13. D.R. Drew and C.J. Keese. Freeway Level of Service as Influenced by Volume and Capacity Characteristics. In Highway Research Record 99, HRB, National Research Council, Washington, D.C., 1965, pp. 1-47.
14. D.L. Gerlough and M.J. Huber. Special Report 165: Traffic Flow Theory--A Monograph, TRB, National Research Council, Washington, D.C., 1975, 222 pp.
15. SAS Users Guide: Basic. Statistical Analysis System Institute, Cary, N.C., 1982.
16. SAS Users Guide: Statistics. Statistical Analysis System Institute, Cary, N.C., 1982.
17. SAS/GRAPH Users Guide. Statistical Analysis System Institute, Cary, N.C., 1981.

Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.

Highlights of the Canadian Capacity Guide for Signalized Intersections

S. TEPLY

ABSTRACT

A unified approach to the treatment of capacity-related issues in urban networks has been emerging in Canada during the last 10 years. In 1982 the Executive of District 7 (Canada) of the Institute of Transportation Engineers appointed a committee to develop a series of documents that, eventually, will form a Canadian Urban Transportation Capacity Guide. The committee decided to proceed with the section on signalized intersections as the first task. The main reason for this decision was that the capacity of traffic signals is usually the key factor in all urban capacity considerations, and, as a result, a chapter on signalized intersections was most urgently needed. Moreover, a number of analytical and design procedures related to traffic signals have been tested in the Canadian context in the past decade. Although capacity research and development have been only marginally coordinated in Canada, a common philosophy has been forming, as may be seen in documents prepared in Ontario and Alberta. The first edition of the Canadian Capacity Guide for Signalized Intersections was preceded by three draft versions that were discussed both within and outside the committee. One of the guide's principal objectives is to test the approach and procedures and to elicit comments from users and researchers on a country-wide basis. The objective of this paper is to inform the North American transportation research community about the document and to highlight its philosophy and associated techniques. In essence, capacity analysis is based on a lane-by-lane saturation flow procedure that allows for calibration to local community conditions.

The need for a specifically Canadian document on capacity arises mainly from differences in climate; driver behavior; structure of cities; traditional traffic engineering practices; and political, judicial, and legal systems compared with those of other countries. In addition, it has been recognized that, in a country as vast as Canada, there is a great need for a common philosophy that can accommodate a wide variety of regional issues. Such a philosophy has been forming (1-3).

The objectives of the guide (4) can be detailed as follows:

- To consolidate current Canadian practice and research and to emphasize common features of the techniques used in different regions,
- To make it possible to incorporate parameters specific to a community or region,
- To identify the "missing links" and to focus future development of Canadian practice on a common philosophy,
- To set up the background for such a philosophy, and
- To provide a direction for the future education of users without restricting the development of regional and individual expertise

Although the document should provide basic guidance for both experienced and novice practitioners, it also leaves room for additional analytical or design considerations and procedures where appropriate or necessary. This is why it is titled a "guide" instead of a "manual."

The foundations of individual techniques of the guide are described in sufficient detail to allow users to judge the applicability to a specific case or to use shortcuts where appropriate. Consequently, no distinction is made between so-called "planning" and "operations" techniques.

USER-RELATED PRINCIPLES

The editor and the authors of the guide have followed the following principles to enhance user accessibility:

1. Understandability. Not all users will enjoy the benefits of an advanced traffic flow theory education. The guide should be a self-contained document for traffic engineering professionals who may have limited practical or research experience.
2. Explainability. The guide has not been written as a textbook. Nevertheless, it is expected that it will be used both in academic and in professional development courses. Consequently, the procedures of the guide should be easily explainable with the use of traffic flow theory and practice.
3. Scientific soundness and practicality. It has been difficult to combine these two aspects. The guide, however, is mainly intended to serve practicing professionals, and, as a result, some compromises with theory were necessary. For example, although Webster's treatment of the left-turning movements with opposing traffic (5) has been considered theoretically most correct, a simplified, more easily understandable procedure has been incorporated. The results are accurate within less than 10 percent, which is justifiable from a practical point of view.
4. Accountability. The procedural setup of the guide should not only make it possible to incorporate local and regional parameters but, possibly more important, provide an opportunity to verify individual computational steps by direct measurements of existing situations. For that reason, volume manipulations have been restricted to a minimum and values of saturation flows adjusted to local conditions are directly verifiable by brief surveys. The use of local insight is advocated throughout the guide.

Most of the techniques have been tested and evaluated in terms of their theoretical soundness and practicality for Canadian conditions. An experienced user can, however, complement the analytical and design techniques outlined in the guide by using more detailed procedures in those cases in which the guide indicates a critical issue.

The guide covers individual, not necessarily isolated, signalized intersections. The strategic and network context is discussed and systemwide objectives are emphasized. Such analytical or design objectives must be reflected in performance goals. For example, although equalizing delays on all approaches may be a worthwhile goal at an intersection of two major arterial roadways, longer delays may be desirable at the collector approach of an intersection with an arterial street in order to minimize shortcutting through a residential neighborhood.

VOLUME: FLUCTUATIONS AND CONVERSIONS

An import distinction is made between "demand" and "supply" volume. Traditional intersection surveys consider only the volumes of individual movements within the intersection space. This represents the supply volume because it is limited by the capacity supplied by the geometric and timing features of the facility. Consequently, the supply volume-to-capacity ratio cannot exceed 1.0.

Demand volume represents the number of vehicles approaching the intersection. It is counted at the end of an intersection approach queue or derived from demand models. As a result, under growing queue conditions, the demand volume-to-capacity ratio is greater than 1.0. The guide generally employs the demand volume.

Changes of the demand in time represent its fluctuations. Although 1 hr is acceptable in many situations, the guide also recommends the use of rate of flow based on shorter periods for other conditions, such as for smaller communities. All flows are, however, expressed as hourly volumes. As will be demonstrated later, delay (the major evaluation parameter) is quite sensitive to the time base.

Vehicle categories are converted into passenger car units (pcu's) both for volumes and for saturation flows. Typical Canadian conversion factors (pcu equivalents) have been determined using a least-squares optimization procedure that reflects the composite effect of individual vehicle categories (6). They are as follows:

Vehicle Category	Passenger Car Unit Equivalent (pcu/veh)
Passenger cars, vans, pickups	1.0
Single-unit trucks	1.5
Multiunit trucks	2.5
Multiunit trucks heavily loaded	3.5
Buses or streetcars	1.75
Motorcycles	0.5
All trucks and buses combined (approximation)	2.0

As a rule, the guide uses lane-by-lane analytical or design techniques. Consequently, all volumes and saturation flows must be expressed separately for each lane.

SAFETY CONSIDERATIONS

Because certain safety parameters form inviolable constraints to capacity considerations, they are explicitly discussed in the guide for both vehicular and pedestrian movements.

Vehicular Requirements

Two features of vehicular safety are included. They involve the duration of the amber interval and the total intergreen period.

Amber interval can be determined by two methods. Both of them use a common formula but differ in the recommended acceleration rates. Nevertheless, they somewhat simplify the true decision- or dilemma-zone problem. As can be seen in Figure 1 the driver of a vehicle that is in the decision zone at the onset of amber has a choice of continuing at a steady speed (v) and legally entering the intersection during the last portion of the amber interval, or of stopping at the stop line at a reasonable deceleration rate. Typical perception and reaction time (t_{pr}) is 1.0 sec; corresponding distance is denoted d_{pr}. Specific adjustments are recommended for steep downhill intersection approaches.

The intergreen period is defined as the time between the end of the green interval for the traf-

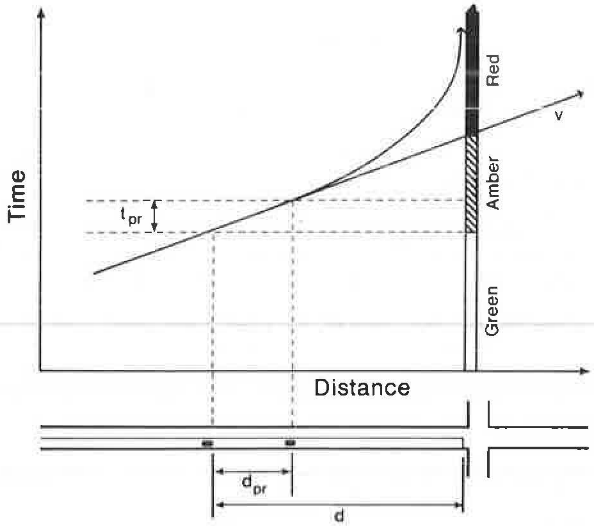

FIGURE 1 Determination of the amber interval.

fic stream losing the right-of-way and the beginning of the green interval for the conflicting traffic stream gaining the right-of-way. It consists of an amber interval and an all-red period.

The proposed technique to minimize potential vehicle-to-vehicle conflicts is based on the need to clear the last vehicles of the ending phase before the approaching vehicles of the starting phase reach the potential conflict area (Figure 2). The last vehicle legally entering the intersection during amber must clear the conflict area (Z_1 or Z_2, respectively) before the first vehicle of the starting phase, legally entering the intersection at the onset of green with a "rolling" start, reaches the conflict area. The formula includes the amber overrun portion, time needed to reach the conflict area, time needed to clear the conflict area (based on the length of a passenger car because longer vehicles act as a barrier), less the time needed by the first vehicle of the starting phase to reach the near end of the conflict area. The suggested range of input values reflects regional differences in driver behavior and in legal practices.

For vehicles clearing and pedestrians approaching, an identical procedure is recommended, but the length of a passenger car is excluded. When a vehicle is in the crosswalk area, it acts as a barrier.

The all-red interval fills up the remaining time between the amber interval and the intergreen period.

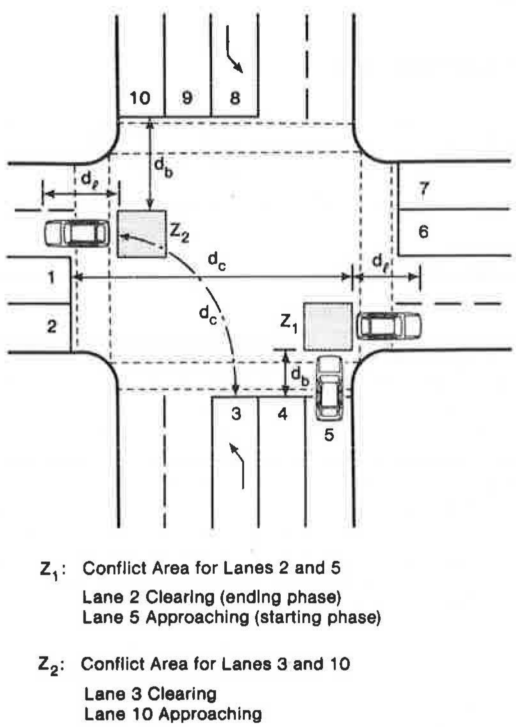

FIGURE 2 Determination of the intergreen period.

Pedestrian Requirements

For pedestrians, duration of walk intervals and clearance periods must be determined. These depend on the availability and dimensions of refuge areas. Again, basic parameters and considerations are identified. Naturally, the sum of the longest pedestrian walk interval and the clearance period for each phase must not exceed the sum of the longest vehicular green interval and the associated intergreen period for that phase.

CAPACITY ANALYSIS AND SIGNAL DESIGN

In signal operations there are two major tasks related to capacity. The first one is the quantitative evaluation of the performance of existing or planned signalized intersections (titled "Analysis" in the guide) and the second one is the design of new facilities. Both tasks are schematically shown in Figure 3.

The analytical task is based on a definition of the basic or the initial saturation flow for a given community or region and identifies the adjustment procedures for specific intersection conditions. Many individual geometric or traffic factors are included.

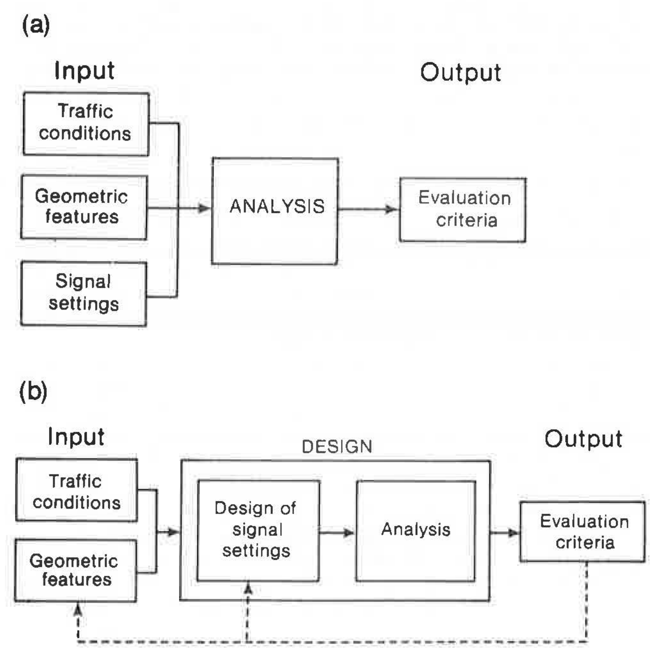

FIGURE 3 Schematic illustration of the signal operations analytical process (a) and schematic illustration of the signalized intersection design process (b).

Quantified performance parameters constitute the output of the analytical task. Capacity is naturally preeminent, but other expressions of capacity, such as volume-to-capacity ratios, reserve capacity, and delays, are also defined.

The design process concentrates on finding the best set of signal settings to suit local conditions, desired objectives, and performance parameters. This process is concerned with phasing schemes, cycle time determination, and green allocations. The suggested procedures use volume-to-capacity ratios or, alternatively, the probability of clearance, delays, and queues as tools to achieve the specified goals.

SATURATION FLOW CONCEPT

The saturation flow concept is shown in Figure 4. Three types of saturation flow are defined in the guide: basic, initial, and adjusted.

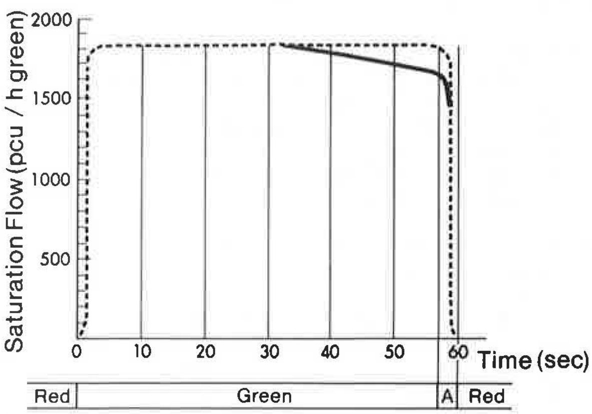

FIGURE 4 Saturation flow concept indicating a decline after about 40 sec of green (solid line).

Basic saturation flow is defined as the number of passenger car units that can discharge across the stop line of an "ideal" intersection lane (width 3.0 to 3.5 m) and move straight through (i.e., no turning movements) without any additional traffic friction (e.g., no parking, no bus stops). Ideal Canadian weather conditions during an optimum length of the green interval must also be included. The value of the basic saturation flow provides a good stable measure of driver behavior in a given community and, as such, can be used as a comparative indicator. Canadian research (6) suggests that not only the population size of a community but also its socioeconomic features influence saturation flows. Another important finding confirmed by international experience (7) indicated that the duration of the green interval should be considered because saturation flow declines after about 30 to 40 sec of green (solid line in Figure 4).

Initial saturation flows reflect a set of typical conditions that modify intersection performance. Long-lasting winter driving conditions and intersection environments are identified in the guide. It is recommended that a set of initial saturation flow values be developed for every community or region (based on local investigations). The differences may be significant as shown in Figure 5, which shows the typical ranges of basic saturation flow for summer and corresponding initial saturation flows for winter conditions as a function of the duration of

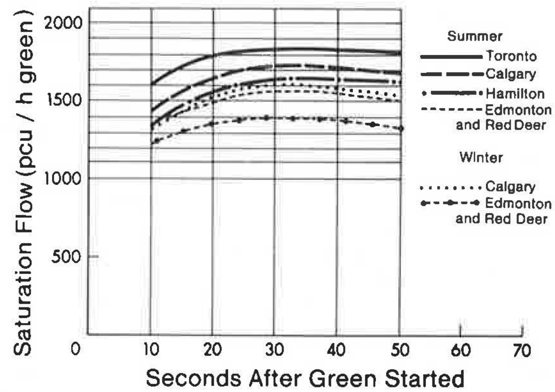

FIGURE 5 Typical ranges of Canadian basic and initial saturation flows in a cumulative average format.

the green interval for five Canadian cities. The values are depicted in a cumulative average format for a given green interval. For example, the values shown at 20 sec after green started show the average saturation flows for green intervals of 20 sec (i.e., between seconds 0 and 20). As a consequence of this format, Figure 5 cannot be directly compared with Figure 4.

It has been found that the impact of weather conditions becomes important only with major changes. Although citizens of other countries may find it somewhat strange, professional traffic engineers will understand that, from an intersection capacity point of view, typical Canadian summer conditions may include temperatures as low as -10°C (as long as the roads are not slippery). Typical winter conditions are characterized in the guide by low temperatures (-10°C to -30°C), pavement dry or well sanded, and exhaust fumes restricting visibility. Extreme winter conditions are defined by lower temperatures or heavy snowfalls.

The recommended intersection environment classification is based on the geometric standards and the general activity level, which is usually associated with adjacent land use. For example, a typical central business district intersection approach lane features a low geometric standard in combination with a high level of adjacent land-use activities, such as many pedestrians, frequent loading and stopping, and dense spacing of access points. This means that the initial saturation flow value for such an intersection is substantially lower than that for an industrial area with a high standard of roadway design and little interference from land-use activities. The user must consider individual approaches to the same intersection independently because they can belong to different categories, depending on their dominant features.

Initial saturation flow is used as a starting point for the incorporation of specific intersection conditions. The resulting value is termed the adjusted saturation flow. For existing intersections, this value can also be determined by direct measurements--or, if it was calculated, it can be verified by short surveys.

Procedures for the determination of the adjusted saturation flow include the following situations for through lanes:

1. Geometric conditions:
   - Lane width,
   - Gradient, and
   - Queueing and discharge space.
2. Traffic conditions:
   - Public transit,

- Parking, and
- Duration of the green interval.

Adjustments for left- or right-turn movements may include applicable procedures for the through lanes. In addition, the following geometric or traffic considerations may be necessary:

1. Geometric condition--turning radius.
2. Traffic conditions:
   - Opposing traffic flows,
   - Pedestrians, and
   - Effect of movement combinations that share one lane.

Figure 6 shows a summary of the applicability of different saturation flow adjustments to various lane function combinations.

Lane Function	Possible Adjustments							
	Lane Width	Radius	Grade	Queueing Space	Discharge Space	Bus Stops	On-street Parking	Length of Green
Straight Through and Left	•		•	•	•	•	•	•
Straight Through and Right	•	•	•	•	•	•	•	•
Straight Through Only	•		•	•	•	•	•	•
Left Only	•		•	•		•		•
Right Only	•	•	•	•		•		•
Straight Right and Left	•	•	•	•	•	•	•	•

FIGURE 6 Overview of initial saturation flow adjustments.

Individual cases are discussed in detail and procedures for the adjustment of initial saturation flows are provided. This section is a major part of the guide because the saturation flow concept constitutes its backbone. Unfortunately, the scope of this paper does not allow a description of the individual procedures. Suffice it to say that the techniques have not only been verified under Canadian conditions, but, perhaps more important, they allow for calibration to specific conditions of a given community or region.

If an approach lane features a combination of several factors for which adjustments of the initial saturation flow are necessary, the resulting adjusted value is not necessarily a multiplicative product of individual adjustments. In many instances, one of the factors will govern. For example, where the saturation flow for right-turning traffic is controlled mostly by a high pedestrian flow rate in the adjacent crosswalk, an additional adjustment for a tight radius is not appropriate. Most right-turning vehicles will have to stop, practically eliminating the effect of the radius.

The techniques suggested for the determination of adjusted saturation flows and the allocation of volumes to lanes with more than one movement (shared lanes) also employ auxiliary turning-movement factors that are determined as ratios of the initial saturation flow and the adjusted saturation flow for individual movements. This factor reflects a specific degree of difficulty in making a right or left turn under given circumstances. However, when the lane assignment has been completed, the volume is converted back to the real, measurable volumes.

INTERSECTION PERFORMANCE CRITERIA

Even though capacity in itself can be used as an absolute comparative measure, it does not reflect the operation of a signalized intersection relative to traffic demand. To this end, the following evaluation criteria are used in the guide:

- Lane (or approach) volume-to-capacity ratios,
- Intersection volume-to-capacity ratio,
- Lane reserve capacity,
- Intersection reserve capacity,
- Average lane delays,
- Average intersection delay, and
- Probability of discharge.

The guide employs the probability of discharge (clearance) as an alternative measure for the design task.

Most of the evaluation criteria that relate volume to capacity are well known and will not be discussed in this paper. It should be noted, however, that none of them in itself can fully represent the complexity of functions and objectives. The guide has not attempted to combine them in a single measure, but instead recommends simultaneous assessment.

Delays for individual lanes and the overall intersection represent the most powerful and practical tool for the evaluation of performance because they relate directly to drivers' perception. Total delay is expressed as a sum of uniform and overflow delay.

The uniform delay equation in the guide uses the queueing theory relationship [see Figure 7(a)].

The TRANSYT-7 computer program provided an overflow delay formula suggested by Whiting (8). The program has been extensively used in Canada for a number of years with satisfactory results. The combination of uniform and overflow delay is shown in Figure 7(b). Naturally, even in well-undersaturated conditions, an occasional cycle may feature an overflow.

The delay equation was tested by independent investigations in Toronto and in Edmonton. The formula matched field conditions with a high degree of accuracy. It should be emphasized, however, that for saturated or oversaturated conditions, the evaluation time (i.e., duration of the congestion) has an overriding effect (Figures 8 and 9). The slopes of the delay functions for 60-, 30-, and 15-min periods differ dramatically. In practical analytical or design problems, the length of the congested period can rarely be determined accurately and, consequently, the delay values for oversaturated conditions should be taken as an indication of the magnitude of the problem, not as absolute, accurate values.

The acceptance of the Whiting delay equation in Canada is also evidenced by the range of users of the SINTRAL computer program system for signalized

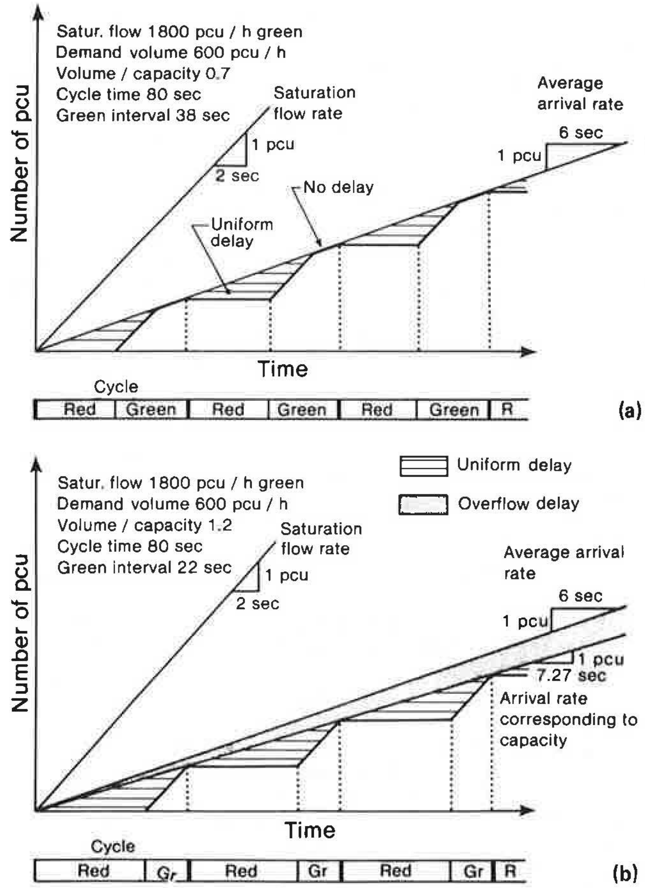

FIGURE 7 Queueing diagrams illustrating the basic delay considerations: idealized conditions well below saturation (volume-to-capacity ratio is 0.7) (a) and idealized conditions when demand exceeds capacity (volume-to-capacity ratio is 1.2) (b).

intersection analysis and design (9) that incorporates the formula.

The guide identifies the detailed delay formula and includes graphic representation of the most common conditions. Figures 8 and 9 are only two of the four graphs used in the guide. These diagrams

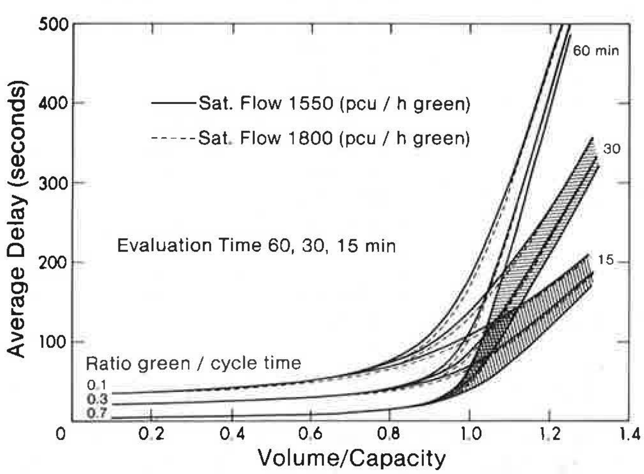

FIGURE 8 Average lane delay as a function of volume-to-capacity ratio (0.1 to 1.3), saturation flow (1,800 and 1,550 pcu/hr green), green interval-to-cycle time ratio (0.1, 0.3, and 0.7), and evaluation period (duration of congestion) (60, 30, and 15 min).

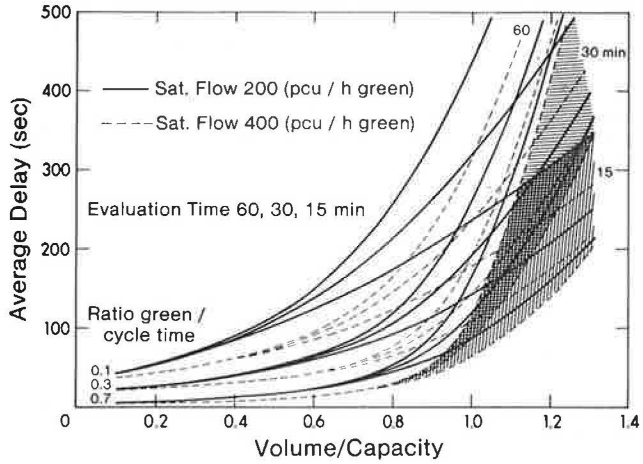

FIGURE 9 Average lane delay as a function of volume-to-capacity ratio (0.1 to 1.3), saturation flow (400 and 200 pcu/hr green), green interval-to-cycle time ratio (0.1, 0.3, and 0.7), and evaluation period (duration of congestion) (60, 30, and 15 min).

can be used for the manual determination of average lane delay.

Because of the shape of the delay function, a volume-to-capacity ratio of 0.9 is generally considered a practical capacity limit. Differences in the delay due to saturation flow and the ratio of the green interval to cycle time become essential for lower values of both parameters. As a consequence of the original Webster cycle time-delay relationship (5) cycle time itself has only a minor impact as long as it remains in the range of 0.75 to 1.5 of the "optimum" cycle time (Figure 10).

DESIGN PROCESS

The principles of signal design are shown in Figure 3(b). The task employs tentative geometric features

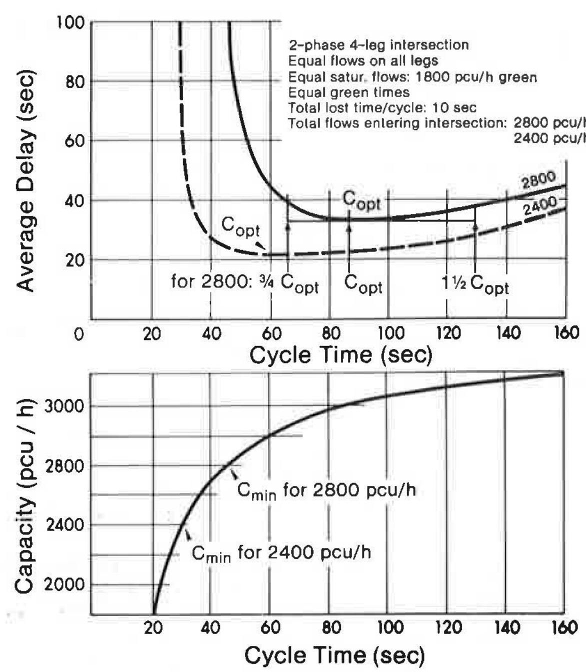

FIGURE 10 Relationship among cycle time, capacity, and delays.

and traffic volumes as the input, and the detailed signal settings constitute the output that may then be compared to the desired performance criteria. Iterative adjustments are usually necessary.

The determination of the minimum and optimum cycle time follows the well-known Webster methodology (5) that needed no adjustment for Canada (Figure 10). In addition, special pedestrian needs in regard to cycle time are considered. The user is also advised to consider systemwide issues, such as coordination.

The following techniques can be used for the allocation of green intervals within cycle time.

- Proportioning volume-to-saturation flow ratios,
- Equalization of the probability of discharge,
- Delay minimization, and
- Congestion management.

The technique of proportioning the volume-to-saturation flow ratio concentrates on the critical lanes. It allocates green intervals for individual phases in the proportion of critical lane volume-to-saturation flow ratios to the total intersection volume-to-saturation flow ratio. This method has been widely used in Canada in the past.

The probability-of-discharge technique attempts to balance the probability of waiting more than one cycle for the critical lanes of individual phases. The Poisson distribution of arrivals in used because it is not only simple (one parameter distribution) but, more important, it accurately represents the traffic conditions in most Canadian situations.

Two applications of this technique are described: starting from green intervals determined by proportioning the volume-to-saturation flow ratio and starting from the highest desired probability of discharge (9).

The delay allocation design technique assigns the green intervals for the critical lanes of individual phases in such a way that the overall intersection delay is minimized or is in agreement with other design objectives.

The goal of the congestion management green allocation technique is to prevent queues from "spilling over" the available storage space. In some instances, a revision of the previously determined cycle time may be needed.

OTHER CONSIDERATIONS

Although the guide is primarily concerned with the operation of individual signalized intersections, system aspects are emphasized. They may be expressed in the strategic objectives of the design, such as the reduction of shortcutting through residential areas. In such a case, the green allocation objectives will be expressed as "minimization of delays on arterial roadways and a maximum allowable delay on the collector or residential approaches." Coordination of signal operation along a route or in a network may significantly modify the arrival pattern and, as a result, the selection of evaluation criteria and the subsequent design method.

CONCLUSIONS

The currently available edition of the Canadian Capacity Guide for Signalized Intersections is based on international as well as Canadian research and practice. Nevertheless, it has been acknowledged during the development stage of this edition that more theoretical as well as empirical research is needed. Many of the outlined procedures and values should be subjected to real-life tests in different regions of Canada. A country-wide uniformity would not be a worthwhile objective in itself if it were not based on common foundations in driver behavior, traffic engineering, and legal practices.

Several new features of signal design and analysis can be identified in the first edition:

1. Calculations are based on demand instead of supply volumes;
2. Typical Canadian passenger car unit equivalents for different vehicle categories have been established on the basis of their interactive flow impact;
3. Amber intervals, intergreen periods, and pedestrian safety requirements are inherent components of the procedure;
4. Basic saturation flow values facilitate the transferability of the process;
5. Saturation flow values vary with socio-economic characteristics of a community not just its size;
6. The effect of ambient conditions is identified;
7. The impact of long green intervals is quantified;
8. Webster's procedure for determining saturation flow for left turns with opposing traffic is simplified;
9. Factors for saturation flow adjustments are not necessarily multiplicative;
10. Turning factors based on saturation flow values are introduced as auxiliary measures in the procedures for volume allocation to lanes and for determination of adjusted saturation flows for lanes with a combination of movements;
11. The procedure allows verification of intermediate results for existing situations;
12. Several simultaneous criteria are used for the assessment of capacity-related intersection performance; and
13. Green interval allocation parameters can be selected on the basis of design objectives.

The editor, the authors, and the committee anticipate significant contributions from users. Several ITE sections have already established committees to this end. Periodic revisions will also be needed in the future.

ACKNOWLEDGMENTS

The author of this paper would like to express his sincere appreciation to the coauthors of the guide. The commitment and effort of Dave Richardson, Brice Stephenson, and John Schnablegger made it possible to incorporate current Canadian research and practice and to devise many of the modifications.

The Canadian District of the Institute of Transportation Engineers has taken a bold step in assuming a leading role in the development of the guide.

The National Sciences and Engineering Research Council of Canada has supported some of the basic research for many years through operations grants.

Toronto, Edmonton, Hamilton, and several other communities assisted in data collection and in the development of the techniques incorporated in the guide.

Last, but certainly not least, the author would like to thank many of the individuals, within or outside the committee, who provided valuable comments or direct assistance on the drafts of the guide. Moral support from many Canadian colleagues was also extremely important, especially during the difficult revision and rewriting stages. The suggestions of the reviewers of this paper are also gratefully acknowledged.

Discussion

Robert H. Wortman*

The Canadian Capacity Guide for Signalized Intersections represents a significant contribution to the literature on highway capacity in that it presents material, concepts, and numerical values that have been found to be pertinent to conditions in Canada. All of those who contributed to the guide are to be commended for their efforts that resulted in this document.

The publication of the guide comes at a time when the signalized intersection chapter of the new Highway Capacity Manual is being put in final form and prepared for release. A review of the two documents reveals similarities as well as marked differences in philosophies and approaches. For example, both documents use saturation flow concepts as the basis for the capacity calculations, and rate of flow is preferred to the use of hourly volumes. Although delay is used as the measure of level of service for signalized intersections in the new Highway Capacity Manual, the Canadian guide suggests delay along with volume-to-capacity ratio and reserve capacity as measures of the adequacy of intersection operation.

Even though delay appears to be a common measure in both documents, there are differences that should be noted by users. The Canadian work uses average delay and the delay equation from TRANSYT-7. In contrast, the new Highway Capacity Manual will employ stop-time delay and a delay equation that has been modified to reflect the findings of field studies. Furthermore, there is some variation in the specific values of delay that define the operational levels for intersections.

In the discussion of capacity values for left-turning vehicles, it is interesting to note the apparent variation in values that was observed in various Canadian cities. Although the equation for permissive left-turn conditions is based on an empirical relationship developed in Edmonton, typical maximum values for other cities are also given. This certainly serves to support the observation that considerable variation in values can be found in different locations. The field data that have been used in the development of the new Highway Capacity Manual show similar results.

The Canadian guide contains material in a number of areas that should be of interest to those who are involved in capacity analyses. There is a quantification of the effect of winter conditions on capacity as well as of the influence of right-turn-on-red situations. Also, there is a discussion of network objectives that may be considered in evaluating operation and design problems. Basically, the network objectives reflect policies that give priority to certain movements or approaches.

Further work in several areas could possibly improve and enhance the current version of the guide. This work should include consideration of the following comments:

1. Average signal delay generally increases as cycle length increases; thus the average delay values as shown in the guide may not be appropriate when cycle lengths are long.
2. It would appear that the quality of progression is a major variable that is not included in computing delay. With volume-to-capacity ratios of less than 0.8, the average delay with excellent progression can be significantly less than for a condition with adverse progression.
3. The maximum delay for acceptable operation is defined as 30 sec; this value may be too large for intersections where motorists expect to benefit from signal progression.
4. The variation in the flows for left turns has been noted; however, it would help the user if the expected variation in all of the values and predictive equations used in the capacity calculations were indicated. In essence, the user should be apprised of the basis and validity of all of the numerical values that are shown in the guide.

In closing, comments should also be directed to all individuals and groups who are involved with the development of capacity procedures as well as to the users of those procedures. For those who are involved in the development of procedures, there is a need to resolve the differences between the various procedures, approaches, and computations. Such differences tend to confuse the user community. With respect to the users, there is a need to become thoroughly familiar with the procedures. The proper application of capacity procedures requires that the user have a certain level of understanding of the material and use good judgment in applying the guidelines that have been developed.

*Department of Civil Engineering, University of Arizona, Tucson, Ariz. 85721

Author's Closure

Robert Wortman's comments on the Canadian Capacity Guide for Signalized Intersections are sincerely appreciated.

During the past 20 years techniques for capacity analysis have converged significantly. Nevertheless, a deep understanding of the applicability of the procedures to local and regional conditions has been lagging somewhat behind the "philosophy." The guide and the new edition of the Highway Capacity Manual as well as other national documents play an important role in the development of a common basis on which we can compare our experience. It is not surprising that some of the specific values are different, but it is encouraging to see that major trends are similar.

The first edition of the guide will soon be critically reviewed. Wortman's suggestions will certainly be included in that review. At this time, however, I would like to point out that the committee deliberately divorced the broader "systems" aspects from individual (not necessarily isolated) intersection issues. Even a relatively simple linear or network coordination of traffic signals introduces an additional dimension to the problem and usually implies a modified set of objectives. Insofar as delay is considered a measure of performance its values at individual intersections may no longer govern. Although an overall delay reduction would be expected in such a system, some intersection approaches may experience a delay increase for the benefit of the larger system. Depending on a designer's objectives, delay may be supplemented by other measures, such as a performance index consisting of delay, running time, and a weighted number of stops. In some systems, the number of stops along certain network links may become the sole criterion.

Having stated that, I should note that I agree with Wortman that a better treatment of these issues is needed. The users must exercise a great deal of judgment and we should provide them with the best information we can give within the scope of the guide.

REFERENCES

1. D.B. Richardson. The Metropolitan Toronto Intersection Capacity Guide, 4th ed. Municipality of Metropolitan Toronto, Ontario, Canada, 1982.
2. Ontario Manual of Uniform Traffic Control Devices. Ontario Ministry of Transportation and Communications, Downsview, Ontario, Canada, 1981.
3. Saturation Flow Manual. The City of Edmonton and the University of Alberta, Edmonton, Canada, 1980.
4. D.B. Richardson, J. Schnablegger, B. Stephenson, and S. Teply. Canadian Capacity Guide for Signalized Intersections. Institute of Transportation Engineers, District 7, University of Alberta, Edmonton, Canada, Feb. 1984.
5. F.V. Webster and B.M. Cobbe. Traffic Signals. Road Research Technical Paper 56. Her Majesty's Stationery Office, London, England, 1966.
6. S. Teply. Saturation Flow at Signalized Intersections Through a Magnifying Glass. Proc., Eighth International Symposium on Transportation and Traffic Flow Theory 1981, Toronto University Press, Ontario, Canada, 1983, pp. 588-622.
7. Traffic Capacity of Major Routes. OECD Road Transport Research, July 1983.
8. D.I. Robertson. Traffic Models and Optimum Strategies of Control--A Review. Proc., International Symposium on Traffic Control Systems, Vol. 1, Berkeley, Calif., 1977, pp. 262-288.
9. J. Schnablegger, B. Stephenson, and S. Teply. Edmonton Version of Critical Lane Analysis: SINTRAL, An Interactive Computer Program System. ITE Journal, Aug. 1981, pp. 20-26.

Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.

Signal Delay with Platoon Arrivals

JAMES M. STANIEWICZ and HERBERT S. LEVINSON

ABSTRACT

Delays at signalized intersections assuming "platoon" flow are analyzed. Graphic analysis of vehicle platoon arrivals is used to develop equations from which the average travel time delay per vehicle can be estimated. Delay for two different, basic conditions is analyzed: (a) when the first vehicle in the platoon arrives during a green interval and is unimpeded and (b) when the first vehicle in the platoon arrives during a red interval or is impeded by queued vehicles. Delay based on the resulting relationships is compared with delay obtained by three conventional methods: the Webster method, May's continuum model method, and the new 1985 Highway Capacity Manual method. Where the platoon leader is unimpeded, there is no delay when the capacity of the through-band equals or exceeds the approach volume. Thus, a high volume-to-capacity ratio may provide a high level of service. This contrasts with delays based on random or uniform arrivals, which are sensitive to the volume-to-capacity ratio. However, where the first platoon vehicle is impeded by a red interval or by queue interference, a chain reaction may occur in which following vehicles are also impeded. This situation may create considerable delay and effectively reduce progression. Effective traffic signal coordination, therefore, can substantially reduce delay and improve levels of service.

Delay has become an important means of assessing level of service at signalized intersections. Consequently, accurate measurements of this delay are essential. Delay computations and computer simulations often assume uniform or random vehicle flow, singly or in combination. However, where signals are spaced closely together or form part of a progressive system, platoon flows are common and more closely represent reality. Such cases result in a different pattern of delays.

Delays at signalized intersections are analyzed assuming platoon flow instead of a random or a uniform arrival pattern. The following question is addressed: What average delay does a platoon of traffic encounter at a signalized intersection? A simple graphic analysis of vehicle platoon arrivals