# Validation of Saturation Flows and Progression Factors for Traffic-Actuated Signals

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**A need for empirical validation of the 1985 Highway Capacity Manual (HCM) arises from its development with limited field data and its adoption of radically new procedures. Chapter 9 of the Manual, Signalized Intersections, contains some of the more extensive changes and is the subject of field validation. Emphasis is placed on comparisons of field saturation flows, delays, and progression factors with those estimated by the manual. Data are obtained from ten intersection approaches for twenty-five 15-minute analysis periods. Saturation flows in the field are significantly higher than those in the manual. A value of nearly 2,000 vehicles per hour of green per lane (vphgpl) is consistently observed at field sites where the HCM estimates values of 1,800 passenger cars per hour of green per lane. The difference in saturation flows significantly affects delay estimates: the delays predicted using the value of 2,000 more closely match field delays than do the estimates using 1,800. Our conclusion is that an ideal saturation flow equal to 2,000 (rather than the HCM value of 1,800) is recommended for the analysis of high-design intersections similar with those analyzed in this project. The progression factors estimated from our data are statistically significant and differ significantly from HCM values. Our platoon factors are lower than the HCM, indicating that greater reductions in delay are necessary than are currently provided in the progression factor adjustments. In addition to being lower than current HCM values, our progression factors are much less sensitive to the platoon ratio (a relative measure of the percent arrivals on green). It appears that our field data for actuated controllers is almost totally inconsistent with the current HCM.**

In August 1985, the Transportation Research Board published a revised Highway Capacity Manual (HCM) (*1*). This third edition of the manual contains significant revisions to the previous manual (*2*) and several entirely new procedures. Many of the most significant changes can be found in Chapter 9, "Signalized Intersections."

Signalized intersections are among the most complex elements in a traffic system. This complexity has, in turn, necessitated a complex methodology to conduct a proper analysis of signalized intersections. This methodology can be used to assess level of service relationships for both existing intersections and proposed designs.

HCM Chapter 9 defines capacity as a function of the saturation flow(s) and the green split (g/C). The level of service is a function of the average stopped delay per vehicle. The methodology employs a series of worksheets and tables to arrive at delays and the corresponding levels of service. One of the key variables in this process is the percentage of all vehicles in the movement arriving during the green phase; this determines the so-called progression factor. The progression factor, as well as the degree of saturation, has the largest effect on level of service.

A detailed literature review was conducted of research related to traffic signal delay estimation and progression (*3*). While there are many simulation-based approaches to delay estimation—including TRANSYT-7F, PASSER II-84, and others—there are virtually no other procedures available to estimate delay in the variety of conditions actually observed in the field. Previous research in Kentucky (*4*) and a more recent study by a consultant (*5*) are the only published attempts to measure saturation flows in the field, other than the measurements at some 40 intersections that were undertaken as part of the formative research on the 1985 HCM. With the exception of ongoing research at the Texas Transportation Institute (*6*), no attempt has been made to validate the progression factors in the 1985 HCM.

There is a clear need for empirical validation of the 1985 HCM, particularly the chapter on signalized intersections and most particularly on delay estimation. This research attempts to respond to that need.

## STUDY OBJECTIVES

The overall goal of the research which forms the basis of this paper is the evaluation of the fit of the 1985 Highway Capacity Manual to the analysis of signalized intersections in Illinois (*3*). The following specific objectives are undertaken to achieve this goal.

The first objective is the investigation of the difference between the field-measured and the HCM-estimated saturation flows. The saturation flow is an important component of the volume to capacity ratio, which strongly influences predicted delays. The implications of differences in saturation flows are explored by comparing delays obtained with the field-measured and HCM-estimated saturation flows.

The second objective is the identification of changes, if necessary, in the progression factor, to better reflect the effect on delay of actuated signal system progression. The progression adjustment is one of the most important factors in Chapter 9 of the HCM because it can reduce the estimated delay by 50 percent or can increase it by 100 percent.

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## STUDY DESIGN

The design sought to explicitly control for factors that were exogenous to the main study objectives. Rather than conduct a very broad study of saturation flow adjustments, an early decision was made to narrow the study scope to a limited but frequently occurring condition. To compare field measured and model estimates of saturation flows, we chose intersection approaches with 12-foot lane widths, left turn lane, no local buses, no parking, right turn channelization, and flat grades. These criteria controlled for all adjustments to saturation flow, except the percentage of heavy vehicles. Thus our observations of saturation flow are clustered around a narrow range of conditions but ones that occur frequently in practice.

The study of progression adjustment factors is limited to through lanes at these high-design intersections. These intersections are frequently controlled by traffic-actuated equipment, therefore, we believed that identification of sites for data collection would be comparatively easy. By examining through lanes only, a much more precise analysis could be conducted of the effect of progression.

In sum, the authors adopted the approach of studying a limited set of problems at great depth rather than a broader but less detailed assessment of many factors. The joint objective of studying the progression adjustment factors and accuracy of lane saturation flow estimates led to a study design that emphasized high-design, suburban-type intersection approaches. The approaches are excellent test sites for progression adjustment studies and also offer the availability of measured saturation flow data. This judicious selection of project scope allows us to gain the most information from each site visit.

## DATA COLLECTION

### Required Data

The data required to meet the analysis objectives of the research are summarized in Table 1. The first seven data items are needed as input to the signalized intersection procedure in the 1985 HCM. We have chosen to count arrivals by cycle according to the method proposed by Berry (unpublished data). Once the cycle-by-cycle counts are obtained, they can easily be aggregated to 15-minute flows.

Data on geometrics, activity pattern, and traffic composition are needed to develop adjustments to saturation flow. By using a careful study design and site selection, all of these adjustment factors equal 1.0 except for the heavy vehicle adjustment factor, which is typically very close to 1.0 for the study's sites.

The duration of green and cycle length are required signal timing parameters. Because the study sites have actuated signal control, these data must also be collected each cycle. It is expected that both green times and cycle lengths will vary significantly at each site because of the control equipment's response to traffic fluctuations.

The last two sets of data are needed to evaluate the HCM procedure. Elapsed discharge times are used to measure saturation flow in the field. These measured values are compared to HCM estimates for each site. Stopped vehicle counts are needed to provide field delay data for comparison with HCM estimates of delay. A 20-second sampling rate seemed reasonable for the cycle lengths that were observed at the sites (typically 120 seconds).

A potential problem in the counting of arrivals is the left

TABLE 1 DATA COLLECTED DURING SITE VISITS

| DATA | PURPOSE |
|---|---|
| 1. VOLUME COUNTS: the number of arrivals per cycle. | Obtain the peak hour, the peak 15 minutes and the peak hour factor (PHF) for the analysis of the intersection and the determination of its performance (LOS). |
| 2. GEOMETRICS: lane widths, grades. | Obtain the $f_w$ and $f_g$ coefficient for the saturation flow. |
| 3. ACTIVITY PATTERN : CBD or non CBD location, parking activities, bus stops. | Obtain the $f_a$, $f_p$ and $f_{bb}$ coefficient for the saturation flow. |
| 4. TRAFFIC COMPOSITION: number of heavy vehicles in the total of arrivals. | Obtain $f_{HV}$ coefficient for the saturation flow. |
| 5. DURATION OF GREEN | Obtain the g/C ratio to calculate capacity. |
| 6. CYCLE LENGTH | Obtain the g/C ratio to calculate capacity and delay. |
| 7. ARRIVALS DURING GREEN | obtain the platoon ratio ($R_p$) to determine the progression factor. |
| 8. ELAPSED TIMES of discharge the 4th and $10^{th}$ vehicle in the queue | Obtain the field measured saturation flow. |
| 9. STOPPED-VEHICLE counts every 20 seconds. | Obtain the field measured delay per vehicle. |

turning vehicles. Vehicles which arrive at the end of a queue that extends beyond a left turn lane may have the intention to turn left. Because of the lack of space to enter the lane, they cannot have immediate access to the turn lane. These vehicles have to be counted as vehicles demanding through movement service because, as long as they are in the through movement lane, they contribute to the queue length and the amount of delay in the through lane. After the queue starts dissipating during the green, these vehicles may shift to the left turn lane. This movement is captured in the field by direct measurement both of the delay and of the saturation flow after the shift occurs. This is an approximate procedure because the vehicles that shift cause only partial delays to through vehicles; they are not discharged by the through lane. Within the queue, they also result in gaps that can reduce the measured saturation flows. For the approaches considered in this study, the left turn lanes were typically six to ten vehicles long, so the effect of the left turn "traps" is considered minor for both saturation flow and delay.

Another potential problem, which also arose during a session of the 66th TRB Annual Meeting (1987), is the definition and use of the term, "vehicle arrivals during green." Although the definition seems clear, the problem is how to successfully apply it to the variety of conditions observed in the field. We chose to define a vehicle arriving during green as any vehicle that joined the queue during green or passed across the stop-line unimpeded during green.

### Data Collection Sites

To fulfill the needs of the study design, a certain type of intersection needed to be chosen. The desirable characteristics of the intersection are:

1. Existence of exclusive lane for right turns, so that the right turn movement does not interfere with the through movement;
2. Existence of left turn bay so that the left turn movement will not interfere with the through movement;
3. Existence of significant rush hour volume so that a meaningful peak period can be identified;
4. Existence of actuated signal operation;
5. A non-central business district (CBD) location so that the analysis will not need to be included in the analysis; and
6. Low pedestrian volume in order to have minimum interference both with the traffic and with the field crew.

The field data collection session should be held under mild and dry conditions during normal weekdays. A summary of the ten intersection approaches used for collection is contained in the detailed project report (*3*).

### Data Collection Methods

There are two feasible methods to collect the field data; first, by filming the chosen approach; and second, by collecting data manually using a team of individuals. There are advantages and disadvantages associated with each method.

The filming alternative requires a camera and film, as well as some experience in its appropriate location and use. This approach requires the least number of persons in the field; two persons are sufficient. On the other hand, to obtain a sufficient field of view to estimate delays, an elevated vantage point has to be available. After the films have been developed, significant manpower is required to translate pictures (frames) into data.

The second alternative is the collection of data manually in the field by a team with specific assignments. One member of the team counts the arrivals and the arrivals during the green and also records the heavy vehicles in the traffic. One or two other members count the stopped vehicles in specific time intervals. One member takes the appropriate measures with respect to the saturation flow and the last member counts the cycle lengths and indicates the beginning and end of the green to the volume counter. There could be an additional member assigned to call out the time intervals but this member can be substituted by a tape player. Therefore, the total size of the crew, for data collection from one approach, is four to six persons. Detailed crew assignments are described in reference (*3*).

The advantages of this method are the flexibility, speed, and convenience which it offers with respect to the positioning in the field and the starting of the data collection session. Additionally, the data obtained are readily available for analysis.

The shortcomings of this method lie in the human factor and the associated potential for errors, especially if the field crew members are inexperienced and/or ill trained. These shortcomings can be largely alleviated with careful training and direct supervision in the field. This alternative was finally chosen as most appropriate, especially considering the tight schedule of the project.

### Summary

While the data collection methods did not use sophisticated technology, they are carefully managed to reduce errors and assure accuracy. The procedures meet the needs of the validation requirements for the existing procedures in the HCM.

## DATA ANALYSIS

### Structure of the Analysis

The structure of the analysis follows generally the statement of objectives from this paper's first section. The accuracy of saturation flow estimates is first assessed along with their implications for delay estimation. The last phase of the analysis is the study of the progression factor and its validity for the conditions observed in the field.

Before presenting specific results, it is useful to discuss several important aspects of actuated signal operation that have affected the analysis. Actuated signalization results in cycle lengths with considerable variation. One must be careful in determining the peak, 15-minute volume because the interval of volume measurement should end at the same time as a signal cycle. This is because all the field measurements of flow and delay are made per cycle. This results in analysis periods that are close to, but not exactly equal to, 15 minutes (*e.g.*, analysis periods of 13.6 to 16.4 minutes). This use of approximate 15-minute analysis intervals must be made to obtain the most precise comparisons with field observations. Of course, the appropriate adjustments are made to flow data to convert to hourly rates. For the rest of this paper, the term 15-minute analysis periods refers to the approximate 15-minute analysis period. The actual length of the analysis period is explicitly stated only when necessary.

## Saturation Flow Accuracy and Its Implications for Delay Estimation

The estimation of the saturation flow(s), from field-measured headways indicates that the true saturation flow is considerably higher than the saturation flow suggested in the HCM. The HCM suggests a saturation flow of 1,800 passenger cars per hour of green per lane (pcphgpl) while the average saturation flow across all sites results in a value of 1,995 vehicles per hour of green per lane (vphgpl) (Figure 1). Because the sites have been selected to control for major geometric and surrounding characteristics, it is possible to obtain this average saturation flow value for all six approaches where measurements were taken. We were able to collect discharge rates only at six of the ten sites we visited, because of lack of data collectors. The confidence interval for this estimate at the 99-percent level of significance is + 98 vphgpl, which indicates that the estimate is reliable and most certainly higher than the value suggested in the HCM. Because of the significant differences in the saturation flows, we conduct several subsequent analyses comparing results for $s_0$ = 1,800 and $s_0$ = 2,000. We have taken the liberty of converting 1,995 vphgpl to 2,000 pcphgpl because nearly all adjustments of saturation flow equal 1.0.

An efficient way to check the implications of alternative values of the saturation flow is to plot field-measured delays and delay estimates using each of the two values. This plot is presented in Figure 2. The diagonal of the graph indicates the ideal line which corresponds to the location of points, had the estimated delays been identical to the field-measured delays. The legend in the middle of the graph explains the points obtained for the two levels of saturation flow ($s$ = 1,800 and $s$ = 2,000). The regression lines corresponding to the alternative levels of saturation flow indicate that estimates obtained with $s$ = 1,800 are consistently higher than the field-measured delays. This nearly constant bias of 5 seconds or more exists over the entire range of delay values.

The estimated delays with $s$ = 2,000 are closer to the field-measured ones, especially for delays less than 30 seconds per

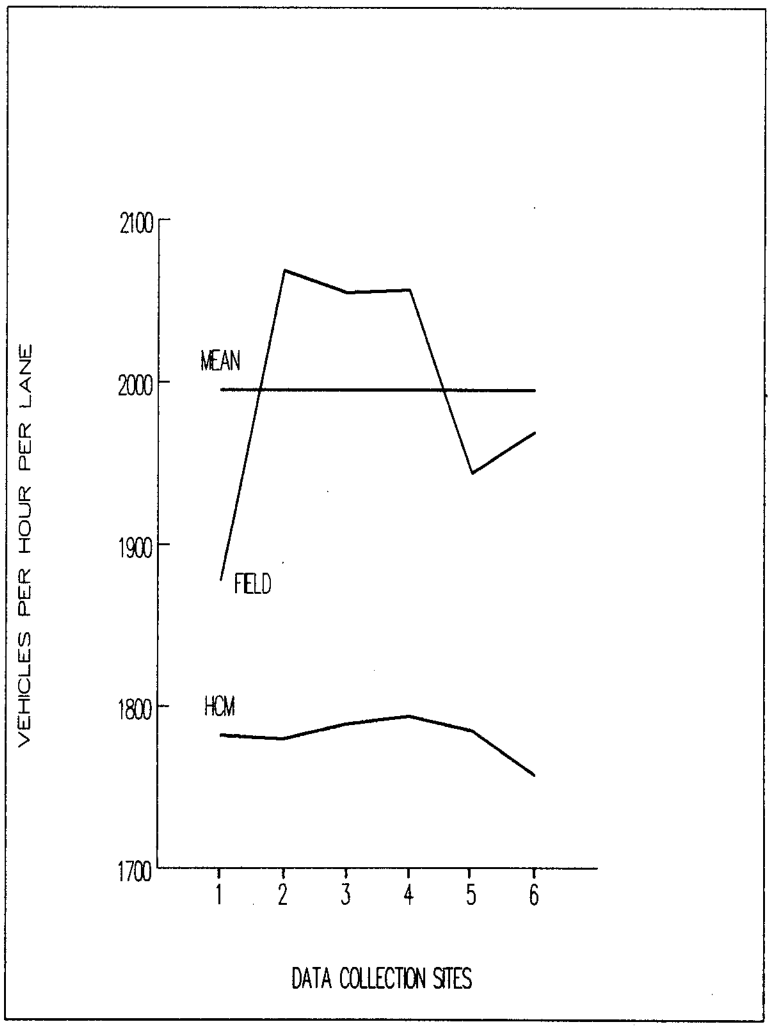


**FIGURE 1 Average saturation flow for six sites.**

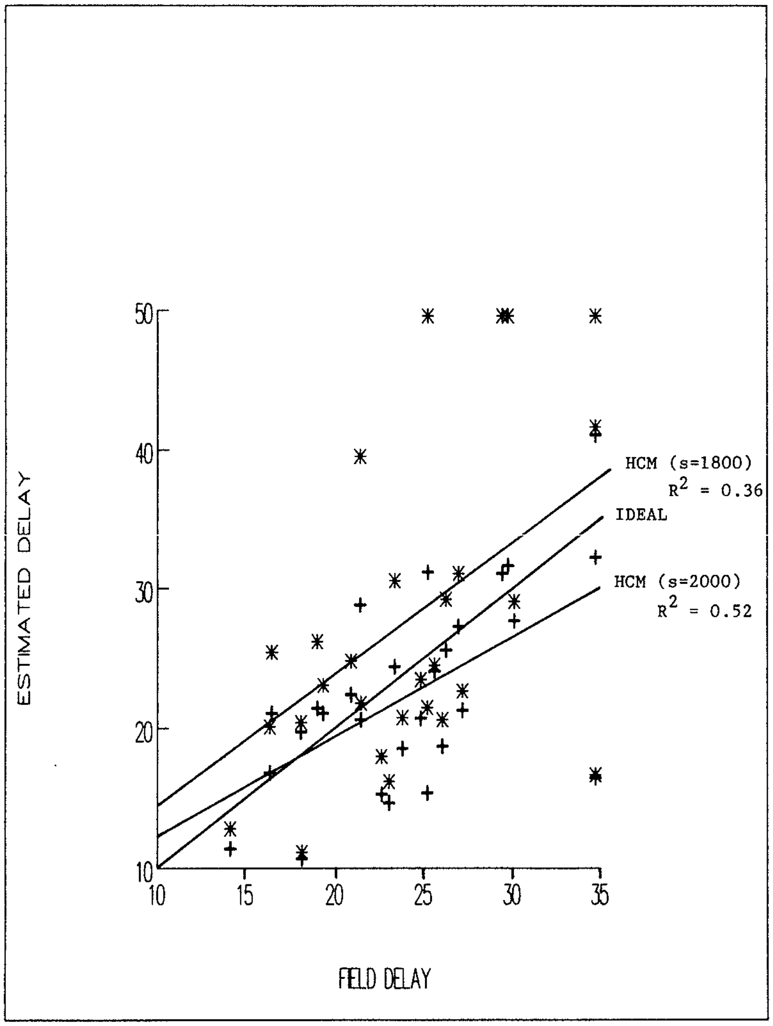


**FIGURE 2 Estimated and field measured delays.**

vehicle, where most of the data are clustered. There is a slight tendency to underestimate the delays at high delay levels. The goodness of fit ($R^2$) of the line corresponding to the estimates with $s = 2{,}000$ is much better than for $s = 1{,}800$. The parameter for the constant term in the regression model is insignificant, indicating a failure to reject the null hypothesis that the line starts from the intersection of the axes.

Further insight into the estimation accuracy can be achieved by investigating the effect of the degree of saturation on the estimated delays, particularly on the error in estimation. The degree of saturation is a major determinant of delay and an indicator of utilization. It is important that the delay model accurately predicts delays at high degrees of saturation, as these are likely to reflect peak period conditions. The level of service assessment under these conditions is very important, as these sites are likely to be candidates for design improvement.

The saturation flow has a direct effect on the degree of saturation; the higher the saturation flow, the lower the resulting degree of saturation. For example, when studying the same approach, the degree of saturation resulting from a saturation flow equal to 2,000 vphgpl will be equal to nine-tenths of the degree of saturation resulting from a saturation flow equal to 1,800 vphgpl.

Let us examine the graphs where the percent estimation error is plotted against the degree of saturation for these two levels of saturation (Figures 3 and 4). The "% ERROR" in estimation is defined as:

$$\% \text{ Error} = 100 \frac{([\text{Estimated delay}] - [\text{Field delay}])}{[\text{Field delay}]}$$

When the saturation flow is equal to 1,800 a large range of errors results (−55 percent to +105 percent). The distribution of errors is rather biased: for low levels of saturation the delays are underestimated while for high levels of saturation the delays are overestimated.

When the saturation flow is equal to 2,000, a much smaller range of errors results (−55 percent to +35 percent). The distribution of errors is unbiased because across the range of the degree of saturation the underestimated delays balance the overestimated ones.

Similar conclusions are reached if one plots the magnitude of the error against the degree of saturation. Errors as large as two levels of service are observed in these figures.

There is conclusive evidence to support the use of a saturation flow value of 2,000 in place of the HCM value of 1,800 for high-design intersections. Because of the significance of this finding, subsequent studies of the progression factor with

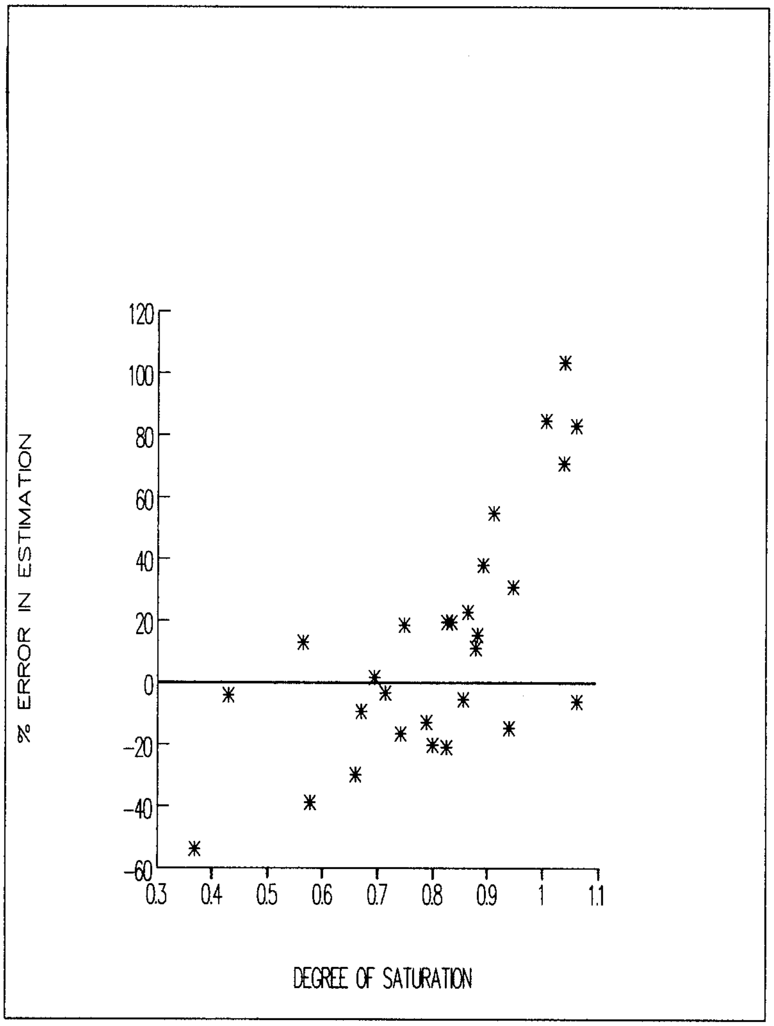


**FIGURE 3 Estimation error and saturation ($s$ = 1,800).**

the more accurate saturation flow value, $s$ = 2,000 vphgpl, were conducted.

### Progression Factor

The progression factor ($PF$) is a factor adjusting the delay to incorporate the benefits of a good progression (*i.e.*, many arrivals during green) and the losses of poor progression (*i.e.*, many arrivals during red). The progression factor has a potentially large effect on delay estimates because it is an adjustment that is applied directly to the delay. Its magnitude can result in halving or nearly doubling the delay for random arrivals. It is the only adjustment factor in HCM Chapter 9 that is applied to delay directly; all other adjustments are inputs to the delay equation, not a final adjustment to it.

To obtain a qualitative comparison of our field data with HCM values, Figures 5 and 6 are constructed. The figure illustrates the delays that result from a given percent of arrivals during green for each 15-minute period. The slope of the lines reflect the effect of platooned arrivals on observed delay (Figure 5) or estimated delay (Figure 6). The authors' interpretation of these data is that the HCM model illustrates a much more direct relation between platooned arrivals, as expressed by the percent of arrivals during green, and delay than does our field data. Estimates of the progression factor from the study data are expected to differ from those in the HCM. (And they do.)

The authors' approach to the analysis is to create models in which the progression factor is the dependent variable while the degree of saturation, the percent of green, the platoon ratio and the percent of arrivals during green are all candidate independent variables. The estimation equations for the progression factor are derived from HCM equations. The starting point is the adjustment to random arrivals to reflect the effect of platooning:

$$\text{Field delay} = (\text{HCM delay})\ PF \tag{1}$$

Solving for $PF$, the following is obtained:

$$PF = \frac{\text{Field delay}}{\text{HCM delay}} \tag{2}$$

Equation (2) expresses the progression factor as a function of the field delay, which is known by measurement in the field, and the estimated delay, which is calculated using the HCM method. Equation (2) thus allows us to calculate an

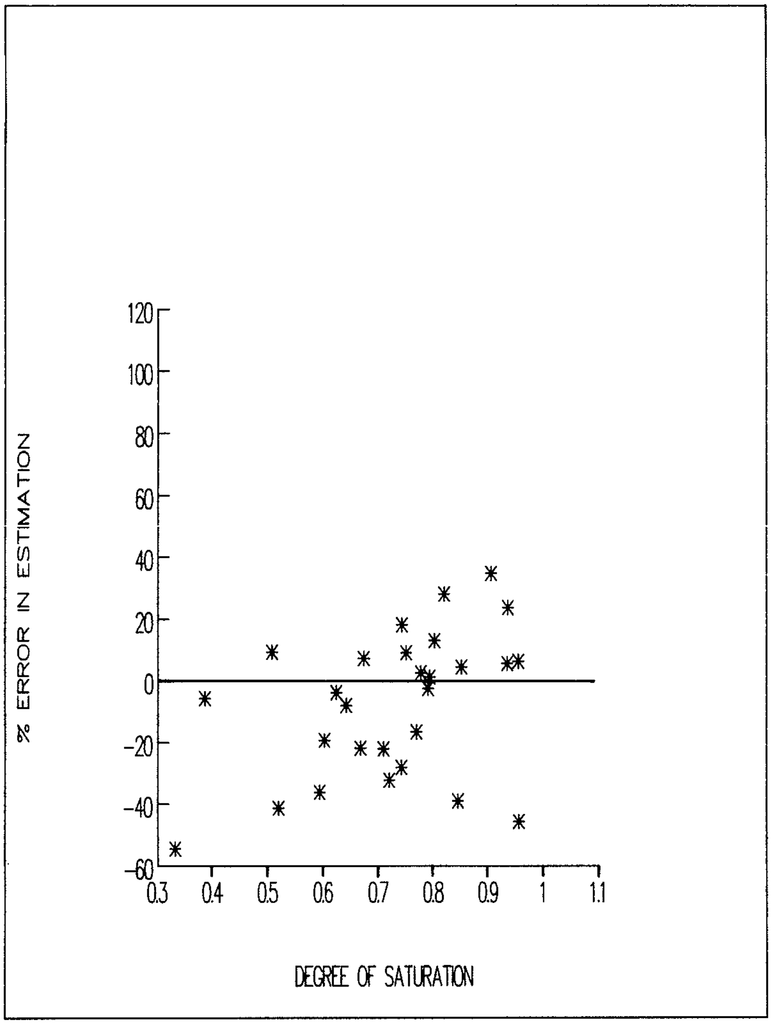


**FIGURE 4 Estimation error for two levels of ideal saturation flow ($s$ = 2,000).**

"observed" progression factor for each 15-minute period. These observed values can then be fit to a variety of models using standard regression techniques.

From the mathematical standpoint, there are several forms of models which can be used to analyze our data. The two forms we select are the linear and multiplicative, which generally are expressed as:

linear:

$$PF = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \qquad (3)$$

multiplicative:

$$PF = \alpha_0 X_1^{\alpha_1} X_2^{\alpha_2} \ldots X_m^{\alpha_m} \qquad (4)$$

The advantage of the multiplicative form is that it cannot result in negative estimates for the dependent variable; the linear model can. A negative value for the progression factor is counterintuitive because negative delays have no physical meaning. We explore both models and determine a preferred model based on the interpretability of parameter estimates and the goodness of fit. We use SPSS on an IBM PC to conduct the estimations. The multiplicative model is estimated by taking the natural logarithm of both sides yielding a linear in parameter specification:

$$\ln PF = \ln \alpha_0 + \alpha_1 \ln X_1 + \alpha_2 \ln X_2 + \ldots + \alpha_m \ln X_m \qquad (5)$$

Note that both model forms treat the independent variables as continuous, rather than discrete, ranges (as in Table 9-13 in the HCM). This is advantageous because it allows us to estimate one model using all our data. It is valid if we expect the independent variables to have the same effect on the progression factor over its entire range of values. If we do not believe this, a piecewise model for the progression factor can be constructed and model parameters compared to the full model. Constraints on sample size require that we estimate one model over the entire range of the progression factor, leaving piecewise tests for future research.

Considering the theoretical validity of the parameters, let us first discuss our expectation for the sign for the degree of saturation. At low to moderate levels of the degree of saturation, progression is expected to have a very strong effect. If small to moderate platoons consistently arrive on red (or

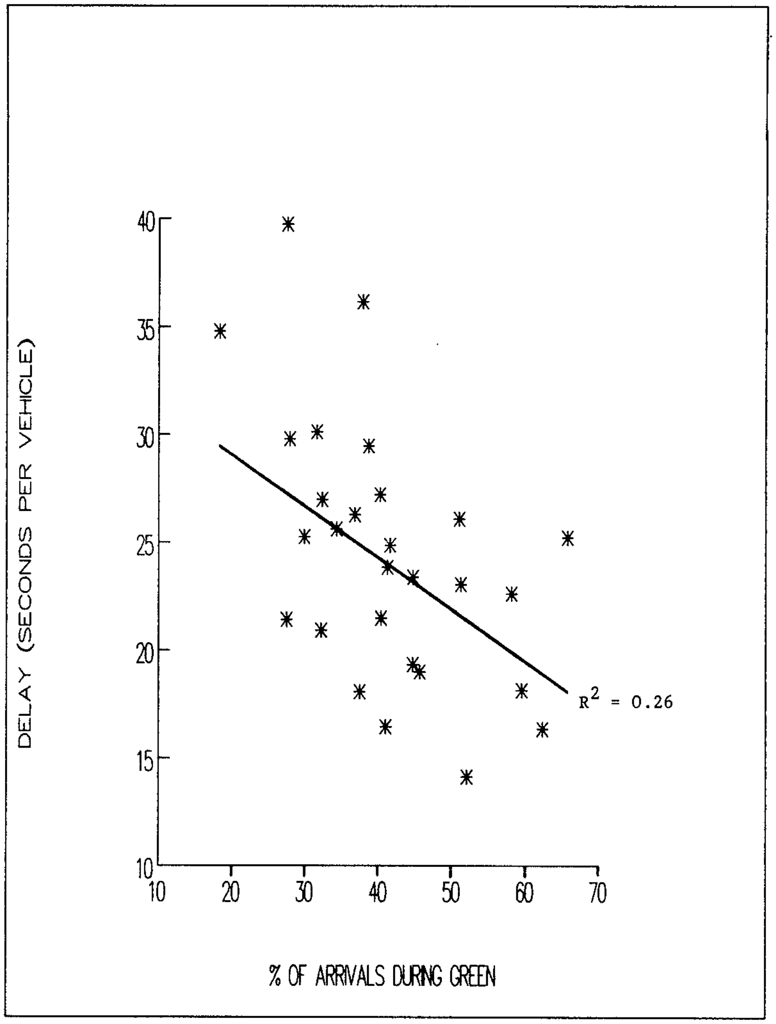


**FIGURE 5 Arrivals during green and field delay.**

green), significant increases (or decreases) in delay are expected, compared to random arrivals. This effect is expected to be the strongest for coordinated signals that have a fixed time relationship between the beginning and end of green and the time of platoon arrival. Over the span of 15 minutes, any variation in signal offset is likely to weaken the effect of progression.

For high levels of saturation ($X > 0.9$) it is difficult to sustain good progression. Long existing queues might not dissipate totally before arrivals from upstream reach the intersection. In this case, the vehicles stop instead of moving smoothly through the signal. At high levels of saturation, progression is likely to have little or no effect. These considerations suggest that a non-linear specification may be best for the degree of saturation. Given the preliminary nature of our analysis, we leave other specifications for future research.

For the available data set, a negative sign is expected as representing the majority of the field conditions. The parameter may not be strongly significant if much of our field data represent nearly saturated conditions or reflect large changes in platoon size, shape, and timing.

Another potentially strong explanatory variable is the platoon ratio. The platoon ratio, ($R_P$), is defined as the ratio of the percent of vehicles arriving during green over the percent of time that the signal indication for the analyzed approach is green (*1*). For this variable, a negative sign was expected because higher values indicate better progression and conceivably lower average delay.

In addition to models using degree of saturation and platoon ratio, a number of analyses were conducted using the percent of arrivals during green and the percent of green time as additional predictors. Several difficulties arose with the use of these last two variables. The percent green is collinear with both $R_P$ and the percent of arrivals during green; therefore, its simultaneous incorporation in a linear model would be erroneous. Models that seek to estimate the progression factor as a function of the percent of arrivals during green and the percent green time had poorer explanatory power than those using the platoon ratio. Therefore, only results using the platoon ratio are included here.

Before proceeding with the results of the validation, plots of the individual major explanatory variables and the progression factor are presented. Figure 7 presents the relation between the field delay and the HCM delay before it is multiplied by the progression factor. There is a clear overestimation of the delays, therefore, the progression factor should be consistently less than 1.0.

Figure 8 indicates that the progression factor is relatively

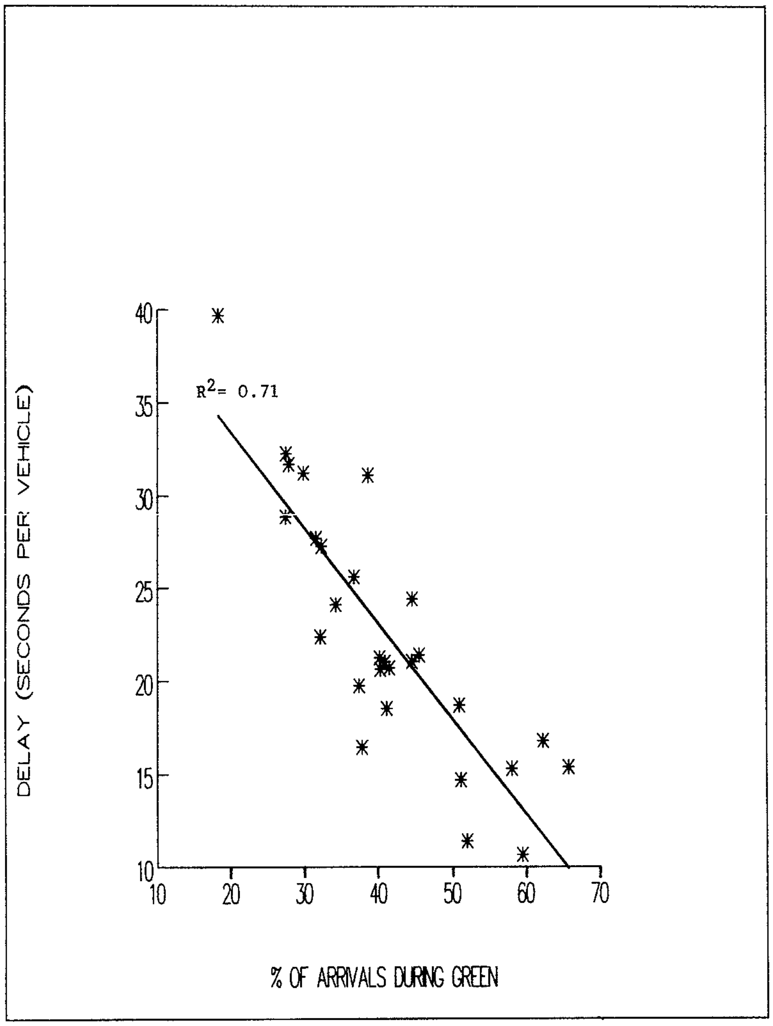


**FIGURE 6 Relation of the field measured and of the estimated delays with the percentage of arrivals during green ($s$ = 2,000).**

indifferent to the level of saturation. This result is somewhat counter to our expectations. The data contain significant scatter, particularly at high degrees of saturation ($X > 0.75$), which contain data with both high and low values for the progression factor. We expect that the full regression models may show, at best, a weak association between the platoon factor and degree of saturation. It appears as though the platoons from the actuated systems that we studied vary greatly from cycle to cycle.

Figure 9 shows clearly that the progression factor decreases as the platoon ratio increases. The effect is strongly significant and is consistent with our hypothesis.

We tested more than 20 alternative model specifications and conclude that the following two models offer not only the best fit to our data but are also theoretically consistent. This fit was achieved after the exclusion of an outlier resulting from erroneous field measurement. The models are:

$$PF = 0.86 - 0.17\,X - 0.24\,R_P$$

$$(R^2 = 0.41,\ F = 7.6) \qquad (6)$$

$$PF = e^{-0.895}\,X^{-0.474}\,R_P^{-0.650}$$

$$(R^2 = 0.40,\ F = 7.4) \qquad (7)$$

These models were estimated from twenty-five independent approximately 15 minute intervals. Table 2 summarizes the results of the bivariate models and equations 6 and 7, including goodness of fit statistics and tests of significance for model parameters and the regression model as a whole.

The results obtained from both models indicate that the values of the progression factor in the HCM are substantially different from the values which are reflected in our data. Although our data set is quite small, the parameter estimates are statistically significant as are the models as a whole. A clearer perspective of the difference between our Model 2 and current HCM values is illustrated in Figure 10, which plots both on the same scale, along with the 95 percent confidence interval for the regression line. It is clear that the model estimated from our data is very different from the HCM values. For the Arrival Type 3, ($0.86 < R_P < 1.15$) which is the most common observation in our data set, our estimates are roughly 60 percent less than the corresponding values in the HCM. This means that the delays estimated from our model are 60 percent less than the ones which are estimated using the *PF* values in the HCM. We are surprised at the magnitude of this difference but confident that the results accurately and significantly reflect field data.

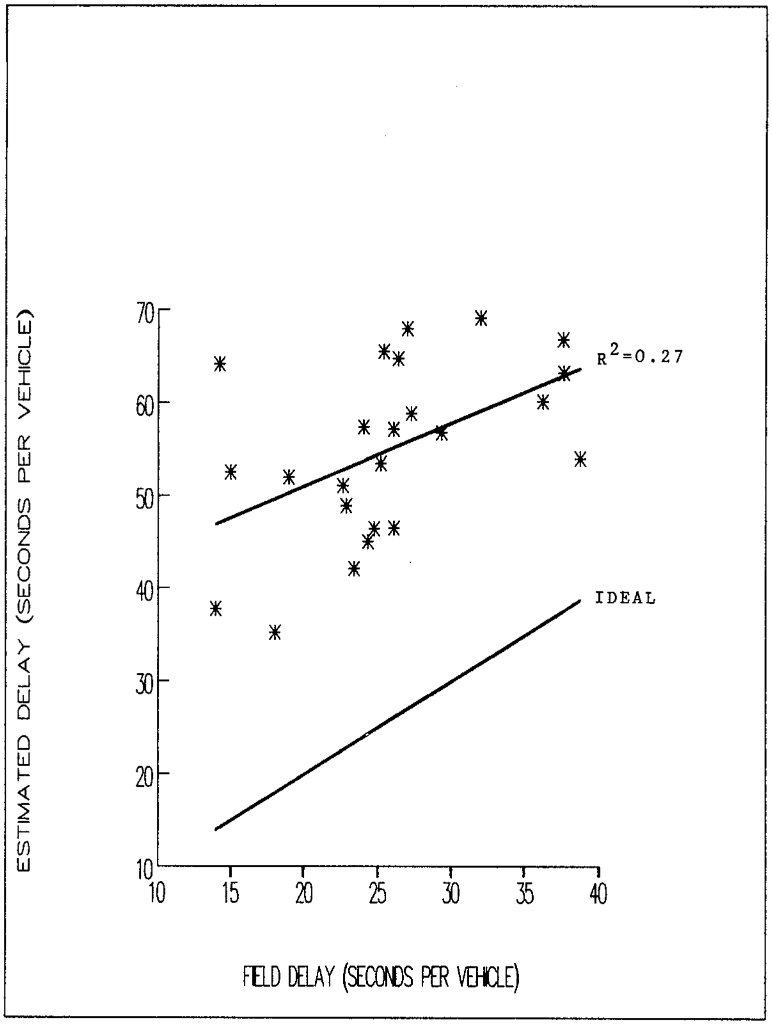


**FIGURE 7 Relationship between the field delay and the HCM-estimated delay without the progression adjustment.**

Arrival Type 3 is the most common type of arrival that we observed in our networks with actuated signals. Because the signal settings and offsets vary cycle by cycle, all types of arrivals are identified with each 15-minute analysis period. Individual cycles with excellent progression (Type 1) are often balanced by subsequent cycles with poor progression (Type 4 or 5). This is in direct contrast to coordinated pretimed systems, which have fixed cycle lengths, splits, and offsets throughout the analysis period. A greater uniformity in arrivals and platooning with pretimed control is expected. This causes us to question if one would ever consistently observe Type 1 or Type 5 (*i.e.*, extreme) arrivals with actuated systems. In fact, our study includes no data for Arrival Type 1 ($0.0 < R_P < 0.50$) and only two observations for Type 5 ($1.51 < R_P$).

## CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

### Conclusions

Saturation flows observed in the field are significantly higher than those in the manual. A value of nearly 2,000 vphgl is consistently observed at field sites where the HCM estimates values of 1,800 vphgpl. The difference in saturation flows significantly affects delay estimates: the delays predicted using the value of 2,000 more closely match field delays than do the estimates using 1,800. Our conclusion is that an ideal saturation flow equal to 2,000 (rather than the HCM value of 1,800) is recommended for the analysis of high design intersections similar with those analyzed in our project.

The evaluation and calibration of the values for the progression factor consumed a significant amount of effort in all the stages of the project. Despite collecting data over a 4-week period at ten sites, data are restricted to random (Type 3) or nearly random (Type 2 and 4) platoon types. Only two observations of Type 1 or 5 platoons are contained in the data. The progression factors estimated from our data are statistically significant, however, and differ significantly from HCM values. Our platoon factors are lower than the HCM, indicating that greater reductions in delay are necessary than are currently provided in the progression factor adjustments. In addition to being lower than current HCM values, the study's progression factors are much less sensitive to the platoon ratio (a relative measure of the percent arrivals on green). It appears that this field data for actuated controllers is almost

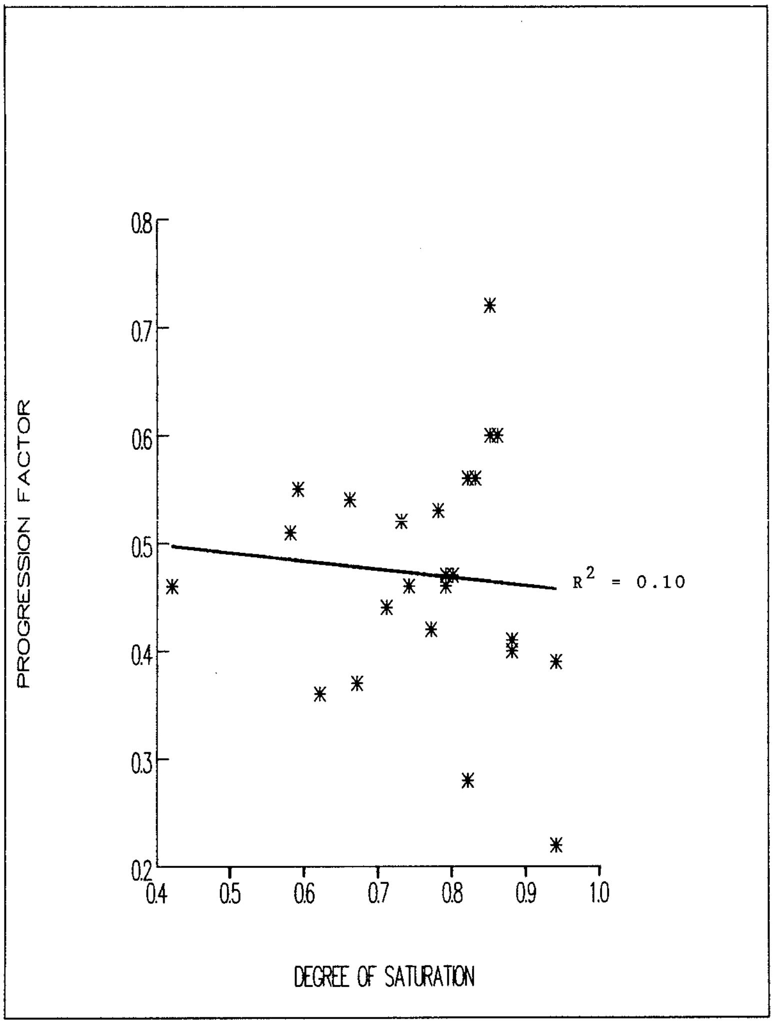


**FIGURE 8 Relationship between the progression factor and the degree of saturation.**

totally inconsistent with the current HCM. The authors believe that their values are more appropriate for high-design traffic actuated intersections and that they should be used in place of the current HCM values.

### Recommendations for Future Research

The large differences in both saturation flows and the progression factor surprised even the current research team. This experience indicates the importance of exploring the validity of HCM procedures that are based on limited field data. During the course of the research, there were a number of instances in which additional studies seemed warranted. The following is a summary of those additional topics.

The measurement of saturation flows (and their effect on delay need to be extended) to a broader range of intersections and lane types. Additional studies could include measurement of saturation flows in smaller urbanized areas in similar geometric conditions. This would allow testing of regional differences in saturation flow rates. Given the importance of saturation flow in delay estimation, this is a very useful project.

During the course of the current research, observations at left turn bays indicated that saturation flows for protected left turns may be higher than for through lanes. This is based on casual observation only; it would be instructive to conduct more detailed measurements.

Much more can be done to validate other adjustments to saturation flow. Nearly all of the saturation flow adjustments are candidates for further study, including: the effect of left turns, grades, lane width, parking, and local buses. Carefully designed site selection should allow for a more precise estimate of each of these effects.

Given the large differences that are observed between HCM delays and field data, it appears that much more needs to be done to better understand delays for systems of actuated controllers. The data set for this study contained very few 15-minute periods with Type 1 or Type 5 arrivals. Is this to be expected? Is this generalizable to other locations? Further study of actuated intersection delay is needed. Much more should be done to improve the accuracy of our delay esti-

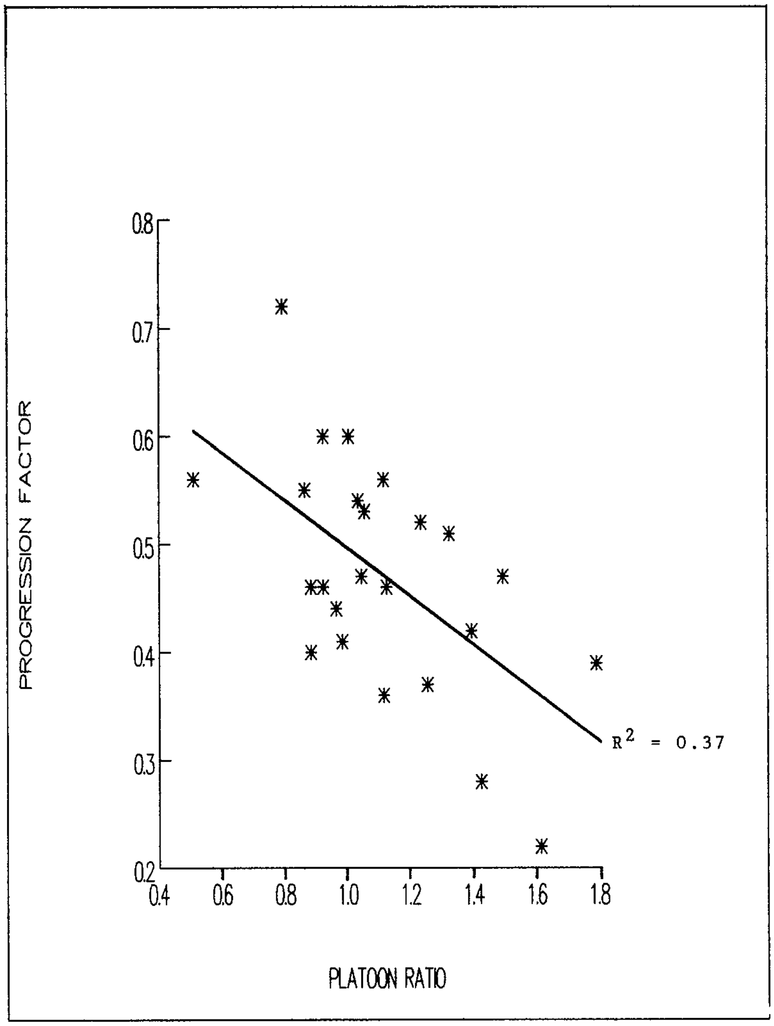


**FIGURE 9 Relationship between the progression factor and the platoon ratio.**

TABLE 2 SUMMARY OF PROGRESSION FACTOR REGRESSION MODELS

| | Model 1 | | Model 2 | | Model 3[a] | | Model 4[a] | |
|---|---|---|---|---|---|---|---|---|
| | $\hat{\beta}$ | (t) | $\hat{\beta}$ | (t) | $\hat{\beta}$ | (t) | $\hat{\beta}$ | (t) |
| <u>Variable Name</u> | | | | | | | | |
| Degree of Saturation | -0.28 | (0.5) | -- | | -0.17 | (1.2) | -0.47 | (1.8) |
| Platoon Ratio | -- | | -0.26 | (3.7) | -0.24 | (3.4) | -0.65 | (3.2) |
| Constant | 0.67 | (3.7) | 0.75 | (9.2) | 0.86 | (6.9) | -0.90 | (9.8) |
| $R^2$ | 0.10 | | 0.37 | | 0.41 | | 0.40 | |
| F Value for Significance of Model | 1.1 | | 13.6 | | 7.6 | | 7.4 | |

[a]Model 3 is a linear additive specification, model 4 is multiplicative.

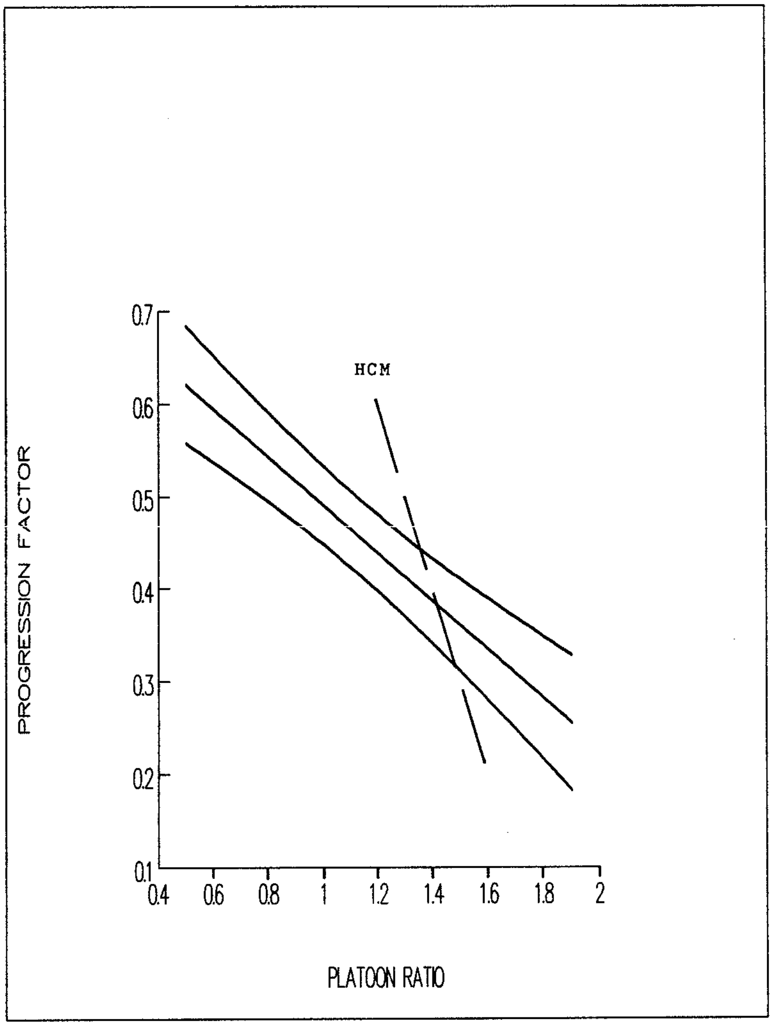


**FIGURE 10 Comparison of values for the progression factor from this analysis and the 1985 HCM (confidence of estimate = 95%).**

mates, as these have a direct relationship to the quality of resource allocation decisions.


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