CALSIG: An Integration of Methodologies for the Design and Analysis of Signalized Intersections

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A proposed procedure for the design and analysis of signalized intersections is described. The procedure is an integration of existing methodologies, with each methodology incorporating a separate capacity and/or level-of-service analysis. The result is a procedure that is modular in form and possesses several levels of analysis. The proposed procedure can be discontinued immediately after each level of analysis. The procedure also incorporates design elements that can generate designs for any intersection parameter that is not established a priori. The procedure's design elements can also aid the user in identifying operational deficiencies and implementing design improvements.

In this paper, a proposed procedure for the design and analysis of signalized intersections is described. This procedure was developed as part of a research project conducted at the Institute of Transportation Studies, University of California, Berkeley. The research project, Calibration and Validation of the 1985 Highway Capacity Manual for California Conditions, was sponsored by the California Department of Transportation and the Federal Highway Administration.

The initial phase of this research consisted of a comprehensive review of the 1985 *Highway Capacity Manual* (HCM) (*1*). The objectives of this effort were to identify and document any areas of the 1985 manual that might not be completely applicable to traffic conditions observed in the state of California.

From this comprehensive review, it was concluded that additional enhancements could be incorporated into the HCM's existing analysis procedures for signalized intersections (*1*, Chapter 9). The reviewers believed that these enhancements might make the existing Chapter 9 procedures more attractive to transportation professionals in California and elsewhere. The enhancements that were added to the existing Chapter 9 procedures resulted in a modular analysis and design methodology, hereafter referred to as CALSIG.

The following section of this paper provides a general overview of the CALSIG procedure. In later sections, CALSIG's analytical framework and details are described, and the CALSIG procedure is discussed in greater detail. Following this explanatory material is an annotated sample problem. Conclusions are discussed in the final section of the paper.

The purpose of this paper is to acquaint the reader with the CALSIG procedure. CALSIG's structure and procedural application are described here in some detail. However, this paper is not intended to serve as a user's manual. Additional information may be required to apply the CALSIG methodology to all scenarios. The complete CALSIG user's manual (*2*) can be obtained from the Institute of Transportation Studies, University of California, Berkeley, Calif. 94720.

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PROCEDURAL OVERVIEW

Before the new procedure was developed, a careful evaluation was performed on all currently available design and analysis techniques for signalized intersections. This evaluation identified both positive and negative features within these existing procedures. CALSIG, the proposed procedure, was subsequently formulated to incorporate desirable features from existing methodologies. CALSIG is in fact an integration of currently available analysis procedures.

A separate analysis is associated with each integrated procedure. Thus CALSIG incorporates several levels of analysis. Each level requires an increasing degree of procedural detail.

Such a framework offers two significant advantages to the user:

- Because CALSIG contains increasing levels of analysis, a signalized intersection analysis may be performed with only the amount of detail appropriate for the specific application.
- Each of CALSIG's analysis levels yields a separate, but dependent, level-of-service (LOS) or operational prediction. By examining and comparing the results yielded by each level of analysis, the user can readily determine which, if any, signalized intersection parameters are contributing to predicted operational problems.

In addition, CALSIG incorporates both analysis and design procedures. CALSIG's design features consist of standards and guidelines typically used by California transportation professionals. A number of these guidelines are taken directly from the 1985 HCM's Chapter 9 appendices.

CALSIG's design features can aid the user in establishing parameters (e.g., approach geometrics, signal timing, etc.) when a signalized intersection is in the planning stages. CALSIG's design criteria can also be used effectively to assist the analyst in establishing operational improvements.

It should be noted that CALSIG is essentially a manual procedure for designing and analyzing signalized intersections. However, a substantial amount of time and effort is required to perform an entire CALSIG procedure manually. For this reason, a user-friendly computerized version of CALSIG was developed as part of the original research project. This software package dramatically reduces the time required to perform CALSIG computations.

ANALYTICAL STRUCTURE

This section describes the basic structure of the CALSIG procedure. Figure 1 is a procedural flow chart that schematically illustrates CALSIG's framework. It should be noted that CALSIG incorporates seven steps or modules and four analysis techniques. The seven modules are

1. Turning movement demand,
2. Approach geometrics,
3. Phase design (phase types and phase sequences),
4. Lane group saturation flow rates,
5. Minimum required green times,
6. Cycle length, and
7. Phase lengths.

CALSIG's four analysis techniques are

1. A *preliminary analysis* that is based on the critical movement analysis and predicts the performance of the overall intersection. The procedure is essentially identical to the 1985 HCM planning analysis.
2. An *intermediate analysis* that evaluates the critical flow ratio, V/S_{crit}, for each signal phase and estimates an aggregate intersection level of service. The procedure is essentially identical to the intersection capacity utilization technique developed by Crommelin (*3*).
3. A *comprehensive analysis* that utilizes the lane group V/c ratios as the primary measure of effectiveness (MOE). This analysis will predict the level of service for each lane group, each approach, and the intersection as a whole.
4. A *comprehensive analysis* that utilizes average stopped delay per vehicle as the primary MOE and is essentially the 1985 HCM operational analysis.

Multilevel Analysis

There is nothing unusual about CALSIG's modules or analysis techniques. In fact, all of the parameters used in CALSIG are accounted for when the existing HCM procedures are used. What is unique about CALSIG's structure is that not all parameters listed (and illustrated in Figure 1) need to be incorporated when performing the CALSIG procedure.

As shown in Figure 1, the procedure can be concluded immediately after each level of analysis. The analysis level at which the procedure is concluded will depend on the degree of detail needed for the specific application. This degree of detail may vary considerably, depending on the specific scenario and user preference. The modules required to perform each of CALSIG's analysis techniques are those modules that precede each analysis in Figure 1. Thus the CALSIG procedure can be performed with varying amounts of comprehensiveness.

At either extreme, the CALSIG procedure parallels the 1985 HCM planning and operational analysis. Thus in some sense the CALSIG methodology represents the existing HCM procedures with additional features incorporated. These additional features do not necessarily make the CALSIG procedure less complex than the HCM's existing operational procedure. In fact, the inclusion of additional analyses may often make the CALSIG procedure more time consuming—although use of the CALSIG microcomputer software will significantly reduce this additional time.

There are scenarios for which use of the existing HCM operational procedure is preferable. The more straightforward procedures of the HCM operational method are most appropriate when an operational analysis is to be performed and average stopped delay is the desired measure of effectiveness.

Nonetheless, CALSIG's multilevel analysis format does offer distinct advantages for many applications. CALSIG's enhancements, in some sense, bridge the gap that currently exists between the simplicity of the HCM planning method and the complexity of the operational analysis. This provides additional flexibility for the CALSIG user.

The results given by each of CALSIG's analyses will not necessarily be compatible when applied to identical scenarios. For example, a scenario analyzed by the CALSIG intermediate analysis may yield a LOS C, but the same scenario may yield a LOS D, or lower, when the CALSIG comprehensive analysis is used. This is not necessarily a deficiency in the CALSIG methodology. Such inconsistencies can be used to determine which parameters are creating predicted operational problems. For example, a comprehensive analysis that yields a lower level of service than the preceding intermediate analysis indicates that improved signal timing should be considered (refer to Figure 1). Conversely, a comprehensive analysis that yields a higher level of service than the preceding intermediate analysis indicates that optimal signal timing has improved an otherwise problematic operation.

There is a particular inconsistency in using V/c rather than average stopped delay as the MOE. Longer cycle lengths generally reduce V/c and increase delay. Conversely, shorter cycle lengths reduce delay and increase V/c values. To deal effectively with this inconsistency, the user should establish, a priori, which measure (V/c or delay) is to be considered as the primary MOE.

Each level of analysis within the CALSIG procedure yields a different measure of effectiveness. This can be confusing at times. In addition, direct comparisons of MOEs from different analysis levels are not possible. However, levels of service and general operational predictions can be compared at all analysis levels. Thus predicted operational quality can be compared, in general terms, at all levels of analysis. A more detailed description of CALSIG's multilevel analysis techniques is offered in the next section.

Design Elements

As stated in the previous section, CALSIG incorporates both design and analysis elements. The dashed vertical lines in Figure 1 delineate the design and analysis portions of the CALSIG procedure. Symbols to the left of the dashed lines denote design elements; symbols located to the right represent analysis elements. Any parameter that is to be included in the procedure but has not yet been established by the analyst can be designed by the CALSIG procedure. CALSIG's design criteria can also serve as guidelines for establishing design improvements. Any design generated by CALSIG can be readily modified on the basis of user judgment or local practice.

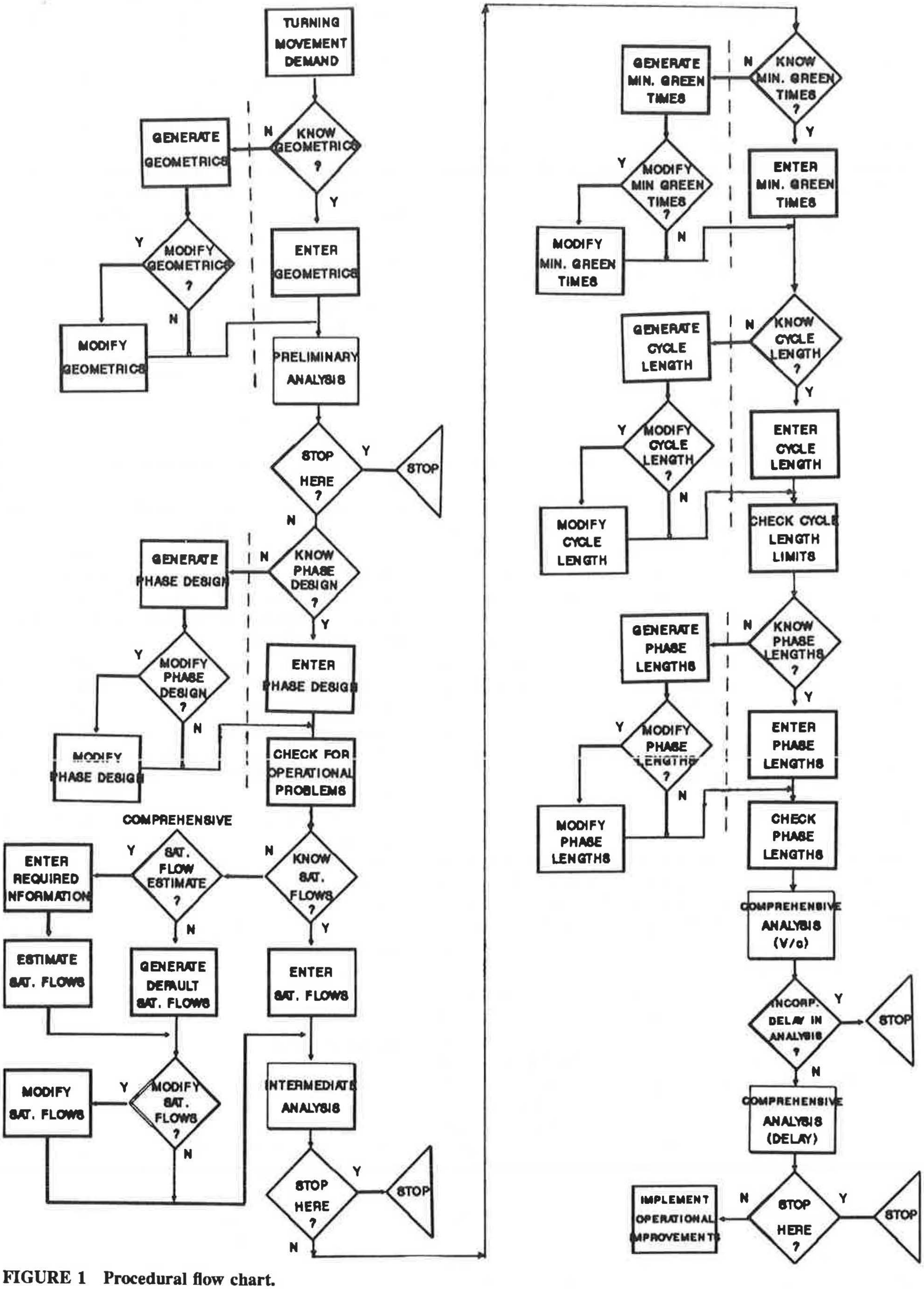

FIGURE 1 Procedural flow chart.

The CALSIG design elements are meant to provide the user with optimal (or near-optimal) design for unknown or poorly designed signalized intersection parameters. It is certainly true that microcomputer software packages have dramatically reduced the time and effort required to perform sensitivity analysis. Thus iterative computer-assisted evaluation can generally reveal optimal (or near-optimal) designs. CALSIG's design features merely simplify optimization. In addition, comparison of an existing design to CALSIG's design criteria can expedite identification of problem areas. CALSIG's design criteria are briefly highlighted in the following section.

ANALYTICAL DETAILS

In this section, the steps to follow when performing the CALSIG procedure are outlined. As stated in the introduction, the objective of this paper is to familiarize the reader with the CALSIG methodology. Additional information on the procedure can be found in the CALSIG user's manual (*1*).

The entire CALSIG procedure can be broken down into the steps or modules previously illustrated in Figure 1. Thus the procedure is documented in modular fashion in this section.

Turning Movement Demand Module

Volume, as defined in the 1985 HCM, is the total number of vehicles passing a point or section of a roadway during a specified time period. Rate of flow is an equivalent hourly rate at which vehicles pass a point or section of roadway for some period of time less than 1 hr.

When the CALSIG procedure is being performed, the traffic flows from each approach movement must first be established. The procedure can be performed with either 15-min rates of flow or full hourly volumes. The choice should be based on the specific design or analysis application and the degree of detail chosen to be incorporated in the procedure. For example, if a comprehensive analysis is to be performed on an existing intersection using existing traffic counts, peak rates of flow should typically be used. However, if the intersection is to be evaluated in a less comprehensive manner or if projected traffic volumes are to be used, full hourly volumes may be the most appropriate choice.

The choice of performing the procedure using either volumes or flow rates will require professional judgment. A more detailed explanation of peak rates of flow may be found in Chapter 1 of the 1985 HCM.

Geometrics Module

If approach geometrics exist or have been established by the user, the individual lane configurations are incorporated in the procedure. These geometrics will subsequently be considered in the preliminary analysis.

Design Procedure

If approach geometrics are not defined by existing conditions or by state or local practice, lane configurations may be determined on the basis of CALSIG's geometric design criteria. The design criteria may also be applied when analysis indicates intersection deficiencies that may be corrected by changes in geometric design. These design criteria are derived from Appendix I, Chapter 9, of the 1985 HCM.

The geometric design of an intersection involves several critical decisions about the number and use of lanes to be provided on each approach. The following material addresses these determinations.

Exclusive Left-Turn Lanes

The following guidelines govern the provision of exclusive left-turn lanes:

- Where fully protected left-turn phasing is to be provided, an exclusive left-turn lane should be used.
- Where left-turn volumes exceed 100 vph, an exclusive left-turn lane should be provided.
- Where left-turn volumes exceed 300 vph, provision of a double left-turn lane should be considered.

Exclusive Right-Turn Lanes

An exclusive right-turn lane should be considered when the right-turn volume exceeds 300 vph and the adjacent main-line volume also exceeds 300 vph per lane.

Number of Lanes

In general, enough main roadway lanes should be provided that the total of through plus right-turn volume (plus left-turn volume if present) does not exceed 450 vph per lane.

Preliminary Analysis

CALSIG's preliminary analysis incorporates the intersection turning movement demand and approach geometrics. The analysis, which is based on the critical movement technique, predicts the general operating performance of the overall intersection. CALSIG's preliminary analysis is identical to the 1985 HCM planning analysis.

- The given traffic demand is distributed over the available lanes as uniformly as flow conditions permit. The concept of uniform flow conditions is discussed in Chapter 9 of the 1985 HCM and is therefore not repeated here.
- The sum of the critical conflicting lane volumes (i.e., through plus opposing left-turn traffic) is computed for both intersecting streets.
- The sum of the critical conflicting lane volumes can be related to a corresponding capacity criteria. Capacity criteria values are taken directly from the 1985 HCM:

Critical Value for Intersection, vph	*Relationship to Probable Capacity*
0 to 1200	Under capacity
1201 to 1400	Near capacity
≥1401	Over capacity

- The preliminary analysis also results in a general statement that describes predicted vehicle queueing.

The results of the preliminary analysis give a general indication of the acceptability of the intersection's capacity. As its name suggests, the analysis is preliminary in nature. The evaluation is carried out entirely in mixed vehicles per hour. The existence of adequate signalization is assumed, as are average values for all prevailing conditions.

This analysis technique is a useful tool for evaluating the overall adequacy of an intersection or comparing alternative geometric design. In addition, this preliminary procedure may be adequate in itself for evaluating intersections by using predicted future volumes.

The CALSIG user has three options once the preliminary analysis has been completed:

- Discontinue the procedure and obtain the preliminary analysis results.
- Modify the turning movement demand, the approach geometrics, or both and repeat the analysis.
- Continue the CALSIG procedure so that a more comprehensive design or analysis will be performed.

The CALSIG user's manual (*2*) and the 1985 HCM provide more complete descriptions of the preliminary (planning) analysis.

Phase Design Module

If the user elects to continue the CALSIG procedure beyond the preliminary analysis, the number and the sequence of phases is the next parameter to be incorporated. If the phase plan is already established, it is used in the procedure. This phase plan will be accounted for in CALSIG's intermediate analysis.

If the phase design has not yet been determined, an appropriate phase number and sequence may be established by using CALSIG's design criteria. As a general rule, the number of phases used by a signal should be kept to a minimum, especially for pretimed controllers. As the number of phases increases, the green time available to other phases is reduced. Additional signal phases create added change intervals, which can increase cycle length and delay. Thus two-phase control should generally be used, unless turn volumes, safety considerations, or special intersection geometrics dictate the need for protective phasing.

Multiphase control is used at intersections that require a protected phase for one or more left or right turns. Local policy and practice most often determine the need for protected phasing. In the absence of local policy, however, the following design guidelines can be used for establishing phase plans.

Geometric Considerations:

- If more than one lane of an approach can turn left, a protected left-turn phase should be provided.
- If left-turn traffic must cross three or more lanes of opposing through traffic, a protected left-turn phase should be provided.

Volume Considerations.

- A protected left-turn phase should be provided if the approach left-turn volume is between 50 and 120 vph and the product of the left-turning and conflicting through volume exceeds 100,000.
- If an approach's left-turn volume is between 120 and 240 vph, a protected left-turn phase should be provided if

$$V_{LT} \times V_o' > 50{,}000$$

where

V_{LT} = approach left-turn volume,
V_o' = V_o (opposing volume) if one opposing lane exists,
= $0.55\ V_o$ if two opposing lanes exist, and
= $0.40\ V_o$ if three opposing lanes exist.

- If an approach left-turn volume exceeds 240 vph, a protected left-turn phase should be provided.

Additional Considerations:

- A protected left-turn phase should be provided if sight distance to opposing traffic is less than 250 ft when the opposing traffic is traveling at 40 mph or more.
- A protected left-turn phase should be provided if an approach left-turn volume exceeds 50 vph and through traffic speed exceeds 45 mph.

Phases that protect left turns can be provided in a variety of ways (e.g., leading protected lefts, protective-permissive, etc.). The CALSIG user's manual contains a more detailed discussion of phase plans.

Saturation Flow Rate Module

Saturation flow rate is defined as the maximum rate of flow that can pass through a given intersection approach or lane group under prevailing traffic and roadway conditions, given that effective green time was available to the approach or lane group 100 percent of the time. Saturation flow rates can be measured in the field by the user, comprehensively computed by using the saturation flow procedures of the 1985 HCM, or estimated by using CALSIG-recommended saturation flow rate default values.

The CALSIG procedure, like the operations procedure of the 1985 HCM, performs a signalized intersection capacity and LOS analysis based on saturation flow rates for each lane group. Thus, to continue with the CALSIG procedure, the intersection's individual lane groups must be determined.

The 1985 HCM defines a lane group as one or more lanes on an intersection approach serving one or more traffic movements. The designation of the individual lane groups within each approach considers both the geometry and the distribution of traffic movements. Guidelines for determining lane groups can be found in the CALSIG user's manual (*2*) and Chapter 9 of the 1985 HCM (*1*).

Once the lane groups have been established, the saturation flows for each lane group must be determined. Lane group saturation flow rates can be established in one of three ways.

Method 1

Field-measured saturation flow rates may be used. If a signalized intersection is to be evaluated under existing conditions, the analyst may wish to incorporate saturation flow values measured directly at the subject intersection. A procedure for directly measuring prevailing saturation flow rates can be found in Appendix IV, Chapter 9, of the 1985 HCM.

The most reliable results will generally be obtained by performing the CALSIG procedure with field-measured saturation flow rates. This method is therefore recommended when such data are readily available.

Method 2

Estimates of lane group saturation flow rates may be computed by the 1985 HCM (*1*) saturation flow rate equation. Computations begin with the selection of an "ideal" saturation flow rate. The term ideal is used here to reflect near-perfect operating conditions, such as wide lanes, no on-street parking, no grades, and so on. The 1985 HCM has selected 1,800 passenger automobiles per hour of green time per lane as a national average value that reflects ideal saturation flow rate. This ideal value is then adjusted to account for a variety of prevailing conditions that are not ideal.

The 1985 HCM saturation flow rate prediction computation is rather complex and is not reproduced in this paper. The CALSIG user's manual and Chapter 9 of the 1985 HCM contain complete discussions of this topic.

Method 3

The third and final option for establishing lane group saturation flow rates is to use default values. These default values may be used when existing data are not readily available or when the analyst feels that the complex saturation flow computations of the 1985 HCM are not warranted for a particular application. CALSIG-recommended default values assume average operating conditions; for example, 10- to 12-ft-wide lanes, 5 to 10 percent heavy vehicles in the traffic stream, no significant approach grades, and minor on-street parking turnovers and bus activity.

A value of 1,600 vehicles per hour of green time per lane (vphgpl) may be used for exclusive through lanes and shared right-turn/through lanes, and a value of 1,550 vphgpl may be used for exclusive left-turn lane traffic with protective phasing. A value of 1,500 vphgpl may be used for exclusive right-turn lane traffic with protected or permitted phasing.

The estimation of default saturation flow rate values for exclusive left-turn lane traffic with permitted phasing will depend on the number of total opposing vehicles. These opposing vehicles impede left-turn traffic. Figure 2 illustrates the relationship between the saturation flow rate of exclusive left-turn traffic, S (in vphgpl), with permitted phasing and the total opposing traffic flow, V_o (in vph). The curve in Figure 2 was constructed for multilane approaches by using the saturation flow equation (Equation 9-8) of the 1985 HCM. Thus Figure 2 may be used to estimate an appropriate saturation flow rate default value for exclusive left-turn lane traffic with permissive phasing.

The default values for unique lane groups with unusual phasing (for example, shared through/right-turn lane traffic with protected plus permitted phasing) may be estimated by using Tables 9–11 and 9–12 of the 1985 HCM. However, for such situations, it may be more appropriate to measure the saturation flow rates in the field or to estimate them comprehensively. If a lane group consists of a shared through/left-turn lane and has permitted phasing, field-measured or comprehensively estimated saturation flow rates should be used.

Intermediate Analysis

CALSIG's intermediate analysis incorporates all of the previously described intersection parameters (i.e., traffic demand, approach geometrics, phase design, and lane group saturation flow rates). This analysis procedure is identical to the "intersection capacity utilization" technique originally developed by Crommelin (*3*):

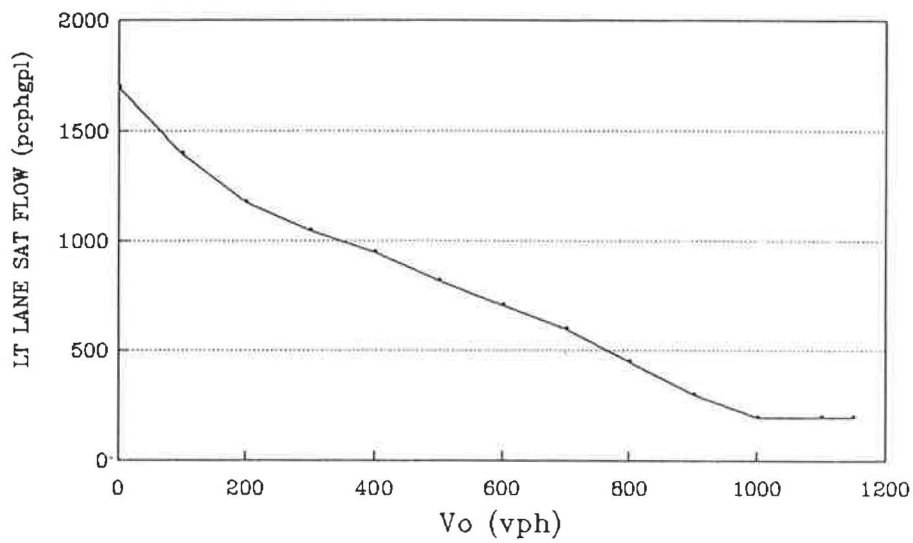

FIGURE 2 Shared left-turn lane (protected phasing) saturated flow rate versus opposing traffic.

• The flow ratio, V/S (volume/saturation flow rate), is computed for each lane group. Each lane group volume can be adjusted to reflect unequal lane distribution by incorporating the lane utilization factor, as explained in Chapter 9 of the 1985 HCM.

• Critical lane groups are then identified. A critical lane group is simply the lane group with the highest flow ratio in each phase.

If there are no overlapping signal phases (concurrent phase timing) in the signal design, there will be only one critical lane group for each signal phase.

Critical lane groups become a little more complicated to determine when overlapping phases exist. Combinations of lane groups that may consume the largest amount of available capacity must be identified on the basis of the phase plan. When a phase design includes an overlap, the critical lane groups for the subject phase sequences will be the highest sum of the through and opposing left-turn (if any) flow ratios. Examples of this technique are contained in the CALSIG user's manual and the 1985 HCM.

If optional phases exist within a phase plan, the analysis considers only the phase sequence that is most likely to occur during the time period that is being analyzed. Optional phases are controlled by the directions that have the heavier traffic flows.

• The flow ratio (V/S) values for each critical lane group are then summed.

• The sum of these critical lane group values can be modified to take into account the yellow and all-red clearance periods.

The equation that can be used to compute this clearance interval is as follows:

$$YA = (\Sigma\ V/S_{crit})\ (c/ny - 1)^{-1}$$

where

YA = clearance internal flow ratio;
$\Sigma\ V/S_{crit}$ = sum of the flow ratios for the critical lane groups;
c = established (or probable) cycle lengths (sec);
n = number of phases; and
y = average clearance interval (yellow and red-all) (sec).

The clearance interval flow ratio computed in this equation is simply added to the sum of the flow ratios for the critical lane groups. Incorporation of this clearance interval flow ratio into the analysis is optional. It should be noted that addition of a clearance interval flow ratio to the flow ratios of the critical lane group implies that longer cycle lengths (with fewer yellow periods) lead to improved operation. Such is not the case.

• The summed flow ratios of the critical lane groups can be related to a specific level of service designation. Table 1 lists flow ratio value ranges for level-of-service values A through F. These V/S values were originally developed by Crommelin (3) and are derived from the signalized intersection load factor diagrams in the 1965 HCM.

TABLE 1 V/S_{crit} AND LEVEL OF SERVICE (LOS)

V/S_{crit}	Level of Service
0.00–0.60	A
0.61–0.70	B
0.71–0.80	C
0.81–0.90	D
0.91–1.00	E
>1.00	F

If the summed flow ratios of the critical lane groups are greater than 1.0, extensive operational problems can be expected to occur at the intersection during the time period analyzed. If $\Sigma\ V/S_{crit} \geq 1.0$, the analyst should consider taking steps to mitigate congestion problems.

• If the analyst desires, the CALSIG computer program can perform a queueing analysis at this point in the program. The analysis utilizes the negative binomial distribution to compute the probability that overflow will occur on a given left-turn lane during the analysis period.

The intermediate analysis is a fairly simple method of relating traffic flows, geometric design, and signal phasing strategies with an overall level of service. However, this intermediate analysis assumes that the intersection is operating under optimal signal timing. This is often not the case. Therefore, if the CALSIG user wishes to perform an analysis that takes the signal timing information into consideration, or if the signal timing is to be established by using CALSIG, the procedure should be continued.

As before, the user has essentially three options once the intermediate analysis has been completed:

• Discontinue the procedure and obtain the intermediate analysis results.

• Modify any of the parameters incorporated into the procedures thus far so that more desirable operating conditions can be achieved.

• Continue the CALSIG procedure so that a more comprehensive design or analysis will be performed.

Minimum Green Time Module

The CALSIG module ensures that adequate green times are provided for crossing pedestrians and/or critical traffic volumes. The concept of establishing minimum time green is applicable to both pretimed and actuated signal timing.

If pedestrian traffic is involved, the minimum green time for the phase can be established on the basis of the time required for pedestrians to cross the approach (i.e., the approach intersecting the movement permitted by the subject phase). Equation 9-5 of the 1985 HCM is as follows:

$$gm = 7.0 + (W/4.0) - Y \qquad (1)$$

where

gm = minimum green time (required for pedestrians) (sec);
W = distance from the curb to the center of the furthest travel lane on the street being crossed or to the nearest pedestrian refuge island (ft); and
Y = change interval (yellow and all-red) (sec).

The 1985 HCM uses 7 sec as the initial pedestrian interval. However, other interval lengths may be used. For example, research has indicated that if fewer than 10 pedestrians cross the subject approach per cycle, a 4-sec initial interval is generally adequate. In Equation 1, 4.0 is used as the pedestrian walking speed (expressed in feet per second). Other values can be used as local policy dictates.

If signals with pedestrian-actuated push buttons are present, the minimum green time, as computed by Equation 1, need only be satisfied when the push buttons are actuated. At all other times, minimum green times can be established on the basis of vehicle demand.

Minimum green times should be established to accommodate given traffic volumes for phases without pedestrian movements. A rough estimate for such a required minimum green time may be computed on the basis of critical lane volumes for each phase. The critical lane volume is the largest flow entering the intersection in a given lane. The following equation can be used for determining the minimum green time to accommodate vehicles (*4*):

$$gm = (Vc/C) \times 2.5$$

where

gm = minimum green time required for vehicles (sec);
Vc = critical lane volume (vph); and
C = established (or probable) cycle length (sec).

The value of 2.5 used in this equation represents an average vehicle headway.

The user should check that minimum green times are not larger than actual green times (the CALSIG computer program checks green times automatically). If the actual green times are less than corresponding minimum green times, changes in the cycle splits should be considered.

Cycle Length Module

The cycle length, C, is the time required for the signal to complete a sequence of signal indications. For pretimed signals the cycle length remains fixed, but for actuated and semi-actuated signals the cycle length may vary from cycle to cycle. Principles involved in determining appropriate cycle lengths are similar for both actuated and nonactuated operation.

When cycle length is incorporated into the CALSIG procedure, the average or typical cycle time is used. This typical cycle length is the one that occurs most often during the time period being analyzed. Methods for determining the typical cycle length for actuated operation are discussed later in this section.

Design Procedure: Pretimed Signals

If the cycle length for a pretimed signal is not yet established, it may be computed by using Equation II. 9-1 of the 1985 HCM (Chapter 9, Appendix II):

$$C = LXc/[Xc - \sum_i V/S_{crit}] \qquad (2)$$

where

C = cycle length (sec);
L = lost time per cycle (sec) (may be assumed equal to the sum of the nonoverlapping phase change intervals for each phase);
Xc = critical V/c ratio (volume/capacity) for the intersection (this can be a desired value, selected by the user); and
$\sum_i V/S_{crit}$ = sum of the critical flow ratios for each phase.

Design Procedure: Actuated Signals

An actuated signal's maximum cycle length is a function of the sum of the maximum green intervals for each actuated phase. An appropriate maximum cycle length can be determined by computing an optimum cycle length with an equation developed by Webster (*5*) and then multiplying the resulting value by a factor ranging from 1.25 to 1.50. Webster's equation is as follows:

$$C = \frac{1.5\,L + 5}{1.0 - \sum_i V/S_{crit}}$$

(All terms have been defined previously.) Note that the resulting value will be multiplied by a factor ranging from 1.25 to 1.50.

The actuated signal's typical cycle length must be used in the CALSIG analysis. The typical cycle length may be determined in two ways:

- The typical cycle can be determined by field observation,

or

- The typical timing can be estimated by computation, again using Equation 2.

For semi-actuated signals, user-selected values of $Xc = 0.80$ to 0.90 are used; for actuated signals, a user-selected value of $Xc = 0.95$ is used. A more thorough discussion of the cycle length module is contained in the CALSIG user's manual.

Phase Length Module

The techniques used to incorporate phase lengths into the CALSIG procedure will vary somewhat, depending on the type of control used at the subject intersection. Green times for pretimed signals are fixed, but green times for actuated and semi-actuated signals will vary from cycle to cycle. Average green times of actuated signals are used in a CALSIG analysis.

Design Procedure: Pretimed Signals

If phase durations for pretimed signals are not yet established, they can be established by allocating green times such that the V/c ratios for critical movements in each phase are equal. The V/c ratio for the overall intersection can be computed using Equation 9-2 of the 1985 HCM:

$$Xc = \sum_i V/S_{\text{crit}}\ C/(C - L)$$

(All terms have been defined previously.)

The resulting value for Xc is then incorporated in Equation II.9-2 of the 1985 HCM:

$$gi = V/S_{\text{crit}} \times (C/Xc)$$

where gi is the green time for phase i (sec), and all other terms have been defined previously.

The sum of all green times plus the total lost time per cycle equals the signal's cycle length. If pretimed greens are less than their minimum greens, allocation of enough additional green to meet the minimum green can be considered.

Design Procedure: Actuated Signals

An actuated phase typically has three timing parameters: the initial interval, the vehicle extension, and the maximum green interval. A thorough discussion of the design and analysis techniques for actuated green times is contained in the CALSIG user's manual. A summary of this topic would be lengthy and is therefore not included in this paper.

Comprehensive Analysis Incorporating V/c as Primary MOE

This comprehensive analysis takes all previously described intersection parameters into account. The procedure yields a LOS value for each lane group, as well as for each approach and the overall intersection.

- The capacity of each approach lane group is computed. The value is the product of the lane group's saturation flow rate and the corresponding green ratio (green time/cycle length).
- The volume to capacity ratio, V/c, is computed for each lane group. Relationships between lane group V/c and level of service are taken directly from *Transportation Research Circular 212* (*6*). These values are presented in Table 2.
- The critical V/c ratio for the entire intersection, Xc, is computed using Equation 9-3 of the 1985 HCM:

$$Xc = \frac{\sum_i (V/S_{\text{crit}})\ C}{C - L}$$

(All terms have been defined previously.) A corresponding LOS can be taken from Table 2.

TABLE 2 V/c AND LEVEL OF SERVICE (LOS)

V/c Ratio	Level of Service
0.00–0.60	A
0.61–0.70	B
0.71–0.80	C
0.81–0.90	D
0.91–1.00	E
>1.00	F

The aforementioned analysis procedure comprehensively estimates the portion of an intersection's capacity that is actually utilized by traffic during a specific time period. When this analysis yields unacceptable results, modifications to one or more of the incorporated parameters can be considered. CALSIG's design elements may be consulted for modification suggestions.

Some transportation professionals prefer to use the intersection V/c ratio as a primary measure of effectiveness. V/c is a measure of facility utilization. The volume to capacity ratio can be used by designers when an intersection's size and geometric layout are being determined. However, the 1985 HCM maintains that the portion of capacity actually used at a signalized intersection is not completely indicative of the intersection's LOS. The new HCM states that delay is a better measure of driver discomfort, frustration, fuel consumption, and lost travel time. Thus the LOS criteria for the final comprehensive analysis is average stopped delay per vehicle.

In summary then, V/c may be thought of as a performance measure of the system. Delay is a performance measure describing operation from a user's perspective.

As before, the CALSIG user has three options once the first comprehensive analysis has been completed:

- Discontinue the procedure and obtain analysis results based on V/c.
- Modify any of the intersection parameters and repeat the procedure.
- Continue the CALSIG procedure so that the intersection LOS can be estimated on the basis of average stopped delay per vehicle.

Comprehensive Analysis Incorporating Delay as Primary MOE

This ultimate step in the CALSIG procedure relates the intersection's level of service to the average stopped delay per vehicle that is estimated to occur during the analysis period. This final comprehensive analysis is identical to the 1985 Capacity Manual's operational procedure.

- Delay on each lane group is computed by using Equation 9-18 of the 1985 HCM:

$$d = 0.38\, C \frac{[1 - g/C]^2}{[1 - (g/C)X]} + 173\, X^2\, [(X - 1)] + [(X - 1)^2 + (16X/c)]^{1/2}$$

where d is the average stopped delay per vehicle (sec) and all other terms have been defined previously.

• A progression adjustment factor, taken from Table 9-13 of the 1985 HCM, is applied to each lane group delay value. The adjustment factor ranges from 0.40 to 1.85 and is multiplied by the delay value. This adjustment factor accounts for the vehicle platooning characteristics and the type of signal control at the intersection.

• Corresponding levels of service can be related to each lane group adjusted delay. Relationships between delay and level of service are presented in Table 3 of this paper and are taken directly from Table 9-1 of the 1985 HCM.

• By computing weighted averages, levels of service can be determined for each intersection approach and for the intersection as a whole.

TABLE 3 DELAY AND LEVEL OF SERVICE (LOS)

Stopped Delay per Vehicle	Level of Service
0.00– 5.0	A
5.1 –15.0	B
15.1 –25.0	C
25.1 –40.0	D
40.1 –60.0	E
>60.0	F

In determining the intersection level of service, this analysis takes into consideration a wide variety of known or projected prevailing conditions. If the comprehensive analysis yields unacceptable results, modifications to one or more of the intersection parameters should be considered. CALSIG's design elements can be consulted for suggestions on methods of implementing operational improvements.

SAMPLE CALCULATION

This section consists of an annotated example problem. Because the CALSIG software dramatically reduces the time and effort required to perform the entire CALSIG procedure, the computations for the following example problem were performed by using this program. Most of the figures for this section are the interactive screens produced by the software. The example illustrates CALSIG's design and analysis elements. The intersection to be evaluated is taken directly from the 1985 Capacity Manual (Calculation 4).

Turning Movement Demand and Geometrics Module and Preliminary Analysis

For this problem, projected turning movement demand and approach geometrics are established by the user. The problem examines future traffic demand, so full hourly volumes are used. It is assumed that an entire CALSIG procedure is to be performed for this intersection.

• Total turning movement volumes are entered in each corner of Figure 3. The figure also illustrates the vehicle distribution per lane. The distribution is computed in the preliminary analysis. This step is performed automatically by the CALSIG computer program.

• The sum of the critical turning movement volumes is illustrated in Figure 4. The analysis predicts that the intersection is operating near capacity.

• To achieve a better predicted operation, CALSIG's geometric design criteria are consulted. The criteria indicate that an exclusive right-turn lane should be added to the eastbound approach. This modified scenario is illustrated in Figure 5. The distribution per lane is again computed.

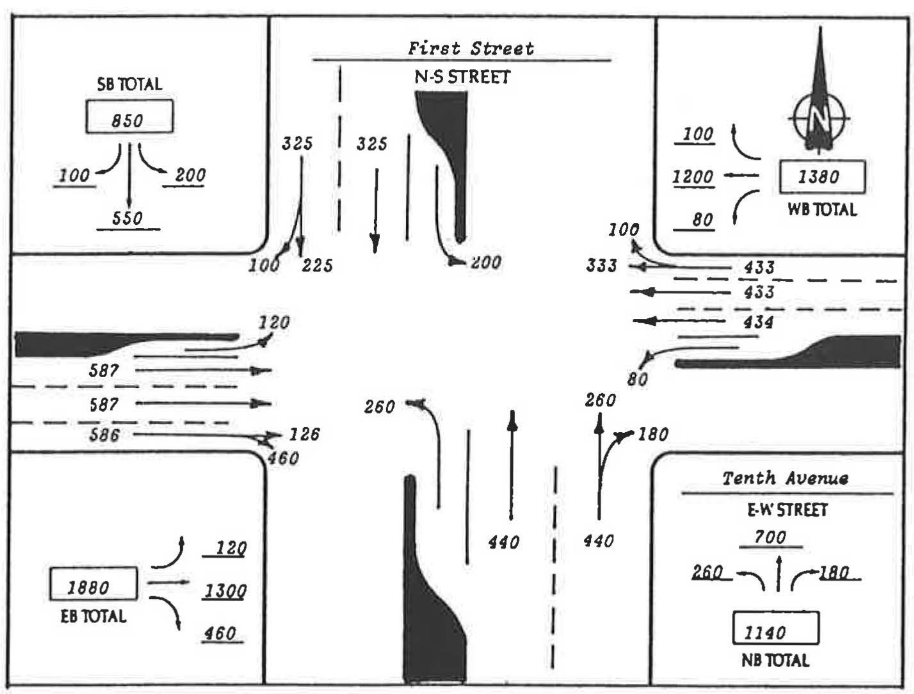

FIGURE 3 Example problem (taken from 1985 HCM).

```
                                                  The 1985 HCM estimates
EBLT =       120          NBLT =        260       Capacity Criteria as
WBTH =       433          SBTH =        325       follows:
       ----------                ----------
             553                        585       MAXIMUM SUM      CAPAC.
                                                  OF CRIT. VOL     LEVEL
WBLT =        80          SBLT =        200
EBTH =       587          NBTH =        440          0 to 1200     under
       ----------                ----------       1201 to 1400     near
             667                        640            > 1400      over
         667                       640             1307
----------------    +     ----------------   =   -----------
E-W Critical              N-S Critical
```

```
According to the 1985 HCM, this intersection is estimated to be
operating  near  capacity.

Extended vehicle queues may occur at the intersection approaches
during the time period analyzed.
```

FIGURE 4 Critical movement analysis.

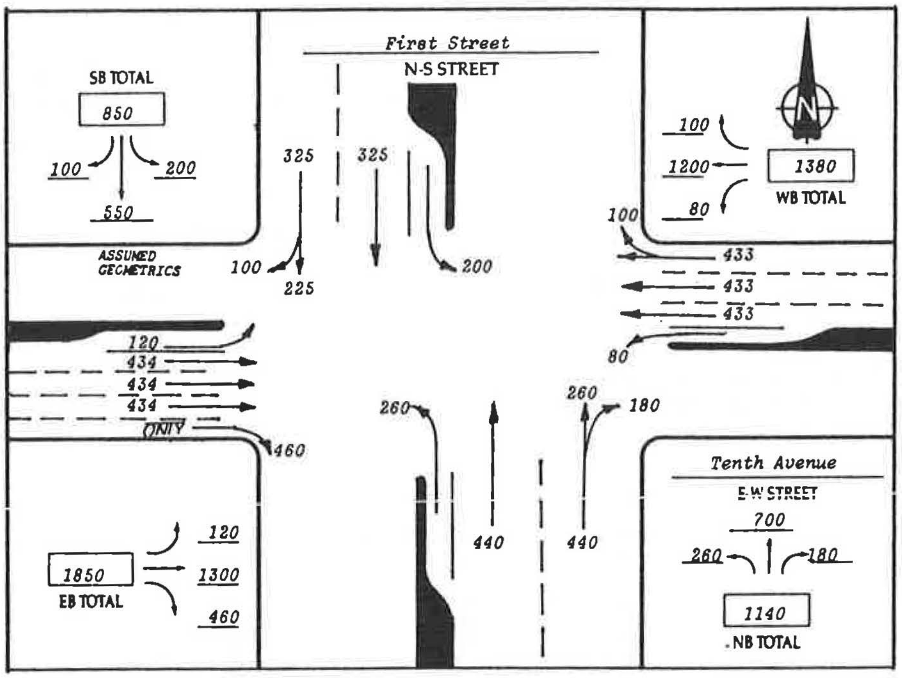

FIGURE 5 Example problem: modified geometrics (taken from 1985 HCM).

• The critical movement analysis now predicts that the intersection will be operating under capacity (Figure 6). This modified geometric plan is therefore adopted by the user.

Phase Design Module

No information concerning the phase design is given in this sample problem. CALSIG's design criteria are therefore used to establish the phase plan. The CALSIG-generated design is shown in Figure 7.

• The CALSIG design criteria have designed a multiphase operation to accommodate heavy left-turn volumes.

The crosses in Figure 7 indicate the movements that occur for each phase. Eastbound and westbound traffic have leading protected left-turn phases. Northbound and southbound traffic have leading protected left-turn (LT) phases, with a phase overlap for NB traffic. (The overlap was designed because the level of NB LT traffic is significantly higher than that of the SB LT traffic.)

• The CALSIG-generated phase design is adopted by the user.

Saturation Flow Rate Module and Intermediate Analysis

Relatively little information is given about the prevailing conditions of this intersection, so CALSIG default values are used for estimating the lane group saturation flow rates. These saturation flows and the intermediate analysis are shown in Figure 8.

```
EBLT =        120              NBLT =         260        The 1985 HCM estimates
WBTH =        433              SBTH =         325        Capacity Criteria as
       ----------                      -----------       follows:
              553                             585
                                                         MAXIMUM SUM       CAPAC.
WBLT =         80              SBLT =         200        OF CRIT. VOL      LEVEL
EBTH =        433              NBTH =         440
       ----------                      -----------          0 to 1200      under
              513                             640        1201 to 1400      near
          553                            640                  > 1400       over
-----------------      +       ---------------- = ------------ 1193
E-W Critical                   N-S Critical

According to the 1985 HCM, this intersection is estimated to be
operating  under  capacity.

Extended vehicle queues are unlikely to occur at the intersection
approaches during the time period analyzed.
```

FIGURE 6 Critical movement analysis: modified geometrics.

		PHASES						SPECIAL PHASES						
		1	2	3	4	5	6		1	2	3	4	5	6
EB	LT	X						EB/WB PED						
	TH		X											
	RT		X											
WB	LT	X						Protected NB RT SB RT						
	TH		X											
	RT		X											
NB	LT			X	X			NB/SB PED						
	TH				X	X								
	RT				X	X								
SB	LT			X				Protected EB RT WB RT						
	TH					X								
	RT					X								

FIGURE 7 Phase design.

	Lane Group	No of Ln	Flow in Lane Group	Satur. Flow p/lane	Lane Group Sat.Fl	LUF	v/s	Cr. v/s
EB	ELT	1	120	1500	1500	1.00	0.08	0.08
	ETH	3	1299	1600	4800	1.10	0.30	0.30
	ERT	1	460	1550	1550	1.00	0.30	
WB	ELT	1	80	1500	1500	1.00	0.05	
	ETH+RTTH	3	1299	1600	4800	1.10	0.30	
NB	ELT	1	260	1500	1500	1.00	0.17	
	ETH+RTTH	2	880	1600	3200	1.05	0.29	
SB	ELT	1	200	1500	1500	1.00	0.13	0.42
	ETH+RTTH	2	650	1600	3200	1.05	0.21	

LOS	Σv/s
A	0.00-0.60
B	0.61-0.70
C	0.71-0.80
D	0.81-0.90
E	0.91-1.00
F	> 1.00

Σv/s=0.80
crit

FIGURE 8 Default saturated flows and intermediate analysis.

		PHASES 1	2	3	4	5	6
EB	LT	X					
	TH		X				
	RT		X				
WB	LT	X					
	TH		X				
	RT		X				
NB	LT			X	X		
	TH				X	X	
	RT				X	X	
SB	LT			X			
	TH					X	
	RT					X	

SPECIAL PHASES	1	2	3	4	5	6
EB/WB Peds						
NB RT Protect. SB RT Protect.						
NB/SB Peds						
EB RT Protect. WB RT Protect.						

MINIMUM GREEN TIMES 1	2	3	4	5	6
3	15	5	1	10	

FIGURE 9 Minimum green times.

An overlap exists for the NB traffic, so the special procedure discussed previously is used to sum the critical flow ratios. The sum of these V/S_{crit} values (0.80) corresponds to a level of service C. No adjustment was made for clearance intervals.

Signal Timing Modules

The CALSIG design elements are used to generate minimum green times, cycle length and phase change intervals, and phase lengths. These values are illustrated in Figures 9–11. It is assumed that pretimed operation is in place.

- Minimum green times are established on the basis of vehicular demand for phases 1, 3, and 4, and on the basis of pedestrian requirements in phases 2 and 5 (Figure 9).
- Computed cycle length is 100 sec. This length was calculated by using Equation II.9-1 of the 1985 HCM (Figure 10).
- Phase lengths are established such that the V/c ratios for critical movements are equal (Equations 9-3 and II.9-2 of the 1985 HCM). Note that the sum of the green times and all nonoverlapping phase change intervals is equal to the cycle

CYCLE LENGTH:100

PHASE CHANGE INTERVAL 1: 3
PHASE CHANGE INTERVAL 2: 3
PHASE CHANGE INTERVAL 3: 3
PHASE CHANGE INTERVAL 4: 3
PHASE CHANGE INTERVAL 5: 3

FIGURE 10 Cycle length and phase change intervals.

length. Also note that all actual green times are larger than their corresponding minimum green times (Figure 11).

Comprehensive Analysis Using V/c as MOE

Lane group capacities are the product of each lane group saturation flow rate and g/C ratio. The computed V/c value for each approach, and the intersection as a whole, indicates LOS D (Figure 12).

		PHASES 1	2	3	4	5	6
EB	LT	X					
	TH		X				
	RT		X				
WB	LT	X					
	TH		X				
	RT		X				
NB	LT			X	X		
	TH				X	X	
	RT				X	X	
SB	LT			X			
	TH					X	
	RT					X	

SPECIAL PHASES	1	2	3	4	5	6
EB/WB Peds						
NB RT Protect. SB RT Protect.						
NB/SB Peds						
EB RT Protect. WB RT Protect.						

ACTUAL GREEN TIMES 1	2	3	4	5	6
9	34	15	9	24	

FIGURE 11 Phase length module.

	Lane Group	Flow in Lane Group	Lane Group Capac.	Lane Group v/c	Lane Group LOS	Appro. v/c	Appro. LOS
EB	ELT	120	135	0.89	D	0.88	D
	ETH	1429	1632	0.88	D		
	ERT	460	527	0.87	D		
WB	ELT	80	135	0.59	A	0.86	D
	ETH+RTTH	1429	1632	0.88	D		
NB	ELT	260	360	0.72	C	0.84	D
	ETH+RTTH	924	1056	0.87	D		
SB	ELT	200	225	0.89	D	0.89	D
	ETH+RTTH	682	768	0.89	D		

V/C (Crit)=0.88

Intersection LOS = D

FIGURE 12 ***V/c* and level of service (LOS).**

	Lane Group	v/c Ratio	Green Ratio (g/C)	Delay d1	Lane Group Capac	Delay d2	Prog Fact	Lane Group Delay	Lane Group LOS	Appr. Delay	Appr LOS
EB	ELT	0.89	0.09	34.20	135	31.71	1.00	65.91	F	31.64	D
	ETH	0.88	0.34	23.57	1632	4.07	1.00	27.64	D		
	ERT	0.87	0.34	23.54	527	10.47	1.00	34.01	D		
WB	ELT	0.59	0.09	33.24	135	4.78	1.00	38.02	D	28.24	D
	ETH+RTTH	0.88	0.34	23.57	1632	4.07	1.00	27.64	D		
NB	ELT	0.72	0.24	26.55	360	4.76	1.00	31.31	D	30.25	D
	ETH+RTTH	0.87	0.33	23.98	1056	5.95	1.00	29.94	D		
SB	ELT	0.89	0.15	31.68	225	22.38	1.00	54.06	E	40.79	E
	ETH+RTTH	0.89	0.24	27.90	768	8.81	1.00	36.71	D		

Intersection Delay:31.93 sec/veh Intersection LOS:D

FIGURE 13 Delay and level of service (LOS).

Comprehensive Analysis Delay as MOE

Average stopped delay per vehicle is computed by using Equation 9-18 of the 1985 HCM. A LOS D is predicted (Figure 13).

An inspection of the results in each analysis shows that all levels of analysis are in fairly close agreement. Because CALSIG ultimately generated all intersection parameters, improvement of the operation by implementing design changes is probably not worthwhile.

CONCLUSIONS

This paper has described a proposed procedure, called CALSIG, for the design and analysis of signalized intersections. CALSIG was developed in an effort to enhance existing procedures in Chapter 9 of the 1985 HCM. The CALSIG procedure is not actually a new procedure but is rather an integration of existing methodologies. As a result of this integration, CALSIG has a multilevel analysis structure. This structure does not necessarily render the procedure less complex than the existing HCM operational analysis; however, the multilevel format does offer additional flexibility.

The CALSIG methodology also possesses design elements. These design guidelines serve to generate unestablished intersection parameters and help to determine effective operational improvements.

CALSIG was designed to aid transportation professionals in the state of California. CALSIG is applicable, however, to any location in the United States. Adjustments for local conditions are always recommended.

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