ACRP Report 40
Airport Curbside and Terminal Area Roadway Operations

Appendix F

A REPRODUCTION OF PORTIONS OF TRB CIRCULAR 212

NCHRP PROJECT 3-28: DEVELOPMENT OF AN IMPROVED HIGHWAY CAPACITY MANUAL

Preface

This research was conducted by JHK & Associates as National Cooperative Highway Research Program (NCHRP) Project 3-28, Phase I. The Traffic Institute at Northwestern University served as subcontractor on the project. Mr. William R. Reilly of JHK & Associates was Principal Investigator, and the principal professional for the Traffic Institute was Mr. Ronald C. Pfefer.

Other key team members were James H. Kell, Ruel H. Robbins, Richard A. Presby, and Iris J. Fullerton of JHK & Associates. Technical editor of these materials was Mr. David A. Kell of JHK & Associates --who also served as production supervisor during final layout and paste-up. For the Traffic Institute, Jack Hutter, Alex Sorton, and Robert Seyfried provided valuable input to the work. Other personnel in both agencies also contributed to the research effort.

Appreciation is extended to the Transportation Research Board's Committee on Highway Capacity and Quality of Service for their cooperation in surveying users, for conducting workshops at the 1978 Annual Meeting of the Transportation Research Board and for reviewing these interim materials prior to publication.

Special acknowledgement is due to two individuals. Mr. Herbert Levinson of Wilbur Smith and Associates served as principal author of the Transit section, and Mr. Jeffrey Zupan of the Regional Plan Association contributed the basic work leading up to the Pedestrian section of these interim materials.

The NCHRP Project 3-28 Panel played an important part in guiding the research, and took an active role as "users" in providing insights and suggestions on the contents and format of the interim sections included in this volume.

Contents

ORGANIZATION OF THESE MATERIALS

This report comprises the first set of interim materials which will be distributed prior to the publication of a new "Highway Capacity Manual" in the mid 1980's. These interim materials are intended for application by HCM users in the 1980-1982 period. A user response form is included at the end of this document to permit users of these materials to communicate their comments to the Transportation Research Board directly. This user response will be vital in identifying desirable revisions to the interim materials prior to their inclusion in the new manual. Users are encouraged to send to TRB their observations, including actual data and analyses.

The interim materials provided in this section are Critical Movement Analysis, Unsignalized Intersections, Transit, and Pedestrians. Development of these sections has been carried out as part of NCHRP Project 3-28, "Development of an Improved Highway Capacity Manual." Project 3-28 was started in 1977, and the final report on Phase I of the Project was submitted to NCHRP in August, 1979. The final report describes the user surveys, the assessment of research and literature, the process used for developing the interim materials included here, and the proposed research program needed to produce documentation for a new Highway Capacity Manual.

Each of the interim materials in this report is introduced with a "DISCUSSION" which explains the background and the conceptual framework for the technique. The technique itself is explained and references are cited. The "USER APPLICATIONS" section then leads the user through a step-by-step description of the calculation, and several numerical examples are provided. Completed calculation forms are provided and shown for each example. Also, a blank form is provided in each section, except for the "Transit" material, which does not utilize a calculation form.

Critical Movement Analysis

Critical Movement Analysis is based on work conducted in the 1960's and 1970's by various researchers and practitioners. Of particular importance are the works of McInerney and Petersen, and of Messer and Fambro. The project team did, however, make major changes in previously reported methods to devise the final technique as presented herein. Mr. William R. Reilly, Principal Investigator of NCHRP Project 3-28, had primary responsibility for deriving the final procedure.

Critical Movement Analysis allows the HCM user to analyze the urban signalized intersection as an entire unit. The overall intersection level of service and the effects on level of service of design and operational changes can be determined. Also, guidelines on ranges of vehicle delay expected under different levels of service are included. The technique is divided into PLANNING applications for relatively simple and quick computations; and OPERATIONS AND DESIGN applications for a more detailed solution. Both applications are similar in concept and both allow the user to analyze intersections operating with pretimed signals, vehicle actuated signals, and multiphase signals with phase overlap.

For determination of capacity or level of service of a single intersection approach, the 1965 HCM remains the principal tool until the new HCM is produced.

Unsignalized Intersections

The procedure for capacity analysis of unsignalized intersections is an adaptation, in content and format, of a German technique reported in the Organisation for Economic Co-Operation and Development (OECD) report, "Capacity of At-Grade Junctions." Mr. James H. Kell, of the NCHRP Project 3-28 team, was most directly responsible for revising and adapting this technique to the point where it can be of use to the HCM user.

Only those unsignalized intersections that are controlled by two-way STOP signs or by YIELD signs can be analyzed by this technique. The procedure is not applicable to uncontrolled intersections or four way STOP sign controlled intersections.

Initially, the capacity or maximum flow of vehicles in passenger car equivalents is calculated for each minor approach movement. These values are then compared to the existing demand for each movement and the probable delay and level of service is estimated.

The assumption is made that major street traffic is not affected by the minor street movements. Left turns from the major street to the minor street are influenced only by the opposing major street through flow. Minor street flows, however, are impeded by all other conflicting movements. The procedure includes adjustments for mutual interference to the minor street traffic streams, such as the additional adverse effect of main street vehicles waiting to make left turns.

In order to treat these potential impedences, it is necessary to structure the computational procedures and deal with individual traffic movements in the following order:

1. Right turns into the major road;
2. Left turns from the major road;
3. Through traffic crossing the major road; and
4. Left turns into the major road.

In addition, the method takes into account the lane configuration on the minor street and includes appropriate adjustments for movements that use the same lane (shared lane).

The application of this technique and subsequent user comments may lead to a linking of this method to standard warrants for traffic signal installation. However, at this time no attempt has been made to relate the two procedures.

Transit

Bus transit on urban streets and expressways and, to a lesser extent, rail transit, is described in the Transit section of this document. This material was developed by Mr. Herbert S. Levinson, of Wilbur Smith and Associates. The NCHRP 3-28 Project Team participated with Mr. Levinson in the final review of the material.

The HCM user will be able to apply these materials to the analysis of capacity and level of service of bus lanes, busways, and rail transit lines. Analysis techniques for determining the number of bus berths needed, given bus flows and passenger service times, are described. Also, considerable data on characteristics of existing transit systems are included, to illustrate the operating experience of transit properties.

Although calculation forms are not included in this section, several example problems do indicate the application of the concepts and numerical values involved with transit capacity.

Pedestrians

Development of the pedestrian section was initiated with Mr. Jeffrey L. Zupan's presentation of his discussion paper, "Pedestrian Facilities," at the 1978 TRB Annual Meeting. Mr. Zupan, of the Regional Plan Association, worked with the NCHRP 3-28 project team during 1978 to expand and finalize the materials. Mr. Ruel Robbins of JHK & Associates and Mr. Alex Sorton of the Traffic Institute were instrumental in developing this section for the project team. These materials provide the HCM user with an analytical tool to analyze the flow characteristics of walkways (e.g., sidewalks) and intersection crosswalks. The section does not address other pedestrian facilities (such as stairways, escalators, and elevators), although standard reference documents describing such facilities are cited.

The analysis procedure is based on the amount of space available per person and walking speed, with space being the principal determinant of level of service. The "effective width" of a walkway is determined by using width adjustments based on the effects of various fixed objects. The technique can be used to either analyze the flow characteristics and levels of service of an existing facility, or to determine a walkway design for a given design level of service. The new concept of "platoon flow" is introduced and can be applied by the HCM user for conditions where peaking is substantial over short periods.

For crosswalks, a method is presented for the analysis of both the intersection reservoir area and for the crosswalk itself. The adequacy of either a planned or an existing crosswalk and reservoir are also determined by applying the technique.

DISCUSSION

Introduction

Critical Movement Analysis is a procedure which allows for capacity and level of service determination for signalized intersections. The analysis incorporates the effects of geometry and traffic signal operation and results in a level of service determination for the intersection as a whole operating unit.

The ability of a line of vehicles to discharge past a point is the key principle involved. Rarely can a discharge rate of 2000 passenger cars per hour of green be surpassed. Because of time lost due to queue start up and signal change intervals the maximum discharge of a single lane at signalized intersections typically varies from 1500 to 1800 passenger cars per hour of green. The 1965 Highway Capacity Manual (HCM) (1) states that a single lane at a traffic signal can accommodate 2000 and 1500 passenger cars per hour of green respectively, for a perfectly coordinated signal where all vehicles pass through without stopping, and for a signal where all vehicles must stop.

Definitions

Approach - The portion of an intersection leg which is used by traffic approaching the intersection.

Capacity - The maximum number of vehicles that has a reasonable expectation of passing over a given roadway or section of roadway in one direction during a given time period under prevailing roadway and traffic conditions.

Change Interval - Yellow time plus all red time occurring between two phases.

Critical Volume - A volume (or combination of volumes) for a given street which produces the greatest utilization of capacity (e.g., needs the greatest green time) for that street. Given in terms of passenger cars or mixed vehicles per hour per lane.

Cycle Time - The period in seconds required for one complete sequence of signal indications.

Delay - Stopped time delay per approach vehicle, in seconds per vehicle.

Green Time - The length of a green phase plus its change interval, in seconds.

Hourly Volume - The number of (mixed) vehicles that pass over a given section of a lane or roadway during a time period of one hour.

Level of Service - A measure of the mobility characteristics of an intersection, as determined by vehicle delay and a secondary factor, volume/capacity ratio.

Local Bus - A bus having a scheduled stop at the intersection under analysis.

Passenger Car Equivalency - For a given vehicle, the number of through moving passenger cars it is equivalent to, based on its headway and delay creating effects.

Passenger Car Volumes - The volumes expressed in terms of passenger cars, following the application of passenger car equivalency factors to vehicular volumes.

Period Volume - A design volume, based on the flow rate within the peak 15 minutes of an hour, and converted to an equivalent hourly volume.

Peak Hour Factor - A measure of peaking characteristics within the peak hour, equal to:

$$\text{PHF} = \frac{\text{Peak Hour Volume}}{4(\text{Highest 15 minute Volume})}$$

Phase - A part of the cycle allocated to any traffic movement or combination of traffic movements receiving right of way simultaneously during one or more intervals.

Probable Phase - A phase within the probable sequence of phases which represents the sequence of a multi-phase signal controller most likely to occur under given traffic conditions.

Through Bus - A bus not having a designated stop at the intersection under analysis.

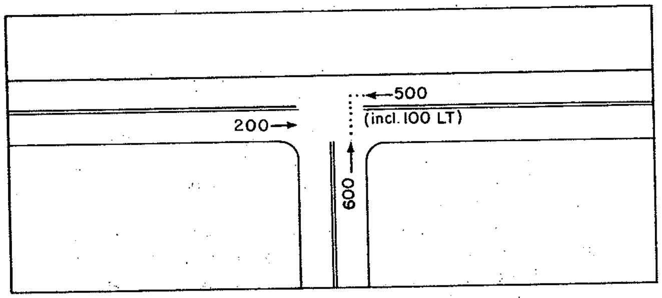
Truck - A vehicle having six or more tires on the pavement.

G/C = Green time/Cycle time ratio
HV = Hourly Volume
LB = Local Bus (Number per hour)
LOS = Level of Service
LT = Left Turn
PCE = Passenger Car Equivalency
pch = Passenger cars per hour
PCV = Passenger Car Volume, in pch
PHF = Peak Hour Factor
PV = Period Volume
RT = Right Turn
T = Truck and Through Bus (Percentage of HV)
TH = Through Traffic
U = Lane Utilization Factor
v/c = Volume/Capacity ratio
V_L = Left Turn Volume, in vph
V_0 = Volume Opposing a V_L, in vph
vph = Vehicles per hour (mixed traffic)
W = Lane Width factor

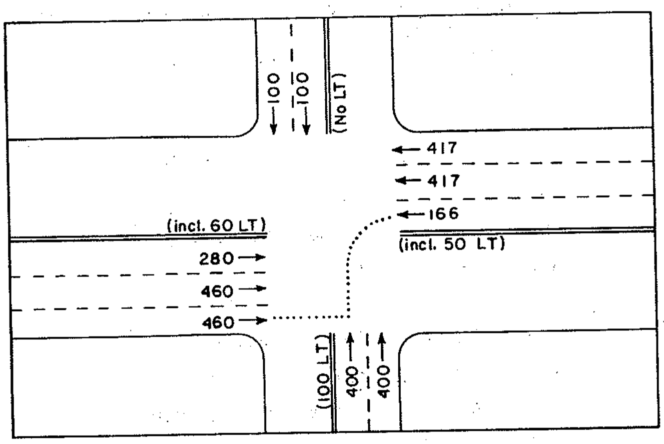
Background

The development of Critical Movement (then called "critical lane") Analysis was first reported in 1961 by Capelle and Pinnell (2) in a study of diamond interchanges. In 1971, McInerney and Petersen (3) explained the technique as applied to traffic planning work. In 1975, Trout and Loutzenheiser (4) reported on field tests and questionnaire results related to application of the method. Messer and Fambro (5) proposed a detailed procedure for critical movement analysis to assess design alternatives. In 1978, it was determined by NCHRP Project 3-28 (6) that many planners and engineers were usng the method, both for detailed traffic signal and geometric design, and for planning studies. The technique seems to be gaining greater acceptance, not only in North America but also overseas. For example, the Swedish Capacity Manual (7) contains a form of critical movement analysis in its chapter on intersections.

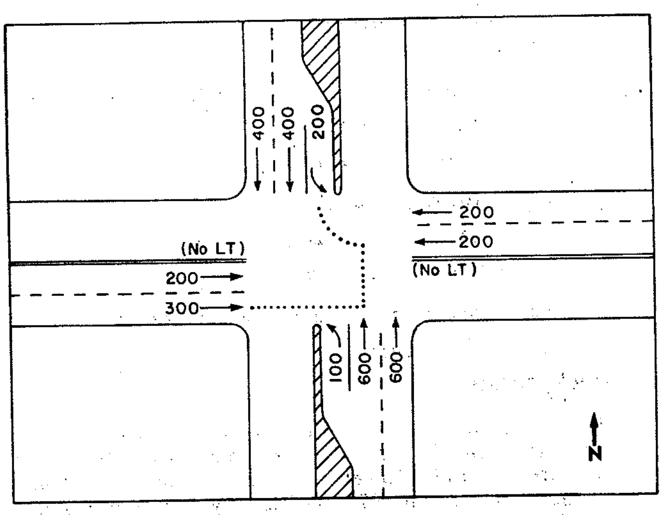
Figure 1. Critical Movements, PLANNING Applications



- Single Lane Approaches
- Two Phase Signal
- Critical Movements:
  500 and 600 vph
- Sum of Critical Volumes:
  500 + 600 = 1100 vph



- Two and Three Lane Approaches
- Two Phase Signal
- Critical Movements, by lane:
  400 and 460 + 50 vph
- Sum of Critical Volumes:
  400 + 510 = 910 vph



- Two and Three Lane Approaches
- Five Phase Actuated Signal
- Note:
  For the east-west street, the critical volume is 300 vph. For the north-south street the greatest demand for green time will occur with the conflicting movement totaling 800 vph (600 + 200 LT). The conflicting movement totaling 500 vph (400 + 100 LT) would require less green time and will be satisfied if the 800 vph critical volume is satisfied.
- Sum of Critical Volumes:
  300 + 800 = 1100 vph.

Note:
The above examples relate to PLANNING applications of Critical Movement Analysis. OPERATIONS AND DESIGN applications of the method use a somewhat different procedure for combining critical volumes, and express volumes in terms of passenger cars per hour (pch) instead of in terms of vehicles per hour (vph)

Analytical Base

There is at each signalized intersection a combination of conflicting movements which must be accommodated. Figure 1 shows several examples of critical movement combinations. Regardless of the complexity of the intersection and its traffic signal operations, the critical volumes (when placed on a per lane basis) cannot physically be accommodated beyond the 2000 passenger cars per hour of green (pchg) limit, and in practice cannot be accommodated beyond about 1500 to 1800 pchg. The latter values take into account the time headway between successive vehicles, the starting delay for a queue of vehicles, and the lost time due to signal change intervals.

Time headway (average headway, once the initial queue start-up time has been experienced), starting delay, and the amount of lost time due to yellow and red intervals must be considered in order to assess the capacity of a single lane. Numerous researchers have proposed formulae for calculating capacity of a single lane based on these factors. Table 1 gives several of the more prominent formulae for

Table 1. Capacity Calculation Techniques

Reference	Formula	Calculated Capacity[a]
1. Berry-Gandhi (8) Method	$\text{Cap (in vph)} = \frac{3600(G + \lambda Y - D + H)}{CH}$ where: Cap = Capacity of the signalized approach D = Starting time delay, in seconds, elapsing from beginning of green indication to the instant the rear wheels of the first vehicle cross the reference line (usually, the stop line) H = Average headway time, in seconds, for all vehicles in a compact platoon that cross the reference line. λ = Proportion of the length of yellow indication, for a loaded cycle, which is utilized up to the time the last vehicle in a compact platoon crosses the reference line C = Length of signal cycle, in seconds G = Length of green indication, in seconds Y = Length of yellow indication, in seconds vph = Vehicles per hour pch = Passenger cars per hour	$= \frac{3600[40 + (0.5)(4) - 3 + 2.1]}{(80)(2.1)}$ = 881 vehicles per hour
2. Capelle-Pinnell (2) Critical Lane Method	$\text{Cap (in vph)} = (\frac{G - D}{H} + 2)(\frac{3600}{C})$ where: D = Starting delay--the time for the first two vehicles to enter H = Average time headway for the third, fourth, fifth, etc. vehicles to enter G = Length of green indication, in seconds C = Cycle length, in seconds	$= (\frac{40 - 5.0}{2.1} + 2)(\frac{3600}{80})$ = 840 vehicles per hour
3. Messer-Fambro (5)	Cap (in pch) = SG/C where: C = Cycle length, in seconds S = Saturation flow, in passenger cars per hour of green, measured empirically as in the Australian Method (9, 10) and assumed as 1800 passenger cars per hour of green in this example (a typical value for a through lane) G = Effective green time, in seconds = green + yellow - 4.0 seconds	= [1800(40 + 4.0 - 4.0)]/[80] = 900 passenger cars per hour
4. Bellis-Reilly (11, 12, 13) Method	$\text{Cap (in pch)} = (\frac{3600}{C})(\frac{G + 3}{H})$ where: G = Length of green indication, in seconds C = Cycle length, in seconds H = Average time headway, in seconds	$= (\frac{3600}{80})(\frac{40 + 3}{2.1})$ = 921 passenger cars per hour
5. British (14) Method	$\text{Cap (in pch)} = \frac{160WG}{C}$ where: W = Width of lane, in feet G = Effective green time, in seconds = green + yellow - 4.0 seconds C = Cycle length, in seconds	$= \frac{(160)(12)(42)}{80}$ = 1000 passenger cars per hour
6. 1965 Highway Capacity Manual (1)	USE: Figure 6.8, p. 135. Use a 24 ft. width to place the analysis in a more representative section of the charts. Assume no turns and no trucks or through buses, and no local buses. Also, assume PHF = 0.85 and Metro Area population = 500,000. THEN: Cap (in pch) = (2100 vphg)(G/C)(PHF/Pop)(Location)(Left Turns)(Right Turns)(Trucks and Buses) = (2100)(40/80)(1.06)(1.25)(1.10)(1.10)(1.05) = 1610 passenger cars per hour per approach	= 805 passenger cars per hour

[a]Problems based on suburban arterial street with 12 ft. lanes, headway average = 2.1 seconds, starting delay for first vehicle only = 3.0 seconds, G/C = 40/80 seconds, yellow time = 4 seconds, with 2 seconds used for traffic movement. **All results are on a per-lane basis.** (1 foot = .305 meter)

estimating capacity, and includes a numerical example.

The computations in Table 1 indicate that very little variation exists in the value used for capacity of a standard 12 foot wide (3.7 m) lane at an urban signalized intersection with ideal traffic conditions (no trucks, buses, or turning motions). Three of the models shown give capacities of approximately 900 pch for a green time/cycle time (G/C) ratio of 0.5. The British method, which has been known to give considerably higher computed values for capacity than North America methods, shows a computed capacity 12 percent higher. The 1965 HCM yields a capacity value of 805 pch (G/C = 0.50), or about 10% below the other methods.

Because of the close agreement between Berry-Gandhi (8), Capelle-Pinnell (2), Messer-Fambro (5), and Bellis-Reilly (11, 12, 13), an average value of 1800 passenger cars per hour of green (pchg) for a 12 foot (3.7 m) through traffic lane--with no trucks, buses, turns, or pedestrian interference--can be used as a base value for capacity in the critical movement analysis technique. It should be noted that the British capacity procedures use—for a 13 foot (4.0 m) wide lane—a capacity of 1950 pchg.

The factors which are considered of prime importance in modifying the capacity value of 1800 pchg for a single 12 foot (3.7 m) lane are as follows:

1. Lane Width
2. Buses and Trucks
3. Bus Stop Operations
4. Left Turns
5. Right Turns and Pedestrian Activity
6. Parking Activity
7. Peaking Characteristics (Peak Hour Factor)

Other factors—such as vertical grade and type of driver using the intersection—may be of importance in modifying the capacity value, but little research has been accomplished in these areas. Also, field measurement of saturation flow allows the HCM user to establish a capacity value for any intersection approach or lane without explicitly defining each modifying factor.

1. Lane Width. The critical movement procedure proposed by Messer and Fambro (5) includes a reduction in calculated capacity of 10 percent for lane widths between 9.0 and 9.9 feet (2.7 m and 3.0 m). For lanes 10.0 feet (3.0 m) or wider, no adjustment in capacity is made. Note that these adjustments increase the passenger car volume (PCV) rather than reduce capacity.

Using the Australian procedures (9, 10), capacity adjustments are made for lanes not falling in the 10.0 to 12.0 foot (3.0 m to 3.7 m) range. Adjustments for the value of capacity are:

Lane Width (feet):	8.0	9.0	13.0	14.0	15.0
Lane Width (meters):	2.4	2.7	4.0	4.3	4.6
Adjustment Value:	-12%	-7%	+3%	+4½%	+6%

Application of the 1965 HCM, with the assumed conditions used in Table 1, gives adjustment values of - 29% for the equivalent of a 9 foot (2.7 m) lane and + 19% for the equivalent of a 14 foot (4.3 m) lane. Table 2 combines these concepts into a readily applied set of values. These adjustments rely principally on the Messer-Fambro work, but include upward adjustments in capacity for wide traffic lanes as included in most other methods.

One important concept to note is that under peak traffic conditions, lane widths in the 10 to 13 foot (3.0 to 4.0 m) range have little effect on saturation flow or capacity. However, it is likely that if comfort and safety were to be considered in intersection level of service (LOS), lane width differences would have a greater impact on LOS than they will in the proposed new HCM; with its emphasis on mobility rather than quality of flow.

2. Buses and Trucks. Trucks, and buses not having a designated stop at the intersection under analysis (called "through" buses), reduce capacity because the time headway of these vehicles tends to be longer than the 2.0 second average implied by a capacity set at 1800 pchg.

There are two means available for including the effects of trucks and buses. First, each truck or bus can be converted to an equivalent number of passenger cars, and the volume used in the analysis

Table 2. Lane Width Adjustments

Reference	Adjustment Factors to Capacity for Lane Width (ft.): 8	9	10	11	12	13	14	15	16
Berry-Gandhi (8)	(Suggest use of Australian factors)								
Messer-Fambro (5)	NA[a]	1.10	1.00	1.00	1.00	1.00	1.00	1.00	NA
Australian (9), (10)	1.12	1.07	1.00	1.00	1.00	0.97	0.96	0.94	--[b]
Recommended[c] Adjustment Factors	8.0-9.9 feet W = 1.10		10.0-12.9 feet W = 1.00			13.0-15.9 feet W = 0.90			

[a]NA denotes data not available.

[b]For 16-foot wide approaches, two 8-foot lanes would be assumed.

[c]Recommended for use in Critical Movement Analysis (OPERATIONS AND DESIGN Application, Step 8)

Source: As cited above and W.R. Reilly (NCHRP Project 3-28) (1 foot = .305 meter) stated in terms of passenger cars per hour rather than (mixed) vehicles per hour. Second, the capacity of the lane can be reduced and the analysis carried out using vehicles per hour. For PLANNING applications of Critical Movement Analysis, average geometric and traffic conditions are assumed and the work is carried out in terms of mixed vehicles per hour (vph). For OPERATIONS AND DESIGN applications, the analysis is performed in terms of passenger cars per hour (pch).

The passenger car equivalency (PCE) for trucks and through buses in the 1965 HCM can be inferred from the adjustment factors used. The approximate PCE value is 2.0. In essence, this means that the time headway for these vehicles is twice that for passenger cars, or 4.0 seconds if the assumption of a 2.0 second average headway for passenger cars is used.

The recommended average PCE value for converting trucks and through buses is 2.0 (recall that six or more tires on the pavement is the working definition of "truck").

3. Bus Stop Operations. As with trucks and through buses, the effect of bus stops in or adjacent to a traffic lane is to increase the average time headway. In the development of the 1965 HCM, PCE values for local buses ranged from 1.0 to 7.0 (16). Future research is expected to result in a clear definition of the impacts on delay and capacity of bus stop operation. For an average value to apply in the critical movement analysis procedure, a PCE value of 5.0 for each local bus appears to be reasonable. This implies an average headway of 10 seconds per bus, and would be applied to all buses having a designated stop at the intersection.

For example, if 30 buses per hour stop at a nearside bus stop, with 33 percent of them stopping on red, and 67 percent on green, a total time headway for all buses is assumed to be (30 × 5.0 × 2 seconds), or 300 seconds. The 300 seconds of headway might principally be used by only 20 buses having to stop on the green for an average of 13 seconds each. The remaining 10 buses, stopping on the red interval, would create only 40 seconds of time headway, or about 4.0 seconds per bus. This latter figure relates to the recommended equivalency of 2.0 PCE for through buses and trucks.

The actual effects of a stopping bus will vary considerably depending upon bus stop location, bus dwell time, parking activity, lane configuration, and traffic volumes. However, until further research is accomplished, the figure of 5.0 PCE per local bus appears to be useful average value.

4. Left Turns. Left turning vehicles are treated in considerable detail in most capacity computation techniques. The reason for this is simple--left turns (unless removed from through traffic lanes by provision of exclusive turn lanes) have a large impact on capacity and on vehicular delay, which will be the principal determinant of level of service in the new HCM.

The most direct means of taking into account the delaying effects of left turn vehicles is to convert them to pch using PCE values. It is anticipated that future research will lead to a range of PCE values for various combinations of geometry, traffic volumes, opposing traffic volumes, and signal phasing for left turns.

Different methods use varying PCE values for left turns. The British method sets 1.75 PCE as the average value for lanes with left turning and through movements. The 1965 HCM uses adjustment factors which show an approximate PCE value of between 4.0 and 2.0 for narrow and wider approaches, respectively. For a single lane, the typical effect can be on the order of 3.0 PCE per left turn operating from a left-through lane. The actual effect varies depending on geometric and traffic factors and especially on the volume of opposing traffic.

The Messer-Fambro method describes a detailed procedure for considering left turns in critical movement calculations. Three distinct factors are described for left turn adjustments. Included are a PCE adjustment to all traffic for approaches without left turn bays, a PCE adjustment to left turn traffic for approaches with left turn bays, and a PCE adjustment to non-left turn traffic for approaches with left turn bays of inadequate length (thus creating blockages in the through lane). Although this latter factor has not been included in the critical movement procedure, the user may wish to refer to Messer and Fambro's research (5) for details on the effects of left turn storage bay lengths.

Table 3 gives the PCE values for left turns for use when applying the critical movement procedure. These values are to be considered as "average" values for a broad range of traffic and geometric conditions. Future research may lead to a more precise formulation of left turn PCE values by incorporating other variables, in addition to "opposing traffic."

Table 3. PCE Values: Left Turn Effects

Left Turns Allowed from Left-Through Lanes[a]					
1. No Turn Phase	Opposing Volume, in vph:	0-299	300-599	600-999	1000 +
	1 left turn equals:	1.0 PCE	2.0 PCE	4.0 PCE	6.0 PCE
2. With Turn Phase	1 left turn equals 1.2 PCE				
Left Turns Allowed from Left Turn Bays Only[b]					
3. No Turn Phase	Opposing Volume, in vph:	0-299	300-599	600-999	1000 +
	1 left turn equals:	1.0 PCE	2.0 PCE	4.0 PCE	6.0 PCE
4. With Turn Phase	1 left turn equals 1.05 PCE				

[a]PCE Values are used in Step 5, PLANNING applications, to develop a distribution of volumes among several traffic lanes. PCE Values are also used in Step 7, OPERATIONS AND DESIGN applications, to convert left turn volumes to passenger car volumes prior to adding them to through and right turn volumes, in pch.

[b]PCE Values are used in Step 7, OPERATIONS AND DESIGN applications, to convert left turn volumes (operating from a turn bay) to passenger car volumes, in pch.

Source: W. R. Reilly (NCHRP Project 3-28), based on a synthesis of various data, including Ref. (5).

5. Right Turns and Pedestrian Activity. For simplicity, the adverse effect of right turns on intersection capacity can be considered as zero if little or no pedestrian interference occurs in the parallel conflicting crosswalk. If considerable pedestrian activity exists, then a right-turning vehicle has a similar effect as a local bus, creating a greater average time headway and producing greater vehicular delay.

A study of the Australian documents (9, 10) indicates that lanes with right turn activity might show a reduction in vehicle capacity of from fifteen to thirty-five percent. The 1965 HCM (1) indicates a PCE value of approximately 1.5 for right turns on a two-lane approach. However, for one-lane approaches this value may rise to 4.0. The British (14) use a PCE value of 1.25 for right turning vehicles (actually left turns in Britain) when the right turns comprise greater than 10 percent of the total traffic. In Australia PCE values of 1.25 and 2.50 are used for right turns of automobiles and heavy vehicles, respectively.

In the Messer-Fambro (5) technique, a right turn adjustment is made, based on the radius of the corner and the percentage of traffic making the turn. Also, an adjustment is made for the vehicles which may turn right on red. Such adjustments are not of prime importance and have not been included in the critical movement procedure presented herein.

The PCE values for right turns recommended for use in Critical Movement Analysis are given in Table 4. The values listed are considered as "average" for a broad range of traffic and geometric conditions and are based on a synthesis of information from many sources. Future research may lead to a more definitive set of PCE values for right turns relative to pedestrian activity.

Table 4. PCE Values: Right Turn Effects

Type of Activity	PCE Value for Right Turning Vehicle
1. Little pedestrian activity (0 to 99 peds. per hour) in parallel conflicting crosswalk	1.00
2. Moderate pedestrian activity (100 to 599 peds. per hour) in parallel conflicting crosswalk	1.25
3. Heavy pedestrian activity (600 to 1,199 peds. per hour) in parallel conflicting crosswalk	1.50
4. Extremely heavy pedestrian activity (1,200 or more peds. per hour) in parallel conflicting crosswalk	2.00 or greater[a]

[a] as determined from local conditions.

Source: W. R. Reilly (NCHRP Project 3-28), based on a synthesis of various data.

6. Parking Activity. Little or no definitive research work on parking and its capacity effects has been completed. However, the British do use a formula to compute these effects, as follows:

Loss in Approach Width, in feet,

$$= 5.5 - \frac{0.9(Z - 25)}{K}$$

where:

Z = Clear distance, in feet, from stop line to parked car

K = Green time, in seconds

(1 foot = .305 meter)

The British formula, assuming a green time of 30 seconds, infers that there is no effect on the approach capacity if parking is approximately 200 feet (61 m) or more away from the stop line.

Most North American techniques do not explicitly consider a reduction in capacity due to parking, if the parking ends 250 feet (76 m) before the intersection. For a curbside lane where parking is allowed, 8 feet (2.4 m) should be allowed for the parking lane and its friction effects, with the remaining width being assigned to the moving lane in the capacity computations. For parking which extends into the 250 foot (76 m) area, the HCM user must use judgment on the value or lack thereof of the additional width gained at the point where parking is prohibited. Because of the lack of definitive research on parking effects, this factor has not been included in the critical movement procedure.

7. Peaking Characteristics. To convert peak 15 minute flow rates to 1 hour volumes, some type of factor must be applied. Messer and Fambro indicate that the peak 15 minute flow along urban arterials consistently exceeds the average 15 minute flow during the peak hours by twenty to thirty percent. In the 1965 HCM (1) an "average" condition at urban intersections is assumed to be that the peak 15 minute flow will exceed the average 15 minute flow by about 15 percent. This results in a peak hour factor (PHF) of 0.85.

Because the HCM user may wish to use either a 15 minute peak flow rate or the peak 1 hour volume for design or analysis, a relationship between the two is needed.

Generally, PHF will vary with such factors as volume/capacity ratio, size of city, and type of adjacent activity. The data leading to the publication of the 1965 HCM indicated (16) that the average value for PHF at all sites was 0.85. Thus, the "average" PHF (if no additional information is available) which can be assumed for analysis is 0.85. The HCM user can easily develop a set of specific Peak Hour Factors by taking a limited amount of field data on different classes of streets.

The importance of PHF is that the base figure of 1800 pchg per lane is based on the assumption that the PHF is 1.0 (i.e., flow in the peak hour is uniform by 15 minute period). If we assume one hundred percent green time in an ideal traffic lane, the maximum flow rate in a 15 minute period would be 450 (i.e., 1800 ÷ 4) passenger cars. If a PHF of 0.85 is used, the corresponding flow rate expressed in terms of hourly volume would be:

Hourly Volume (HV), in pch,

= (PHF)(4)(Highest 15 min. Flow)

= (0.85)(4)(450) = 1530 pch

This represents a fifteen percent reduction in volume on an hourly basis when compared with conditions where PHF is equal to 1.0.

Lane Utilization

Critical Movement Analysis is based on "per lane" volumes. Thus, for movements (e.g., left turn, through, and right turn) which take place from more than one lane, it is necessary to estimate the volume in each of the lanes affected. In this manner, the highest lane volume can be identified and used in the analysis.

Reilly and Bellis (11, 12, 13) indicate that a traffic movement carried in two lanes could break down into a 55% / 45% split, by lane. A traffic movement carried in three lanes might divide into a 40% / 35% / 25% split.

In the critical movement analysis proposed by Messer and Fambro (5) a lane utilization factor is applied. For two lanes, a 55% / 45% split in volume is assumed. For three lanes, 40% of the total movement is assumed to occur in the most heavily used lane. Many HCM users have used analyses based on the assumption that volume is distributed approximately equally by lane, especially under peak conditions.

Lane utilization factors (U) were developed by the NCHRP 3-28 Project Team, based on the research cited above, and modified according to operational experience. The value for U when 2 lanes are utilized represents a 52.5% / 47.5% split. The value for U when 3 lanes are utilized assumes that approximately 37% of the volume is carried in the most heavily used lane. This represents a compromise between the HCM and Messer-Fambro procedures.

Table 5 contains the adjustment factors to be applied for lane utilization. For use in OPERATIONS AND DESIGN applications, average adjustments for lane utilization of 1.05 and 1.10 are recommended for two lane and three lane situations. These adjustments increase the passenger car volume for vehicles in the two or three lanes due to volume imbalances by lane.

Table 5. Lane Utilization Adjustments

Lanes Utilized	1	2	3
Utilization Factor (U)	1.00	1.05	1.10

Source: W. R. Reilly (NCHRP Project 3-28), based on a synthesis of various data.

An example of the effects of lane distribution can be seen by assuming two approach lanes, each capable of carrying 900 pch with a G/C ratio of 0.50. When a volume of 900 pch is reached in the most heavily traveled lane, a volume of only 814 pch will be using the second lane, assuming a 1.05 lane utilization factor. Thus a total capacity of 1714 pch (five percent less than the ideal 1800 pch) can be achieved by two lanes.

Levels of Service

As part of the critical movement technique, a set of guidelines on volume/capacity (v/c) ratio, average delay values, and sum of critical volumes is presented for use, review, and comment by HCM users. Table 6 gives the recommended thresholds for the sum of critical volumes for Levels of Service A through E for both the PLANNING and the OPERATIONS AND DESIGN applications.

Table 6. Level of Service Ranges

PLANNING Applications (in vph)

Level of Service	Maximum Sum of Critical Volumes: Two Phase	Three Phase	Four or more Phases
A	900	855	825
B	1050	1000	965
C	1200	1140	1100
D	1350	1275	1375
E	1500	1425	1225
F	---------not applicable---------		

OPERATIONS AND DESIGN Applications (in pch)

Level of Service	Maximum Sum of Critical Volumes: Two Phase	Three Phase	Four or more Phases
A	1000	950	900
B	1200	1140	1080
C	1400	1340	1270
D	1600	1530	1460
E	1800	1720	1650
F	---------not applicable---------		

Source: W. R. Reilly (NCHRP 3-28) and Ref. (5)

In comparing the v/c ranges used in Table 6 with those implied from the 1965 HCM (1), the following can be noted (using the example conditions given in Table 1): Levels of Service (LOS) A, B, C, D, and E are represented by v/c ratios of approximately 0.71, 0.75, 0.81, 0.92, and 1.00, respectively. Thus, the recommended values in Table 6 closely follow the 1965 HCM for defining LOS C, D, and E, but produce more ample ranges of v/c values for levels A and B. The threshold volume levels of Table 6 are expressed in vehicles per hour (vph) for the PLANNING application and in passenger cars per hour (pch) for the OPERATIONS AND DESIGN application. The levels of service defined in Table 6 relate to the critical approaches and/or lanes at the intersection. "Non-critical" lanes will tend to operate at better levels.

Delay

Because delay will be the principal determinant of signalized intersection level of service in the new HCM, Table 7 is included. The delay values given are not yet an integral part of the Critical Movement Analysis procedure but are presented as an initial step in developing a range of delay values which can be related to intersection level of service. The values of Table 7 do not take into account the offset relationship between adjacent signals. Synthesis of data from a number of sources has been used to produce Table 7. HCM users may find it useful to compare the table with locally obtained delay data.

Table 7. Delay and Level of Service

Level of Service	Typical v/c Ratio	Delay Range[a] (secs. per veh.)
A	0.00-0.60	0.0-16.0
B	0.61-0.70	16.1-22.0
C	0.71-0.80	22.1-28.0
D	0.81-0.90	28.1-35.0
E	0.91-1.00	35.1-40.0
F	varies	40.1 or greater

[a]Measured as "stopped delay" as described in Ref. (17). Delay values relate to the mean stopped delay incurred by all vehicles entering the intersection. Note that traffic signal coordination effects are not considered and could drastically alter the delay range for a given v/c ratio.

Source: W. R. Reilly (NCHRP Project 3-28), based on a synthesis of various data.

Summary

Table 8 contains a summary list of values used in the conceptual and applied aspects of the critical movement technique.

Critical Movement Analysis: Strategy

Critical Movement Analysis can be used in two general categories of problems: PLANNING applications and OPERATIONS AND DESIGN applications. In each case the fundamentals are the same. However, the level of detail is greater for OPERATIONS AND DESIGN applications.

Critical Movement Analysis is a tool to be used for study of the intersection as an operating whole. For specific analysis of a single approach, the procedure outlined by the 1965 HCM (1) remains a valuable tool.

The key assumption in the technique is that there is a combination of lane volumes which must be accommodated in 1 hour through the middle of a signalized intersection. The sum of these volumes, termed "critical volume" by Capelle and Pinnell (2), cannot exceed the saturation flow characteristics of the intersection. In essence, 1800 pch would be the maximum value under ideal conditions for the critical volume, with 1500 vph being an average value for typical conditions.

PLANNING Applications

In these applications, an important reference work is that of McInerney and Petersen (3). The only tabular material used is that found in Table 6 which gives a single value for the maximum sum of critical lane volumes, in vehicles per hour, assuming "average" traffic, signal, and geometric conditions, and Table 3, which is used to apportion traffic among several lanes.

The focus of this tool is to allow for a rapid approximation of level of service. None of the detailed individual adjustment factors need be applied to obtain a solution. The solution is for typical average conditions and should not necessarily be used for detailed design or operational decisions.

OPERATIONS AND DESIGN Applications

A principal source used for developing this more detailed application of Critical Movement Analysis is Messer and Fambro's 1977 paper (5). Many of the concepts and values from this work have been revised or extended to reflect work found in other source documents.

Table 6 gives the level of service standards which apply to this detailed application. Previous sections contain descriptions of various adjustment procedures and factors used. Table 8 provides a summary of these factors.

An explanation and examples of the step-by-step procedure is given under the heading of "USER APPLICATIONS" later in this section.

Table 8. Summary Factors for Critical Movement Analysis

Element	Values
1. Capacity, per lane ideal conditions	1800 pch
2. Capacity, per lane average-to-good urban conditions	1500 vph
3. Green time	Assumed as actual green time plus change interval time
4. PCE values for vehicle type	1.0 = passenger car or motorcycle 2.0 = truck or through bus 5.0 = local bus
5. Peak Hour Factor	0.85 = typical, or use actual field measurements
6. PCE values for left and right turns	Left turns (see Table 3) Right turns (see Table 4)
7. Lane Utilization (U)	Two lanes, volume divides 52.5% / 47.5% Three lanes, volume in heaviest lane is 36.6% of total
8. Lane Width (W)	8.0-9.9 feet, W = 1.1 10.0-12.9 feet, W = 1.0 13.0-15.9 feet, W = 0.9

Source: W. R. Reilly (NCHRP Project 3-28)

USER APPLICATIONS

Methodology

The intent of this section is to set forth the detailed procedures, with example problems, to be used in Critical Movement Analysis. The examples are divided into two groups: PLANNING applications with quick and simple solutions, and OPERATIONS AND DESIGN applications with more complex detailed solutions. A Calculation Form has been developed for each of the two groups of applications. These forms are shown in the following pages. Detailed definitions, the analytical framework, and references used in Critical Movement Analysis, are described in the preceeding section entitled "DISCUSSION."

PLANNING applications are carried out in terms of mixed vehicles per hour (vph). OPERATIONS AND DESIGN applications are carried out in terms of passenger cars per hour (pch).

Definitions

The abbreviations and symbols used in critical movement analysis are defined below. A more detailed set of definitions of concepts and terms is found in the preceeding "DISCUSSION".

G/C = Green time/Cycle time ratio
HV = Hourly Volume
LB = Local Bus (Number per hour)
LOS = Level of Service
LT = Left Turn
PCE = Passenger Car Equivalency
pch = Passenger cars per hour
PCV = Passenger Car Volume, in pch
PHF = Peak Hour Factor
PV = Period Volume
RT = Right Turn
T = Truck and Through Bus (Percentage of HV)
TH = Through Traffic
U = Lane Utilization Factor
v/c = Volume/Capacity ratio
V_L = Left Turn Volume, in vph
V_0 = Volume Opposing a V_L, in vph
vph = Vehicles per hour (mixed traffic)
W = Lane Width factor

PLANNING Applications: Procedure

The PLANNING application of Critical Movement Analysis is based on average or better conditions of geometry and traffic. The solutions can resolve the following questions:

1. What is the operating level of service for a signalized intersection as a whole?

2. If a design level of service is set, what changes in lane geometry or demand volume will be necessary to achieve that level?

3. What changes in lane configuration or signal phasing will have the greatest impact on operating level of service?

Step-By-Step Approach

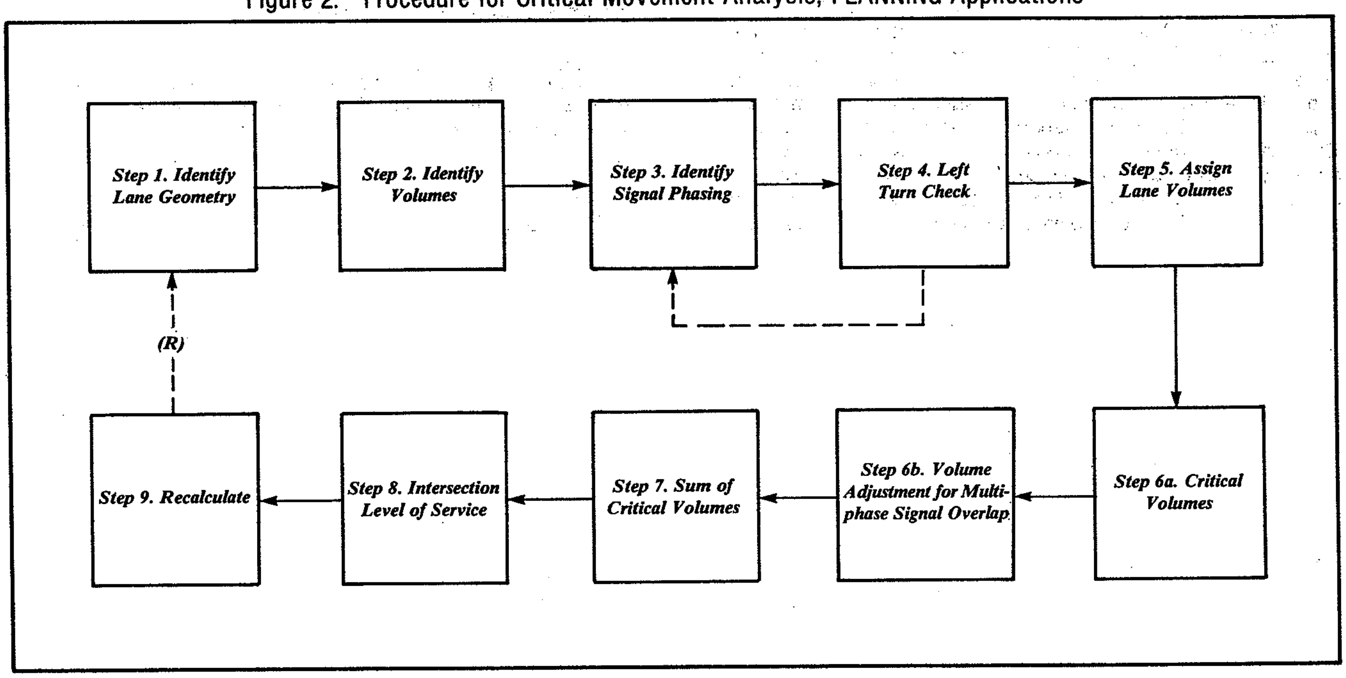
The steps followed in solving a problem by this technique are described below. Figure 2 contains an illustration of the steps followed, which are:

Step 1. Identify Lane Geometry – the assumed or known lane configuration for each approach is identified, by type of lane.

Step 2. Identify Volumes – the assumed or known traffic volumes for the design hour or analysis hour are identified in vehicles per hour. Left turn volumes, through, and right turn volumes are identified for each intersection approach.

Step 3. Identify Phasing – the signal phasing to be used for analysis is identified.

Figure 2. Procedure for Critical Movement Analysis, PLANNING Applications



Step 4. Left Turn Check - for an assumed phasing with no left turn phases, a check is made on the probability of clearing the identified left turn volume. On the change interval, 2.0 times the number of cycles per hour gives the maximum number of lefts that can clear on the change interval. Use 90 left turns per hour if no information on number of cycles per hour is available. Additionally, the number of vehicles per hour that can clear through opposing traffic during the green interval is estimated by:

$$V_L = (G/C)(1200) - V_0$$

where:

V_L = Left Turn Volume, in vph, that can clear through opposing traffic on the green interval

G/C = Green time/Cycle time ratio for opposing flow (V_0). If no other design information is available, estimate by lane volume ratio.

V_0 = Volume of Opposing through plus right turn traffic, in vph.

Note that the green time in the G/C ratio is considered as the green interval plus the change interval. If the sum of the two left turn volumes described above is less than the analysis volume, a separate left turn phase can be considered, by returning to Step 3. If the sum is greater than the left turn analysis volume, no special left turn phasing needs to be considered and the analysis moves to Step 5.

The purpose of the left turn check is to determine whether all left turn movements not controlled by an exclusive turn phase can be accommodated. If not, the assumption on signal phasing can be changed to provide for left turn phasing. In many cases (e.g., analysis of existing conditions), no change in phasing is assumed and the analysis continues, with the analyst knowing that the non-satisfied left turns will create operating difficulties and be subject to excessive delay.

Step 5. Assign Lane Volumes - the volumes are assigned to the appropriate lanes. If no left turn lanes exist, the left turn volume is converted to a pch volume (Table 3) and the remaining through plus right turn volume is assumed to be in pch units. The sum of these two pch volumes is then divided equally among all approach lanes, However, in all cases. the entire left turn volume must be assigned to the lane(s) from which the turns are made, and the remaining pch volume for through and right turn traffic is distributed equally among the remaining lanes. Following this distribution, the pch volume is converted back to vehicles per hour for the lane carrying the left turn.

If a left turn lane exists, the left turn volume in vehicles per hour is assigned to that lane and the through plus right turn volume is divided equally among the through and through-right lanes. For the special case of a double left turn lane, fifty-five percent of the total left turn volume is assigned to one left turn lane and forty-five percent to the other.

Step 6. Critical Volumes - for each signal phase, the highest total of conflicting traffic (on a per lane basis) is identified. For a two phase signal, the "highest total of the through (or through plus right turn if no exclusive right turn lane exists) plus the opposing left turn volume" is selected. For a three-to-eight phase ("multiphase") signal, each phase listed in the typical (i.e., most probable) phase sequence has one critical volume. The most probable phase sequence represents the sequence of a multiphase signal most likely to occur under the volume conditions assigned in Step 5. Where an exclusive right turn lane exists, such a lane is often not included in the critical analysis if right turns on red are permitted. However, such a lane can be included if the analyst believes that it might carry the most critical volume for that approach. Some reduction (30 percent is typical) in the assigned right turn volume (Step 5) may be made to allow for right turns made on red. If right turns on red are not permitted, an exclusive right turn lane is included in the analysis. Note that Calculation Form 1 contains Step 6a, which is used for two phase signals, and Step 6b, which is used for multiphase signals. In Steps 6a and 6b, a street operating without separate turn phases must have the opposing left turns added to the through volume to obtain the critical volume for that street.

Step 7. Sum of Critical Volumes - the critical volumes, for each phase, are summed.

Step 8. Intersection Level of Service - the sum of critical volumes is compared with Table 6, and an intersection level of service is identified.

Step 9. Recalculate - depending on the solution found in Step 8, a change in geometry, demand volume, or signal phasing can be made, and a recalculation --Steps1(R) through 9(R)--is performed.

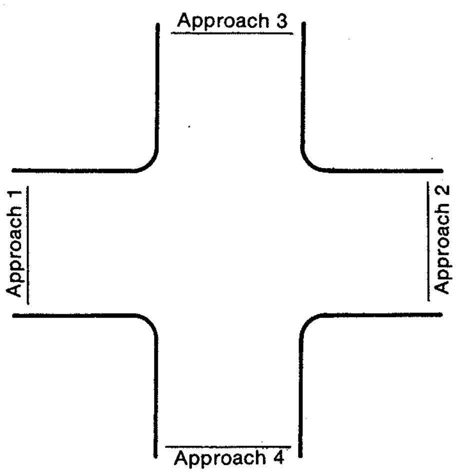
Calculation Form 1 is used for PLANNING applications.

Critical Movement Analysis: PLANNING
Calculation Form 1

Intersection ______________________________ **Design Hour** ____________

Problem Statement ____

Step 1. Identify Lane Geometry



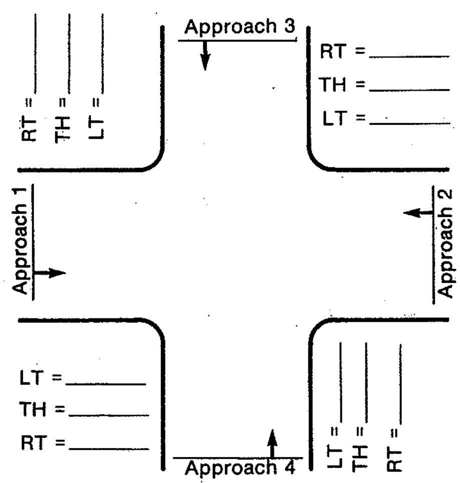
Step 4. Left Turn Check

	Approach 1	2	3	4
a. Number of change intervals per hour				
b. Left turn capacity on change interval, in vph				
c. G/C Ratio				
d. Opposing volume in vph				
e. Left turn capacity on green, in vph				
f. Left turn capacity in vph (b + e)				
g. Left turn volume in vph				
h. Is volume > capacity (g > f)?				

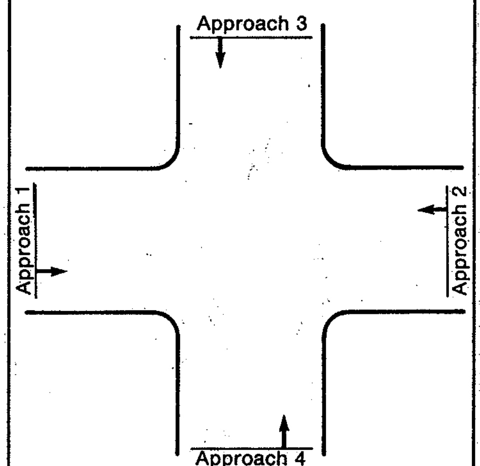
Step 6b. Volume Adjustment for Multiphase Signal Overlap

Probable Phase	Possible Critical Volume in vph	Volume Carryover to next phase	Adjusted Critical Volume in vph

Step 2. Identify Volumes, in vph



Step 5. Assign Lane Volumes, in vph



Step 7. Sum of Critical Volumes

_______ + _______ + _______ + _______

= _________ vph

Step 8. Intersection Level of Service

(compare Step 7 with Table 6)

Step 9. Recalculate

Geometric Change ____________________

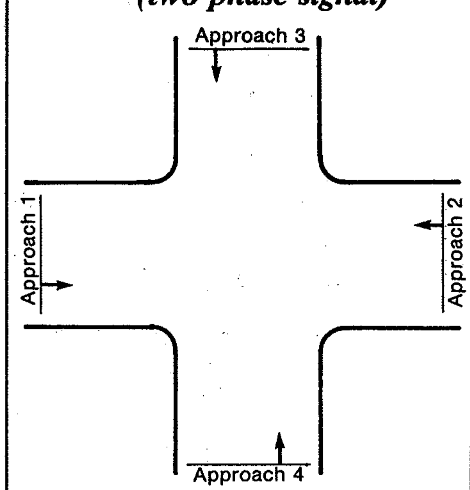
Signal Change ____________________

Volume Change ____________________

Step 3. Identify Phasing

A1 →	A3 ↓	B1	B3
A2 ←	A4 ↑	B2	B4

Step 6a. Critical Volumes, in vph (two phase signal)



Comments

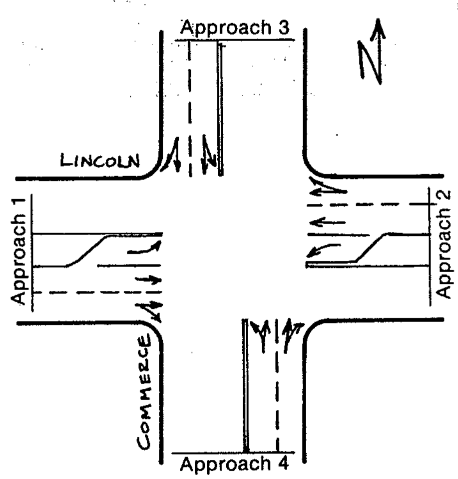
Critical Movement Analysis: PLANNING
Calculation Form 1

Example 1

Intersection LINCOLN AND COMMERCE **Design Hour** 4:30 - 5:30 p.m.

Problem Statement FIND EXISTING LOS. CAN LT BE HANDLED WITH 2 ϕ ?

Step 1. Identify Lane Geometry



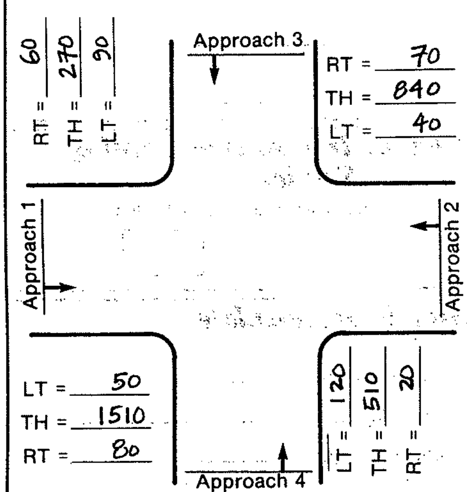
Step 4. Left Turn Check

	Approach 1	2	3	4
a. Number of change intervals per hour	40	40	40	40
b. Left turn capacity on change interval, in vph	80	80	80	80
c. G/C Ratio	.55	.55	.45	.45
d. Opposing volume in vph	910	1590	530	330
e. Left turn capacity on green, in vph	0	0	10	210
f. Left turn capacity in vph (b + e)	80	80	90	290
g. Left turn volume in vph	50	40	90	120
h. Is volume > capacity (g > f)?	No	No	No*	No

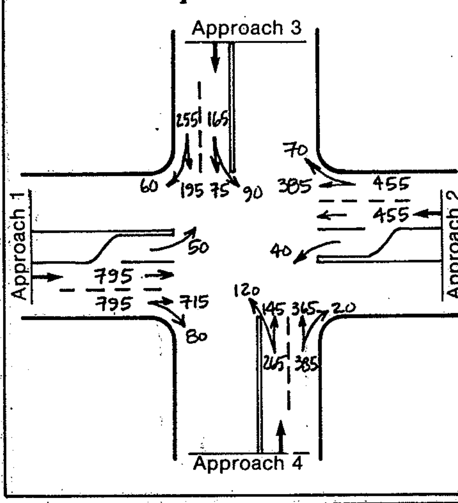
Step 6b. Volume Adjustment for Multiphase Signal Overlap

Probable Phase	Possible Critical Volume in vph	Volume Carryover to next phase	Adjusted Critical Volume in vph
	2ϕ		

Step 2. Identify Volumes, in vph



Step 5. Assign Lane Volumes, in vph



Step 7. Sum of Critical Volumes

795 + 40 + 385 + 90

= 1310 vph

Step 8. Intersection Level of Service

(compare Step 7 with Table 6)

D

Step 9. Recalculate

Geometric Change ADD LT LANES TO APPROACHES 3 AND 4

Signal Change

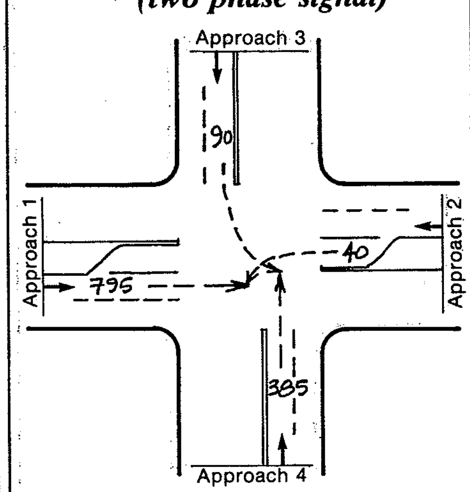
Volume Change

Step 3. Identify Phasing 2ϕ

→ ←	A1B2 or A2B1
↓ ↑	A3B4 or A4B3

A1 → A3 ↓	B1 ↰ B3 ↰
A2 ← A4 ↑	B2 ↱ B4 ↳

Step 6a. Critical Volumes, in vph (two phase signal)



Comments

*NOTE THAT LEFT TURN DEMAND FOR APPROACH 3 EQUALS CAPACITY

PLANNING Applications: Example 1

Problem

Lane configuration and peak hour volumes are shown on Calculation Form 1 for an existing urban intersection. The following three questions must be answered:

1. What is the intersection level of service?

2. Can left turns be handled without installing an exclusive phase?

3. If left turn lanes are added on Approaches 3 and 4 what changes, if any, may be expected in the level of service?

Analysis

Step 1. Identify Lane Geometry. Existing lane configuration is shown on Calculation Form 1.

Step 2. Identify Volumes. Existing peak hour volumes (vph) are shown on Calculation Form 1. Approaches are numbered 1, 2, 3, and 4, from the west, east, north, and south, respectively.

Step 3. Identify Phasing. A two phase signal operation exists.

Step 4. Left Turn Check. A 90 second peak hour cycle length is used. Forty cycles per hour times 2.0 left turns per cycle result in 80 left turns per hour made on the change interval. Additionally, left turns made through opposing traffic on the green interval, assuming a 0.55 G/C ratio for Approaches 1 and 2 and a 0.45 G/C ratio for Approaches 3 and 4 are calculated by the formula:

$$V_L = (G/C)(1200) - V_0.$$

For all directions, the capacity for left turns is equal to or greater than left turn demand. Therefore, the two phase signal operation is adequate. Note that for left turns from Approach 3, demand and capacity are equal at 90 vph.

Step 5. Assign Lane Volumes. For Approaches 1 and 2, left turn volumes are assigned to the left turn lanes and through plus right turn volumes are divided equally between the remaining lanes.

For Approaches 3 and 4, factors from Table 3 are used to convert 90 and 120 left turns (with 530 vph and 330 vph opposing, respectively) to 180 and 240 pch, respectively. Thus, a total pch volume of 510 (from Approach 3) and 770 (from Approach 4) is computed. On a per lane basis, 255 pch and 385 pch, from Approaches 3 and 4, respectively, are computed.

For Approach 3, the left lane is assigned 255 pch, of which 180 pch is due to left turn vehicles. The right lane is also assigned 255 pch, comprised of through and right turn traffic. Therefore, the left lane carries 165 vph (90 left turns plus the difference between 180 and 255) and the right lane carries 255 vph.

For Approach 4, the left lane is assigned 385 pch, of which 240 pch are due to left turn vehicles.

Table 6. Level of Service Ranges

Level of Service	Maximum Sum of Critical Volumes — PLANNING Applications (in vph): Two Phase	Three Phase	Four or more Phases
A	900	855	825
B	1050	1000	965
C	1200	1140	1100
D	1350	1275	1375
E	1500	1425	1225
F	---------not applicable---------		
OPERATIONS AND DESIGN Applications (in pch)	(deleted)		

The right lane is also assigned 385 pch, comprised of through and right turn traffic. Thus, the left lane carries 265 vph (120 left turns plus the difference between 240 and 385) and the right lane carries 385 vph.

The per lane volumes are entered in Step 5 of Calculation Form 1.

Step 6. Critical Volumes. Critical volumes for phase A1A2, on Approaches 1 and 2, is 795 + 40 LT or 455 + 50 LT. Use 835. Critical Volumes for phase A3A4 on Approaches 3 and 4 is 255 + 120 LT or 385 + 90 LT. Use 475. These volumes are graphically shown in Step 6A on the form.

Step 7. Sum of Critical Volumes. The sum of critical volumes is 835 + 475 or 1310 vph.

Step 8. Intersection Level of Service. Using Table 6, this value falls within the range of 1201 to 1350 vph or Level of Service D for two phase signals. The left turns can be handled using the geometry shown and a two phase signal.

Step 9. Recalculate. To determine the effect on level of service of adding left turn lanes on Approaches 3 and 4, return to Step 1 and recompute.

(Continued)

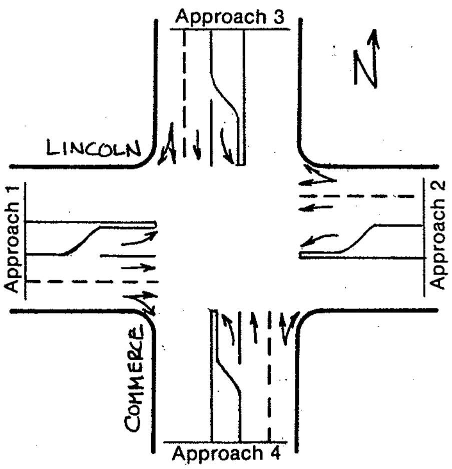
Critical Movement Analysis: PLANNING
Calculation Form 1

Example 1
(Recalculation)

Intersection Lincoln and Commerce **Design Hour** 4:30 - 5:30 p.m.

Problem Statement Find change in LOS by adding left-turn lanes

Step 1. Identify Lane Geometry



Step 4. Left Turn Check

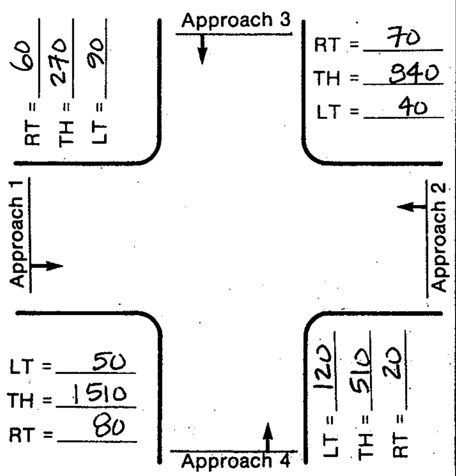
	Approach 1	2	3	4
a. Number of change intervals per hour	40	40	40	40
b. Left turn capacity on change interval, in vph	80	80	80	80
c. G/C Ratio	.55	.55	.45	.45
d. Opposing volume in vph	910	1590	530	330
e. Left turn capacity on green, in vph	0	0	10	210
f. Left turn capacity in vph (b + e)	80	80	90	290
g. Left turn volume in vph	50	40	90	120
h. Is volume > capacity (g > f)?	No	No	No*	No

Step 6b. Volume Adjustment for Multiphase Signal Overlap

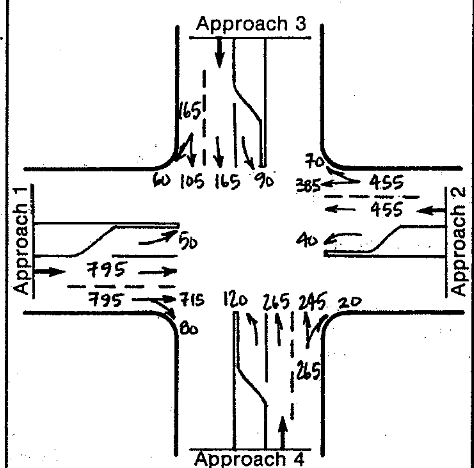
Probable Phase	Possible Critical Volume in vph	Volume Carryover to next phase	Adjusted Critical Volume in vph

2φ

Step 2. Identify Volumes, in vph



Step 5. Assign Lane Volumes, in vph



Step 7. Sum of Critical Volumes

795 + 40 + 265 + 90

= 1190 vph

Step 8. Intersection Level of Service

(compare Step 7 with Table 6)

C

Step 9. Recalculate

Not necessary

Geometric Change

Signal Change

Volume Change

Step 3. Identify Phasing 2φ

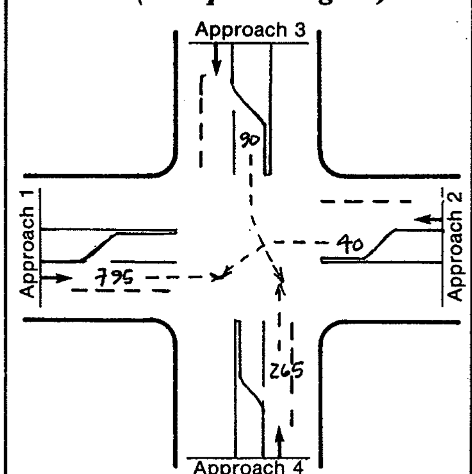
→ ← A1B2 or A2B1

↓ ↑ A3B4 or A4B3

A1 → A3 ↓ B1 B3

A2 ← A4 ↑ B2 B4

Step 6a. Critical Volumes, in vph (two phase signal)



Comments

*Note that left turn demand for approach 3 equals capacity.

(Example 1)

Note: "(R)" denotes a recalculation.

Step 1(R). Identify Lane Geometry. Left turn lanes are added on Approaches 3 and 4.

Step 2(R). Identify Volumes. Volumes, in vph are shown on the form.

Step 3(R). Identify Phasing. The existing two phase signal will be analyzed.

Step 4(R). Left Turn Check. Step 4(R) is identical to the preceeding Step 5.

Step 5(R). Assign Lane Volumes. Left turns are assigned to left turn lanes and through plus right turn volumes are distributed equally to the remaining lanes.

Step 6(R). Critical Volumes. Critical volumes for phase A1A2 on Approaches 1 and 2 are 795 + 40 LT or 455 + 50 LT. Use 835. Critical volumes for phase A3A4 on Approaches 3 and 4 are 165 + 120 LT or 265 + 90 LT. Use 355.

Step 7(R). Sum of Critical Volumes. The sum of the critical volumes is (835 + 355) or 1190 vph.

Table 6. Level of Service Ranges

PLANNING Applications (in vph)

Level of Service	Maximum Sum of Critical Volumes: Two Phase	Three Phase	Four or more Phases
A	900	855	825
B	1050	1000	965
C	1200	1140	1100
D	1350	1275	1375
E	1500	1425	1225
F	---------not applicable---------		

OPERATIONS AND DESIGN Applications (in pch)

(deleted)

Step 8(R). Intersection Level of Service. Using Table 6, the value of 1190 vph falls within the range of 1051 to 1200, or Level of Service C for two phase operation.

Step 9(R). Recalculate. No recalculation is necessary as it is demonstrated that left turn lanes alter the intersection Level of Service D to C.

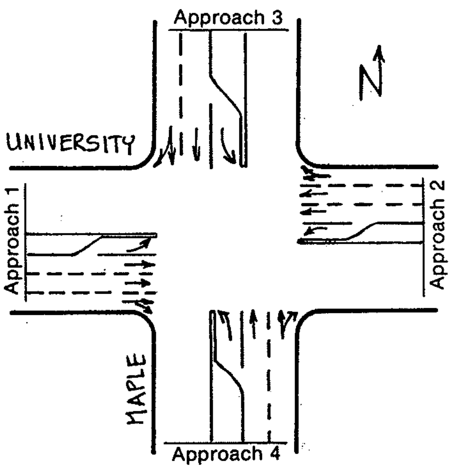
Critical Movement Analysis: PLANNING
Calculation Form 1

Example 2

Intersection UNIVERSITY AND MAPLE **Design Hour** 4:30 - 5:30 p.m.

Problem Statement FIND EXISTING LOS

Step 1. Identify Lane Geometry



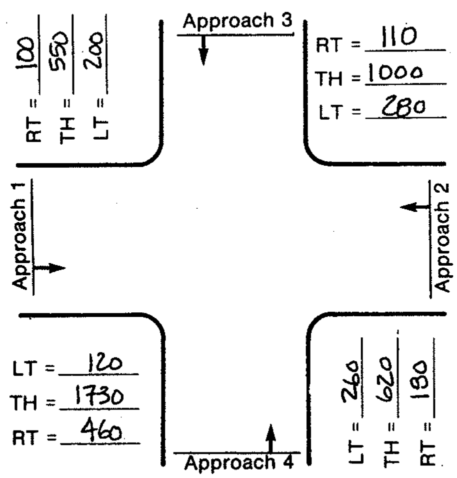
Step 4. Left Turn Check

	Approach 1	2	3	4
a. Number of change intervals per hour		8φ		
b. Left turn capacity on change interval, in vph				
c. G/C Ratio				
d. Opposing volume in vph				
e. Left turn capacity on green, in vph				
f. Left turn capacity in vph (b + e)				
g. Left turn volume in vph				
h. Is volume > capacity (g > f)?				

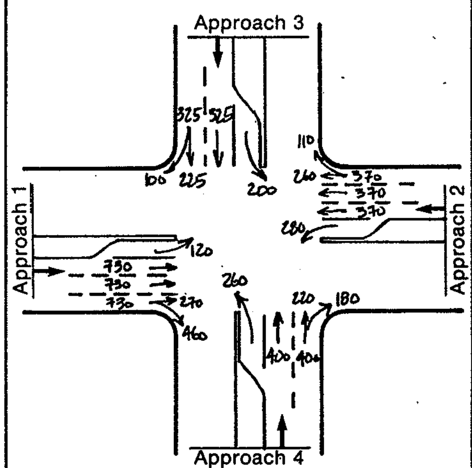
Step 6b. Volume Adjustment for Multiphase Signal Overlap

Probable Phase	Possible Critical Volume in vph	Volume Carryover to next phase	Adjusted Critical Volume in vph
B2B1	120(B2)	280-120=160(B1)	120 LT from 2
A2B1	160 (B1)	370-160=210(A2)	160
A1A2	730(A1) or 210(A2)		730
B4B3	200(B4)	260-200=60(B3)	200 LT from 4
A4B3	60(B3)	400-60=340(A4)	60
A3B4	325(A3) or 340 (A4)		340

Step 2. Identify Volumes, in vph



Step 5. Assign Lane Volumes, in vph



Step 7. Sum of Critical Volumes

280 + 730 + 260 + 340

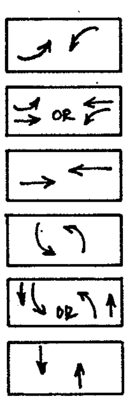
= 1610 vph

Step 8. Intersection Level of Service

(compare Step 7 with Table 6)

FAILURE * —

Step 3. Identify Phasing 8φ



B2 B1

A1 B2 or A2 B1

A1 A2

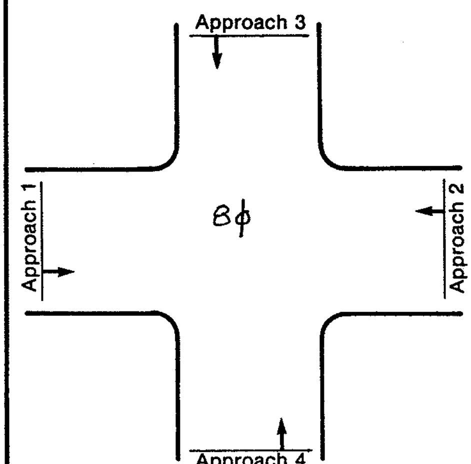
B4 B3

A3 B4 or A4 B3

A3 A4

A1 → A3 ↓	B1 B3
A2 ← A4 ↑	B2 B4

Step 6a. Critical Volumes, in vph (two phase signal)



Step 9. Recalculate

Geometric Change 1 THRU LANE-APPROACHES 3 & 4; 1 RT LANE-APPROACHES 1 & 2

Signal Change

Volume Change

Comments

* INTERSECTION WILL NOT OPERATE WITHOUT VERY LONG QUEUES AND EXCESSIVE DELAYS.

PLANNING Applications: Example 2

Problem

Lane configuration and design hour volumes (with left turn lanes on all approaches) are shown on the calculation form for a major new suburban intersection. The following information is needed.

1. The whole intersection level of service if an eight phase signal operation is used.

2. Change in level of service if an additional through lane is added to Approaches 3 and 4, and a right turn lane to Approaches 1 and 2.

Analysis

Step 1. Identify Lane Geometry. The assumed lane configuration is shown on the form.

Step 2. Identify Traffic Volumes. Design hour volumes are shown on the form.

Step 3. Identify Phasing. An eight phase signal is planned, with left turn arrows for each direction. The left turns are allowed only on the arrow (in a protected mode).

Step 4. Left Turn Check. Each left turn movement has a protected phase. Therefore, the left turn check is not needed.

Step 5. Assign Lane Volumes. Left turns are assigned to left turn lanes and through plus right turn volumes are distributed equally to the remaining lanes.

Step 6. Critical Volumes. Using Step 3, the phase sequence which most likely will appear under the volumes of Step 5 is: B2B1, A2B1, A1A2, B4B3, A4B3, and A3A4. For example, since left turn volume from Approach 2 (B1) is greater than left turn volume from Approach 1 (B2), B1 will continue receiving a green arrow after B2 has been terminated. Thus, A2B1 is selected as the most probable phase, rather than A1B2.

Using the most probable phase sequence, the through plus right turn volume which moves during the concurrent display of a left arrow is subtracted from the total through plus right turn volume and the remaining volume is carried over to the next phase. This calculation is listed in Step 6b on the form.

Step 7. Sum of Critical Volumes. The sum of critical lane volumes for all phases is 120 + 160 + 730 + 200 + 60 + 340, or 1610 vph.

Step 8. Intersection Level of Service. Using Table 6, the critical sum of 1610 vph falls beyond Level of Service E (1375 vph) for eight phase control. Therefore, the intersection will not operate without unacceptable delays.

Step 9. Recalculate. Return to Step 1 and recalculate to determine the effects of adding a through lane on Approaches 3 and 4, and a right turn lane on Approaches 1 and 2.

Table 6. Level of Service Ranges

Level of Service	PLANNING Applications (in vph): Maximum Sum of Critical Volumes — Two Phase	Three Phase	Four or more Phases
A	900	855	825
B	1050	1000	965
C	1200	1140	1100
D	1350	1275	1375
E	1500	1425	1225
F	---------not applicable---------		

OPERATIONS AND DESIGN Applications (in pch)

(deleted)

(Continued)

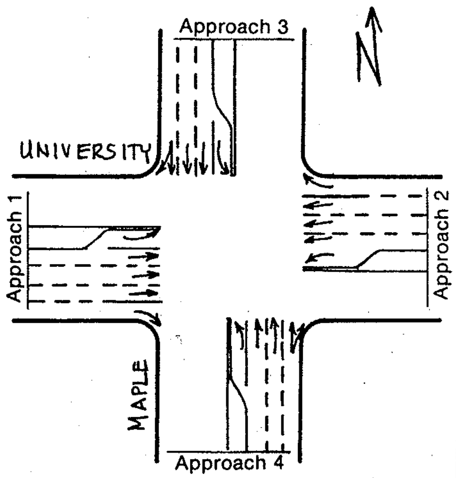
Critical Movement Analysis: PLANNING
Calculation Form 1

Example 2
(Recalculation)

Intersection UNIVERSITY AND MAPLE **Design Hour** 4:30 - 5:30 p.m.

Problem Statement FIND CHANGE IN LOS BY ADDING ADDITIONAL THRU AND RT LANES

Step 1. Identify Lane Geometry



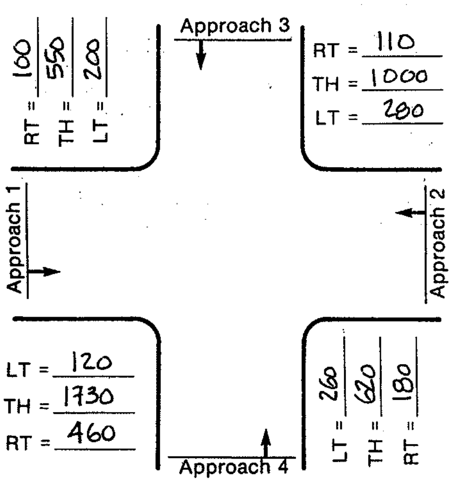
Step 4. Left Turn Check

	Approach 1	2	3	4
a. Number of change intervals per hour		8ϕ		
b. Left turn capacity on change interval, in vph				
c. G/C Ratio				
d. Opposing volume in vph				
e. Left turn capacity on green, in vph				
f. Left turn capacity in vph (b + e)				
g. Left turn volume in vph				
h. Is volume > capacity (g > f)?				

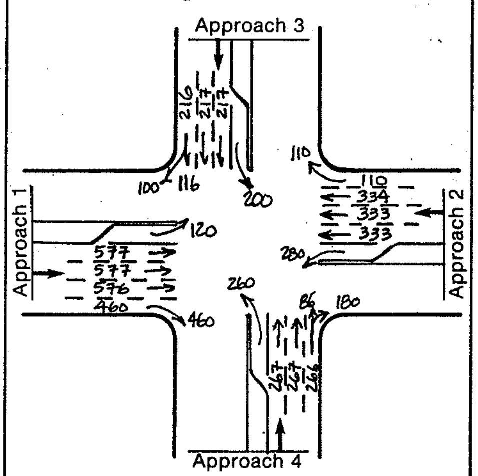
Step 6b. Volume Adjustment for Multiphase Signal Overlap

Probable Phase	Possible Critical Volume in vph	Volume Carryover to next phase	Adjusted Critical Volume in vph
B2B1	120(B2)	280-120= 160(B1)	120 (LT from 2)
A2B1	160 (B1)	334-160=174(A2)	160 (LT from 2)
A1A2	577 (A1) OR 174 (A2)		577
B4B3	200 (B4)	260-200= 60(B3)	200 (LT from 4)
A4B3	60(B3)	267-60=207(A4)	60 (LT from 4)
A3A4	217(A3) OR 207(A4)		217

Step 2. Identify Volumes, in vph



Step 5. Assign Lane Volumes, in vph



Step 7. Sum of Critical Volumes

280 + 577 + 60 + 217

= 1334 vph

Step 8. Intersection Level of Service

(compare Step 7 with Table 6)

E

Step 9. Recalculate

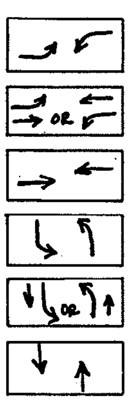
NOT NECESSARY

Geometric Change ______

Signal Change ______

Volume Change ______

Step 3. Identify Phasing 8ϕ



B2 B1

A1B2 OR A2B1

A1A2

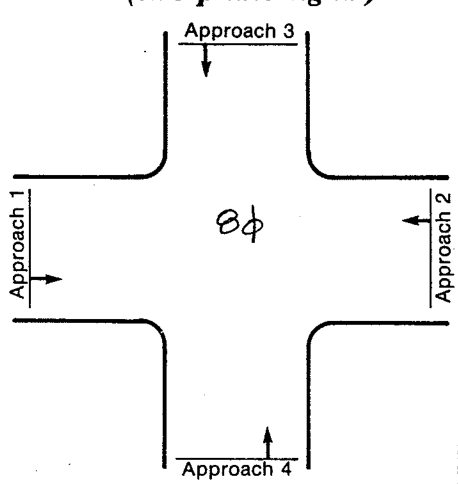
B4 B3

A3B4 OR A4B3

A3A4

A1 → A3 ↓	B1 ↰ B3 ↰
A2 ← A4 ↑	B2 ↱ B4 ↳

Step 6a. Critical Volumes, in vph (two phase signal)



Comments

(Example 2)

Note: "(R)" denotes a recalculation.

Step 1(R). Identify Lane Geometry. The new lane geometry to be analyzed is shown on the form.

Step 2(R). Identify Volumes. Design hour volumes are shown on the form.

Step 3(R). Identify Phasing. An eight phase signal is assumed, with left turn arrows for each direction. Left turns are allowed only on the arrow (in a protected mode).

Step 4(R). Left Turn Check. Each left turn movement has a protected phase. Therefore, the left turn check is not needed.

Table 6. Level of Service Ranges

PLANNING Applications (in vph)			
	Maximum Sum of Critical Volumes		
Level of Service	Two Phase	Three Phase	Four or more Phases
A	900	855	825
B	1050	1000	965
C	1200	1140	1100
D	1350	1275	1375
E	1500	1425	1225
F	---------not applicable---------		
OPERATIONS AND DESIGN Applications (in pch)			
(deleted)			

Step 5(R). Assign Lane Volumes. Left turns are assigned to left turn lanes and right turns are assigned to exclusive right turn lanes, on Approaches 1 and 2. Remaining volumes are distributed equally to the remaining lanes.

Step 6(R). Critical Volumes. Using Step 3, the phase sequence which most likely will appear under volumes of Step 5 is; B2B1, B1A2, A1A2, B4B3, A3B4, and A3A4. For example, since the left turn volume from Approach 2 (B1) is greater than left turn volume from Approach 1 (B2), B1 will continue receiving a green arrow after B2 has been terminated. Thus, A2B1 is selected as the most probable phase, rather than A1B2.

Using the most probable phase sequence, the through plus right turn volume (except where right turns have an exclusive lane) which moves during a left arrow is subtracted from the total through plus right turn volume and the remaining volume is carried over to the next phase. Note that exclusive right turn lanes are not included in the critical volume analysis when right turns on red are permitted unless the analyst considers this lane to be critical. In this example, right turns on red are permitted.

Step 7(R). Sum of Critical Volumes. The sum of critical volumes for all phases is 120 + 160 + 577 + 200 + 60 + 217, or 1334 vph.

Step 8(R). Intersection Level of Service. Using Table 6 1334 vph falls within the range of 1226 to 1375, for Level of Service E for eight phase control.

Step 9(R). Recalculate. Recalculations could be made to determine the improvement in level of service from other geometric or signal changes, such as addition of double left turn lanes.