# Progression Adjustment Factors at Signalized Intersections

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**This paper presents a set of analytical models for estimating progression adjustment factors (PAFs) to delays at signalized, coordinated intersection approaches. The derived models are sensitive to the size and flow rate of platoons, which in turn are affected by the travel time between intersections. The procedure requires data that are readily available from time-space diagrams and flow counts. A comparison of the factors estimated in this study and their *Highway Capacity Manual* (HCM) counterparts reveals the limitations of the HCM method in predicting levels of service for coordinated approaches, especially under excellent or very poor progression scenarios. Finally, an interactive, computerized procedure is presented that carries out the necessary PAF calculations with minimal input requirements.**

The research presented in this paper represents an application of a previously developed methodology for modeling traffic flow at coordinated intersections. The paper that describes this methodology (*1*) provides detailed derivations of the delay models used to develop the progression adjustment factors (PAFs).

A distinct feature of the 1985 *Highway Capacity Manual* (HCM) (*2*) is its use of stopped delay as the sole determinant of level of service (LOS) at signalized intersections. A key element in determining delay is the quality of progression afforded to the lane group. An examination of Tables 9.1 and 9.13 in the HCM reveals that progression significantly affects LOS. For example, a lane group operating at the midrange of LOS C under random arrival conditions (Arrival Type 3, Table 9.13) operates at LOS B under favorable progression (Arrival Type 5, Table 9.13) and LOS D under unfavorable progression (Arrival Type 1, Table 9.13) at a volume-to-capacity ratio of 0.60. In other words, there are three possible LOS designations for that lane group based on the degree of signal progression provided.

The PAFs in Table 9.13 of the HCM are expressed as the ratio of vehicle delay under a specific progression scenario to delay encountered with random arrivals. While the factors are applied to the overall delay (i.e., uniform plus random delay components), it is not yet clear from the literature whether the random (or overflow) delay component is truly affected by progression. Earlier studies by Hillier and Rothery (*3*) and Robertson (*4*) indicate that progression has little impact on the overflow delay. This is also evident in the TRANSYT-7F model (*5*), where the random delay component is insensitive to offset variations (see Sadegh and Radwan (*6*)). On the other hand, Akcelik (*7*) suggests reducing the random delay component by 50 percent under favorable progression. Pending future evidence to the contrary, it is assumed that progression effects are limited to the uniform delay component.

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A schematic of the traffic modeling concept for coordinated lane groups in the HCM is shown in Figure 1. In the figure, vehicle arrivals occur at two different rates in red ($q_r$) and green ($q_g$), and the proportion of arrivals that occur in the effective green phase is termed *PVG*. If arrivals are random (Line A), then $PVG = g/C$ or $PVG/(g/C) = 1$, where $g$ equals effective green time in seconds and $C$ equals cycle length. The total uniform delay per cycle is equivalent to the area under the arrival rate curves (the shaded area in Figure 1). It is evident that delay decreases as *PVG* increases, and vice versa. Thus, $PVG/(g/C)$ represents the relative traffic density in green. At a relative density of 1, lane group traffic arrives at random and its relative delay (compared with the isolated case) is also 1. In the HCM, the relative density in green is termed the "platoon ratio" ($R_p$), and the relative delay is referred to as the "progression adjustment factor." The platoon ratio is subdivided into five ranges, each designating an "arrival type" as shown in Table 9.13 of the HCM.

## LITERATURE REVIEW

The rather limited calibration data base upon which the PAFs were estimated has spurred a flurry of research activities to calibrate and validate the factor values in Table 9.13 of the HCM. A comprehensive study is nearing completion at the Texas Transportation Institute that will develop empirical models of PAFs on the basis of delay data collected nationwide (*8*). Jovanis et al. (*9*) have reported the findings of a limited validation effort of PAFs in Illinois. Data obtained from 10 intersection approaches controlled by traffic-actuated controllers indicate (a) that PAFs are lower than those listed in the HCM and (b) that PAFs are much less sensitive to the platoon ratio than indicated. These results are depicted graphically in Figure 2. Thus, while a predictive association exists between PAFs and $R_p$, the Illinois data suggest that this association is not strong.

A recent paper by Courage et al. (*10*) compares the HCM's estimated PAFs with corresponding values generated in the TRANSYT-7F model (*5*). This evaluation was performed both for a hypothetical link and for an 85-link network. TRANSYT values were derived through a process of linking and delinking, whereby delay values at a given platoon ratio (via offset manipulation) are divided by their counterpart values when the approach is de-linked, or disconnected, from adjacent signals. The study found that, in general, there was good agreement between the two models: the mean percentage deviation between them was 2.36 percent. It was also observed that the platoon ratio as defined in the HCM is a better predictor of delays with heavy traffic volumes and that a wider

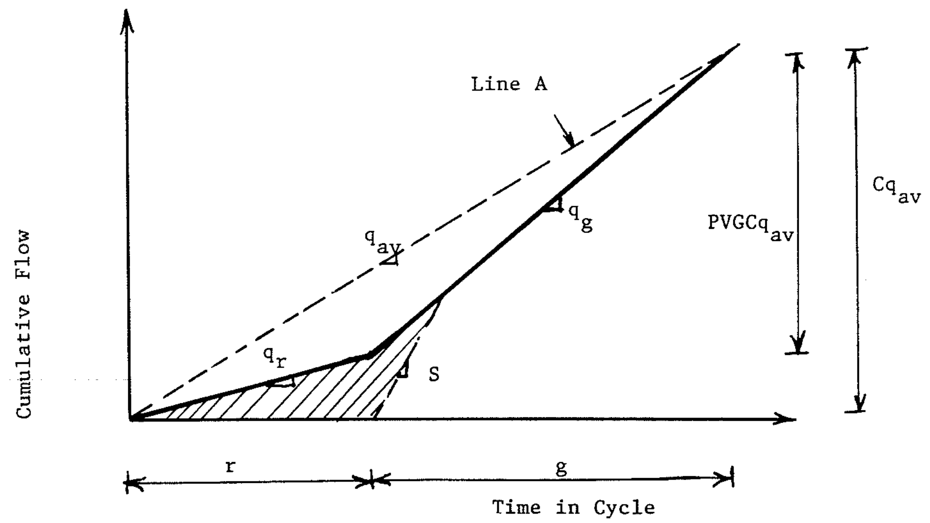


**FIGURE 1 Model of progressed traffic in the HCM (*2*).**

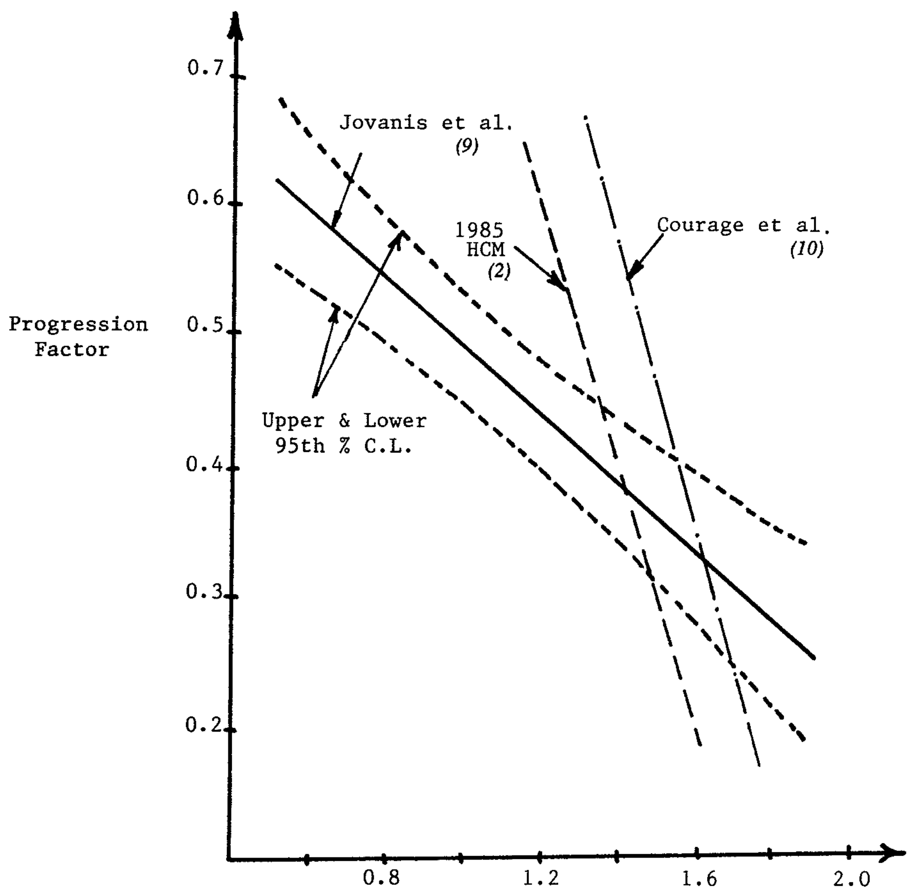


**FIGURE 2 Estimation of progression adjustment factors from literature.**

range of PAFs exists than the HCM recognizes. Therefore, some extrapolation of the HCM values may be warranted to cover exceptionally good or exceptionally poor progression. The study also considers the use of an estimator for $R_p$ based on information derived from time-space diagrams (discussed in detail later in this paper). The regression line of PAF versus $R_p$ from the Courage et al. study (*10*) is shown in Figure 2 for comparison with the Illinois study.

## CRITIQUE OF PLATOON RATIO METHOD

Previous efforts have been directed primarily toward the development of improved PAF estimates based on observations of $R_p$ and other explanatory variables and conforming with the basic structure of the HCM procedure, specifically Table 9.13. While the platoon ratio method is rational and simple, it suffers from many drawbacks, some of which may explain why good correlations were not observed between PAFs and $R_p$. For example

- There is no mechanism in the HCM method for estimating delays under projected conditions. The value of *PVG* must be observed in the field before delays can be estimated. This problem was addressed in the study by Courage et al. (*10*), in which a "band ratio" ($R_b$) estimator is used to predict $R_p$. The formula for $R_b$ is based on the assumption that the density of platoon arrivals in green is proportional to the bandwidth size and the amount of progressed traffic. Nonplatoon arrivals are assigned proportionally to the remainder of the green for nonprogressed traffic. The comparison of $R_p$ and $R_b$ provided in Figure 3 indicates a very close agreement. Note that all elements of $R_b$ (such as cycle length, bandwidth, green times, and percent flow progressed) can be derived from a typical time-space diagram of the arterial.
- The coarse designations of arrival types generate delay estimates that are insensitive to a wide range of platoon ratios. For example, for a lane group with $g/C = 0.50$, Type 2 arrivals are applicable when 25.5 to 42.5 percent of all arrivals occur in green. Clearly, intermediate delay estimates are appropriate in this case. To resolve this problem, current and future research work will focus on developing continuous estimates of PAFs as demonstrated in the studies by Jovanis et al. (*9*) and Courage et al. (*10*).
- The underlying traffic model in the platoon ratio method (depicted in Figure 4a) is not responsive to delays caused by secondary queues. An alternate modeling concept (see Figure 4b) is to consider traffic as two separate and contiguous streams: a platoon of size *B* seconds and flow rate $q_{pl}$ vehicles per second (veh/sec), and secondary flows of duration $C - B$ seconds and flow rate $q_s$ veh/sec (*1*). This concept represents a simplification of the TRANSYT model histograms by averaging flow rates in only two distinct segments. Length *B* can be viewed as the bandwidth size commonly available in time-space diagrams or as the length of the platoon leaving an upstream intersection. An interesting comparison arises between Figures 4a and 4b. Assume in both models that the degree of saturation (*X*) and *PVG* (or $R_p$) are identical; thus, a unique PAF value would exist according to the HCM. In Figure 4b, two conditions are illustrated: an early platoon release in which a dense platoon arrives at the beginning of the green (a Type 5 arrival in the HCM), and a late platoon release in which arriving platoons do not interfere with secondary queues accumulated during the red phase. According to the HCM, this would be categorized as a Type 4 arrival (a dense platoon arriving in the middle of the green). Clearly, there is no unique delay solution even though there were no changes in $R_p$. This example also demonstrates a flaw in the definition of arrival types, since the delay for Arrival Type 5 (the best progression in the HCM) is higher than that for Arrival Type 4. Indeed, it is possible to demonstrate that, unless secondary flows are truly negligible, arrivals of Type 5 are seldom optimal in terms of delay. The difference between the two modeling concepts is more pronounced for relatively short (small *B*) and dense (high $q_{pl}$) platoons since the platoon ratio method tends to spread all arrivals in the green and red periods (see Figure 4a).
- The platoon ratio method does not consider the platoon structure. For instance, adjusting offsets and bandwidths on an arterial to achieve maximum progression is ineffective if platoons experience significant dispersion between intersections. The traffic model in Figure 4b allows for this variable by means of an explicit functional relationship between the flow rates ($q_{pl}$ and $q_s$) and the average platoon travel time (*t*).

## PROPOSED METHODOLOGY

The method proposed in this paper involves three basic steps:

1. The estimation of platoon size and flow rate,
2. The identification and calculation of delay models, and
3. The estimation of PAFs.

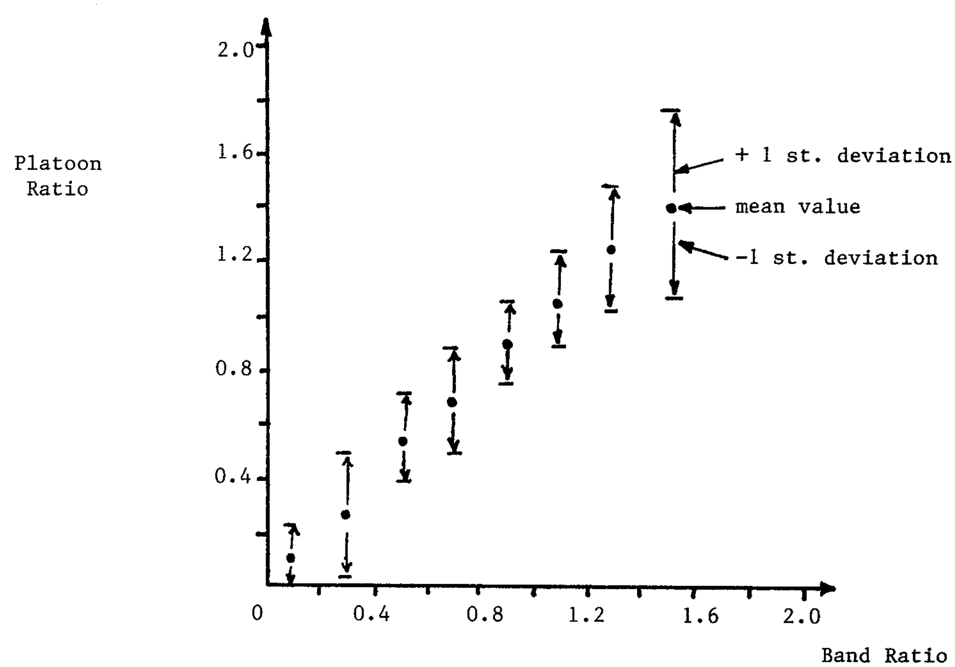


**FIGURE 3 Estimation of platoon ratio from band ratio (*10*).**

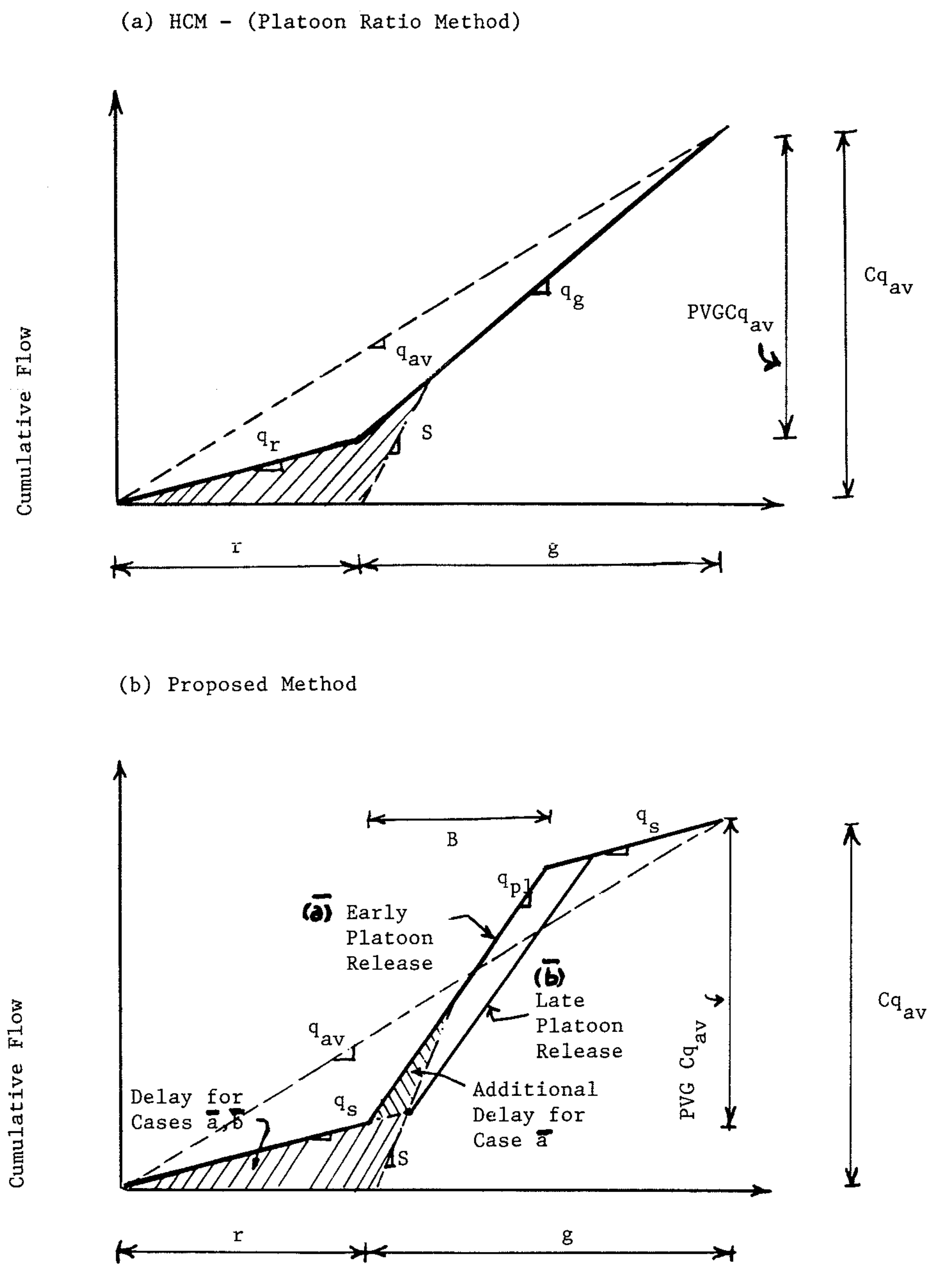


**FIGURE 4 Comparison of model concepts.**

### Estimation of Platoon Size and Flow Rate

Flow rate estimates were derived in a previous paper (*1*) and are summarized below:

$$q_{pl} = q_{av} + (S - \alpha * q_{av}) * \exp(-0.01215 * t) \quad (1)$$

$$q_s = (C * q_{av} - B * q_{pl})/(C - B) \quad (2)$$

$$B = (C - g_u) * \alpha * q_{av}/(S - \alpha q_{av}) \quad (3)$$

where

$q_{pl}$ = average platoon flow rate (veh/sec),
$q_s$ = average secondary flow rate (veh/sec),
$q_{av}$ = average lane group flow rate entering (veh/sec),
$\alpha$ = proportion of traffic that is progressed from the upstream intersection,
$t$ = average platoon travel time (distance/progression speed),
$S$ = saturation flow rate (veh/sec),
$B$ = platoon size (equivalent to the bandwidth size from time-space diagrams or estimated from Equation 3), and
$g_u$ = effective green time at the upstream intersection.

### Identification and Calculation of Delay Models

Uniform delay models were derived in a previous paper by Rouphail (*1*) for the entire range of bandwidth, or platoon, offsets. Offsets measure the time difference between the green start at the subject intersection and the arrival time of the platoon. Offset values thus range from $-r$ (when the platoon arrives $r$ seconds before the green start) to $+g$ (when the platoon arrives $g$ seconds after the green start). Four problem types emerged from those definitions, and they are designated as I,A, I,B, II,A, and II,B based on two selection criteria (see Table 1). Each problem type has a predetermined sequence of delay models for various offset ranges. Delay calculations for the numbered models depicted in Table 1 are given in Appendix I of the source paper (*1*). The paper also provides a thorough evaluation of the generated delay ($d_p$).

### Estimation of Progression Adjustment Factors

In this study, PAFs were applied to both the uniform and random delay components. Random delays, $d_r$, were assumed to be identical to the HCM value:

$$d_r = 173*X^2*\{(X - 1) + [(X - 1)^2 + 16*X/c]^{\frac{1}{2}}\} \quad (4)$$

where $X$ equals lane group volume-to-capacity (V/C) ratio and $c$ equals lane group capacity (vph).

Uniform delays with random arrivals were also assumed to be identical to their HCM counterpart:

$$d_u = .38*C*(1 - g/C)/(1 - X*g/C) \quad (5)$$

The PAF is then expressed as

$$\text{PAF} = (0.76*d_p + d_r)/(d_u + d_r) \quad (6)$$

The 0.76 term converts the approach delays developed in this study to stopped delays consistent with the HCM definition (*6*).

## NUMERICAL APPLICATION

The following example provides a comparison of PAF estimates obtained using the HCM method and the study approach.

An intersection approach services a demand rate of 720 vph in the peak period at a saturation level of 1,800 vphg. Cycle length is 60 sec, and effective green time is 30 sec. About 83 percent of this traffic originates from an intersection 1/3 mi upstream of the approach at a travel speed of 40 mph. The effective green time at the upstream intersection was observed to be 20 sec.

For the five arrival types listed in the HCM, the PAFs were obtained using the two methods and compared.

The following variables were defined:

$q_{av}$ = 720/3,600 = 0.20 veh/sec,
$S$ = 1,800/3,600 = 0.50 veh/sec,
$t$ = 5,280/(3*0*1.467) = 30 sec,
$\alpha$ = 0.83,
$C$ = 60 sec,
$g$ = 30 sec, and
$g_u$ = 20 sec.

TABLE 1 DESIGNATION OF PROBLEM TYPE AND DELAY MODELS (*1*)

| Problem Type | I,A | I,B | II,A | II,B |
|---|---|---|---|---|
| Selection Criteria 1. | $B > r/(1 - q_{pl}/S)$ | $B > r/(1 - q_{pl}/S)$ | $B \le r/(1 - q_{pl}/S)$ | $B \le r/(1 - q_{pl}/S)$ |
| 2. | $B \le g-rq_s/(S-q_s)$ | $B > g-rq_s/(S-q_s)$ | $B \le g-rq_s/(S-q_s)$ | $B > g-rq_s/(S-q_s)$ |
| Applicable Delay Models | | | | |
| Min BW Offset | $-r$ | $-r$ | $-r$ | $-r$ |
| Max BW Offset | $rq_s/(S-q_s)$ | $g - B$ | $\{q_s r-B(S-q_{pl})\}/(S-q_s)$ | $\{q_s r-B(S-q_{pl})\}/(S-q_s)$ |
| Delay Model # | 2 | 2 | 1 | 1 |
| Min BW Offset | $rq_s/(S-q_s)$ | $g - B$ | $\{q_s r-B(S-q_{pl})\}/(S-q_s)$ | $\{q_s r-B(S-q_{pl})\}/(S-q_s)$ |
| Max BW Offset | $g - B$ | $C-B+rq_{pl}/(S-q_{pl})$ | $rq_s/(S-q_s)$ | $rq_s/(S-q_s)$ |
| Delay Model # | 3 | 4 | 2 | 2 |
| Min BW Offset | $g - B$ | $C-B+rq_{pl}/(S-q_{pl})$ | $rq_s/(S-q_s)$ | $rq_s/(S-q_s)$ |
| Max BW Offset | $C-B+rq_{pl}/(S-q_{pl})$ | $g$ | $g - B$ | $g$ |
| Delay Model # | 4 | 5 | 3 | 4 |
| Min BW Offset | $C-B+rq_{pl}/(S-q_{pl})$ | | $g - B$ | |
| Max BW Offset | $g$ | N/A | $g$ | N/A |
| Delay Model # | 5 | | 4 | |

Source: Rouphail (1988)

**Step 1. Platoon Size and Flow Rate Estimates**

From Equation 3, $B$ was estimated as

$$B = 40*0.83*0.20/(0.50 - 0.83*0.2) = 20 \text{ sec} \quad (7)$$

and from Equations 1 and 2, respectively,

$$q_{pl} = 0.20 + (0.50 - 0.83*0.20) *\exp(-0.01215*30) = 0.43 \text{ veh/sec} \quad (8)$$

and

$$q_s = (0.2*60 - 0.43*20)/(60 - 20) = 0.085 \text{ veh/sec} \quad (9)$$

**Step 2. Delay Model Identification and Calculation**

From "Selection Criteria" in Table 1, the following applies:

$$30/(1 - 0.43/0.50) = 214 > 20 \text{ (Problem Type II)} \quad (10)$$

$$30 - 30*0.1/(.50 - .085) = 22.77 > 20 \text{ (Problem Type II,A)} \quad (11)$$

Thus, the following offset (Ofs) ranges and models apply (see Figure 5):

- $-30 \leq \text{Ofs} \leq +2.88$ for Model 1,
- $+2.88 \leq \text{Ofs} \leq +6.14$ for Model 2,
- $+6.14 \leq \text{Ofs} \leq +10.0$ for Model 3, and
- $+10.0 \leq \text{Ofs} \leq +30.0$ Model 4.

To compare the results of the various arrival types, offset values were set at −30, −15, 0, and +15 sec for HCM Arrival Types 1, 2, 5, and 4, respectively. Hence, Model 1 was used to estimate delays for Arrival Types 1, 2, and 5, while Model 4 was used for Arrival Type 4. Referring to Appendix I in the paper by Rouphail (*1*), the following results were obtained:

- For Ofs = −30 sec, $d_p$ = 21.63 sec/veh (Arrival Type 1);
- For Ofs = −15 sec, $d_p$ = 15.08 sec/veh (Arrival Type 2);
- For Ofs = 0 sec, $d_p$ = 8.53 sec/veh (Arrival Type 5); and
- For Ofs = +15 sec, $d_p$ = 10.39 sec/veh (Arrival Type 4).

**Step 3. Estimation of Progression Adjustment Factors**

Delays for a random arrival pattern were computed on the basis of Equations 4 and 5, yielding

$$d_u = 9.5 \text{ sec/veh} \quad (12)$$

and

$$d_r = 3.64 \text{ sec/veh} \quad (13)$$

The resulting PAFs, computed from Equation 6, are summarized in Table 2 along with their HCM counterparts. Surprisingly, the two methods were quite comparable at all offset values (or arrival types) except Arrival Type 1, which was

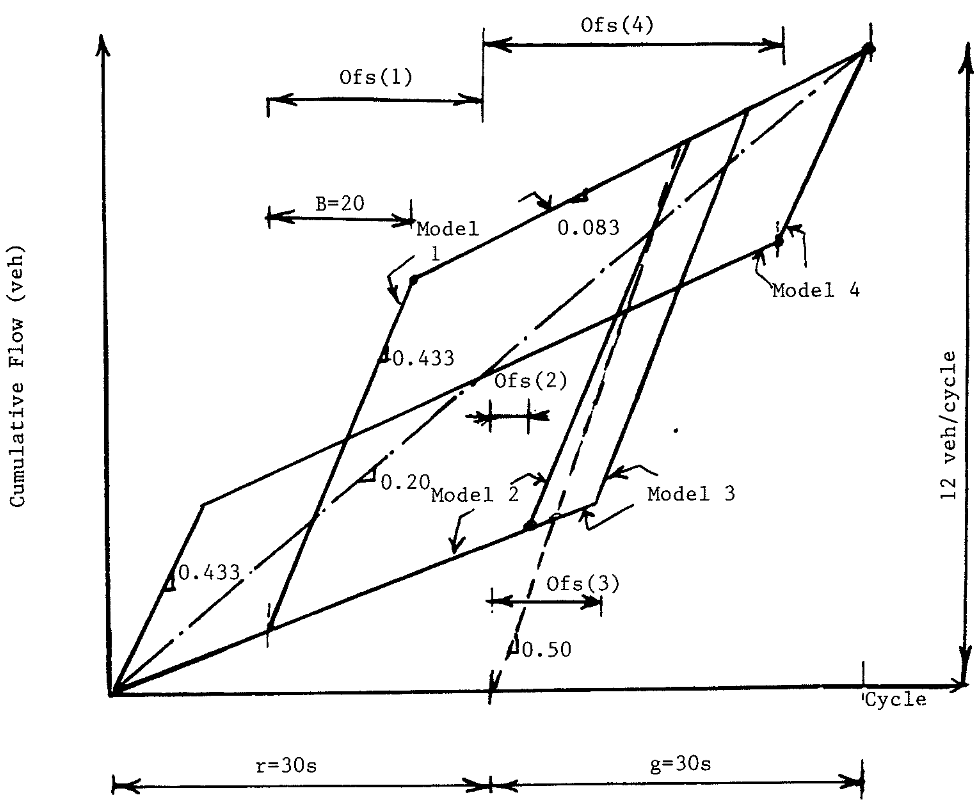


**FIGURE 5 Platoon and secondary flow arrival models for numerical example.**

about 10 percent higher under the proposed model. In addition, the range of PAFs (best to worst progression) was generally higher under the proposed model than with the HCM method. Interestingly, Courage et al. (*10*) observed this same phenomenon with the TRANSYT model. It appears that the platoon ratio method, because of its tendency to spread the arrivals over the entire green and red periods, is less sensitive to short, dense platoons, especially at both ends of the spectrum (Arrival Types 1 and 5). This is demonstrated in Table 3, which replicates the numerical problem but for a shorter platoon (by artificially reducing the red time at the upstream approach). In this case, $g_u$ = 30 sec and the resulting platoon length ($B$) = 15 sec. Both the study and HCM methods show a smaller progression effect, since fewer vehicles arrive in the platoon compared with the original case. But, because the HCM method does not account for the actual size of the platoon, it underestimated the detrimental effect of poor progression (by 18 percent) as well as the beneficial effect of excellent progression (by 30 percent). In fact, the HCM method recognized only two arrival types in this case based on the value of the platoon ratio. Finally, this study shows that a platoon arriving in the middle of the green phase (Arrival Type 4) can result in lower delays for the lane group than if it was set to arrive at the beginning of the green (Arrival Type 5). This is because (a) the remaining green is long enough to clear the platoon and (b) the platoon does not interfere with secondary queues, which use up the initial portion of the green. The proposed model estimated the secondary queue clearance time to be about 10 sec; within that 5-sec "window" ($+10 \le$ Ofs $\le +15$), the platoon does not experience any stopped delay.

TABLE 2 COMPARISON OF PROGRESSION ADJUSTMENT FACTORS BY TWO METHODS WITH PLATOON SIZE OF 20 SECONDS

| Platoon Offset[a] (sec) | Study Delay (sec/veh) | Study PAF | Platoon Ratio | Arrival Type[b] | HCM PAF[c] |
|---|---|---|---|---|---|
| −30.0 | 21.63 | 1.64 | 0.43 | 1 | 1.50 |
| −15.0 | 15.08 | 1.14 | 0.71 | 2 | 1.22 |
| 0.0 | 8.53 | 0.64 | 1.57 | 5 | 0.67 |
| +15.0 | 10.39 | 0.79 | 1.29 | 4 | 0.82 |

[a]Measured from the start of the green to the leading edge of the platoon or bandwidth (negative values indicate arrivals in red).
[b]Taken from Table 9.2 in the HCM.
[c]Taken from Table 9.13 in the HCM for $X$ = 0.80.

TABLE 3 COMPARISON OF PROGRESSION ADJUSTMENT FACTORS BY TWO METHODS WITH PLATOON SIZE OF 15 SECONDS

| Platoon Offset[a] (sec) | Study Delay (sec/veh) | Study PAF | Platoon Ratio | Arrival Type[b] | HCM PAF[c] |
|---|---|---|---|---|---|
| −30.0 | 19.51 | 1.48 | 0.62 | 2 | 1.22 |
| −15.0 | 16.60 | 1.15 | 0.62 | 2 | 1.22 |
| 0.0 | 10.77 | 0.81 | 1.39 | 4 | 0.82 |
| +15.0 | 8.30 | 0.63 | 1.39 | 4 | 0.82 |

[a]Measured from the start of the green to the leading edge of the platoon or bandwidth (negative values indicate arrivals in red).
[b]Arrival types are identified from Table 9.2 in the HCM based on the platoon ratio calculations. If the textual definition is used (for example, Arrival Type 1 occurs when a dense platoon arrives at the start of red), then PAF values would be identical to those in Table 2 of this paper.
[c]Taken from Table 9.13 in the HCM for $X$ = 0.80.

## SENSITIVITY ANALYSIS

A series of experiments was performed with the PAF models to test the effect of individual parameters on the final results. Of particular interest was the effect of the two parameters currently included in the HCM procedure: the lane group degree of saturation and the arrival type. Additionally, the models incorporate the effect of platoon size and dispersion via parameters $B$ and $t$, respectively. The base condition consisted of the values given in the numerical example above with the following range of independent variables:

- Lane group degree of saturation ($X$)—varying from 0.60 to 1.0,
- Platoon travel time ($t$)—varying from 10 to 90 sec,
- Platoon size ($B$)—varying from 3 to 20 sec, and
- Proportion of lane group traffic progressed ($\alpha$)—varying from 60 to 100 percent.

The results are depicted graphically in Figures 6 through 9 and discussed below.

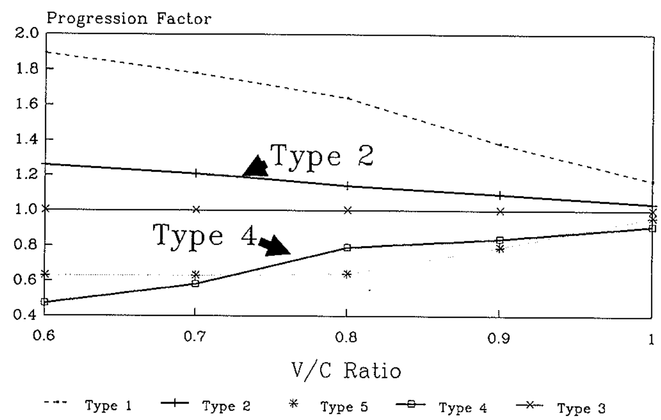


**FIGURE 6 PAF versus V/C ratio by arrival type.**

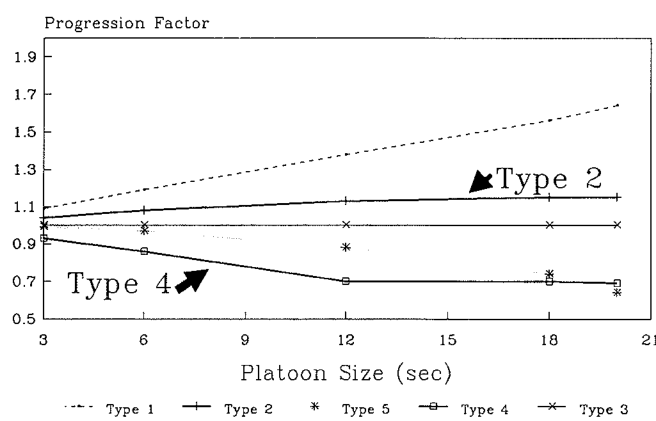


**FIGURE 7 PAF versus platoon size by arrival type.**

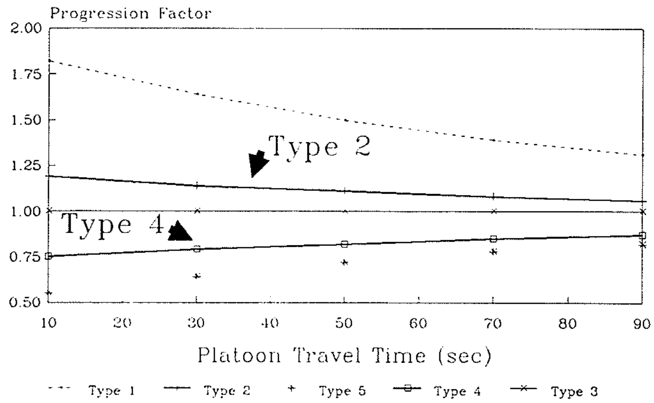


**FIGURE 8 PAF versus travel time by arrival type.**

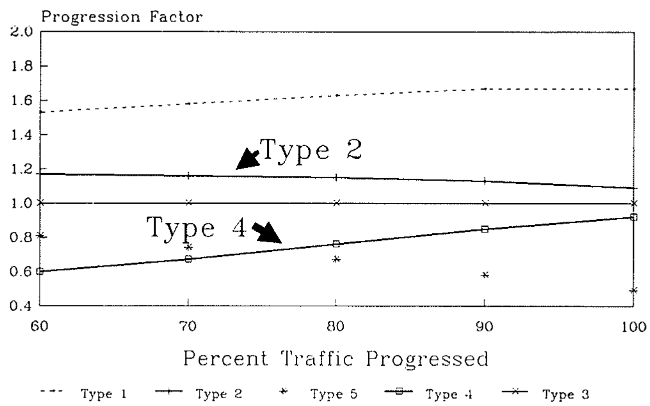


**FIGURE 9 PAF versus percent progressed by arrival type.**

### Degree of Saturation

As the lane group V/C ratio increased, the effect of progression diminished significantly (see Figure 6). This is consistent with Table 9.13 in the HCM. The effects are more dramatic for Arrival Types 1 and 5, and less so for intermediate arrival types. These results must be viewed with caution since all progression adjustments are applied to the uniform delay component only; thus, as the V/C ratio increases, the relative effect of $d_r$ on the PAF becomes more significant, and the overall progression effect tends to diminish.

### Platoon Size

The size of the platoon was artificially manipulated by varying the red time at the upstream intersection. Since the models are only valid for undersaturated conditions, there were constraints on the length of the platoon (or, in other words, on the duration of the upstream red phase). The results are depicted in Figure 7. For Arrival Type 1, the combination of heavy platooning and poor offset selection increased the PAF substantially, while the opposite was true for Arrival Type 5. Furthermore, as long as the platoon length did not exceed one-half of the green phase, Arrival Type 4 consistently yielded lower PAF values than Arrival Type 5. This indicates an offset value that allows secondary queues to clear before the platoon arrival time and allows the platoon to clear the approach in the remaining portion of the green.

### Platoon Travel Time

As suspected, the effect of progression decreased as platoon travel time increased. This is evident from Figure 8, which depicts the relationship between PAF and travel time. The effects were more pronounced at the extreme progression levels designated by Arrival Types 1 and 5.

### Proportion of Progressed Traffic

This parameter represents the percentage of through traffic flow that is progressed from the upstream intersection. This factor is related to the platoon size since the amount of progressed traffic dictates the maximum size of the platoon at the upstream approach. Because of this constraint, it was assumed that an increase in $\alpha$ would correspond directly to an increase in platoon size. The results, which are shown in Figure 9, paralleled those in Figure 7. For Arrival Type 1, an increase in $\alpha$ resulted in higher delays, while the opposite was true for Arrival Type 5. As with the previous finding, Type 4 arrivals were optimal when the platoon size did not exceed half the length of the green phase. This corresponded to values of $\alpha \leq 70$ percent.

## MODEL IMPLEMENTATION

The PAF estimation procedure described in this paper is implemented using an interactive microcomputer program on an IBM PC (or compatible) computer. The program, which is written in BASIC, prompts the user for the following input data:

- Lane group flow rate (veh/sec),
- Lane group saturation flow rate (veh/sec),
- Cycle length (sec),
- Effective green time for the lane group (sec),
- Distance and travel speed from the upstream intersection (ft and mph, respectively),
- Effective green time at the upstream intersection (to estimate platoon size) (sec), and
- Percentage of traffic that is progressed.

A sample input screen for the numerical example described earlier is depicted in Figure 10. The program estimates the platoon and secondary flow rates ($q_{pl}$ and $q_s$, respectively) and determines the sequence of delay models that apply (according to Table 1). This information is displayed in Figure 11.

Finally, the user is prompted to enter an offset interval for displaying the results. For each offset value, the following information is given (see Figure 12):

- Average uniform delay per vehicle in the platoon (sec),
- Average uniform delay per vehicle in secondary flows (sec),

- Average uniform delay per vehicle in the lane group (sec),
- Average total delay per vehicle (uniform plus random) for the lane group (sec), and
- Progression adjustment factor.

In addition, offset values corresponding to Arrival Types 1, 2, 4, and 5 are identified for comparison with Table 9.13 of the HCM. Note that delays for Arrival Type 3 are assumed to be identical to HCM Equation 9.18.

The method described herein requires only two more input items than the HCM procedure—namely, platoon travel time and effective green at the upstream intersection—and is not dependent on field data or estimates of the platoon ratio. It is thus applicable for both design and operational analysis procedures at signalized intersections.

## SUMMARY AND CONCLUSIONS

This paper has presented an application of a methodology for estimating stopped delays at signalized, coordinated intersections. The basic premise was that traffic arrives at two distinct flow rates inside and outside a platoon. This modeling concept was applied to the derivation of PAFs similar to those listed in Table 9.13 of the 1985 *Highway Capacity Manual* (*2*). A comparison of both methods revealed some shortcomings of the platoon ratio method adopted in the HCM. The following summarizes the study results:

- Averaging flow rates within and outside platoons provides better delay estimates than averaging flow rates in the red and green phases.
- The proposed models provide continuous estimates of the PAF as opposed to the discrete values currently used in the HCM method.
- Platoon adjustment factors derived from the study models directly incorporate the effects of upstream conditions on the platoon size and flow rate.
- The HCM factors tend to underestimate the effects of excellent and very poor progression (Type 1 and Type 5 arrivals), as previously determined by Courage et al. (*10*).
- Type 5 arrivals are not always optimal from a delay standpoint as stipulated in the HCM. If the green phase is long enough to clear the secondary queues accumulated in the red phase as well as the main platoon, then Type 4 arrivals may indeed produce shorter delays.

```
A DELAY MODEL FOR MIXED PLATOON AND RANDOM FLOWS
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ENTER AVERAGE THRU FLOW RATE ON APPROACH ,IN VEH/SEC AS QAV ? .20
ENTER SATURATION FLOW RATE FOR APPROACH IN VEH/SEC AS S? .50
ENTER CYCLE LENGTH C IN SECONDS ? 60
ENTER THE EFFECTIVE APPROACH GREEN TIME G IN SEC ? 30
ENTER PROGRESSION SPEED IN MPH ? 40
ENTER DISTANCE FROM UPSTREAM INTERSECTION ,FT ? 1760
ENTER PROPORTION OF APPROACH FLOW (QAV) THAT IS PROGRESSED, IN PERCENT ? 83
NOTE: UPSTREAM GREEN MUST BE >= 19.92 SEC TO MAINTAIN A V/C RATIO <=1
ENTER GREEN TIME AT UPSTREAM INTERSECTION ? 20
```

**FIGURE 10 Sample program input screen.**

```
GENERATED DELAY MODELS AND THEIR BOUNDARIES

ALL OFFSETS ARE MEASURED FROM START OF GREEN PHASE
IF OFFSET < 0 , PLATOON LEADER ARRIVES IN RED ,> 0 IN GREEN
RANGE OF OFFSETS IS - 30 AT RED START TO + 30 AT GREEN END
PLATOON SIZE IS 20 SEC
PLATOON^a FLOW RATE = .43 VEH/SEC AND SEC. FLOW RATE^b = .08 VEH/SEC

OFFSET RANGE      FROM      TO       DELAY MODEL^c #

OFFSET IN SEC     -30       2.88         1

OFFSET IN SEC      2.88     6.14         2

OFFSET IN SEC      6.14     10.11        3 *

OFFSET IN SEC      10.11    30           4

NOTE :FOR MODEL TYPE 3 , NO PLATOON DELAY OCCURS IN THIS RANGE

PRESS ANY KEY TO MOVE TO NEXT SCREEN
```

Legend: (a) $q_{pl}$

(b) $q_s$

(c) See Table 1, Problem Type II, A

**FIGURE 11 Determination of delay model and parameters.**

```
            DELAYS AT SPECIFIED  OFFSETS FOR  80 % SATURATION
      AVERAGE  DELAY FOR TYPE 3 ARRIVALS =  13.13789  SEC/VEH(a)
          PERCENTAGE OF APPROACH VOLUME OCCURING IN PLATOON=  71  %
           PLATOON RATIO FOR ZERO PLATOON OFFSET=  1.574751(b)

              AVERAGE  VEHICLE DELAY FOR SPECIFIC SUBGROUPS IN SEC/VEH
```

| OFFSET | PLATOON | NON-PLAT. | UNIFORM | OVERALL | PROGR. FACTOR[c] |
|---|---|---|---|---|---|
| -30 | 21.77 | 8.5 | 17.99 | 21.63 | 1.64 |
| ABOVE OFFSET REPRESENTS TYPE 1 ARRIVALS IN THE 1985 HCM | | | | | |
| -25 | 18.61 | 8.75 | 15.81 | 19.45 | 1.48 |
| -20 | 15.46 | 9.01 | 13.63 | 17.26 | 1.31 |
| -15 | 12.31 | 9.27 | 11.44 | 15.08 | 1.14 |
| ABOVE OFFSET REPRESENTS TYPE 2 ARRIVALS IN THE 1985 HCM | | | | | |
| -10 | 9.14 | 9.52 | 9.26 | 12.9 | .98 |
| -5 | 6 | 9.78 | 7.07 | 10.71 | .81 |
| 0 | 2.85 | 10.04 | 4.89 | 8.53 | .64 |
| ABOVE OFFSET REPRESENTS TYPE 5 ARRIVALS IN THE 1985 HCM | | | | | |
| 5 | .12 | 10.26 | 3 | 6.64 | .5 |
| 10 | 0 | 10.27 | 2.92 | 6.55 | .49 |
| 15 | 5.53 | 9.82 | 6.75 | 10.39 | .79 |
| ABOVE OFFSET REPRESENTS TYPE 4 ARRIVALS IN THE 1985 HCM | | | | | |
| 20 | 11.07 | 9.37 | 10.59 | 14.23 | 1.08 |
| 25 | 16.48 | 8.93 | 14.34 | 17.97 | 1.36 |
| 30 | 21.77 | 8.5 | 17.99 | 21.63 | 1.64 |
| ABOVE OFFSET REPRESENTS TYPE 1 ARRIVALS IN THE 1985 HCM | | | | | |

```
DO YOU WISH TO TEST ANOTHER SET OF OFFSETS? Y/N ?
```

Legend: (a) Computed from Eq. 9.18 in HCM *(2)*.
(b) $R_p$ for Arrival Type 5 in HCM.
(c) Progression Factors → Compare with Table 9.13 in HCM.

**FIGURE 12 Sample output display screen.**

• While the procedures described in this paper are amenable to manual computations, they are readily applied in an interactive programming environment. Only eight input values are needed to run the program, two of which are not currently used in the HCM method but can be easily estimated.

• The Study method requires no field data collection of platoon ratios and thus is applicable to both operational analysis and design procedures for signalized intersections.

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