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Management Systems Registered to ISO 9001
ABN 79 088 889 687

REPRINT

Progression Factor for Queue Length and Other Queue-Related Statistics

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REFERENCE:

R. AKÇELIK (1996). Progression Factor for Queue Length and Other Queue-Related Statistics. *Transportation Research No. 1555, pp 99-104.*

NOTE:

This paper is related to the intersection analysis methodology used in the SIDRA INTERSECTION software. Since the publication of this paper, many related aspects of the traffic model have been further developed in later versions of SIDRA INTERSECTION. Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further research.

Progression Factor for Queue Length and Other Queue-Related Statistics

RAHMI AKÇELIK

A method is presented that extends the U.S. *Highway Capacity Manual* (HCM) delay progression factor method to the prediction of queue length, queue clearance time, proportion queued (stopped), and queue move-up rate. These predictions are achieved by the introduction of an additional progression factor and adoption of the HCM overflow term adjustment factor, providing a simple method to allow for the effects of platooned arrivals on the performance of coordinated signalized intersections. The method is useful at the level of basic capacity and performance analysis of a single intersection where detailed platooned arrival patterns generated at upstream signal stop lines are not available. The arrival types defined by the HCM as the basic input to define the characteristics of platooned arrivals are adopted for use in calculating the additional progression factor in the same way as the original HCM progression factor for delay. It is assumed that the reader has a good knowledge of the subject area.

The latest edition of the U.S. *Highway Capacity Manual* (HCM) (*1*) describes a progression factor method that allows for the effects of platooned arrivals on delay at coordinated signalized intersections, which is much improved compared with the method in the 1985 edition of the HCM. This paper presents an extension of the HCM delay progression factor method to the prediction of queue length, queue clearance time, proportion queued (stopped), and queue move-up rate. These predictions are achieved by the introduction of an additional progression factor (PF_2) and adoption of the HCM adjustment factor used in the overflow term of the delay model (f_{p2}) for use in the formulas to predict the back of a queue and the queue move-up rate.

The use of a platooned arrivals model is important as most intersections in urban areas are under some form of signal coordination. For example, a recent survey of Australian practice indicated that about 70 percent of signalized intersections (total of over 7,100) and about 45 percent of signalized pedestrian crossings (total of over 1,950) operate under coordinated signal systems (*2*).

The basis of the HCM delay progression factor and the additional progression factor introduced in this paper is a simple platooned arrivals model that assumes different arrival rates during the green and red periods (*1,3,4*).

In contrast to the platooned arrivals model, the uniform arrivals model employed in traditional traffic signal performance analysis for isolated signals (*5–9*) assumes a constant arrival flow rate throughout the signal cycle. The use of the progression factor concept helps to retain the basic form of the traditional performance models, and the uniform arrivals case for isolated signals becomes a special case of platooned arrivals.

The HCM defines six arrival types as the basic input to specify the characteristics of platooned arrivals. These arrival types are adopted for use in calculating the additional progression factor in the same way as that for the original HCM progression factor for delay.

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NOTATION AND BASIC RELATIONSHIPS

- c = average cycle time (sec), $c = r + g$;
- d = average delay per vehicle (sec); the formulas given in this paper do not include geometric delays to turning vehicles;
- d_1, d_2 = first and second terms of the delay formula;
- D = total (aggregate) delay (veh-hr/hr), $D = dq$ (where q is in vehicles/sec);
- f_{d1}, f_{b1} = first-term calibration factors in the formulas for delay and back of queue, respectively; $f_{d1}(x = 1)$, f_{b1} $(x = 1)$ are the values at $x = 1$;
- f_{p1} = adjustment factor in the progression factor formula for delay (for early and late platoon arrivals);
- f_{p2} = overflow term adjustment factor for platooned arrival effects;
- f_{pq} = calibration factor for proportion queued (stopped);
- f_q = calibration factor for queue clearance time;
- g = average effective green time (sec);
- g_s = average queue clearance time (saturated part of the green period) (sec);
- g_u = unsaturated portion of the green period (sec), $g_u = g - g_s$;
- h_{qm} = queue move-up rate (average number of acceleration-deceleration cycles while in queue before clearing intersection);
- k_d, k_b, k_{qm} = overflow term parameters in the formulas for delay, back of queue, and queue move-up rate, respectively;
- N_b = average back of queue (vehicles);
- N_{b1}, N_{b2} = first and second terms of back-of-queue formula;
- N_c = cycle-average queue (vehicles);
- p_q = proportion queued (stopped);
- p_a = platoon arrival ratio (defined as ratio of average arrival flow rate during green period to average arrival rate during cycle (R_p in HCM notation), $P_A = q_{ag}/q_{ac}$;
- P_G = proportion of traffic arriving during green period, (P in HCM notation), $P_G = P_A u = q_{ag}g/q_{ac}c$;
- PF_1 = progression factor for delay;
- PF_2 = progression factor for back of queue, queue clearance time, proportion queued, and stop rate;
- q = flow rate (vehicles/sec or vehicles/hr): number of vehicles per unit time passing (arriving or departing) a given reference point;
- q_a = arrival (demand) flow rate (vehicles/sec or vehicles/hr), i.e., the average number of vehicles per unit time as measured at a point upstream of back of queue, for uniform arrival pattern;

$q_{ac}c$ = number of arrivals (vehicles) per cycle as measured at the back of queue (for nonplatooned arrivals: $q_a c$);
q_{ac} = average arrival flow rate (vehicles/sec or vehicles/hr) during the signal cycle, (for nonplatooned arrivals: $q_{ac} = q_a$), $q_{ac} = (q_{ar}r + q_{ag}g)/c$;
q_{ag} = arrival flow rate (vehicles/sec or vehicles/hr) during green period (for nonplatooned arrivals: $q_{ag} = q_a$), $q_{ag} = P_A q_{ac}$;
q_{ar} = arrival flow rate (vehicles/sec or vehicles/hr) during red period (for nonplatooned arrivals: $q_{ar} = q_a$), $q_{ar} = q_{ac}(c - P_A g)/r = q_{ac}(1 - P_A u)/(1 - u)$;
Q = capacity (vehicles/hr): maximum arrival flow rate that can be served under prevailing flow conditions, $Q = sg/c$ (where s is in vehicles/hr),
QT_p = throughput (maximum number of vehicles that can be discharged during peak flow period);
r = average effective red time (sec), $r = c - g$;
s = saturation flow rate (vehicles/hr or vehicles/sec);
sg = cycle capacity (vehicles) (s in vehicles/sec, g in sec);
T_p = peak flow period (analysis period) in (hr);
u = green time ratio, $u = g/c$;
x = degree of saturation, i.e., ratio of arrival (demand) flow rate to capacity, equivalent to ratio of arrivals per cycle ($q_{ac}c$ vehicles) to maximum number of vehicles that can depart per cycle (sg vehicles), $x = q_{ac}/Q = (q_{ac}c)/(sg)$ (for nonplatooned arrivals, $x = q_a/Q$);
x_0 = degree of saturation below which average overflow queue is 0;
y = flow ratio, i.e., ratio of arrival flow rate during signal cycle to saturation flow rate, $y = q_{ac}/s$ (for nonplatooned arrivals, $y = q_a/s$); and
z = performance model parameter used in overflow term, $z = x - 1$.

GENERAL MODEL FOR INTERSECTION PERFORMANCE

A comprehensive set of performance models has been developed for fixed-time signals, roundabouts, and unsignalized intersections and implemented in SIDRA, Version 4.1, including allowance for the HCM progression factor for delay (PF_1) (*10–12*). These models are further generalized here by the introduction of the additional progression factor (PF_2) and the overflow term adjustment factor (f_{p2}). The performance models are followed by the expressions for relevant model parameters (fixed-time coordinated signals). Refer to the notation and basic relationships given in the previous section for the symbols used in the formulas.

For more detailed information on the performance models including equations to predict effective stop rate and percentile queue lengths, see work by Akçelik and Chung (*10*) and Akçelik (*13*). The calibration of the general model for vehicle-actuated signals can be found in a more recent paper (*14*). The formulas for progression factors PF_1 and PF_2 are given in the following section.

The general form of the model for delay, queue length, and effective stop rate is a two-term formula that can be expressed as $P = P_1 + P_2$. The first term (P_1) represents nonoverflow cases, which occur under low demand conditions, and includes the effect of randomness in arrival (demand) flow rates under such conditions. This differs significantly from previous types of two-term models in which the first term does not include any randomness effects (*1,5,6,15,18*). The queue clearance time and proportion queued are related to the first term of the general performance model (P_1).

The second term (P_2) is an incremental term associated with overflow delay, overflow queue, and queue move-up rate. Overflow conditions (cycle failures) can occur when the average demand is below capacity (temporary cycle oversaturation because of random variations in arrival flow rates) or when average demand is above capacity (permanent oversaturation that lasts for a period of time). This integrated model framework provides consistency in modeling of different performance measures and in modeling of different intersection types.

Delay Model

$$d = d_1 + d_2 \tag{1}$$

$$d_1 = f_{d1}\frac{0.5r(1-u)}{1-y} \quad \text{for } x \le 1.0$$
$$= f_{d1}(x=1)^{0.5r} \quad \text{for } x > 1.0 \tag{1a}$$

$$d_2 = 900T_p\left[\left(z + \sqrt{z^2 + \frac{8k_d(x-x_0)}{QT_p}}\right)\right] \quad \text{for } x > x_0$$
$$= 0 \quad \text{otherwise} \tag{1b}$$

$$D = dq_{ac} \tag{1c}$$

Queue Length Model

$$N_b = N_{b1} + N_{b2} \tag{2}$$

$$N_{b1} = f_{b1}\frac{q_{ac}r}{1-y} \quad \text{for } x \le 1.0$$
$$= f_{b1}(x=1)q_{ac}c \quad \text{for } x > 1.0 \tag{2a}$$

$$N_{b2} = 0.25QT_p\left[\left(z + \sqrt{z^2 + \frac{8k_b(x-x_0)}{QT_p}}\right)\right] \quad \text{for } x > x_0$$
$$= 0 \quad \text{otherwise} \tag{2b}$$

$$N_c = dq_{ac} = D \tag{2c}$$

Queue Move-Up Rate Model

$$h_{qm} = \frac{0.25QT_p}{q_{ac}c}\left[\left(z + \sqrt{z^2 + \frac{8k_{qm}(x-x_o)}{QT_p}}\right)\right] \quad \text{for } x > x_o$$
$$= 0 \quad \text{otherwise} \tag{3}$$

Proportion Queued Model

$$p_q = f_{pq}\frac{1-u}{1-y} \quad \text{subject to } p_q \le 1.0 \tag{4}$$

Queue Clearance Time Model

$$g_s = f_q\frac{yr}{1-y} \quad \text{subject to } g_s \le g \tag{5}$$

Model Parameters (Fixed-Time Coordinated Signals)

$$fd_1 = PF_1[1 + 0.4(sg)^{-0.5}y^{0.1}] \tag{6a}$$

$$f_{b1} = PF_2[1 + 0.4(sg)^{-0.5}y^{0.1}] \quad (6b)$$

$$f_{pq} = PF_2[1 + 0.07(sg)^{-0.1}y^{0.2}] \quad (6c)$$

$$f_q = PF_2 \quad (6d)$$

$$x_0 = 0.4(sg)^{0.20} \quad \text{subject to } x_0 \leq 0.95 \quad (7a)$$

$$k_d = [0.55(sg)^{0.75}y]f_{p2} \quad (7b)$$

$$k_b = [0.55(sg)^{0.9}y]f_{p2} \quad (7c)$$

$$k_{qm} = [0.6(sg)^{0.6}y^{0.2}]f_{p2} \quad (7d)$$

Nonplatooned (Uniform) Arrivals

For uniform arrivals, use $P_A = 1.0, f_{p1} = 1.0$, and $f_{p2} = 1.0$; therefore $PF_1 = 1.0$ and $PF_2 = 1.0$, in Equations 6*a* to 7*d*.

HCM Delay Model

First term (Equation 1a): $f_{d1} = PF_1$. Second term (Equation 1b): $x_o = 0.0$, $k_d = 0.50f_{p2}$, $T_p = 0.25h$ (15-min peak demand period), and an additional factor of x^2 applies. HCM uses a further factor of 0.77 to multiply both terms of the delay equation to estimate the stopped delay. See work by Akçelik et al. (*12*) for a detailed discussion of various definitions of delay.

Pedestrian Movements

For pedestrian movements (*5*), the second terms of all performance statistics are ignored, and $y = 0$ is used in Equations 1*a* and 2*a*; therefore $f_{d1} = PF_1, f_{b1} = PF_2$ and so on.

Actuated Control

To estimate delay at vehicle-actuated signals, the HCM method uses a delay adjustment factor for vehicle-actuated control effect, $CF = 0.85$ (constant), instead of PF_1 in Equation 6*a*. The actuated control factor (CF) and the signal progression factor (PF_1) are used in a mutually exclusive way since CF applies to noncoordinated signals only. For semiactuated signals, $CF = 0.85$ applies to both actuated (side street) and nonactuated (main road) lane groups under noncoordinated (isolated) control. $CF = 1.0$ applies for all lane groups at coordinated signals including actuated lane groups.

This delay adjustment method is a simplistic (and unrealistic) method for modeling delay at vehicle-actuated signals. Recent research by Akçelik (*2*) and Akçelik and Chung (*14*) has established new performance formulas for actuated signals, and the performance formulas for fixed-time signals have been recalibrated as adopted in this paper. Following the HCM method, the performance formulas for actuated signals and progression factors are used in a mutually exclusive way. However, the subject of actuated coordinated signals needs to be further investigated, including calibration of the overflow-term adjustment factors for platooned arrivals.

PROGRESSION FACTORS

The progression factors for delay, PF_1, and queue-related statistics, PF_2, are derived using a simple platooned arrivals model that assumes different arrival rates during the green and red periods, as shown in Figure 1. The progression factors are derived as the ratio of first-term value, assuming platooned arrivals to the first-term value and assuming uniform arrivals (ignoring variational effects). For detailed information on the derivation of PF_2, see report by Akçelik (*13*).

The HCM method defines Arrival Types 1 through 6 for specifying different conditions of signal coordination. These arrival types and the associated default values of P_A, f_{p1}, and the overflow term adjustment factor f_{p2} are given in Table 1.

Progression factors PF_1 and PF_2 are given by

$$PF_1 = \frac{(1 - P_A u)f_{p1}}{1 - u} \quad (8)$$

subject to $P_A \leq 1/u$ and $PF_1 \leq 1.0$ for Arrival Types 4 through 6, and

$$PF_2 = \frac{(1 - P_A u)(1 - y)}{(1 - u)(1 - P_A y)} \quad (9)$$

subject to $P_A \leq 1/u$ and $P_A < 1/y$ and $PF_2 \leq 1.0$ for Arrival Types 4 through 6, where $P_A = q_{ag}/q_{ac}$ is the platoon arrival ratio (R_p in HCM notation), that is, ratio of the average arrival rate during the green period to the average arrival rate during the cycle. The associated parameter $P_G = q_{ag}g/q_{ac}c = P_A u$ is the proportion of traffic arriving during the green period ($u = g/c$, and P in HCM notation).

Parameter f_{p1} in Equation 8 is an adjustment factor specified by the HCM to allow for arrival of the platoon during the green (for early

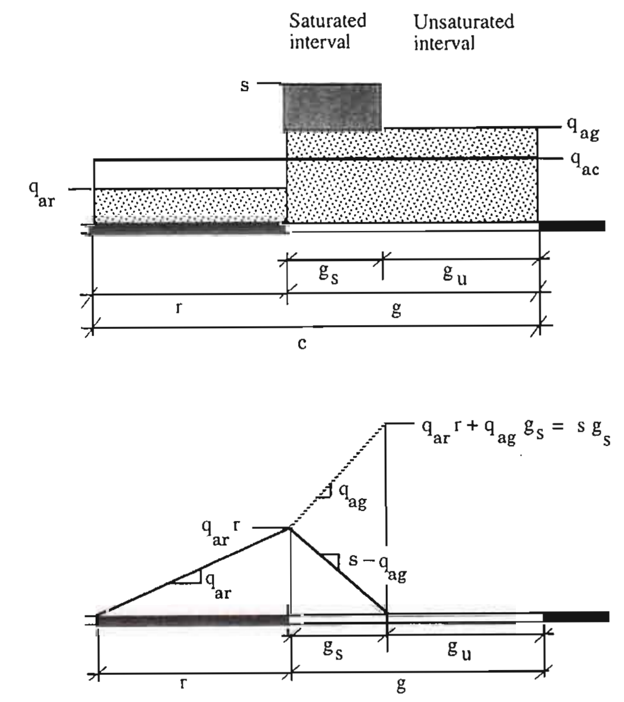

FIGURE 1 Simple platooned arrivals model.

TABLE 1 Arrival Types and Default Parameter Values of Platoon Ratio and Adjustment Parameters for Signal Coordination Effects

Arrival Type	Platoon Description	Progression Quality	P_A	f_{p1}	f_{p2}
1	Dense platoon arriving at the start of the red period	Very poor	1/3	1.00	0.50
2	Moderately dense platoon arriving in the middle of the red period	Non-favourable	2/3	0.93	0.75
3	Random arrivals	Isolated (not coordinated)	1.0	1.00	1.00
4	Moderately dense platoon arriving in the middle of the green period	Favourable	4/3	1.15	0.75
5	Dense to moderately dense platoon arriving at the start of the green period	Highly favourable	5/3	1.00	0.50
6	Very dense platoon progressing with very little delay	Exceptional	2.0	1.00	0.25

P_A Platoon arrival ratio (= q_{ag} / q_{ac})

f_{p1} An adjustment factor for when the platoon arrives during the green (for early and late arrivals)

f_{p2} Overflow term adjustment factor

and late arrivals). The values of f_{p1} for various arrival types (as specified by the HCM) are given in Table 1. Equation 8 is the HCM formula for the delay progression factor, which is a simplified form of a more complex formula, but it represents a reasonable approximation, as shown by Fambro et al. (*3*) and discussed by Akçelik (*13*).

Parameter f_{p2} is based on parameter m in the second term of the HCM delay model (HCM Table 9-13). The value of f_{p2} for each arrival type was derived as a ratio of the value of parameter m for that arrival type to the value of m for Arrival Type 3 (isolated case). The values of f_{p2} derived for the delay model are adopted for use in the formulas to predict the back of the queue and the queue move-up rate. This may be simplistic, but it provides a reasonable working model until further research is carried out.

Figures 2 and 3 show the values of the progression factor PF_2 as a function of the flow ratio y for Arrival Types 1 and 5 with green time ratios u = 0.3, 0.4, and 0.5. Various values of PF_1 and PF_2 are tabulated in Table 2. It has been found that PF_1 is less sensitive to the flow ratio, whereas PF_2 approaches a value of 1.0 at high flow ratios (*13*).

Equations 8 and 9 are subject to various conditions such as the following:

1. The condition $PF \leq 1.0$ ($PF = PF_1$ or PF_2) for Arrival Types 4 through 6 is needed to ensure that, for good coordination represented by these arrival types, delay is less than the isolated signal delay (Arrival Type 3). If $PF_1 > 1.0$ results caused by the use of factor f_{p1} = 1.15 for Arrival Type 4, or caused by $P_G < u$ for Arrival Types 4 through 6, then PF = 1.0 will be set. In SIDRA, the user can specify an arrival type or a value of P_G. When P_G is specified, the corresponding P_A value is calculated and used to choose an

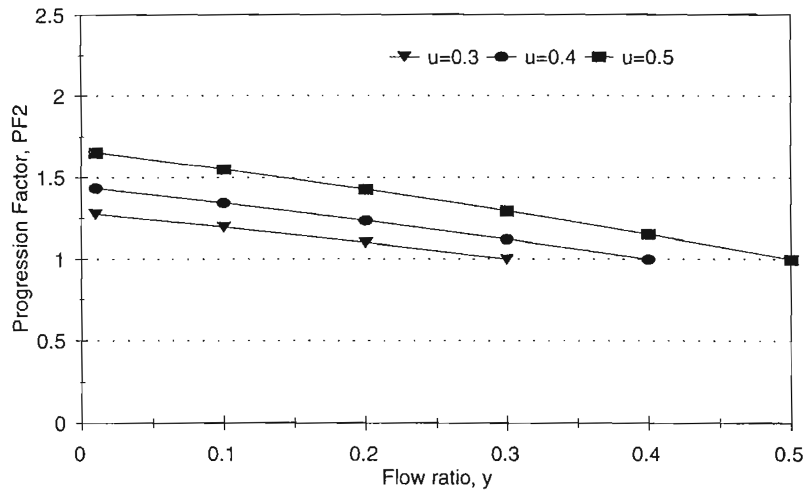

FIGURE 2 Progression factor PF_2 as a function of the flow ratio (y) for Arrival Type 1 (green time ratios u = 0.3, 0.4, and 0.5).

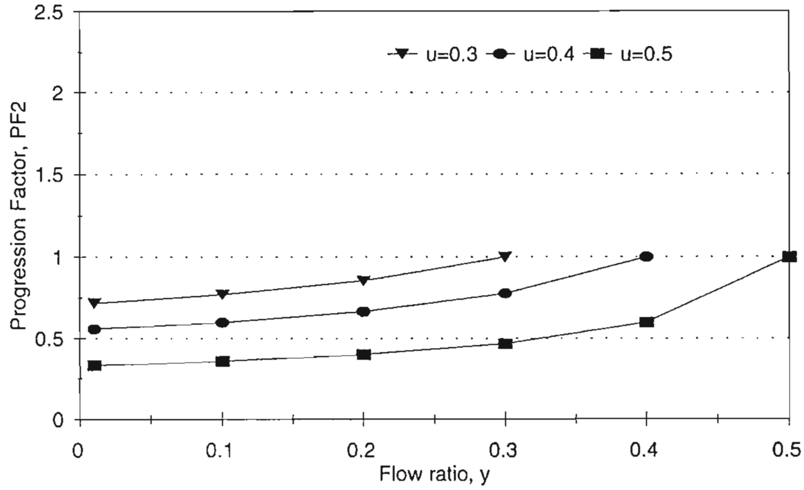

FIGURE 3 Progression factor PF_2 as a function of the flow ratio (y) for Arrival Type 5 (green time ratios u = 0.3, 0.4, and 0.5).

TABLE 2 Progression Factors PF_1 and PF_2 for Default Ratios (P_A) and Various Values of Green Time Ratio ($u = g/c$) and Flow Ratio ($y = q_{ac}/s$)

Arrival Type	P_A	u = g/c	$P_G = P_A u$	$y = q_{ac}/s$	x = y/u	PF_1	PF_2
1	1/3	0.2	0.067	0.10	0.50	1.167	1.086
				0.18	0.90	1.167	1.018
		0.4	0.133	0.20	0.50	1.444	1.238
				0.36	0.90	1.444	1.051
2 (f_{p1} = 0.93)	2/3	0.2	0.133	0.10	0.50	1.008	1.045
				0.18	0.90	1.008	1.009
		0.4	0.267	0.20	0.50	1.137	1.128
				0.36	0.90	1.137	1.029
3	1.0	0.2	0.200	0.10	0.50	1.00	1.00
				0.18	0.90	1.00	1.00
		0.4	0.400	0.20	0.50	1.00	1.00
				0.36	0.90	1.00	1.00
4 (f_{p2} = 1.15)	4/3	0.2	0.267	0.10	0.50	1.00	0.952
				0.18	0.90	1.00	0.989
		0.4	0.533	0.20	0.50	0.894	0.848
				0.36	0.90	0.894	0.957
		0.6	0.800	0.30	0.50	0.575	0.583
				0.54	0.90	0.575	0.821
5	5/3	0.2	0.333	0.10	0.50	0.833	0.900
				0.18	0.90	0.833	0.976
		0.4	0.667	0.20	0.50	0.556	0.667
				0.36	0.90	0.556	0.889
		0.6	1.000	0.30	0.50	0.00	0.00
				0.54	0.90	0.00	0.00
6	2.0	0.2	0.400	0.10	0.50	0.750	0.844
				0.18	0.90	0.750	0.961
		0.4	0.800	0.20	0.50	0.333	0.444
				0.36	0.90	0.333	0.762
		0.6	1.000	0.30	0.50	0.00	0.00
			(P_A = 1.667)	0.54	0.90	0.00	0.00

arrival type and the corresponding f_{p1} and f_{p2} values. Thus, $P_G < u$ would result in $P_A < 1.0$; this would mean Arrival Types 1 or 2 (poor progression).

2. The condition $P_A < 1/y$ is equivalent to the condition $q_{ag} < s$, that is, the average arrival rate during the green period must be less than the saturation flow rate.

3. The condition $P_A \leq 1/u$ is equivalent to the condition $P_G \leq 1.0$, that is, the proportion of traffic arriving during the green period must not exceed 1.0 by definition. For Arrival Types 4 through 6 with high green time ratios (u), the default P_A values shown in Table 1 may result in $P_G = P_A u > 1.0$, in which case $P_G = 1.0$ will be set, and P_A will be recalculated as $P_A = P_G/u = 1/u$. When $P_G = 1.0$ is calculated, this will result in $PF_1 = 0$ and $PF_2 = 0$, and zero values of delay, back of queue, and so forth, may be predicted. If this is found unrealistic, a value of $P_G < 1.0$ (equivalent to $P_A < 1/u$) should be specified.

CONCLUDING REMARKS

The progression factor method is a simple way of allowing for the effect of platooned arrivals on traffic performance at coordinated signals. It is useful at the level of basic capacity and performance analysis of a single intersection where detailed platoon patterns generated at upstream signal stop lines are not available.

More sophisticated analytical models could be developed to improve both the nonrandom and the overflow terms of the performance formulas given in this paper (*15–18*). For full analysis of closely spaced (a network of) signalized intersections, a more detailed model is preferable, using, for example, a step-by-step formulation of arrival, departure, and queue patterns as in the TRANSYT program (*19,20*). A detailed model would also help with the implementation of the queue interaction model (*17,21*). However, the progression factor method still would be useful in making allowance for platooned arrivals at external links of the network under consideration.

The derivation of the progression factors PF_1 and PF_2 is based on the comparison of the first-term values of the relevant performance model for uniform arrivals and platooned arrivals. The calibration factors for variational effects (f_{d1}, f_{b1}, etc.) were derived for the isolated intersection case (nonplatooned arrivals). The values of parameter f_{p2} in the formulas for back of queue and queue move-up rates were adopted from the values of f_{p2} in the HCM delay formula. All the aspects of the model given in this paper should be further investigated through simulation of platooned arrivals at coordinated signals as well as through field data where possible. Similarly, the subject of actuated coordinated signals needs to be further investigated, considering both the first-term and second-term adjustment factors for platooned arrivals.

Application of progression factors to the cases of two green periods per cycle (e.g., protected and permitted turns), shared lanes, opposed turns, and short lanes is discussed by Akçelik (*13*). The progression factor method for queue-related performance statistics described in this paper is being incorporated into the SIDRA software package (*12*).

ACKNOWLEDGMENTS

The author thanks Ian Johnston of ARRB Transport Research, Ltd., for permission to publish this paper. The author also thanks Nagui Rouphail and Mark Besley for their comments on various aspects of the work reported in this paper.

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