search Laboratory, Crowthorne, Berkshire, England, 1978.
3. R. Sumner and C. Baguley. Speed Control Humps on Residential Roads. TRRL Report LR878. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1979.
4. C. Baguley. Speed Control Humps--Further Public Road Trials. TRRL Report LR1017. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1981.
5. D. Smith and D. Appleyard. Improving the Residential Street Environment. Report FHWA/RD-81/031. FHWA, U.S. Department of Transportation, 1981.
6. J.P. Clement. Speed Humps and the Thousand Oaks Experience. ITE Journal, Vol. 53, No. 1, Jan. 1983.
7. P.C. Box. Letters to the Editor. ITE Journal, Vol. 53, No. 3, March 1983.
8. K.K. Mak. Evaluation of Undulation as a Speed Control Device. Final Report: SwRI Project 06-9342. Southwest Research Institute, San Antonio, Tex., June 1983.

Publication of this paper sponsored by Committee on Traffic Control Devices.

Abridgment

Analytical Warrant for Separate Left-Turn Phasing

NAGUI M. ROUPHAIL

ABSTRACT

The development of a new volume warrant for left-turn phasing at signalized intersections is presented. The concept is to maintain a fixed volume-to-capacity (V/C) ratio for all intersection movements. Thus left-turn phasing would be warranted when the unprotected left-turn V/C ratio exceeds that of through traffic. Left-turn capacity is derived from formulas in the Highway Capacity Manual and the Australian Road Research Board Capacity Manual. The warrant also combines both signal-timing and capacity-analysis procedures. The proposed warrant has been compared with other methods found in the literature and the results are, in general, favorable. This study is preliminary in nature; its scope is limited to four-legged intersections with one through lane and an exclusive left-turn lane of adequate length on all approaches. No adjustments for trucks, buses, or pedestrian interference are considered. Finally, it is understood that traffic signal parameters are selected according to Webster's optimum settings for fixed-time signals.

The provision of separate left-turn phasing at intersections has been the subject of considerable research. The need for developing guidelines for left-turn phasing stems from an absence of uniform criteria in the Manual on Uniform Traffic Control Devices (MUTCD) (1) and the need to formulate consistent policies regarding left-turn treatments at signalized intersections.

The majority of left-turn warrants follow these general criteria:

1. Left-turn delay exceeds a prespecified threshold (e.g., 30 sec),
2. Left-turn volume exceeds a threshold [e.g., 100 vehicles per hour (vph)],
3. The product of left-turn volume and opposing traffic exceeds a prespecified threshold (e.g., 50,000 or 100,000),
4. Left-turn volume-to-capacity (V/C) ratio exceeds a threshold (e.g., 0.70 to 0.90), and
5. Number of left-turn-related accidents reaches a prespecified threshold (e.g., four accidents per approach per year).

Department of Civil Engineering and Metallurgy, University of Illinois at Chicago, P.O. Box 4348, Chicago, Ill. 60680.

Methodologies for developing these guidelines have included microscopic simulation modeling (2,3), analytical models calibrated with field observations (4), and comprehensive studies of accidents, conflicts, delay, and gap-acceptance parameters (5).

Several observations are noted from the literature:

1. Although it is evident that left-turn capacity is affected by the amount of volume and green time to the opposing flow (V_0 and g/c, respectively), many studies have dealt with these two parameters independently. Yet all signal-timing methods relate signal splits (g/c) to the critical-flow ratio (V/S). In fact, Messer has shown that improved unprotected left-turn operations can be expected by optimizing the signal settings alone (6).

2. None of the prescribed criteria relate left-turn operation to through-traffic operation.

3. Left-turn through passenger-car equivalents (PCEs) vary with the signal settings and opposing-flow rate (7). Thus, an exact solution would require iterating between the two values until an equilibrium is reached.

The proposed warrant avoids many of these pitfalls by ensuring that the unprotected left-turn movement does not become critical under two-phase operation. It should be realized that although the V/C ratio is maintained constant for all movements, left-turn delay is still higher, on the average, than through-traffic delay. This is because delay is a function of both V/C and the flow ratio V_1/S_1, where S_1 is the unprotected left-turn saturation flow rate. Because S_1 is in all cases less than its through-traffic counterpart, operation at the left-turn volume warrant values will always result in higher left-turn delays. The numeric delay values will vary according to the intersection V/C ratio. The proposed warrant is now stated as follows:

> For a given combination of critical lane volumes at isolated, signalized intersections with one through lane and an exclusive left-turn lane of adequate length on all approaches, a separate left-turn phase should be considered whenever the degree of saturation for any left-turn movement exceeds the critical intersection V/C ratio.

Subsequently, PCE values are calculated as the ratio of critical through-lane volume and the left-turn volume warrant.

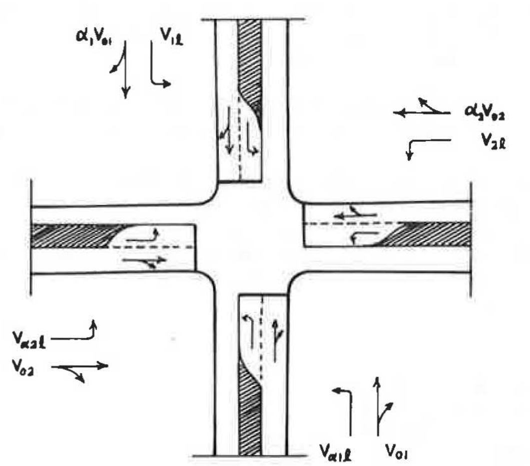

FIGURE 1 Intersection layout considered.

ANALYTICAL DEVELOPMENT

Consider the intersection layout in Figure 1. Critical lane volumes are denoted V_{01}, V_{02} and noncritical volumes $\alpha_1 V_{01}$ and $\alpha_2 V_{02}$, where α_1 and $\alpha_2 < 1$. Assume a fixed through saturation flow rate of S_T. The left-turn warrants are shown as $V_{\alpha 11}$, V_{11}, $V_{\alpha 21}$, V_{21}. On the basis of the warrant definition, a left-turn phase is considered when

$$V_{j1}/C_{j1} \geq V_{0j}/C_{jT}$$

where

V_{0j} = opposing volume in phase j, j = 1, 2;
C_{j1} = left-turn capacity in phase j, j = 1, 2; and
C_{jT} = through-lane capacity in phase j, j = 1, 2.

Note that for through movements,

$$C_{jT} = S_T * g_j/C_0$$

where

g_j = effective green time in phase j,
C_0 = Webster's optimum cycle length (8) = $(1.5 * L + 5)/[1 - (V_{01} + V_{02})/S_T]$, and
L = lost time per cycle (sec).

And for the left-turn movements, note that

$$C_{j1} = (S_{0j} * g_{j1}/C_0) + (3{,}600 * K/C_0)$$

where

S_{0j} = unprotected left-turn saturation flow rate in phase j = $S_{u1} - V_0/(g_j/C_0)$,
S_{u1} = unopposed left-turn saturation flow rate, and
g_{j1} = effective green time in phase j in which left turns may proceed in gaps of opposing traffic. This time can be estimated as (9)

$$(S_T * g_j - V_{0j} * C_0)/(S_T - V_{0j})$$

WARRANT FORMULATION

From the foregoing analysis, the following left-turn volume warrant is proposed for movement V_{11} in Figure 1:

$$V_{11} \geq V_{01}/(S_T * g_1/C_0) * \Big(\{S_{u1} - [V_{01}/(g_1/C_0)]\} * \{(S_T g_1 - V_{01}C_0)/[C_0 * (S_T - V_{01})]\} + 3{,}6000 * K/C_0\Big)$$

or, with some manipulation,

$$V_{11} \geq V_{01} * \Big(\{(S_{u1}/S_T) - [V_{01}/(S_T * g_1/C_0)]\} * \{[(S_T - V_{01}C_0)/g_1]/(S_T - V_{01})\} + [3{,}600 * K/(S_T * g_1)]\Big)$$

provided that $V_{01} \leq S_{u1} * g_1/C_0$ and

$$V_{11} \geq (3{,}600 * V_{01} * K)/(S_T * g_1) \text{ for } V_{01} > S_{u1} * g_1/C_0$$

Similar warrants can be derived for the remaining three movements.

COMPARISON WITH EXISTING WARRANTS

The proposed warrant is compared with four existing ones:

1. Volume product warrants of 50,000 and 100,000, respectively;
2. Critical left-turn volume warrants from the TEXAS model (2);
3. A left-turn peak-hour volume of 150 vph; and
4. Two or more left-turn arrivals per cycle.

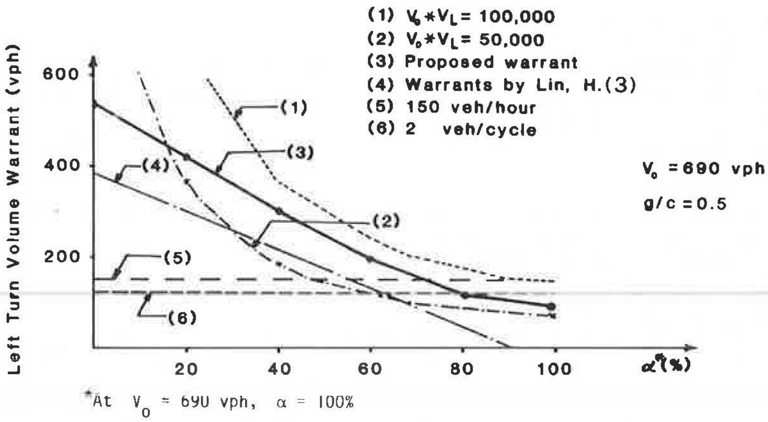

FIGURE 2 Left-turn volume warrants: a comparison at g/c = 0.50.

The results are shown in Figure 2 for various opposing flow rates and g/c = 0.50. In general, the proposed warrant appears to fit quite well within the existing literature. It lies between the two volume product warrants; thus a volume product warrant of 75,000 appears to be valid theoretically when g/c = 0.50 and V_0 is greater than 200 vph. On the other hand, the volume product warrants tend to overestimate the left-turn volume warrant at low values of g/c and V_0, as shown in Figure 3 (and vice versa for g/c < 0.4). The TEXAS estimates gave very conservative values of critical left-turn volumes, which could be explained from the simulation run parameters used in the model, such as minimum acceptable gaps and through-traffic saturation flow rates. Finally, fixed left-turn volume warrants were only valid under heavy opposing flows, that is, when the capacity is primarily developed in the clearance interval.

Limited sensitivity analyses performed on the model indicate that the proposed warrants are very sensitive to the unopposed left-turn saturation flow rate S_{ul}; an increase in S_{ul} by 200 vehicles per hour of green (vphg) results in a 100-vph increase in the proposed warrant. The effect of lost time per cycle (L) and clearance capacity per cycle (K) was not significant, however.

IMPLEMENTATION

On the basis of the literature and sensitivity analyses, it is recommended that the following parameter values be used for typical traffic conditions:

S_T = 1,750 vphg,
S_{ul} = 1,440 vphg,
L = 7 sec, and
K = 2 veh/cycles.

The recommended warrants are summarized in Table 1 along with the conditions for applying the formulas. In addition, an interactive microcomputer-based program was developed to perform these calculations and generate intersection performance measures. A sample screen of the program output is shown in Figure 4.

CONCLUSIONS AND RECOMMENDATIONS

This paper has presented an analytical signal-timing-based approach to determine left-turn volume warrants for two-phase pretimed intersections. The following conclusions are offered:

1. The proposed volume warrants were found to be consistent with existing models of left-turn capacity and warrants.
2. A simple volume-product warrant is not feasible when V_0 is less than 200 vph or when g/c is significantly different from 0.50.
3. The critical left-turn volumes derived from the TEXAS model appear to be unrealistically conservative.

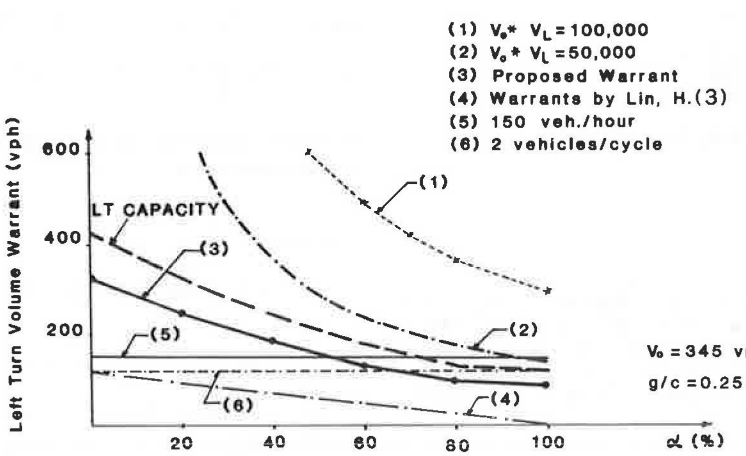

FIGURE 3 Left-turn volume warrants: a comparison at g/c = 0.25.

TABLE 1 Summary of Proposed Warrants

Phase	Movement	Condition	Left-Turn Volume Warrant (vph)
1	V_{01}, $V_{1\ell}$	$V_{01} < \frac{1440g_1}{C_o}$ (2)	$V_{1\ell} = V_{01}\left\{\left[0.82 - \frac{V_{01}/1750}{g_1/C_o}\right] * \left[\frac{1750 - V_{01}C_o/g_1}{1750 - V_{01}}\right] + \frac{4.11}{g_1}\right\}$ (3)
		$V_{01} \geq \frac{1440g_1}{C_o}$	$V_{1\ell} = \frac{4.11V_{01}}{g_1}$
1	$V_{\alpha1\ell}$, (1)α_1V_{01}	$V_{01} < \frac{1440g_1}{\alpha_1C_o}$	$V_{\alpha1\ell} = V_{01}\left\{\left[0.82 - \frac{\alpha_1V_{01}/1750}{g_1/C_o}\right] * \left[\frac{1750 - \alpha_1V_{01}C_o/g_1}{1750 - \alpha_1V_{01}}\right] + \frac{4.11}{g_1}\right\}$
		$V_{01} \geq \frac{1440g_1}{\alpha_1C_o}$	$V_{\alpha1\ell} = \frac{4.11V_{01}}{g_1}$
2	$V_{2\ell}$, V_{02}	$V_{02} < \frac{1440g_2}{C_o}$	$V_{2\ell} = V_{02}\left\{\left[0.82 - \frac{V_{02}/1750}{g_2/C_o}\right] * \left[\frac{1750 - V_{02}C_o/g_2}{1750 - V_{02}}\right] + \frac{4.11}{g_2}\right\}$
		$V_{02} \geq \frac{1440g_2}{C_o}$	$V_{2\ell} = \frac{4.11V_{02}}{g_2}$
2	α_2V_{02}, $V_{\alpha2\ell}$	$V_{02} < \frac{1440g_2}{\alpha_2C_o}$	$V_{\alpha2\ell} = V_{02}\left\{\left[0.82 - \frac{\alpha_2V_{02}/1750}{g_2/C_o}\right] * \left[\frac{1750 - \alpha_2V_{02}C_o/g_2}{1750 - \alpha_2V_{02}}\right] + \frac{4.11}{g_2}\right\}$
		$V_{02} \geq \frac{1440g_2}{\alpha_2C_o}$	$V_{\alpha2\ell} = \frac{4.11V_{02}}{g_2}$

(1)α_i = Ratio of lowest to highest through lane volume in phase (i).
(2)g_i = Effective green time in phase (i).
(3)$PCE_j = V_{oj}/V_{j\ell}$, $j = 1,2,\alpha_1$ and α_2

```
R E S U L T S   F O R   P H A S E  1

CRITICAL LANE VOLUME = >> 500 VPH <<

C= 60   GREEN= 20  G/C= .3397436   VOPP= 500   DESIRED LT V/C RATIO = .7

LEFT TURN CAPACITY--------> 175   OR APPROX   3   VEH PER CYCLE
LEFT TURN WARRANT --------> 147   OR APPROX   3   VEH PER CYCLE
WARRANT FROM DESIRED V/C--> 123   OR APPROX   3   VEH PER CYCLE
P . C . E .   -----------> 3.381938
EQUIVALENT THRU VOLUME =>> 499  VPH <<
THRU LANE CAPACITY--------> 594
DESIGN V/C RATIO  --------> .8409704

PRESS 1 TO CALCULATE DELAYS , 0 TO CONTINUE >
```

FIGURE 4 Sample screen output: signal timing and left-turn warrant program.

4. The proposed warrants are very sensitive to variations in the unopposed left-turn saturation flow rate. Other factors such as lost time and number of left turners per cycle were not significant.
5. Simple left-turn volume warrants are not sufficient indicators of the presence of left-turn problems. Supporting data regarding accidents, conflicts, delays, and sight distance restrictions must be considered before implementation.
6. The feasibility of applying the foregoing warrants to intersections with two or more opposing lanes needs to be addressed.
7. There is a need for developmental research on left-turn phasing warrants for coordinated signals.

REFERENCES

1. Manual on Uniform Traffic Control Devices. Institute of Transportation Engineers, Washington, D.C., 1971.
2. F.B. Lin. Estimation of Left-turn Traffic Parameters. Journal of Transportation Engineering, Vol. 109, No. 3, May 1983.
3. H.J. Lin and R.B. Machemehl. Developmental Study of Implementation Guidelines for Left-Turn Treatment. In Transportation Research Record 905, TRB, National Research Council, Washington, D.C., 1983.
4. D. Fambro, C. Messer, and D. Andersen. Estimation

of Unprotected Left-Turn Capacity at Signalized Intersections. In Transportation Research Record 644, TRB, National Research Council, Washington, D.C., 1977.
5. K. Agent. Development of Warrants for Left-Turn Phasing. Research Report 456. Department of Transportation, Commonwealth of Kentucky, Frankfort, Aug. 1976.
6. C. Messer and D. Fambro. Effects of Signal Phasing and Length of Left-Turn Bay on Capacity. In Transportation Research Record 644, TRB, National Research Council, Washington, D.C., 1977.
7. Highway Capacity Manual. Special Report 209. TRB, National Research Council, Washington, D.C., 1985.
8. F. Webster and B. Cobbe. Traffic Signals. TRRL Technical Paper 56. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1966.
9. Australian Road Capacity Guide. Bulletin 4. Australian Road Research Board, Nunawading, Victoria, June 1968.

Publication of this paper sponsored by Committee on Traffic Control Devices.

Accident Experience of Flashing Traffic Signal Operation in Portland, Oregon

M. FEROZ AKBAR and ROBERT D. LAYTON

ABSTRACT

Traffic signals affect the safety and efficiency of traffic operations. Flashing-signal operation reduces delays during low-volume periods and may conserve energy. However, flashing operation has been found to affect the safety of the intersection adversely. The relative accident impacts of flashing-signal operation versus regular signal operation in the city of Portland are evaluated. Analyses were conducted to determine whether an increase in accidents occurred at the intersections when the control devices were operated in the flashing mode during low-volume nighttime hours. For the intersections studied, the accident levels, volume levels, intersection geometry, and speed and parking data were collected. A statistical analysis was made to determine the safety of flashing operation for intersections with various volume ratios, street classifications, types of approaches, approach speed limits, and parking conditions. Intersections at which the major-street volumes were more than twice the minor-street volumes experienced a significant increase in accidents when flashing operation was used. Significant increases in accidents were also found when flashing signals were installed at intersections with major-street approach speeds in excess of 30 mph. Accidents also increased with flashing operation when both streets were two-way and where parking was allowed on both streets. Accident severity increased for many situations, often because there was an increase in right-angle accidents.

Traffic signals affect the efficiency and safety of traffic operations. When traffic volumes are high, signals eliminate traffic conflicts by alternating the assignment of right-of-way. However, when traffic volumes drop substantially below the stated volume warrants for two or more consecutive hours, it may be desirable to replace the conventional signal for that period with a flashing signal (1). Flashing-signal operation reduces delays during low-volume periods and may conserve energy. The major argument for retaining 24-hr "full-color" operation may be that flashing operation may adversely affect the safety of the intersection.

This paper contains the summary of a research effort begun at Oregon State University in 1984 to analyze statistically the accidents experienced at 30 intersections in Portland, Oregon, at which the installation of flashing traffic signals was carried out in accordance with accepted guidelines. The specific objective of this study was to investigate the safety of use of flashing versus full-color

M.F. Akbar, Haynes, Hollon & Associates, P.O. Box 35481, Dallas, Tex. 75235. R.D. Layton, Civil Engineering Department, Oregon State University, Corvallis, Oreg. 97331.