. *Canadian Capacity Guide for Signalized Intersections.* University of Alberta, Edmonton, Canada, Feb. 1984.
6. D. S. Berry. Volume Counting for Computing Delay at Signals. *ITE Journal*, March 1986, pp. 21–23.
7. M. G. Buehler, T. J. Hicks, and D. S. Berry. Measuring Delay by Sampling Queue Backup. In *Transportation Research Record 615*, TRB, National Research Council, Washington, D.C., 1976, pp. 30–36.
8. S. E. Weber. An Investigation of Three Delay Types and Two Sampling Types for Estimating Delay at Congested Signalized Traffic Intersections. M.S. thesis. Northwestern University, Evanston, Ill., June 1978.

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