Modeling the Effect of Traffic Signal Progression on Delay

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The Highway Capacity Manual (HCM) offers a new model for assessing the effect of signal progression on delay at a signalized intersection. This paper discusses a comparison between the HCM progression model and the progression model used in TRANSYT, a signal design and evaluation program which has been in use for several years. The TRANSYT-7F program is used to compare the delays estimated for various qualities of progression with the delays estimated for random arrivals. Comparisons are made on a single pair of links under controlled conditions and on a network of 85 links under simulated field conditions. It was demonstrated that the two techniques agree quite closely. It was also observed that the platoon ratio, R_p as defined in the HCM, provides a better predictor of progression quality with heavy traffic volumes. The TRANSYT results suggest that a wider range of progression adjustment factors exist than the HCM recognizes, and that some extrapolation of the HCM values may be warranted to cover exceptionally good and exceptionally poor progression. An independent indicator of progression quality was also developed and tested. It is derived from the ratios of bandwidth measured on the time-space diagram and is therefore termed the "band ratio." The advantage of the band ratio is that, unlike the platoon ratio, it may be computed without field studies. From the studies reported in this paper, it appears that the band ratio may be used as a cost-effective substitute for the platoon ratio for most purposes.

The need to coordinate the operation of two or more traffic signals which operate in close proximity is self evident. A wealth of literature exists on the subject of coordinated signal systems. A variety of techniques, ranging from simple graphic approaches to microscopic computer simulation programs, is available to the analyst. Each technique deals with some aspect of the system performance, expressed in terms of delay, stops, bandwidth efficiency, or other measures of effectiveness.

The most recent entry in the field of traffic analysis models is the 1985 Highway Capacity Manual (HCM) technique for determining delay at signalized intersections (1). This technique recognizes the axiom that delay at any given signal is influenced by the quality of traffic progression from its neighbors. A progression adjustment factor, PF, is given in table 9-13 of the HCM. The PF is a scalar multiplier which increases or decreases the delay as a function of the progression quality, the degree of saturation, and the type of control equipment (pretimed, traffic actuated, etc.). The values contained in HCM table 9-13 range from 0.40 to 1.85, indicating that the quality of progression, as viewed by the HCM, exerts a substantial effect on the delay at a signalized intersection.

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Other traffic control system models which have been in use for several years also recognize the effect of the quality of progression on delay. One such model, the Traffic Network Study Tool (TRANSYT) (2), has been used widely in several countries. This paper will compare the TRANSYT and HCM progression modes.

In the following discussion, the computational aspects of the two models will be compared. The results will then be examined on a single pair of links with controlled conditions and on a network with approximately 85 links with varying quality of progression.

The scope of this paper is limited to the effects of progression. No comparisons of the absolute values of delay are appropriate to the methods used in this study. This is simply a comparison of the relative degree of improvement attributable to progression as seen by two different analysis models.

BACKGROUND

The TRANSYT model was developed initially by Dennis I. Robertson in 1968. Subsequently it has been improved primarily by the Transport and Road Research Laboratory and others in several nations. It has been extensively tested and used throughout the world for design and evaluation of traffic signal timing.

The program has evolved substantially since its original development and several versions have been released. The specific version of TRANSYT used in the study was TRANSYT-7F (3). The HCM has also evolved since its first release in 1950. The 1985 version incorporates significant enhancements over its predecessors, especially in the analysis of traffic signal operations.

COMPUTATION OF DELAY

There are some important similarities and differences between the TRANSYT and HCM delay models. They are similar in the sense that they both use variations of the general two-component delay model originally proposed by Webster (4). In this model, delay is expressed as the sum of two separate functions:

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

where

D = the delay per vehicle (seconds);
d_1 = the delay which would result if the traffic volumes were uniform from cycle to cycle; and

TABLE 1 COMPARISON OF TRANSYT AND HCM DELAY MODELS

Delay element	TRANSYT	HCM
Uniform Delay (d_1)	Arrivals are projected on each step of the cycle (may 60 steps per cycle) from the previous intersection. Queues are stored on the red and released on the green to be projected to the next signal on a step by step basis.	The average delay per vehicle is computed based on the assumption of uniform arrivals. No consideration is green to adjacenet signals.
Random and saturation delay d_2	An emperically derived formula is applied. The formulation differs somewhat between the two models. The degree of saturation exerts the strongest influence in both cases.	
Quantification of progression quality	There is no progression adjustment in TRANSYT. The detailed treatment of arrivals in the uniform delay computation accounts for the effect of progression.	Progression quality is grouped into one of five categories. Assessment may be subjective or based on the observed proportion of vehicles arriving on the green.
Progression adjustment (PF)		An adjustment factor is determined by table look up based on the arrival category and the degree of saturation.

d_2 = the additional delay which results from variability of volumes throughout the analysis period. This is generally referred to as the "random and saturation" delay.

On the other hand, the two models differ in the way that both terms are derived and applied. A detailed comparison of the computational aspects of the two models is given in table 1. The main difference evident from this comparison is that TRANSYT accounts for the effect of progression by dividing the cycle into as many as 60 equal time steps and performing a discrete analysis of traffic flow for each time step. The HCM, on the other hand, makes the original computations with no consideration of progression, then performs a final progression adjustment based primarily on arrival type and degree of saturation.

The determination of the arrival type requires some further consideration. The arrival type is the sole measure of progression quality. It must be assigned a value between 1 and 5. Higher values indicate better progression. The middle of the range (i.e., Type 3) indicates the neutral condition resulting from random (or uniform) arrivals.

Progression quality is difficult to assess subjectively. The HCM provides some guidance here in the form of a "platoon ratio," R_p, which reflects the proportion of vehicles arriving on the green relative to the proportion of green time given to the approach.

Table 9-2 in the HCM suggests a relationship between platoon ratio and the arrival type. The platoon ratio is defined in the HCM as:

$$R_p = PVG/PTG \qquad (2)$$

where PVG is percentage of vehicles arriving during the (effective) green; and PTG is percentage of the cycle that is green for this movement.

Since the comparisons between these two models must be made on a quantitative basis, the platoon ratio will be used as an indication of arrival type for purposes of this paper.

ANALYSIS PROCEDURE

Both the platoon ratio and the progression adjustment factor must be obtained from TRANSYT before any comparisons may be made with the HCM procedure. Neither of these items are direct outputs of the TRANSYT program. The derivation of both quantities required some innovative applications of TRANSYT combined with some external programming for data reduction purposes. In neither case was the TRANSYT model modified in any way. Instead, maximum use was made of the graphics data file (GDF) produced by TRANSYT-7F for analysis purposes. The graphics data file is described in Appendix D of the TRANSYT-7F User's Manual (3).

The complete analysis procedure is illustrated in figure 1, which shows the data flow through the various computational steps. To compare the effect of progression in TRANSYT, it is necessary to have two TRANSYT runs which are identical in all respects, except that one of the runs must have the progression linkages established and the other must have them removed. This is accomplished by a "delinking" process which will be described later.

TRANSYT outputs, in the form of GDFs, were obtained for both conditions of progression (linked and delinked). At
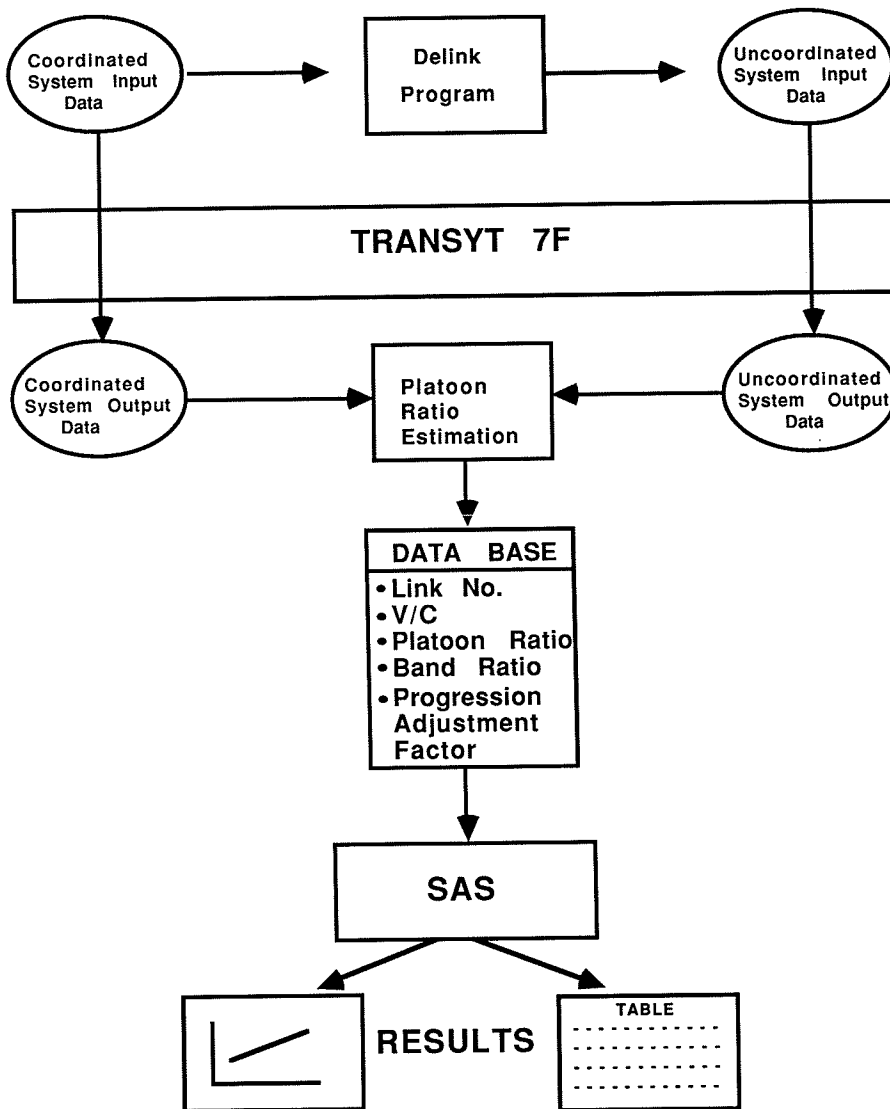
FIGURE 1 Data reduction and analysis procedure.

this point, a separate data reduction program [a modified version of the Platoon Progression Diagram (PPD) program, which is described in Appendix I of the *TRANSYT-7F User's Manual* (*3*)] was run to determine the platoon ratios by simply accumulating the arrivals on the red and green phases on a step-by-step basis. This information was obtained from the stopline flow profile data contained in the GDF.

Since the GDF also contains delay information for each link, the progression adjustment factor was easily determined by dividing the computed delay for the linked operation by the computed delay for the delinked operation. Similarly, the other independent variables, degree of saturation, was obtained directly from the GDF. All of the data items generated by the data reduction program were placed in a data base for analysis by Statistical Analysis System (SAS) (*5*) to produce the results which will be presented later.

THE BAND RATIO

The platoon ratio, R_p, is essentially a field measurement. This places some limits on its value as an element of capacity analysis because it is possible to measure only for existing conditions. The platoon ratio is also costly and time consuming to measure. An alternative measure which could be applied without specialized field studies would be a definite asset.

The time-space diagram (TSD) provides a good starting point for the derivation of a progression quality measure because the TSD represents progression quality graphically in terms of the relative widths of progression bands.

Assume for the moment that traffic approaches a signal with one of two platoon densities which are represented by the relative proportion of vehicles entering at the upstream signal on the artery and on the cross street. Then:

P_a = the proportion of traffic entering upstream from the artery, and

$1 - P_a$ = the proportion of traffic entering upstream from the cross street.

With this simplifying assumption, the TSD for a single link would appear as shown in figure 2. The arrivals on the green
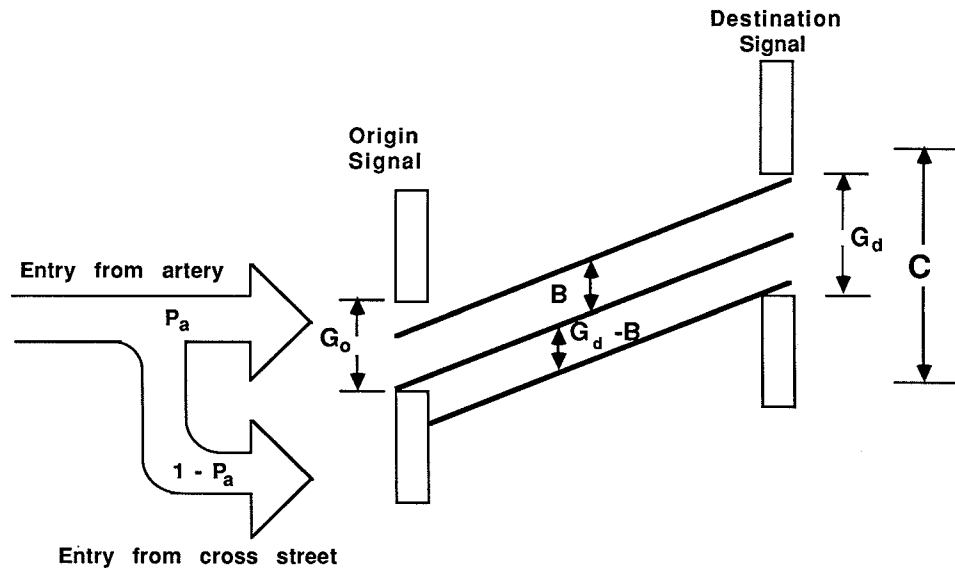
FIGURE 2 Time-space diagram of a single link with progression.

phase at the downstream intersection would be at relative density P_a within the band and at relative density $1 - P_a$ outside of the band. Now, let:

C = the cycle length,
B = the band width,
G_o = the green time at the origin signal and
G_d = the green time at the destination signal.

Then the proportion of vehicles arriving on the green at the downstream signal within the band will be:

$$P_1 = P_a \cdot \frac{B}{G_o} \qquad (3)$$

The proportion of vehicles arriving on the green at the downstream signal outside of the band will be:

$$P_2 = (1 - P_a) \frac{G_d - B}{C - G_o} \qquad (4)$$

So the total proportion of vehicles arriving on the green at the downstream signal will be the sum of the two proportions just computed.

Now, the platoon ratio is defined by the HCM as the proportion of arrivals on the green relative to the proportion of green time available. So, an estimator of the platoon ratio would be given as:

$$R_b = \frac{PVG}{PTG} = \frac{P_1 + P_2}{G_d/C}$$

$$= \frac{C}{G_d} \left[\frac{P_a B}{G_o} + \frac{(1 - P_a)(G_d - B)}{C - G_o} \right] \qquad (5)$$

R_b will be called the band ratio for the remainder of this discussion.

One of the objectives of this paper will be to determine how well the band ratio serves as a quantitative indication of the quality of progression. In other words, is it possible to make a realistic assessment of arrival types given only the traffic volumes and the time-space diagram?

THE DELINKING PROCESS

TRANSYT's traffic simulation model has gained a well-deserved reputation for the realism with which it macroscopically models traffic flow in a coordinated system. The macroscopic model, although not as ultimately realistic as a stochastic microscopic simulation model, is necessary to TRANSYT because it is used identically in the optimization process.

The value of the model is primarily due to the propagation of traffic from multiple upstream sources (links) to downstream movements (also links) and the dispersion of traffic from link to link. The user establishes the link-to-link relationships through data inputs. Specifically, for each interior link, at least one, and up to four, upstream links are identified as source, or feeder links to the current link. Indeed, it is this link-to-link relationship, which "coordinates" adjacent signalized intersections.

Coordinated link flows propagate along the assigned "paths" passing through the platoon dispersion model. The relative position of the green phase at the downstream intersection affects the number of vehicles queued, and thus delayed.

A way of approximating uncoordinated operation is to "delink" the link-to-link relationships. This is easily accomplished by simply deleting the upstream input link number(s) and volume(s) from the link data cards in the TRANSYT input file. The length and primary link speed are retained to enable measures of effectiveness (MOEs) such as total travel, total travel time, and fuel consumption to be comparable.

The delinking process was accomplished in this study using the DELINK program. DELINK is quite simple to use. The network is coded normally with the link-to-link connections in place. DELINK locates all links at each intersection to be delinked as well as the inputs of that intersection to its neighbors and removes the data from the fields which represent the input links. For those familiar with the TRANSYT-7F coding scheme, the values in fields 7, 8, and 10–15 of the link data card (type 28) are deleted. The speed in field 9 is retained.

The DELINK program was used in this study to transform

many "coordinated" links, with platooned arrivals randomized by link, to completely randomized arrivals on all links. This is analogous to many links having arrival types varying randomly from 1 to 5, to a fixed index of 3 on all links.

The DELINK program has been incorporated, along with a number of other useful programs, into a "Signal Utility Package" (SIGUTIL) available from the McTrans Center.

STUDY RESULTS

This study addresses two specific questions:

1. How does the progression adjustment factor (*PF*) computed by TRANSYT compare with the *PF* computed by the HCM based on platoon ratios and volume/capacity ratios estimated by TRANSYT; and
2. How well does the band ratio, R_b, proposed earlier in this paper, serve as an estimator of the platoon ratio, R_p?

The first question will be addressed using a single link pair with controlled volumes and offsets to produce the full range of simulated conditions. The second question will use a more extensive network which was analyzed by TRANSYT using input data from the field.

The Single Link Pair Study

A pair of links was created hypothetically using two interconnected signals. The TRANSYT runs were made for three traffic volume levels representing 50, 70, and 90 percent saturation. There were no turning movements. These represent mid-range values for each of the three degrees of saturation represented in the progression adjustment factor table in the HCM. The signal timing was based on a 60-second cycle with 50 percent green time. The controller offset was varied by 5-second intervals throughout the cycle. The forward and reverse direction links were given unequal lengths for added variability in the data.

By this method, 72 observations (12 × 2 × 3) were created for platoon ratio, band ratio, coordinated delay, and uncoordinated delay. The progression adjustment factor, PF, was determined for each observation by dividing the coordinated delay by the uncoordinated delay.

The results of this study are shown in figure 3. The observations of progression factor are plotted against platoon ratio separately for each of the three saturation levels. The progression factors computed from the HCM are shown on each plot. The HCM progression factors were obtained from HCM table 9-13 as a function of arrival type estimated from the platoon ratios using HCM table 9-2. Since TRANSYT models pretimed control explicitly, the pretimed control section of HCM table 9-13 was used to determine the HCM progression factors.

There are three observations which stand out clearly on figure 3. The first is that there is excellent general agreement between the progression factors computed by the HCM and by TRANSYT for each of the three saturation levels. The "staircase" function of the HCM method provides a very close visual fit to the data points which were obtained from the
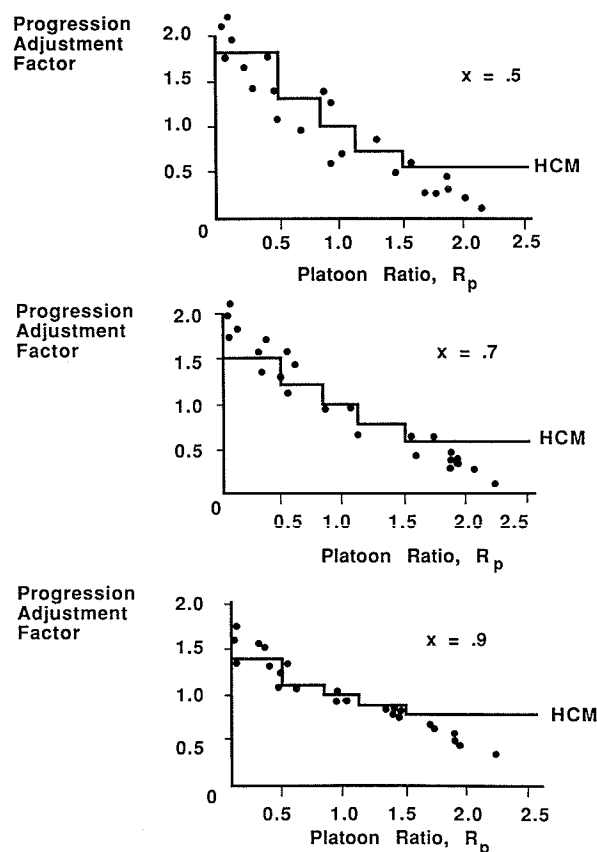

FIGURE 3 Platoon ratio versus progression adjustment factor for pretimed control.

TRANSYT runs. This finding lends credibility to both methods, since the two were developed independently.

A second look at figure 3 suggests that the saturation level affects the predictability of the progression adjustment factor. At high levels of saturation, as indicated by the plot for *X* = .9, the data points adhere very closely to the line which represents the HCM results. At low saturation levels, represented by the plot for *X* = .5, the data points still follow the HCM function, but with much more dispersion. At the saturation level represented by *X* = .7 the dispersion is clearly between the two extremes. This suggests that the platoon ratio is a better predictor of the quality of progression at higher levels of saturation.

The third observation apparent from figure 3 is that the range of progression adjustment factors computed by TRANSYT exceeds the range specified in the HCM at both ends of the scale. This suggests that, from TRANSYT's point of view, extremely good progression will reduce delay by a greater amount than indicated by the HCM. It also suggests that extremely bad progression will cause more delay than the HCM would predict.

The implications of this observation are most important in the area of good progression. The minimum value of the progression factor in HCM table 9-13 for pretimed control is 0.53. TRANSYT, on the other hand, estimated values much lower than this when progression was "perfect." Because of this study's controlled conditions, it was possible to achieve better progression in the computer than would normally be
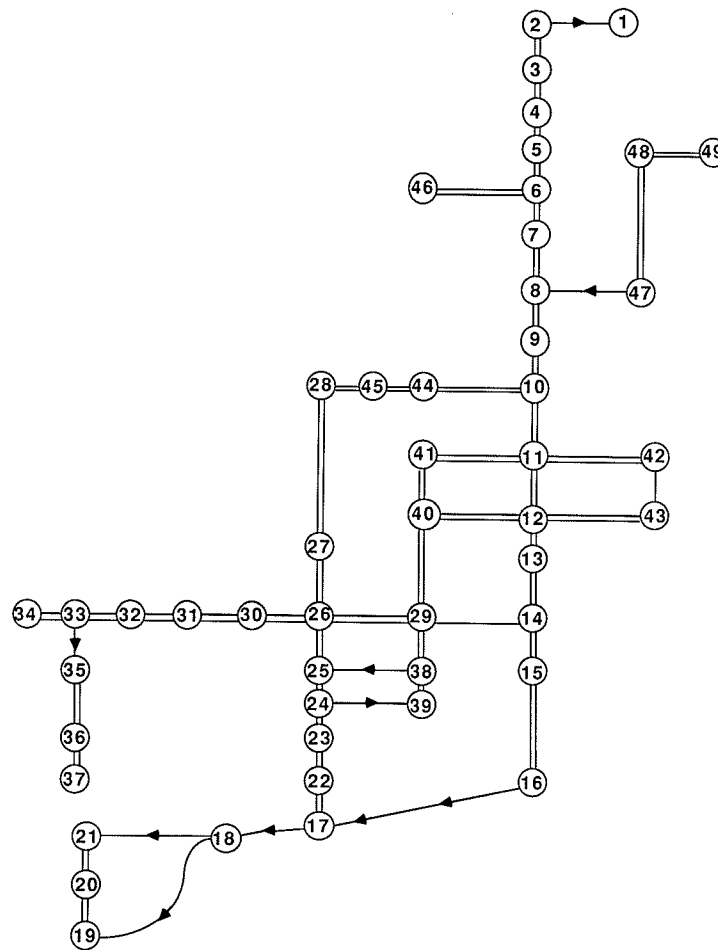
FIGURE 4 TRANSYT-7F network configuration for progression delay study.

observed in the field. However, it is reasonable to conclude from these results that when truly "ideal" progression exists in the field, for example at intersections with extremely short spacing and no significant entry from cross-street turning movements, then the delay is probably being overestimated by the current HCM method.

Network Study Description

While highly controlled conditions were appropriate for the previous analysis, an actual network with field data can better assess the value of the quantitative relationships between the variables. The network chosen for this study contains 49 intersections and 85 links as figure 4 illustrates. The information was obtained from an available TRANSYT data set coded for Port Huron, Michigan. The network configuration and signal phasing reflect actual field conditions. The traffic volumes were, however, increased selectively to create a wider variety of saturation levels. The controller offsets were manipulated artificially also to ensure a wide range of progression quality. Twenty-four TRANSYT runs were performed on this network with the controller offsets established randomly. By this process, 2,040 separate observations were generated. The degree of saturation (v/c ratio) ranged from .06 to .93, with

a mean value of .63. The progression quality, as indicated by the PF, ranged from .22 to 2.81, with a mean value of 1.06. This suggests that the randomized controller offsets have produced neutral progression on the average.

Platoon Ratio vs. Band Ratio

Each of the 2,040 observations included a platoon ratio, R_p, and a band ratio, R_b. To assess the value of R_b as an estimator of R_p, these two quantities were plotted and a regression analysis was performed.

The results are presented in figure 5. The relationship between the two progression quality indicators is plotted to illustrate both the central tendency and the dispersion inherent in this relationship. It is quite apparent from figure 5 that a strong relationship exists. A visual inspection suggests a linear relationship with a 1:1 slope and zero intercept. The equation obtained by linear regression is:

$$R_p = 0.99R_b + 0.012 \qquad (6)$$

The correlation coefficient, r^2, for this model is 0.55, indicating that approximately 55 percent of the variation may be explained by the model. This is not exactly a deterministic relationship; however, considering the relative ease with which
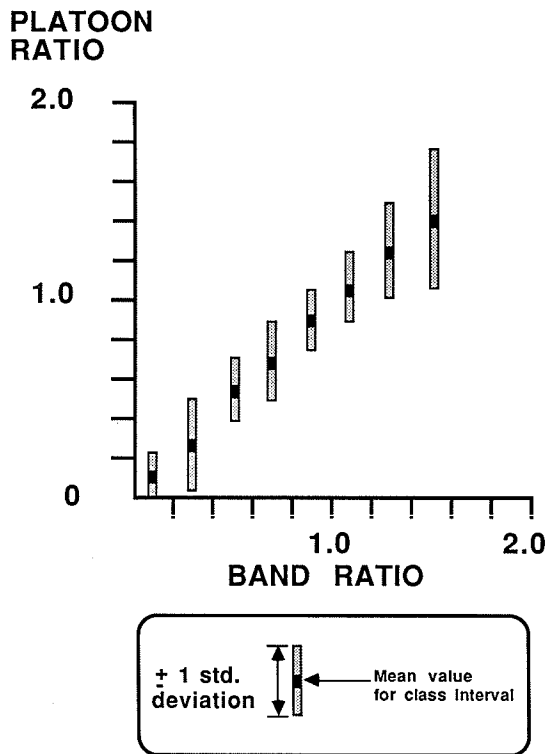
**PLATOON
RATIO**

FIGURE 5   Platoon ratio versus band ratio as computed by TRANSYT.

the band ratio may be determined compared to the platoon ratio (which requires field studies), it is reasonable to conclude that the band ratio could be used as a cost-effective substitute for the platoon ratio for most purposes.

Progression Factor Comparison

The progression factor for each observation was computed in two ways. The ratio of linked delay to delinked delay gave the progression factor as computed by TRANSYT. The HCM progression factor was determined from HCM table 9-13, based on the value of the platoon ratio (also a TRANSYT computation). The error between the two values was defined by

$$E = \frac{PF_T - PF_H}{PF_T + PF_H} \times 200$$

where

E = percent error referenced to the average value of the two estimates,

PF_T = progression factor computed by TRANSYT, and

PF_H = progression factor computed by HCM.

Figure 6 illustrates the distribution of the error. The mean error for the entire sample was 2.36 percent, which indicates a very small average discrepancy between the two methods. The standard deviation, on the other hand, was 29 percent, indicating that individual errors were sometimes substantial.

Neither the degree of saturation nor the progression quality showed a significant effect on the magnitude of the error.
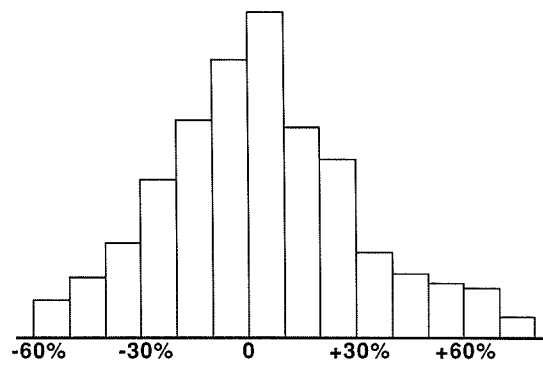

FIGURE 6   Distribution of error in progression factor computations.

Progression Factor vs. Platoon Ratio

The comparison of the platoon ratio and the progression factor was originally carried out for a single link pair and illustrated in figure 3. A more quantitative study of this relationship was performed on the network data. The results are shown in figure 7, which shows the mean and standard deviation of the progression factor computed by TRANSYT as a function of the platoon ratio. The regression equation was

$$PF = 2.19 - 1.14\,R_p$$

The correlation coefficient, r^2, was .51. These results suggest that the platoon ratio is indeed an indicator of the quality of progression in a coordinated signal system, as suggested by the HCM.
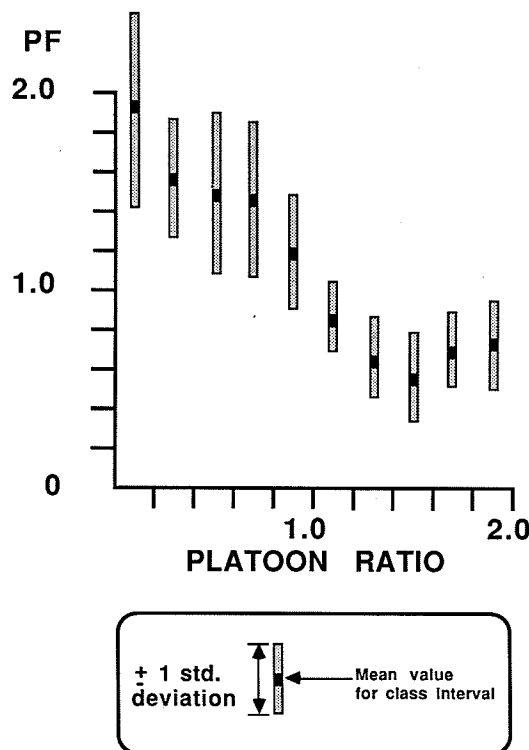

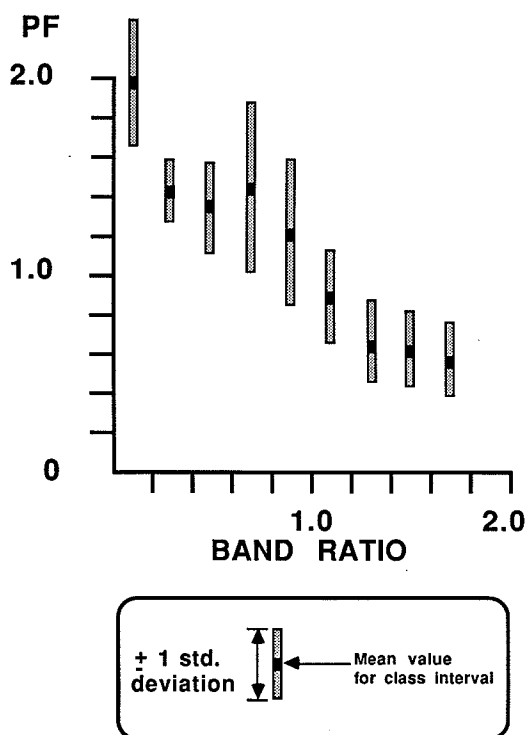**FIGURE 7   Progression factor versus platoon ratio as computed by TRANSYT.**

FIGURE 8   Progression factor versus band ratio
as computed by TRANSYT.

Progression Factor vs. Band Ratio

It has already been established that the platoon ratio and the
band ratio are strongly correlated. Therefore, it is a reason-
able hypothesis that the band ratio could function as a prac-
tical surrogate for the platoon ratio in quantifying the arrival
type. The relationship between progression factor and band
ratio is shown in figure 8, which has the same format as the
progression factor-platoon ratio relationship shown in figure
7. On the surface, the two relationships appear to be very
similar. The regression equation for the band ratio is

$$PF = 2.26 - 1.20\,R_b$$

which agrees very closely with the platoon ratio equation. The
correlation coefficient was .32 compared to a value of .51 for
the platoon ratio equation. This suggests that, while field
measurement of platoon ratio provides a more reliable indi-
cator of progression quality, the band ratio should offer an
acceptable substitute when field data are not available.

A further test of the validity of the band ratio was per-
formed by comparing the progression factor estimated from
HCM table 9-13 using the computed values of the platoon
ratio and the band ratio. The band ratio produced the same
estimated progression factor as the platoon ratio in 69 percent
of the cases. Of the remaining 31 percent, the band ratio
produced closer agreement with the TRANSYT progression

factor in 19 percent of the cases, and the platoon ratio pro-
duced better agreement in the final 12 percent. This offers
further support for the band ratio as an estimator of pro-
gression quality.

CONCLUSIONS

Within the limitations of this study, the following conclusions
are offered.

There appears to be excellent general agreement between
the HCM method and the TRANSYT model on the effect of
the arrival type (as measured by the platoon ratio) on the
progression adjustment factor. The average discrepancy
between the two models was extremely small, although larger
differences were observed on individual data points. The pla-
toon ratio is a better predictor of the arrival type when the
saturation level is high. The TRANSYT model suggested that
some extrapolation of the current values in HCM table 9-13
may be desirable to account for extremely good and bad
progression.

The band ratio, R_b, developed in this paper is considerably
easier to measure than the platoon ratio, R_p, defined in the
HCM. The platoon ratio is based on field measurements,
whereas the band ratio is based on simple bandwidth ratios
taken from the time-space diagram. A comparison of these
two measures suggests that the band ratio is an adequate
predictor of the platoon ratio for most purposes. It is highly
cost effective and provides estimates of the quality of pro-
gression for hypothetical situations where the platoon ratio
cannot be measured.

It is important to remember that the data presented in this
paper are the result of a modeling application and do not
represent actual field observations of the relationships which
are reported. They are, however, based on a model which
has been extensively used and accepted throughout the world.
The agreement between TRANSYT and the HCM reported
herein should be considered as a "plus" for both techniques.

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