Preferential Control Warrants of Light Rail Transit Movements

A. Essam Radwan
Department of Civil Engineering, Arizona State University
Tempe, Arizona

Kuo-Ping Hwang
Department of Civil Engineering, Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Light rail transit (LRT) is catching the attention of people in numerous cities across North America today. New LRT operations were initiated in Edmonton and Calgary, Alberta, in 1978 and 1981, respectively (1,2). New systems are in an advanced stage of construction in Buffalo, and others are being considered for upgrading in Pittsburgh, San Diego, and San Francisco.

LRT, as defined by the Transportation Research Board Committee on Light Rail Transit, is a mode of urban transportation that uses predominantly reserved but not necessarily grade-separated rights-of-way. Electrically propelled rail vehicles operate singly or in trains. Most of the LRT operating environment is at grade but with predominantly controlled rights-of-way. Separated right-of-way, on-street operation, and transit-pedestrian malls are the most common forms of at-grade operating environments. Median LRT treatment is a special design in which the light rail line is accommodated in an existing wide median of a multilane arterial. Such designs may be used for heavily traveled arterials where signal timings should be carefully studied to maximize the passenger throughput of the system. A common preferential control technique for LRT is traffic signal preemption in favor of the LRT; however, this technique may adversely affect the overall performance of the system. The major objective of this study is to investigate preferential control of LRT, using different signal preemption strategies, and to attempt to develop control warrants for these strategies.

BACKGROUND

The use of unconditional traffic signal preemption generally results in some loss in intersection capacity. This loss is proportional to the LRT frequency and the particular preemption strategy used. In a recent study (3) the impact of signal preemption on intersection capacity was evaluated. It was concluded that at a standard intersection where all other traffic must stop to allow the LRT vehicle to pass, around 10 percent of the available signal time would be lost if preemption occurred every 3 min. Furthermore, for a multilane arterial with far-side transit stops, a constant main-street traffic volume of 20,000 vehicles per day and cross-street volume range of from 10,000 to 20,000 vehicles per day, it was found that a multiphase traffic signal makes LRT preemption feasible in every third cycle. If simple two-phase signals are used and left turns are prohibited, LRT preemption in every second cycle is feasible. Similar capacity analyses performed for a midblock crossing of four-lane arterials showed that preemption is feasible as often as every 2 min for traffic volumes as high as 25,000 vehicles per day.

In another study (4) the use of the level-of-service criterion to evaluate LRT impacts on traffic flow over arterials was criticized because it significantly favors the automobile mode over the LRT mode and does not consider the volume of people carried by transit. A factor that indicates the percentage of theoretical capacity of the intersection that is being used (intersection utilization factor) was used to evaluate the impact on street traffic performance of operating LRT within the same vehicular right-of-way. Utilization factors were calculated for three alternative operational strategies:

- Left turns from the arterial onto the cross street (across the LRT tracks) controlled with a special signal phase,
- Left turns prohibited from the arterial onto the cross street, and
- All traffic stopped during LRT passage.

The utilization factors without LRT preemption were also included for comparison. Analysis of these results pointed out a key conceptual difficulty with the use of the traditional level-of-service approach. The results imply that, as the frequency of the LRT operation increases, the feasibility of preemption decreases; it causes an "unacceptable" impact on cross traffic. However, higher frequency LRT operation actually may mean that greater numbers of transit passengers are traversing the intersection. Thus the true situation may be the opposite from that implied by the utilization factor results.

A parametric analysis was conducted in the same study, using a delay model developed by May and Pratt (5), to alleviate the problems with the level-of-service approach. Two major conclusions were

drawn: First, the justification for priority treatment for LRT generally increases as the line volume increases, until the headways are so short and cross-street volumes are so high as to begin to greatly increase automobile delay. Second, it was found that preemption can be justified for a large number of LRT headways and cross-street volume combinations, whereas the utilization factor criterion resulted in many more design combinations falling into the so-called unacceptable category. Other studies (6,7) involved the development of two macroscopic delay models for the purpose of evaluating the impact of bus signal preemption on street vehicular delay.

The literature review revealed that previous studies have used simple delay models with no capability of evaluating different preemption strategies (green extension and red truncation) and, more important, that they all failed to define general warrant guidelines for using signal preemption in association with LRT traffic.

RESEARCH OBJECTIVES

The major objectives of this research study are to develop a mathematical model that estimates private automobile and LRT delays for signalized intersections operating under preemption scenarios, to apply the model to three operational strategies and check its validity, and finally to use the model to develop warrants for signal preemption of LRT movements.

DELAY MODEL

A modified version of Webster's delay model was selected for this research (8), and the average delay per vehicle is determined from

$$d = 9/10\ \{[c(1-\lambda)^2/2(1-\lambda x)] + [x^2/2q(1-x)]\} \qquad (1)$$

where

- d = average delay per vehicle on the particular intersection approach,
- c = cycle time,
- λ = proportion of the cycle that is effectively green for the phase under consideration (g/c),
- q = flow,
- s = saturation flow, and
- x = degree of saturation.

Equation 1 was used to estimate the average delay per private automobile and LRT. For each LRT detection event, the probability of signal preemption was estimated. Signal cycle length and corresponding phase splits were also determined for each detection scenario. The average delay per vehicle and the probabilities were combined, and the estimated delays for preemption and non-preemption cases were calculated and compared.

Model Assumptions

The following assumptions were made to formulate the analytical model:

1. Pretimed signal controller with a two- or three-phase plan and a cycle length determined from Webster's optimum cycle formula (8).
2. Minimum red phase durations for main and cross streets determined from Webster's minimum cycle formula.
3. Absolute minimum cycle length of 40 sec for two-phase and 50 sec for three-phase plans and absolute maximum cycle length of 120 sec for two-phase plans and 150 sec for three-phase plans.
4. Minimum green phase duration of 12 sec for through maneuvers and 15 sec for left-turn maneuvers.
5. Left-turn adjustment factor of 1.75 for private automobiles.
6. LRT arrivals that follow a discrete uniform distribution or a Poisson distribution. The model was formulated so as to give the user the option of using either distribution.

Pedestrian movement can adversely affect signal preemption. If the cross-street green phase is constrained by pedestrian clearance considerations, red truncation may not be feasible and the minimum green phase duration threshold (12 sec) has to be increased. This study did not include the impact of pedestrian movement on LRT priority schemes; however, the model can be adjusted to take those impacts into account.

Probability Expressions

Probability expressions for LRT arrivals during different time periods of the signal cycle were derived for three signal-timing strategies. The first strategy (Option 0) is a two-phase plan with prohibition of left-turn maneuvers from the major arterial to the side street; the second strategy (Option 1) is a three-phase plan in which a 15-sec exclusive phase is dedicated to LRT movements; and the third strategy (Option 2) is a three-phase plan in which an exclusive left-turn phase is provided for automobile traffic to turn from the major arterial to the side street. The signal phase durations are shown in Figure 1 and the probability expressions for a selected option (Option 0) are given in Table 1. The detailed derivation of the five probability expressions is beyond the scope of this paper. The probability expressions of Options 1

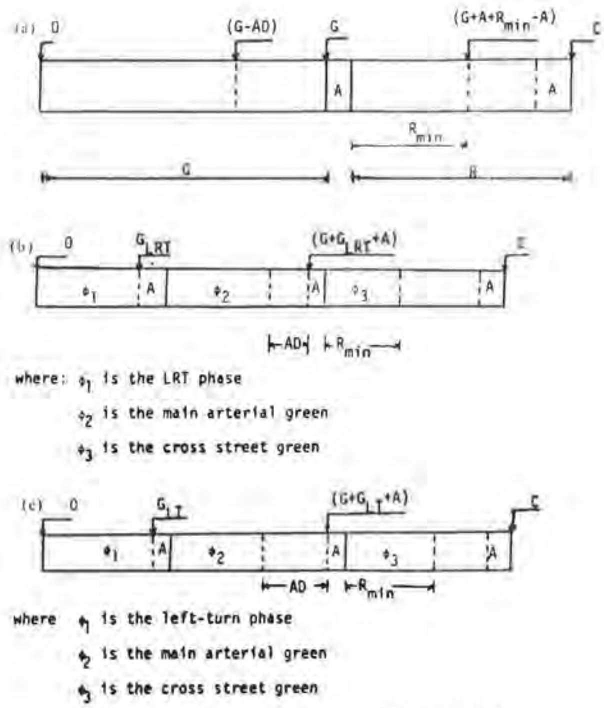


FIGURE 1 Signal phase durations: (a) Option 0, (b) Option 1, and (c) Option 2.

TABLE 1 Probability Expression

Event
No LRT arrival during a cycle
LRT arrives in a cycle and no preemptio
LRT arrives during a cycle and there is r
LRT arrives during a cycle such that red occurs after Rmin
LRT arrives during a cycle such that a gr occurs

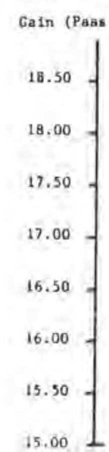
Note: LRT = light rail transit flow, C = cycle l

^{a}If $M < 1$, $P_1 = 1 - M$; if $M \geq 1$, $P_1 = 0$, $M = 1$,

and 2, and the mathemati obtained from the authors.

MODEL TESTING AND VALIDATIO

The probability expression were coded into a computer calculation of delays. Th total delay of private a both preemption and non-p



FIGURE

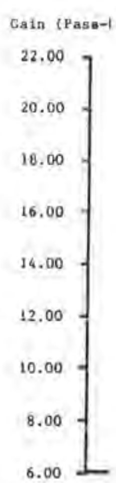


FIGURE 3

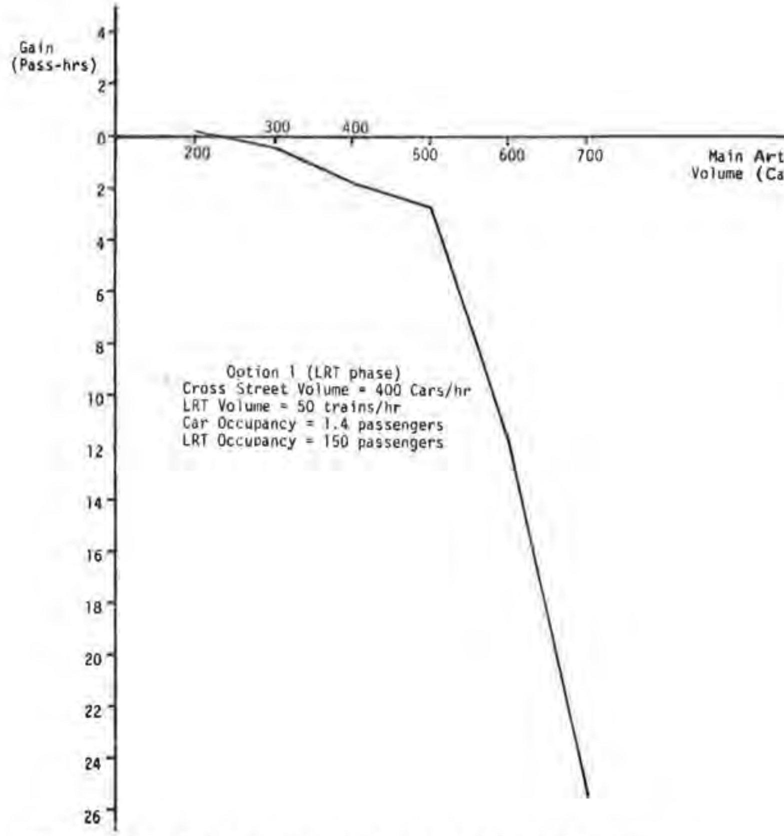


FIGURE 6 Results of testing various levels of main-arterial volume.

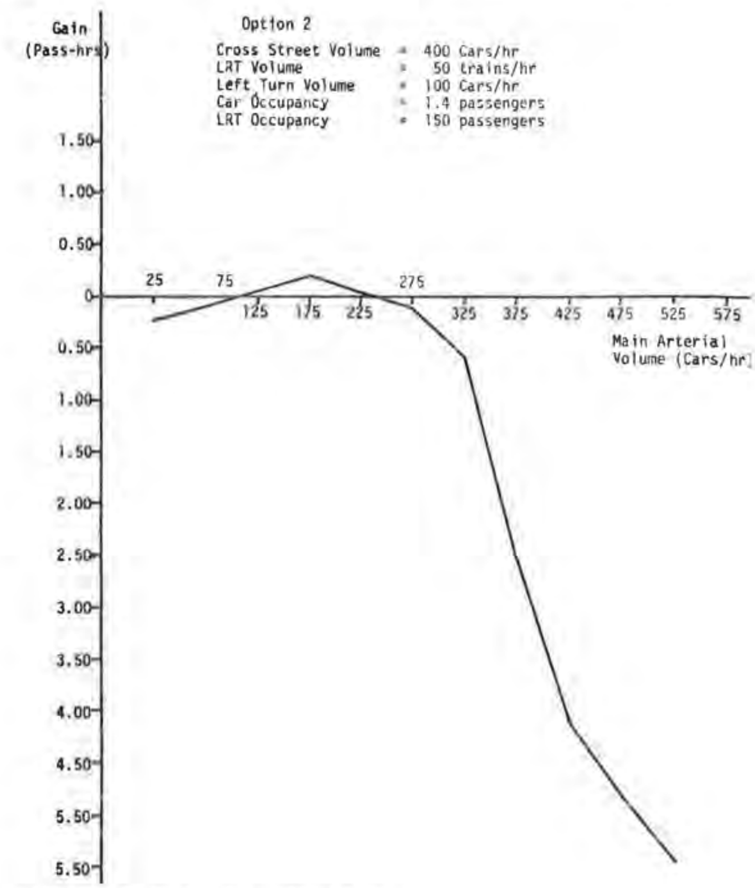


FIGURE 7 Option 2—results of testing.

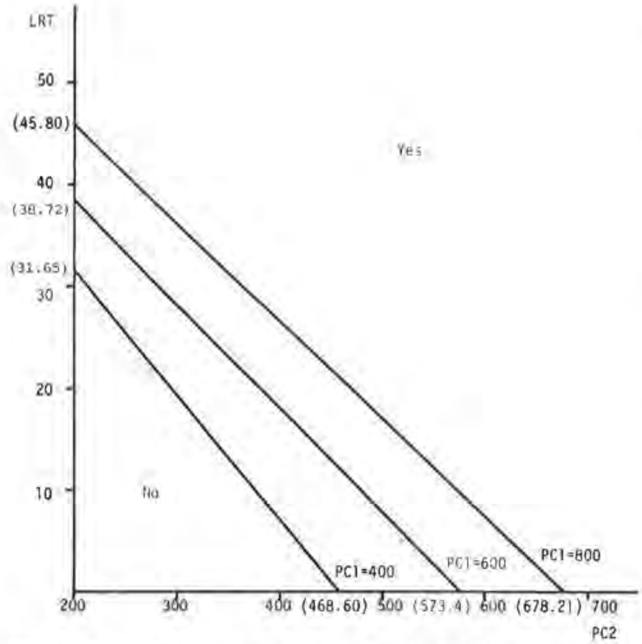


FIGURE 8 Boundary lines of control warrant regions.

these variables with total intersection gain was attempted, and the following model was attained:

$$\text{Gain (passenger-seconds)} = -30481.75 + 1742.70\ \text{LRT} - 61.68\ \text{PC1} + 117.70\ \text{PC2} \quad (R = 0.88) \qquad (2)$$

where

PC1 = main-arterial volume (cars/hr),
PC2 = cross-street volume (cars/hr), and
LRT = light rail transit volume (trains/hr).

The signs of the independent variables confirm the previous findings, and the regression equation was used to develop signal preemption warrants under different demand levels. By substituting zero in Equation 2 and using PC1 constant values of 400, 600, and 800, boundary lines of the control warrant regions were developed (Figure 8).

For Option 1, it was found earlier that no gain can be realized under any demand levels and therefore no attempt was made to develop warrant regions. For Option 2, the process was repeated, and a regression model was calculated:

$$\text{Gain} = 1163.80 - 34.79\ \text{LRT} + 2878.2\ \text{PLT} + 2.15\ \text{PC2} \quad (R = 0.904) \qquad (3)$$

where

LRT = light rail transit volume (trains/hr),
PLT = percent left turn, and
PC2 = cross-street volume (cars/hr).

The negative sign of LRT is expected because as LRT volume increases, total LRT passenger delay increases during the exclusive left-turn phase and, consequently, overall intersection gain decreases. On the other hand, as the percentage of left turns increases, more left-turn traffic uses the third phase and overall intersection gain increases. The control warrant regions for this option are shown in Figure 9.

SUMMARY AND CONCLUSIONS

The purpose of this paper was to demonstrate a method for evaluating and testing signal preemption strategies for LRT movements in existing arterial medians. Three operational options were identified and the probability expressions for a selected option were documented. Webster's delay model was adopted to

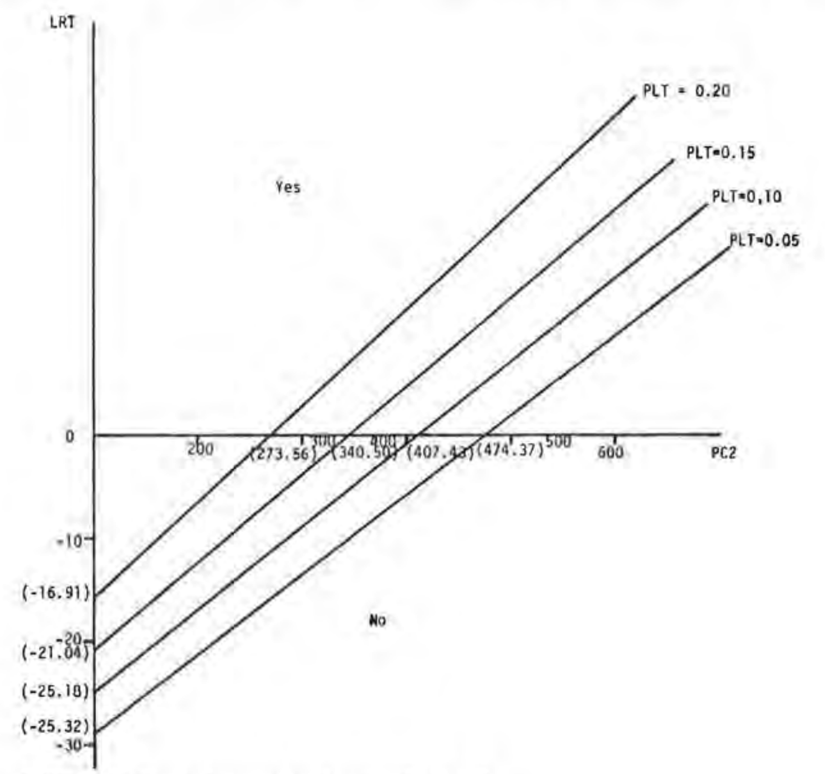


FIGURE 9 Control warrant regions for Option 2.

estimate the average delay per vehicle per approach. The model was tested using a set of hypothetical demand parameters. The results of the model testing proved that the model parameters consistently produce reasonable results and that the model is sensitive to variations in main-arterial and cross-street volumes.

Furthermore, it was concluded that, for the two-phase signal plan (Option 0), the overall intersection gain due to signal preemption is linearly proportional to LRT volume, and that there was no impact of advance detection duration on intersection gain.

For the three-phase signal plan with a separate LRT phase (Option 1), no intersection gain was observed for almost all main-arterial volume levels. For the three-phase signal with an exclusive left-turn phase (Option 2), it was found that there exists an optimum main-arterial volume at which the overall intersection gain is maximum for a given constant left-turn volume. Finally, boundary lines of the control warrant regions for Options 0 and 2 were developed.

REFERENCES

1. Light-Rail Transit in North America: What's Going On? ITE Journal, March 1980.
2. E. Guillot. LRT Design Choices: Edmonton and Calgary. Transportation Quarterly, July 1983.
3. H. Korve. Traffic Engineering for Light-Rail Transit. In TRB Special Report 182: Light-Rail Transit: Planning and Technology, TRB, National Research Council, Washington, D.C., 1978, pp. 107-115.
4. T. Stone and W. Wild. Design Consideration for LRT in Existing Medians: Developing Warrants for Priority Treatments. In TRB Special Report 195: Light Rail Transit: Planning, Design, and Implementation, TRB, National Research Council, Washington, D.C., 1982, pp. 170-175.
5. A. May, Jr., and D. Pratt. A Simulation Study of Load Factor at Signalized Intersection. Traffic Engineering, Feb. 1968.
6. A. Radwan and J. Hurley. Analytical Model of Bus Preemption Signal System: A Macroscopic Approach. Transportation Quarterly, Jan. 1982.
7. A. Radwan and J. Hurley. Macroscopic Traffic Delay Model of Bus Signal Preemption. In Transportation Research Record 881, TRB, National Research Council, Washington, D.C., 1982, pp. 59-65.
8. F. Webster. Traffic Signal Settings. Road Research Technical Paper 39. Road Research Laboratory, London, England, 1958.