Having stated that, I should note that I agree with Wortman that a better treatment of these issues is needed. The users must exercise a great deal of judgment and we should provide them with the best information we can give within the scope of the guide.

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Signal Delay with Platoon Arrivals

JAMES M. STANIEWICZ and HERBERT S. LEVINSON

ABSTRACT

Delays at signalized intersections assuming "platoon" flow are analyzed. Graphic analysis of vehicle platoon arrivals is used to develop equations from which the average travel time delay per vehicle can be estimated. Delay for two different, basic conditions is analyzed: (a) when the first vehicle in the platoon arrives during a green interval and is unimpeded and (b) when the first vehicle in the platoon arrives during a red interval or is impeded by queued vehicles. Delay based on the resulting relationships is compared with delay obtained by three conventional methods: the Webster method, May's continuum model method, and the new 1985 Highway Capacity Manual method. Where the platoon leader is unimpeded, there is no delay when the capacity of the through-band equals or exceeds the approach volume. Thus, a high volume-to-capacity ratio may provide a high level of service. This contrasts with delays based on random or uniform arrivals, which are sensitive to the volume-to-capacity ratio. However, where the first platoon vehicle is impeded by a red interval or by queue interference, a chain reaction may occur in which following vehicles are also impeded. This situation may create considerable delay and effectively reduce progression. Effective traffic signal coordination, therefore, can substantially reduce delay and improve levels of service.

Delay has become an important means of assessing level of service at signalized intersections. Consequently, accurate measurements of this delay are essential. Delay computations and computer simulations often assume uniform or random vehicle flow, singly or in combination. However, where signals are spaced closely together or form part of a progressive system, platoon flows are common and more closely represent reality. Such cases result in a different pattern of delays.

Delays at signalized intersections are analyzed assuming platoon flow instead of a random or a uniform arrival pattern. The following question is addressed: What average delay does a platoon of traffic encounter at a signalized intersection? A simple graphic analysis of vehicle platoon arrivals is used to develop equations for estimating average travel time delay per vehicle. Two basic conditions are investigated: (a) when the first vehicle in the platoon arrives during a green interval and is unimpeded and (b) when the first vehicle in the platoon arrives during a red interval or is impeded by queued vehicles. The delay based on the resulting relationships is compared with the delay obtained by three conventional methods: the Webster method, May's continuum model method, and the new 1985 Highway Capacity Manual method.

BASIC ASSUMPTIONS AND PARAMETERS

The analyses relate to arterial street traffic approaching traffic signals. It is assumed that the vehicles have been grouped in platoons by signals upstream of the intersection under study. The procedures for estimating delay depend on the arrival condition of the first platoon vehicle. The platoon leader may arrive during a green interval and proceed unimpeded (Case 1) or arrive during a red interval or be impeded by queued vehicles (Case 2).

Analytical relationships were derived from graphic analysis of each time-space pattern. These relationships were keyed to vehicular volume as measured by the number of through passenger car units per lane per cycle. Green and red periods include the usable and unusable portions of the clearance interval, respectively.

The following assumptions underlie the two delay models:

- All vehicles approaching the intersection arrive in a platoon;
- All vehicles in the platoon follow each other at a uniform time spacing (headway);
- All vehicles in the platoon travel at the same speed (speed of progression);
- The upstream approach speed equals the downstream departure speed; and
- The approach volume per cycle equals the departure volume per cycle; there are no oversaturated conditions.

Travel time delay is used in the analysis. It represents the difference between (a) the time it takes a vehicle whose approach speed to an intersection is altered to recover that speed downstream and (b) the travel time required if that vehicle were able to continue at its approach speed unimpeded. Thus, it includes the time decelerating from an approach speed, stopped time, reaction time, and the time to accelerate back to the same speed as on the approach (1). The average travel time delay per vehicle is the sum of the individual travel time delays divided by the number of vehicles involved.

For a vehicle that stops at an intersection, the rate of deceleration per se does not influence the travel time delay because that vehicle cannot enter and clear the intersection until the signal turns green. Therefore, it is the red time incurred assuming instantaneous deceleration at the stop line that effectively contributes to the travel time delay.

When the signal turns green, there is an initial reaction time. This time loss is followed by the time required to accelerate to resume the desired speed, which is assumed to be equal to the approach speed. A summary of the total reaction and acceleration time loss (L) is given in the following table and derived in Appendix A.

Speed (mph)	Lost Time (L) (sec)
20	4.5
25	5.2
30	5.9
35	6.6
40	7.3

When there are no queued vehicles at a signal approach, to avoid deceleration of a vehicle that is approaching an intersection while a red signal is displayed, the signal must turn green at or before the time when the vehicle would begin to decelerate. Values of this time offset (t_d) for various approach speeds are given in the following table and derived in Appendix B.

Speed (mph)	t_d (sec)
20	2.7
25	3.1
30	3.6
35	4.7
40	6.1

When vehicles are queued at an intersection,

$$t_d = L + H_D(S) \tag{1}$$

where

t_d = travel time offset to avoid deceleration of first platoon vehicle (sec),
L = lost time (reaction and acceleration loss) in seconds,
H_D = departure headway (sec/vehicle), and
S = number of queued vehicles (vehicles/cycle/lane).

PLATOON FLOW MODELS

The delay equations vary for each of the two basic flow models. Accordingly, it is important to determine whether the first vehicle in the platoon is (a) unimpeded or (b) impeded. A graphic check of the time-space diagram will readily indicate when the first vehicle arrives in relation to the start of the green interval. A further check is needed to ensure that, if the first vehicle arrives during a green interval, it is not impeded by queued vehicles.

Case 1: First Vehicle in Platoon Arrives on Green and Is Unimpeded

This arrival condition is shown in Figure 1. The first vehicle arrives at the intersection during a portion of the green interval and is not impeded by any queued vehicles. However, the tail portion of the platoon may arrive at the intersection on the red and then leave at the beginning of the next green interval.

If the first vehicle arrives at the intersection during a green interval and is not impeded by any queued vehicles, the number of vehicles that may pass unimpeded (T) can be determined from the following expression:

$$T = (W - t_d + H_A)/H_A \tag{2}$$

where

T = through-band capacity (vehicles/lane/cycle),
W = bandwidth (sec),

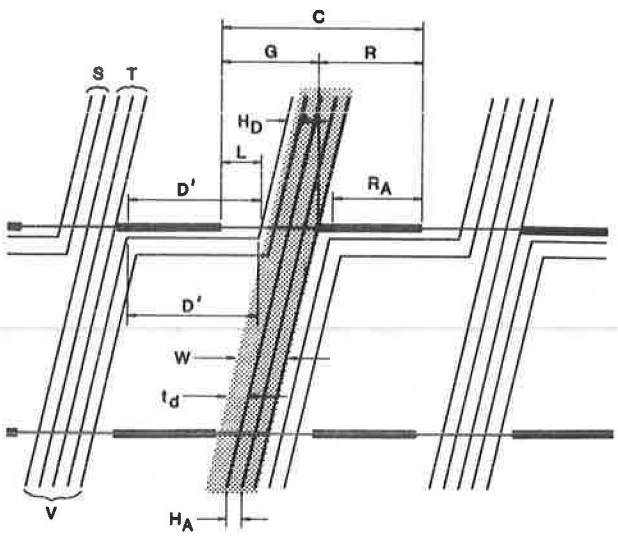


FIGURE 1 Case 1—graphic simulation, platoon leader unimpeded.

t_d = time offset to avoid deceleration of the first vehicle (sec), and
H_A = approach headway (sec).

The number of impeded vehicles (S) is the difference between the approach volume (V) and the number of unimpeded vehicles (T):

$$S = V - T \tag{3}$$

Total Delay

The length of the effective red time (R_A) that the first stopped vehicle must wait is equal to the red interval (R) minus one approach headway:

$$R_A = R - H_A \tag{4}$$

This is because the definition of the red interval (R) includes the unused portion of the clearance interval and commences when the last through vehicle in the platoon enters the intersection. Thus, the next vehicle in this platoon stops on the red but arrives one approach headway later.

The delay to the first stopped vehicle (D') equals the length of the red time (R_A) that it must wait until the start of the green, plus the reaction time and acceleration loss (L):

$$D' = R_A + L = \text{Effective impedance time} \tag{5-1}$$

The delay to each successive stopped vehicle is as follows:

$$\text{Delay to second stopped vehicle} = R_A + L + H_D - H_A \tag{5-2}$$

$$\text{Delay to third stopped vehicle} = R_A + L + 2(H_D - H_A) \tag{5-3}$$

and so forth, and

$$\text{Delay to last stopped vehicle (S)} = R_A + L + (S-1)(H_D - H_A) \tag{5-S}$$

where

R_A = effective red time (sec),
L = time loss due to driver reaction and acceleration (sec),
S = number of stopped vehicles (vehicles/lane/cycle),
H_A = arrival headway (sec/vehicle), and
H_D = departure headway (sec/vehicle).

The total delay (D_T) to S stopped vehicles represents the sum of the delays to the first, second, third . . . and Sth vehicle (i.e., the sum of Equations 5-1 through 5-S).

Thus,

$$D_T = S(R_A + L) + [0 + 1 + 2 + \ldots + (S - 1)] \times (H_D - H_A) \tag{6}$$

This may be expressed as

$$D_T = S(R_A + L) + \sum_{i=1}^{i=S} (i - 1)(H_D - H_A) \tag{7}$$

where i represents the number of stopped vehicles ranging from 1 to S, or

$$D_T = S(D') + F(H_D - H_A) \tag{8}$$

where

$$F = \sum_{i=1}^{i=S} (i - 1)$$

Calculated values of F are given in the following table.

S	F	S	F
1	0	11	55
2	1	12	66
3	3	13	78
4	6	14	91
5	10	15	105
6	15	16	120
7	21	17	136
8	28	18	153
9	36	19	171
10	45	20	190

Average Delay

The average travel time delay per vehicle (D) is the sum of the individual delays (D_T) divided by the approach volume (V). It is given by the following expression:

$$D = D_T/V = [S(D') + F(H_D - H_A)]/V \tag{9}$$

where V is approach volume per lane per cycle.

This equation may be simplified as follows when the approach headway is equal to the departure headway:

$$D = S(D')/V = S(R_A + L)/V \tag{10}$$

Because S = V - T, Equation 10 becomes

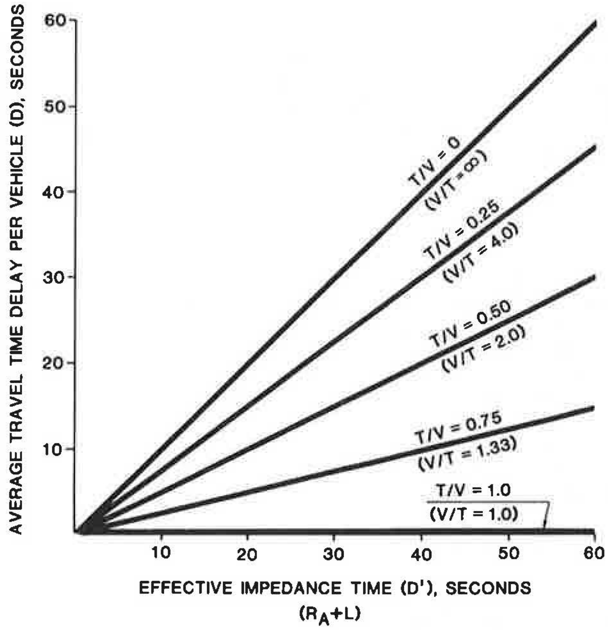
$$D = (R_A + L)(V - T)/V = (R_A + L)[1 - (T/V)] \tag{11}$$

or

$$D = (R_A + L)[1 - 1/(V/T)] \tag{12}$$

Thus, when the approach volume and the through-band volume are equal, there is no delay.

Figure 2 shows how the average travel time delay per vehicle (D) relates to the effective impedance time (D') for various percentages of through-band



*Assumes Base Speed = 30 M.P.H., Headway = 2.1 Seconds

FIGURE 2 Case 1–average travel time delay per vehicle versus effective impedance time.

volume (T) versus approach volume (V), assuming equal approach and departure headways.

As an example, when the effective impedance time is 30 sec and the ratio of the approach volume to through-band capacity (V/T) is 1.0, there is no delay. However, when this ratio is 2.0, the average delay per vehicle is 15 sec. Appendix C contains a sample calculation.

Case 2: First Vehicle in Platoon Arrives During a Red Interval or Is Impeded by Queued Vehicles

This arrival condition, shown in Figure 3, requires a somewhat different delay estimation procedure.

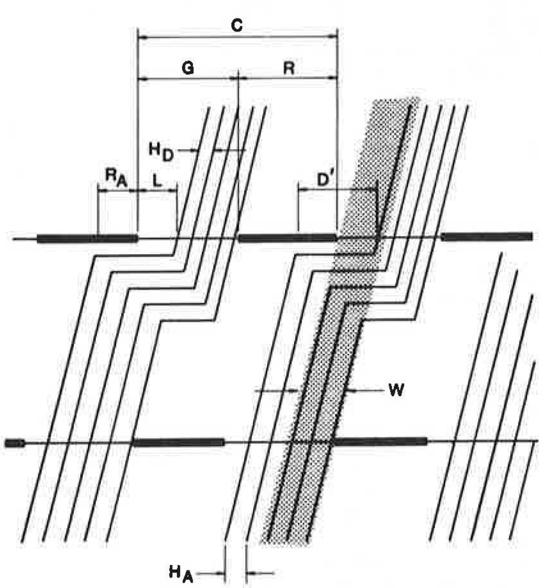


FIGURE 3 Case 2–graphic simulation, platoon leader impeded.

Because the first vehicle in the platoon arrives during a red interval or is impeded by queued vehicles, a chain reaction may result in which following vehicles are also impeded. The number of impeded vehicles and the total delay must be determined.

Total Delay

The delay to each stopping vehicle is calculated by the same method as in Case 1. However, in this second case the number of stopping vehicles first must be determined.

The number of stopping vehicles may be found by solving the delay equation (Equation 5-S) for the condition when the delay equals zero. This condition will occur for vehicle (S + 1). Substituting in Equation 5-S yields the following equation:

$$R_A + L + [(S + 1) - 1](H_D - H_A) = 0 \qquad (13)$$

Solving for S, the number of stopping vehicles, gives

$$S = -(R_A + L)/(H_D - H_A)$$

or

$$S = (R_A + L)/(H_A - H_D) \qquad (14)$$

The value of S calculated from Equation 14 cannot exceed the total number of arriving vehicles per cycle (i.e., $S \leq V$). Where a calculated value of S is greater than the approach volume (V), the value of S should be assumed to be equal to the approach volume (V). A graphic representation of this limit is shown in Figure 4.

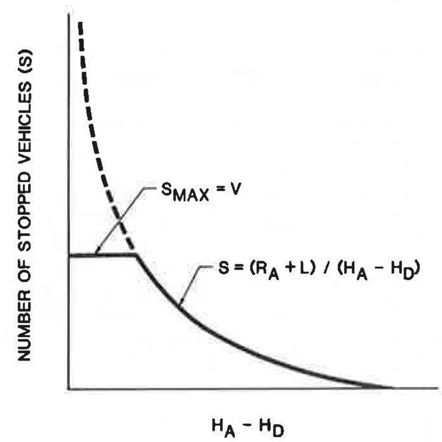


FIGURE 4 Case 2–Equation 14 limit.

The delay to the first stopped vehicle (D') is algebraically the same as for the first case (Equation 5-1):

$$D' = R_A + L$$

where R_A is effective red time (i.e., remaining red time after arrival of first impeded vehicle) in seconds and L is lost time (sec).

However, in this second case, the length of red time (R_A) that the first stopped vehicle must wait is determined graphically from the time-space diagram or relationship.

Average Delay

The average travel time delay per vehicle (D) is also the same as for the first case (Equation 9):

$$D = [S(D') + F(H_D - H_A)]/V$$

where

S = maximum number of vehicles impeded (vehicles/lane/cycle),
D' = delay to first stopped vehicle (sec),
$F = \sum_{i=1}^{i=S} (i - 1)$,
H_D = departure headway (sec),
H_A = arrival headway (sec), and
V = approach volume (= departure volume) in vehicles per lane per cycle.

For most applications, the approach headway will equal or exceed the departure headway of the impeded vehicles. When the approach headway equals the departure headway and the first vehicle is impeded, each vehicle in the platoon will be delayed the same amount of time. When the approach headway is greater than the departure headway, each subsequent stopping vehicle will be delayed less than the first and, depending on the difference between the approach and departure headways, some vehicles may not be impeded as the turbulence clears. Appendix D contains a sample calculation.

COMPARISON WITH OTHER METHODS

The delay estimates for both arrival conditions are compared with delays obtained from equations of three conventional methods: the Webster method, May's continuum model method, and the new 1985 Highway Capacity Manual method.

- The Webster delay formula adjusts uniform delay for random (Poisson) arrivals (2). (See Appendix E.)
- May's continuum model (2) assumes uniform, or regular, arrivals as a continuous function at a signal. (See Appendix F.)
- The new 1985 Highway Capacity Manual (HCM) (3) method employs uniform arrivals and includes an additional term to account for random arrivals. It then adjusts the delay based on platooning characteristics by reducing the delay for effective signal progression and increasing the delay for adverse progression conditions. (Appendix G contains the basic equation for average conditions.)

Delay may be measured in many forms. The Webster method uses approach delay, the continuum model method appears equivalent to approach delay, the HCM method uses stopped delay, and the platoon equations herein use travel time delay. Accordingly, adjustments were necessary so that all methods could be compared in terms of travel time delay.

Approach delay is similar to travel time delay except that it does not include acceleration losses beyond the intersection being evaluated. Assuming a 30-mph base speed and employing Greenshield's departure model (4,p.351), the additional acceleration losses beyond the intersection for each vehicle in the queue are given in the following table:

Vehicle in Queue	Additional Acceleration Loss Beyond Intersection (sec)
1	2.1
2	1.1
3	0.5
4	0.2
5 or more	0.1

In the Webster method or May's continuum model method, the estimated average travel time delay per vehicle (D) is equal to the approach delay (A) obtained directly from the method's equations, plus the sum of the additional acceleration losses beyond the intersection (Z) divided by the approach volume per lane per cycle (V):

$$D = A + Z/V \qquad (15)$$

The second term in this equation (Z/V) represents the average acceleration loss beyond the intersection. This term has a relatively small contribution, typically less than 1 sec.

Stopped time delay represents the time spent while the vehicle is motionless. One source (1) estimates that approach delay equals the stopped delay multiplied by a factor of 1.3. Using the stopped delay (d) from the new 1985 HCM method, the average travel time delay per vehicle (D) was estimated by the following equation:

$$D = 1.3(d) + Z/V \qquad (16)$$

Case 1: Comparison

Given in Table 1 and shown in Figure 5 is a comparison of the average travel time delay per vehicle for unimpeded platoons arriving on the green with delays estimated for the other methods. These exhibits show data for the following conditions:

- 60-sec cycle, 29 sec green, 31 sec red;
- Base speed = 30 mph;
- Departure headways = 2.1 sec per vehicle;
- Signal capacity per lane per cycle = 12 vehicles;
- Approach volumes for 3, 6, 9, and 12 vehicles per lane per cycle;
- Band capacities (platoon flow) for 3, 6, 9, and 12 vehicles per lane per cycle; and
- Arrival headways (platoon flow) = 2.1 sec per vehicle.

With platoon flow arrivals, there are no delays when the volume-to-band capacity ratio is less than or equal to 1.0. When the volume-to-band capacity ratio is greater than 1.0, delays will result. In some cases, the delays exceed those obtained by other methods.

To illustrate, for a volume-to-capacity ratio of 0.75, the following delays are computed:

Method	Delay (sec)
Webster	19.8
May	15.0
New HCM	
Average conditions	19.0
Ideal progression	11.8
Platoon Method at volume-to-band capacity ratio of	
3.0	23.2
1.5	11.6
1.0	No delay
0.75	No delay

Platoon delay depends on the volume-to-band capacity ratio instead of the traditional volume-to-capacity ratio. This is because the arrivals are "controlled" and concentrated and, therefore, are able to use available green time relatively efficiently. Thus, unused green time, which implies a greater capacity or lower volume-to-capacity ratio, does not reduce delay. This finding contrasts with

TABLE 1 Delay Comparison: Case 1, Average Travel Time Delay per Vehicle[a] (sec/vehicle)

		Delay			Platoon Method			
Volume (veh/cycle/lane)	Volume/Signal Capacity	Webster's Method[a] (sec/veh)	May's Method[b] (sec/veh)	New 1985 HCM Method[c] (sec/veh)	Bandwidth Capacity (veh/cycle/lane)	Volume-to-Bandwidth Capacity Ratio	Bandwidth Capacity-to-Signal Capacity Ratio	Delay (sec/veh)
					3	1.0	0.25	0
					6	0.5	0.50	0
3	0.25	12.8	12.1	12.2	9	0.33	0.75	0
					12	0.25	1.00	0
					3	2.0	0.25	17.4
					6	1.0	0.50	0
6	0.50	15.3	13.4	13.8	9	0.67	0.75	0
					12	0.50	1.00	0
					3	3.0	0.25	23.2
					6	1.5	0.50	11.6
9	0.75	19.8	15.0	19.0	9	1.0	0.75	0
					12	0.75	1.00	0
					3	4.0	0.25	26.1
					6	2.0	0.50	17.4
12	1.00	630	17.6	51.0	9	1.33	0.75	8.7
					12	1.0	1.00	0

[a]Given: C = 60 sec, G = 29 sec, R = 31 sec, signal capacity = 12 veh/cycle/lane, base speed = 30 mph, H_D = 2.1 sec/veh; with platoon flow: first vehicle arrives unimpeded, H_A = 2.1 sec/veh.
[b]Adjusted to obtain average travel time delay per vehicle.
[c]Average conditions; adjusted to obtain average travel time delay per vehicle.

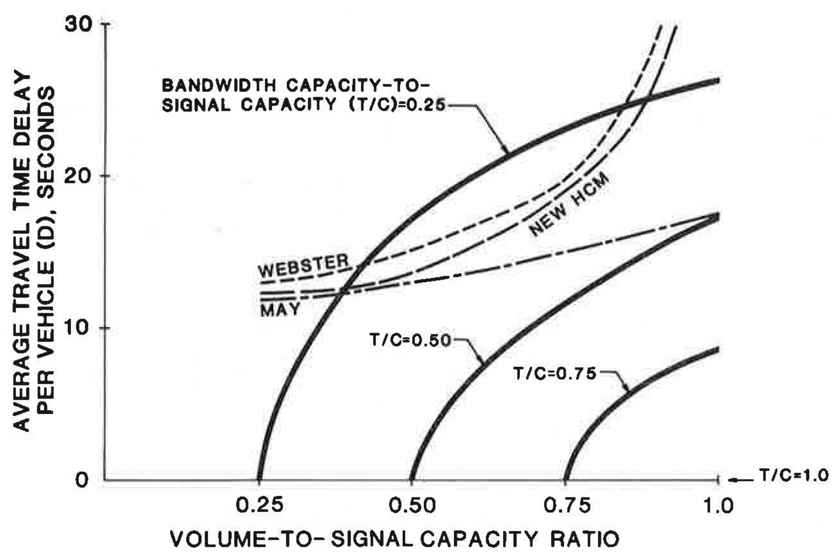


FIGURE 5 Delay comparison: Case 1 (refer to Table 1).

methods that employ random arrivals or uniform arrivals because these arrival patterns are more dispersed throughout the signal cycle. Therefore, random arrivals or uniform arrivals use the additional signal capacity to reduce delay.

Case 2: Comparison

Given in Table 2 and shown in Figure 6 is a comparison of the average travel time delay for impeded platoon arrivals with delays estimated for the other methods. Three different lengths of red time that the first vehicle arriving must wait (R_A = 10, 20, and 30 sec) and two different arrival headway situations (H_A = 3.0 and 2.1 sec) are considered. Other assumptions are the same as for Case 1.

As may be expected, delay is higher the longer the first vehicle of the platoon must wait through the red period. Also, the more the arrival headway exceeds the departure headway, the more the delay tends to reduce. When the arrival headway equals the departure headway, each vehicle is delayed the same amount of time.

SUMMARY AND CONCLUSIONS

Several findings have important traffic capacity and performance implications:

1. Platooning of traffic is desirable to minimize delay along arterial streets. However, the advantages of platooning may be lost if the leading vehicle is forced to stop because the following vehicles may be delayed as well.
2. The through-band of a standard time-space diagram is most meaningful when the first vehicle (or the "leading edge") of the platoon is unimpeded. This is because it describes the unimpeded flow of vehicles through a series of signals and assumes that the platoons travel at the progressive speed.

TABLE 2 Delay Comparison: Case 2, Average Travel Time Delay per Vehicle[a] (sec/vehicle)

		Delay			Platoon Method		
						Delay	
Volume (veh/cycle/lane)	Volume/Signal Capacity	Webster's Method[b] (sec/veh)	May's Method[b] (sec/veh)	New 1985 HCM Method[c] (sec/veh)	Red Time (R_A) 1st Vehicle Waits (sec)	Arrival Headway = 3.0 Sec	Arrival Headway = 2.1 Sec
					10	15.0	15.9
3	0.25	12.8	12.1	12.2	20	25.0	25.9
					30	35.0	35.9
					10	13.7	15.9
6	0.50	15.3	13.4	13.8	20	23.7	25.9
					30	33.7	35.9
					10	12.3	15.9
9	0.75	19.8	15.0	19.0	20	22.3	25.9
					30	32.3	35.9
					10	11.0	15.9
12	1.00	630	17.6	51.0	20	21.0	25.9
					30	31.0	35.9

[a]Given: C = 60 sec, G = 29 sec, R = 31 sec, signal capacity = 12 veh/cycle/lane, base speed = 30 mph, H_D = 2.1 sec/veh; with platoon flow; first vehicle arrives on red and is impeded.
[b]Adjusted to obtain average travel time delay per vehicle.
[c]Average conditions; adjusted to obtain average travel time delay per vehicle.

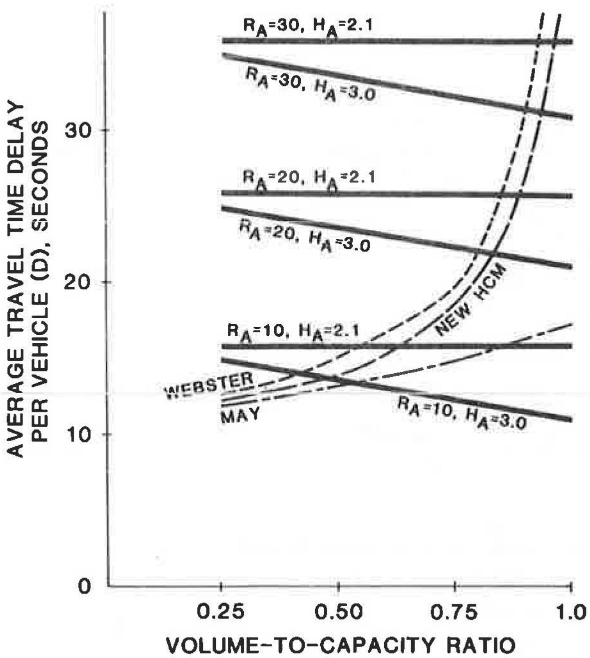


FIGURE 6 Delay comparison: Case 2 (refer to Table 2).

However, when the first vehicle in the platoon arrives during a red interval or encounters queued vehicles, the platoon experiences turbulence and the through-band representation becomes less valid.

3. Where the lead vehicle in the platoon is unimpeded, there is no delay when the capacity of the through-band equals or exceeds the approach volume. Thus, a high volume-to-capacity ratio may provide a high level of service. This contrasts with delays based on random or uniform arrivals, which are sensitive to the volume-to-capacity ratio.

4. However, where the first platoon vehicle is impeded by a red interval or by queue interference, a chain reaction may be introduced in which following vehicles are also impeded. This situation may create considerable delay and effectively reduce progression.

5. The concept of band capacity emerges as an important index of arterial street performance. For minimum delay conditions, volumes should not exceed the band capacity and the platoon leader should arrive at the intersection unimpeded.

6. Effective traffic signal coordination along arterial streets, therefore, can substantially reduce delay and improve levels of service.

The suggested methods provide a realistic means of estimating intersection performance in a progressive signal system. Accordingly, it may be desirable to reassess current delay formulations and computer simulation assumptions, especially where effective signal coordination exists.

Logical next steps include investigating techniques that account for nonplatoon traffic and turning movements, preparing additional delay tables for other signal timing assumptions, and conducting field tests to experimentally verify the research findings and to identify any needed adjustments.

Discussion

Edmond C. Chang*

This study analyzes the coordinated signal delay at signalized intersections mainly from the assumed platoon flow on the arterial street travel directions. A set of graphic analyses was used to investigate the signal delay with respect to the theoretical platoon arrival flow. This method suggested a theoretical approach to estimate the intersection performance between two intersections under its specified assumptions. Two major conditions studied are

- Platoon arrives on green or unimpeded flow (Case 1) or
- Platoon arrives on red or impeded flow (Case 2).

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To simplify the study environment, several assumptions were made:

1. There is no random delay; only uniform delay is used in the study;
2. No platoon dispersion exists;
3. No queue spill-back passes over to another intersection or continues through another signal cycle;
4. All vehicles travel in the progression platoon;
5. All vehicles travel at the same free-flowing speed between intersections;
6. All vehicles travel with uniform headway;
7. Vehicular speeds, arriving from an upstream intersection, are the same as they are leaving the downstream intersection; and
8. Traffic operates under the undersaturated condition with arrival flow rate less than departure flow rate.

The most important measurement of effectiveness used in this study is travel time delay defined as the travel time consumed between the time required for a vehicle to recover the downstream approach speed as it approaches the upstream intersection and the time required to continue its unimpeded approach speed. Microscopic traffic characteristics, such as perception and reaction time, acceleration and deceleration rate, lost time and number of vehicle in queue, were considered explicitly by the modified Greenshields departure model. A deterministic delay estimation model was made separately for each successive stopped vehicle in the queue to estimate the total travel time delay under the given arrival rate, approach headway, progression bandwidth, and time offset to avoid deceleration of the first vehicle in the platoon.

The concept of band capacity was introduced in this paper as another important index for measuring arterial street performance. It was suggested that, for minimum delay operations, volumes should not exceed the band capacity and the platoon leader should arrive at the intersection unimpeded. A platoon delay calculation procedure depending on the volume-to-band capacity ratio instead of the traditional volume-to-capacity (V/C) ratio was developed. Most of the traffic is assumed to arrive in the "controlled" and "concentrated" progression band; therefore, vehicles are able to use available green time more efficiently in this study. Under this particular study assumption, the adjustment of progression bandwidth within the unused green time does not reduce delay. This unused green time may be a result of greater capacity or lower V/C ratio. On the other hand, methods that employ random arrivals or uniform arrivals indicate a totally different result because those arrival patterns are more dispersed throughout the signal cycle. Therefore, random arrivals or uniform arrivals can be guided to use the additional signal capacity provided by the slack green time to further reduce delay.

Effective traffic signal coordination can substantially reduce delay and improve levels of service. However, unsynchronized traffic signal operations will impede the progression band for carrying the through traffic movements. This inefficient progression operation will not only create undue signal delay but will also propagate these delays throughout the signalized network. Therefore, it is believed that the bandwidth and time offset as employed in Equation 2 to estimate the arterial travel time delay can heavily influence the calculations of through-band capacity. The method used to derive the bandwidth and offsets can significantly affect how efficiently the progression platoon can use the through green time for better signal coordinations.

In this study, the approach headway was assumed to be greater than or equal to the departure headway of the impeded vehicles. When the approach headway equals the departure headway and the first vehicle is impeded, each vehicle in the platoon is assumed to be delayed the same amount of time. When the approach headway is greater than the departure headway, each subsequent stopping vehicle will be delayed less than the first and, depending on the difference between the approach and departure headways, some vehicles may not be impeded as the vehicular queue clears the intersection.

In reality, because the first platoon vehicle is impeded by a red signal phase or by queue interference, a chain reaction phenomenon may be developed in which following vehicles are also impeded. This situation may create considerable "shock-wave" delay and effectively reduce progression especially onto the downstream intersections. [See Messer et al. (5) and papers by Chang et al. and Chang and Messer in this Record.] Therefore, it is suggested that the further revision of the assumption of "all platooned traffic" be enhanced to consider the random arrival flow rate onto the downstream intersection. It can be more helpful in estimating the through-bandwidth capacity and the resultant signal delay calculation. An approach, similar to the platoon interconnection factor, as used by PASSER II-84 to adjust for the difference in arrival rates between green and red phase of the cycle, is suggested for possible consideration in the further development and application of this study. Essentially, a version of the tentative NCHRP delay estimation equation was modified to adjust the arrival flow rate, especially the downstream through movements as affected by the effect of travel time on platoon dispersion. Techniques that account for nonplatoon traffic, platoon dispersion effects of the progression band beyond the downstream intersections, and additional delay tables for revised study assumptions are also recommended in order to provide more realistic applications of this research effort.

Authors' Closure

Edmond C. Chang sets forth an interesting overview of our paper and suggests some possible directions for further study. We agree that it is important to accurately identify the width of the real or effective through-band, account for random perturbations in platoons, and consider the consequences of turn-in or turn-off traffic. Certainly, such additional analyses can produce more realistic results. Even more important, however, are actual field studies that analyze delays under conditions of optimal progression. Analyses of delays along one-way streets with near-perfect progression or arterial streets with preferential offsets would prove useful for comparing our "boundary" formulations with actual observations. Such real-world analyses will permit our delay tables to be revised for practical application in determining levels of service at intersections.

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APPENDIX A--REACTION AND ACCELERATION LOSS (L)

Refer to Figure A-1. Assumptions made are:

1. Time after start of green that first stopped vehicle crosses intersection curb line = t_g = 3.8 seconds (4),
2. Reaction time = t_r = 1.0 sec,
3. Distance from stop bar to intersection curb line = d_s = 15 ft, and
4. Acceleration rate = a = 3.3 mph/sec (A. French. Vehicle Operating Characteristics. In Transportation and Traffic Engineering Handbook, W.S. Homburger, Ed., 2nd ed. Institute of Transportation Engineers; Prentice-Hall, Englewood Cliffs, N.J., 1982, p. 168).

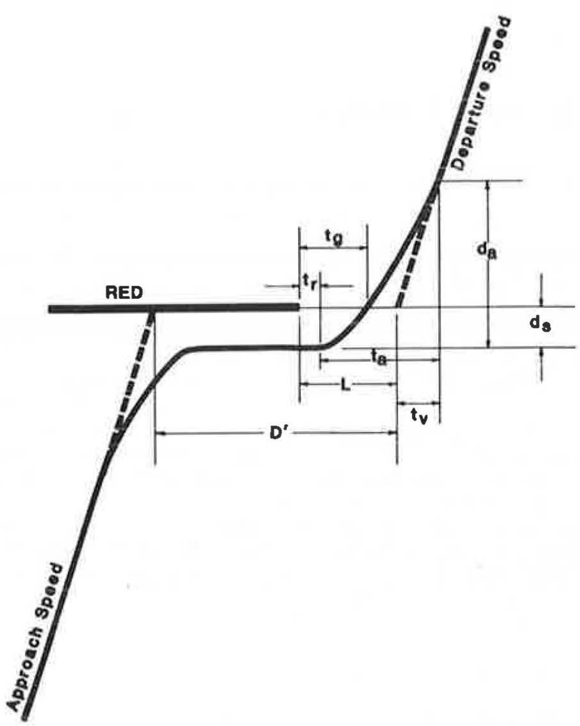

FIGURE A-1 Illustration of terms used to determine L.

General equations are as follows:

Time during acceleration (t_a) is

$$t_a = (v - v_o)/a \tag{A-1}$$

where

v = velocity after speed change;
v_o = initial velocity (e.g., zero velocity at stop); and
a = acceleration rate.

Distance traveled during acceleration (d_a) is

$$d_a = v_o\ (t) + 0.5\ (a)\ t_a^2 \tag{A-2}$$

Time traveled at base speed (t_v) is

$$t_v = (d_a - d_s)/v \tag{A-3}$$

Reaction time and acceleration time loss (L) is

$$L = t_r + t_a - t_v \tag{A-4}$$

Values of L are as follows:

Speed (mph)	L (sec)
20	4.5
25	5.2
30	5.9
35	6.6
40	7.3

APPENDIX B--TIME OFFSET (t_d) TO AVOID DECELERATION OF FIRST PLATOON VEHICLE

Refer to Figure B-1. Assumptions made are:

1. There are no queued vehicles at the signal approach. (Note: If queued vehicles are present, then $t_d = L + H_D(S)$, where L, H_D, and S are as defined in the text.)
2. Deceleration rate = a and
a = -4.6 mph/sec for velocity changes ranging from 0 to 30 mph and
a = -3.3 mph/sec for velocity changes ranging from 30 to 40 mph (A. French. Vehicle Operating Characteristics. In Transportation and Traffic Engineering Handbook, W.S. Homburger, Ed., 2nd ed. Institute of Transportation Engineers; Prentice-Hall, Englewood Cliffs, N.J., 1982, p. 168).
3. Distance from front of stopped vehicle to curb of intersection = d_s = 15 feet.

General equation are as follows:

Time during deceleration (t) is

$$t = (v - v_o)/a \tag{B-1}$$

where

v = velocity after speed change (e.g., zero velocity at stop),
v_o = approach velocity, and
a = deceleration rate.

Distance traveled during deceleration (d_d) is

$$d_d = v_o\ (t) + 0.5\ (a)\ t^2 \tag{B-2}$$

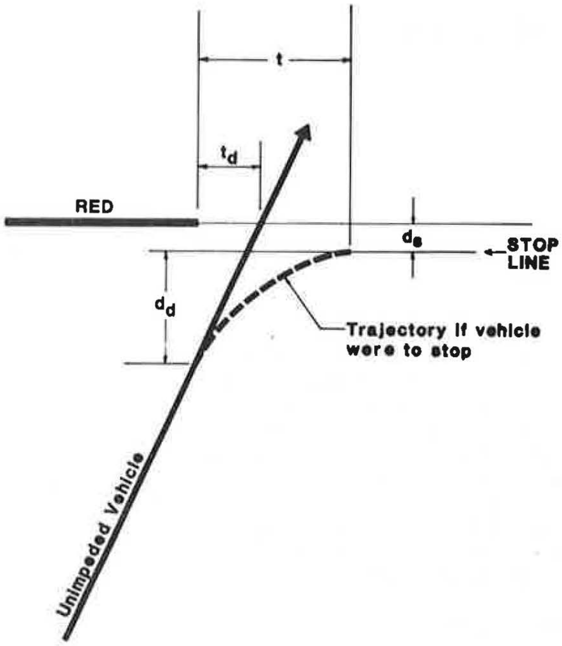

FIGURE B-1 Illustration of terms used to determine t_d.

Time offset to avoid deceleration of first platoon vehicle (t_d) is

$$t_d = (d_d + d_s)/v_o \qquad \text{(B-3)}$$

Values of t_d are as follows:

Speed (mph)	t_d (sec)
20	2.7
25	3.1
30	3.6
35	4.1
40	6.1

APPENDIX C--EXAMPLE OF PLATOON ARRIVALS WHEN FIRST VEHICLE ARRIVES DURING GREEN INTERVAL

Given: C = 60 sec, R = 31 sec, G = 29 sec, H_A = 3 sec, H_D = 2.1 sec, V = 9 vehicles/lane/cycle, base speed = 30 mph, W = 19 sec, first vehicle is not impeded, and no queued vehicles at upstream signal.
Find average travel time delay per vehicle (D):

$T = (W - t_d + H_A)/H_A$
$T = (19 - 3.6 + 3)/3 = 6$ vehicles/lane/cycle (C-1)

$S = V - T$
$S = 9 - 6 = 3$ vehicles/lane/cycle (C-2)

$R_A = R - H_A$
$R_A = 31 - 3 = 28$ sec (C-3)

$D' = R_A + L$
$D' = 28 + 5.9 = 33.9$ sec (C-4)

$D = [S(D') + F(H_D - H_A)]/V$
$S = 3,\ F = 3$
$D = [3(33.9) + 3(2.1 - 3)]/9 = 11$ sec/vehicle (C-5)

APPENDIX D--EXAMPLE OF PLATOON ARRIVALS WHEN FIRST VEHICLE ARRIVES DURING RED INTERVAL

Given: C = 60 sec, R = 31 sec, G = 29 sec, H_A = 3.0 sec, H_D = 2.1 sec, V = 9 vehicles/lane/cycle, base speed = 30 mph, and first vehicle arrives 10 sec before start of green (therefore, R_A = 10 sec).
Find average travel time delay per vehicle (D):

$S = (R_A + L)/(H_A - H_D)$
$S = (10 + 5.9)/(3 - 2.1) = 18$ (D-1)
S cannot be greater than V; therefore, use S = 9

$D' = R_A + L$
$D' = 10 + 5.9 = 15.9$ sec (D-2)

$D = [S(D') + F(H_D - H_A)]/V$
$D = [9(15.9) + 36\ (2.1 - 3.0)]/9$
$= 12.3$ sec/vehicle (D-3)

APPENDIX E--WEBSTER'S DELAY EQUATION

$$A = c(1 - \lambda)^2/[2(1 - \lambda x)] + x^2/[2q(1 - x)] - [0.65(c/q^2)^{1/3}]\ [x^{(2+5\lambda)}]$$

where

- A = average delay to passenger car unit (pcu) on the approach (sec);
- c = cycle time (sec);
- g = effective green time (sec);
- r = effective red time (sec);
- s = saturation flow on the approach (pcu/sec);
- λ = g/c, proportion of the cycle that is effectively green;
- y = q/s, ratio of average arrival rate to saturation flow; and
- x = qc/gs, ratio of average number of arrivals per cycle to the maximum number of departures per cycle.

APPENDIX F--MAY'S UNIFORM DELAY EQUATION

$$A = r^2/[2c(1 - q/s)]$$

where

- A = average delay to pcu on approach (sec),
- r = effective red time (sec),
- c = cycle length (sec),
- q = average arrival rate of traffic on the approach (pcu/sec), and
- s = saturation flow on the approach (pcu/sec).

APPENDIX G--NEW 1985 HIGHWAY CAPACITY MANUAL EQUATION (AVERAGE CONDITIONS)

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

where

- d = average stopped delay per vehicle (sec/vehicle),
- C = cycle length (sec),
- g/C = ratio of effective green time to cycle length,
- x = volume-to-capacity ratio, and
- v_a = adjusted volume (vehicles/hour/lane).

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