# Preferential Control Warrants of Light Rail Transit Movements

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ABSTRACT

The goal of this paper is to demonstrate a method for evaluating a preferential treatment technique for light rail transit (LRT) in urban areas. A mathematical delay model, which uses probability expressions, is presented to evaluate two LRT preemption signal strategies in existing arterial medians. The model permits the user to evaluate three operational options: a two-phase signal plan, a three-phase signal plan with a separate LRT phase, and a three-phase signal plan with an exclusive left-turn phase for main arterial vehicles. The signal controller modeled in this paper has green extension and red truncation capabilities. Model testing and validation proved that the model parameters consistently produced reasonable results. Control warrant guidelines were developed for two operational options.

Light rail transit (LRT) is catching the attention of numerous cities across North America today. New LRT operations were initiated in Edmonton and Calgary, Alberta, Canada, 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 are 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 design may occur for a heavily traveled arterial, in which case the signal timings should be carefully studied to maximize system passenger throughput. A common preferential control technique for LRT is to use traffic signal preemption in favor of the LRT; however, this technique may adversely affect overall system performance. The major objectives of this study are to investigate preferential control of LRT by using different signal preemption strategies and to attempt to develop control warrants for these strategies.

## BACKGROUND INFORMATION

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 at which 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 and a constant main-street traffic volume of 20,000 vehicles per day and a cross-street volume range of 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 a four-lane arterial indicated 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 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 it 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 of operating LRT within the same vehicular right-of-way on street traffic performance. Utilization factors were calculated for three alternative operational strategies:

1. Left turns from the arterial onto the cross street (across the LRT tracks) controlled with a special signal phase,
2. Left turns prohibited from the arterial onto the cross street, and
3. 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 the situation implied by the utilization factor results.

A parametric analysis was conducted in the same study, using a delay model developed by May and Pratt (4), 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 that they begin to greatly increase automobile delay. Second, it was found that preemption can be justified for a large number of LRT headways and combinations of cross-street volumes, whereas the utilization factor criterion resulted in many more design combinations falling into the so-called unacceptable category. Other studies (5,6) 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, 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 (7); the average delay per vehicle is determined from

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

where

- $d$ = average delay per vehicle on the particular intersection approach,
- $c$ = cycle time,
- $\lambda$ = 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. The probability of signal preemption was estimated for each LRT detection event. 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 delay for preemption and nonpreemption 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 are determined from Webster's optimum cycle formula (7);
2. Minimum red phase durations for main and cross streets are determined from Webster's minimum cycle formula;
3. Absolute minimum cycle length is 40 sec for two-phase and 50 sec for three-phase plans, and absolute maximum cycle length is 120 sec for two-phase plans and 150 sec for three-phase plans;
4. Minimum green phase duration is 12 sec for through maneuvers and 15 sec for left-turn maneuvers;
5. Left-turn adjustment factor is 1.75 for private automobiles; and
6. LRT arrivals follow a discrete uniform distribution or a Poisson distribution (the model was formulated in a manner to give the user the option of using either distribution).

Pedestrian movement can adversely affect the signal preemption process. 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 into account those impacts.

### 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 an exclusive phase is dedicated to LRT movements of 15 sec duration; 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 and 2, and the mathematical derivations, can be obtained from the authors.

## MODEL TESTING AND VALIDATION

The probability expressions and the delay equations were coded into a computer program to facilitate and speed up the calculation of delays. The program calculates internally the total delay of private automobiles and LRT under both preemption and nonpreemption strategies and provides the total delay saving (or losses) caused by the preemption. The major input parameters to the model are as follows:

1. Major arterial volume (private automobiles),
2. Cross-street volume (private automobiles),
3. LRT volume per hour,
4. Private automobile occupancy (passengers),
5. LRT occupancy (passengers),
6. Saturation flow rates for major and cross streets, and
7. Advance detection period (sec).

The output measures of effectiveness are as follows:

1. Main arterial nonpreemption delay (private automobile and LRT),
2. Cross-street nonpreemption delay (private automobile and LRT),
3. Main-street preemption delay (private automobile and LRT),
4. Cross-street preemption delay (private automobile and LRT), and
5. Total intersection saving (or losses).

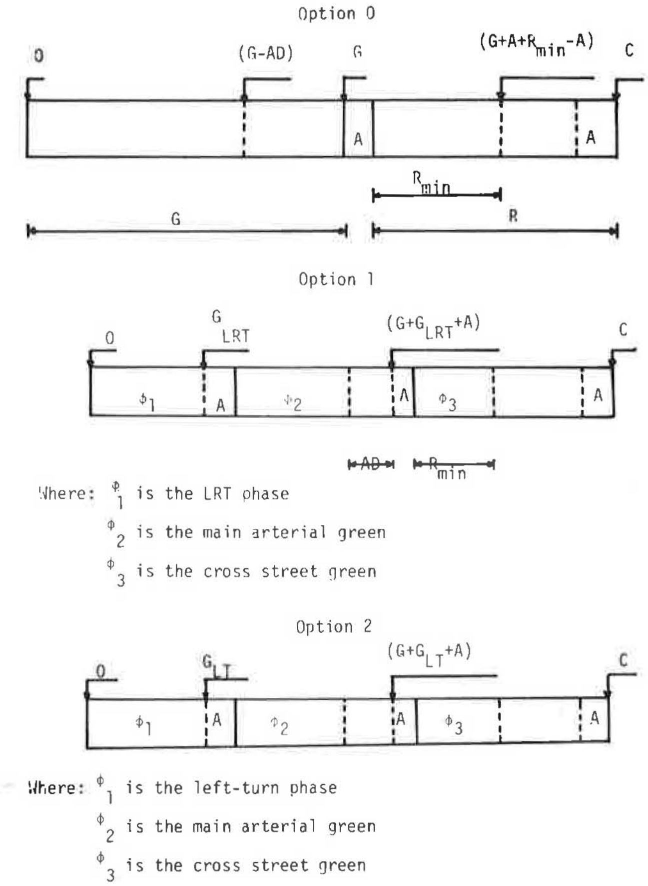


**FIGURE 1** Signal timing components for the three options.

A series of runs was conducted to evaluate the model consistency and validity. First, for Option 0, the model was tested for four variations:

1. Variations in main-arterial private automobile volume,
2. Variations in cross-street private automobile volume,
3. Variations in LRT volume, and
4. Variations in advance detection duration.

The results of these runs are shown in Figures 2-5. Figure 2 shows parabolic-like shaped relationships between the main arterial volume and the total intersection gain. One plot corresponds to the uniform distribution of LRT arrivals and the second corresponds to the Poisson distribution. As the plots show, little difference between the two distributions is observed; therefore, it was decided to use the Poisson distribution for the remaining plots only for demonstration purposes. An opposite parabolic shape was observed between cross-street volume and the total intersection gain as shown in Figure 3. The impact of LRT volume on the total intersection gain was observed to be directly linear as depicted by Figure 4, and little variation was noticed between the eight levels of advance detection period as shown in Figure 5.

A second testing was conducted for Option 1 in which a three-phase signal plan was valuated with a dedicated phase for LRT traffic. Different levels of main arterial volume were tested, and the results are shown in Figure 6. It was concluded that the addition of an exclusive LRT phase adversely affects the total intersection gain. As for Option 2, a fixed left-turn volume was assumed at 100 cars per hour, and different levels of main arterial volume were evaluated. Figure 7 shows the results of Option 2 testing, in which a sharp decline in the total intersection gain with the increase in main arterial volume is observed.

## PREFERENTIAL CONTROL WARRANTS

The model was applied to a wide range of traffic volumes on main arterials, cross streets, and LRT for Option 0, and a regression analysis was attempted to correlate these variables with the total intersection gain. The following model was attained:

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

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 agree with 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 (see Figure 8).

As 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

**TABLE 1** Probability Expressions for Option 0

| No. | Event | Discrete Uniform Distribution | Poisson Distribution |
|---|---|---|---|
| 1 | No LRT arrival during a cycle | $M = (c)(LRT)/3{,}600$ If $M < 1$, $P_1 = 1 - M$; If $M \geqslant 1$, $P_1 = 0$, $M = 1$ | $P_1 = EXP(-LRT \bullet C/3{,}600)$ |
| 2 | LRT arrives in a cycle and no preemption occurs | $P_2 = (G + A - AD)(M)/C$ | $P_2 = EXP[-(LRT)(C - A - G + AD/3{,}600)] - EXP[-(LRT \cdot C/3{,}600)]$ |
| 3 | LRT arrives during a cycle and there is red truncation | $P_3 = (Rmin)(M)/c$ | $P_3 = EXP(-LRT \cdot AD/3{,}600) - EXP[-(LRT)(AD + Rmin)/3{,}600]$ |
| 4 | LRT arrives during a cycle such that red truncation occurs after Rmin | $P_4 = (C - A - G - Rmin)(M)/C$ | $P_4 = EXP[(-LRT)(Rmin + AD)/3{,}600] - EXP[-(LRT)(C - A - G + AD)/3{,}600]$ |
| 5 | LRT arrives during a cycle such that a green extension occurs | $P_5 = (AD)(M)/C$ | $P_5 = 1 - EXP(LRT \quad AD/3{,}600)$ |

Note: LRT = light rail transit flow, C = cycle length, G = main arterial green period, A = amber phase duration, AD = advance detection period, and Rmin = red phase due to red truncation.

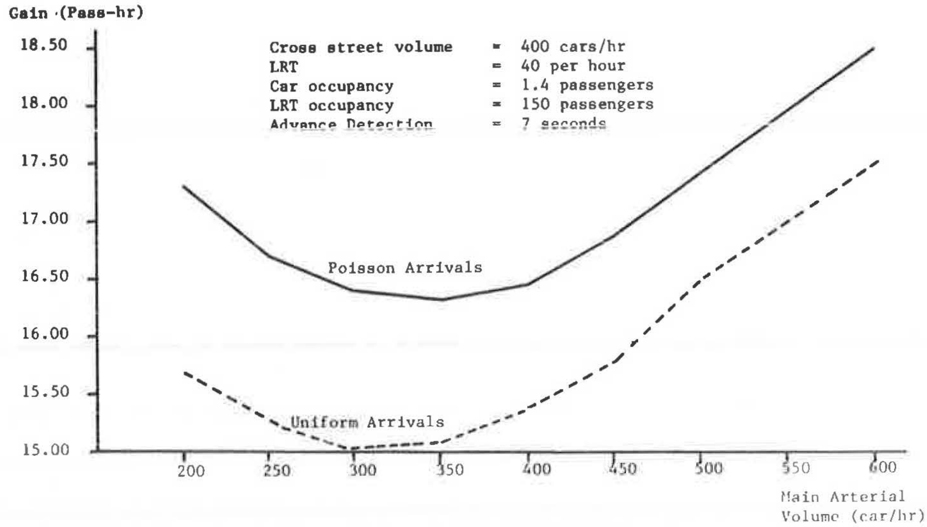


**FIGURE 2** Passenger delay gains due to variations in main arterial volume.

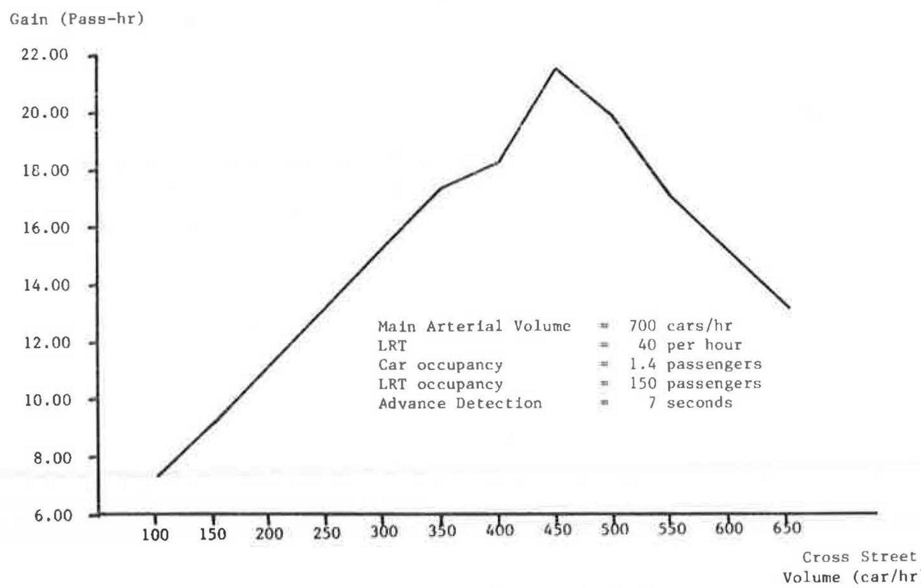


**FIGURE 3** Passenger delay gains due to variations in cross-street volume.

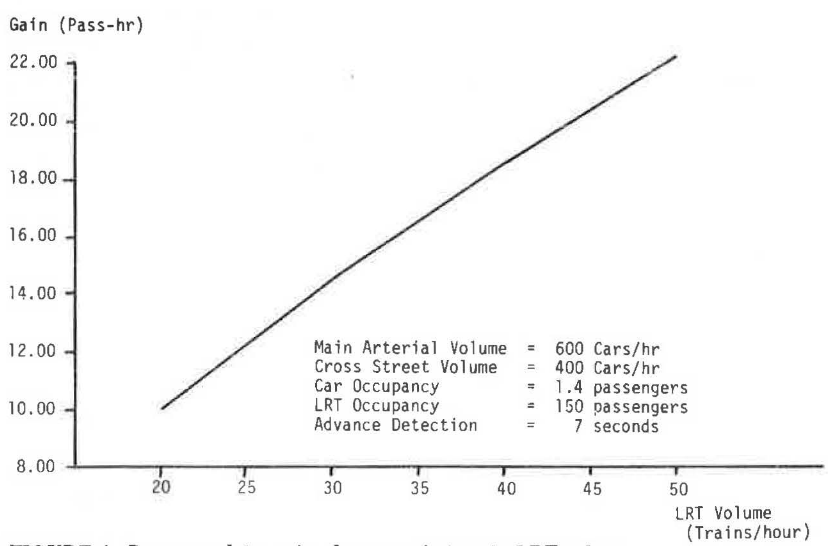


**FIGURE 4** Passenger delay gains due to variations in LRT volume.

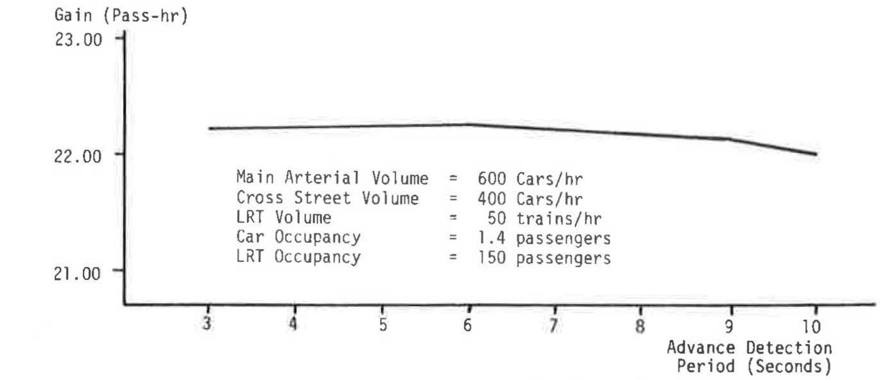


**FIGURE 5 Passenger delay gains due to variations in advance detection durations.**

regions. For Option 2, the process was repeated, and a regression model was calculated:

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

$(R = 0.904)$

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 the LRT volume increases the total LRT passenger delay increases during the exclusive left-turn phase, and consequently the overall intersection gain decreases. On the other hand, as the percentage of left turns increases, more left-turn traffic uses the third phase and the 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 of LRT movements in existing arterial medians. Three operational options were identified,

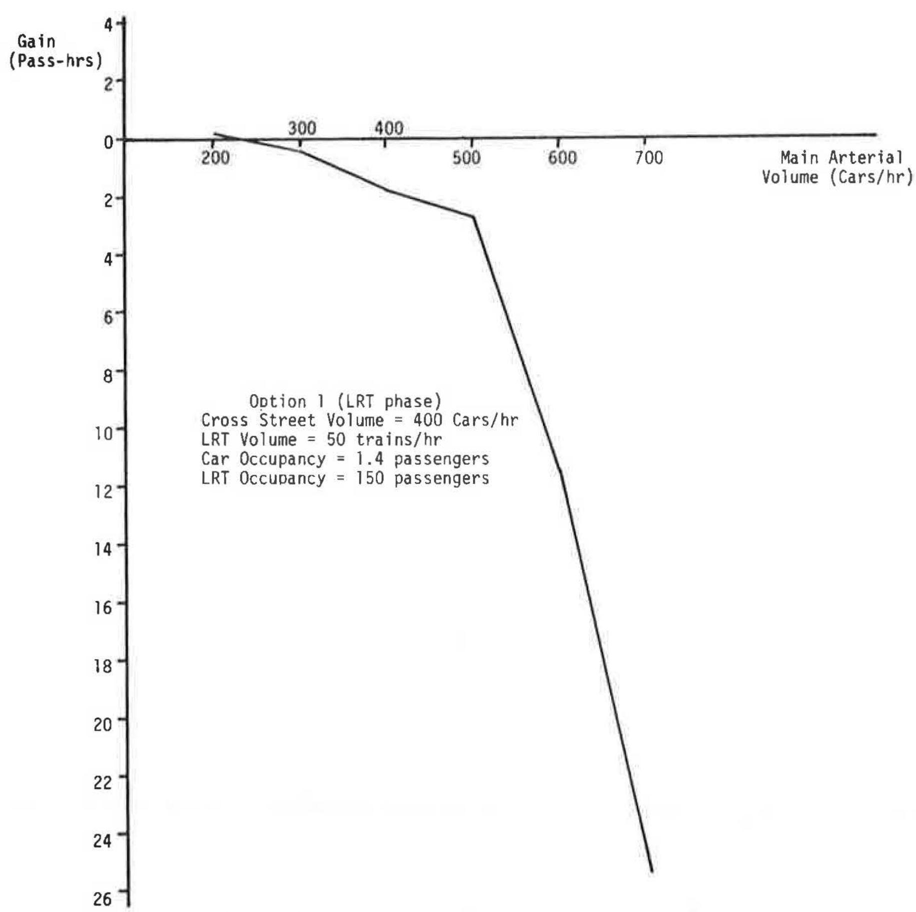


**FIGURE 6 Passenger delay gains due to variations in main arterial volume for Option 1.**

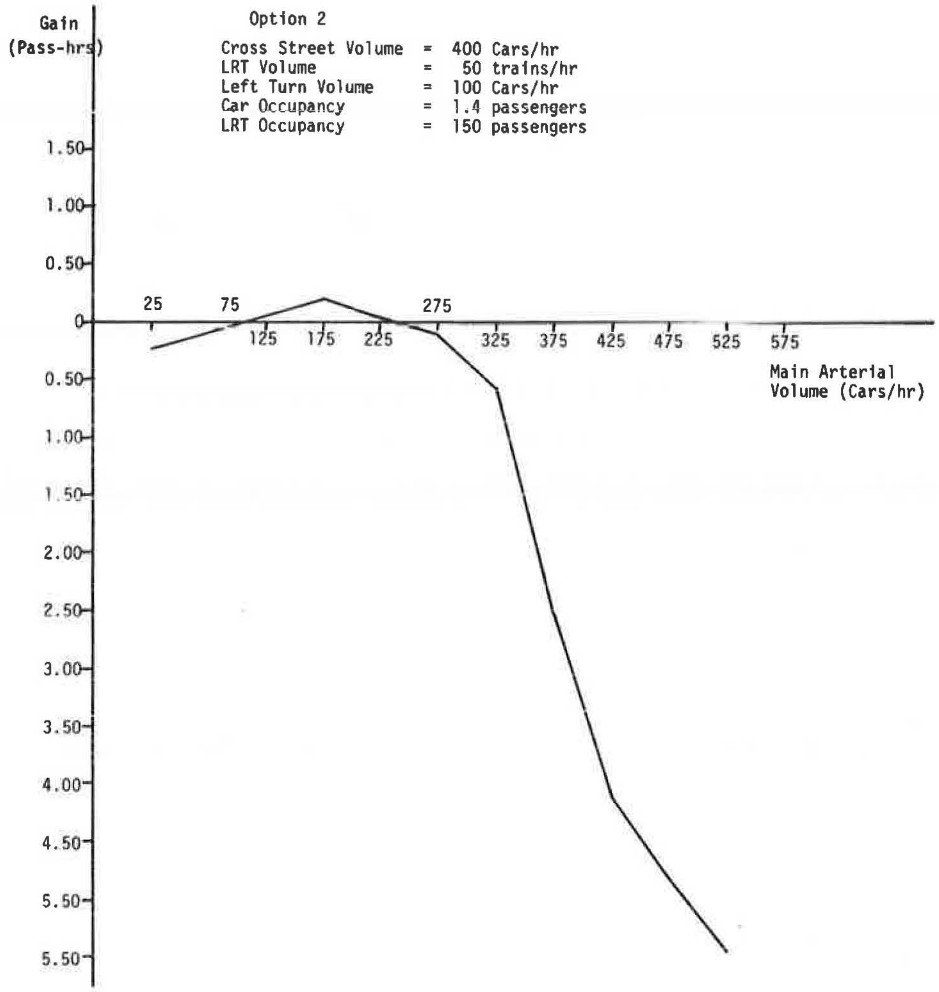


**FIGURE 7** Passenger delay gains due to variations in main arterial volume for Option 2.

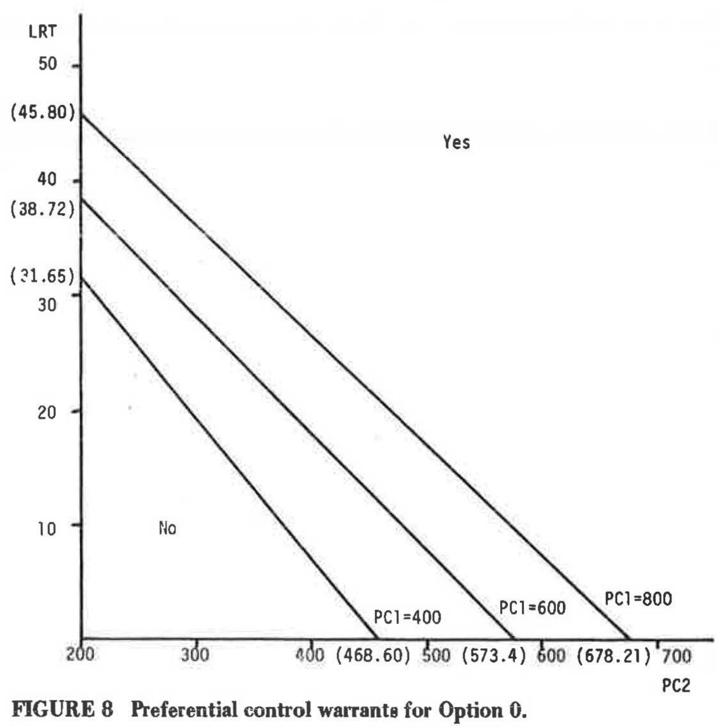


**FIGURE 8** Preferential control warrants for Option 0.

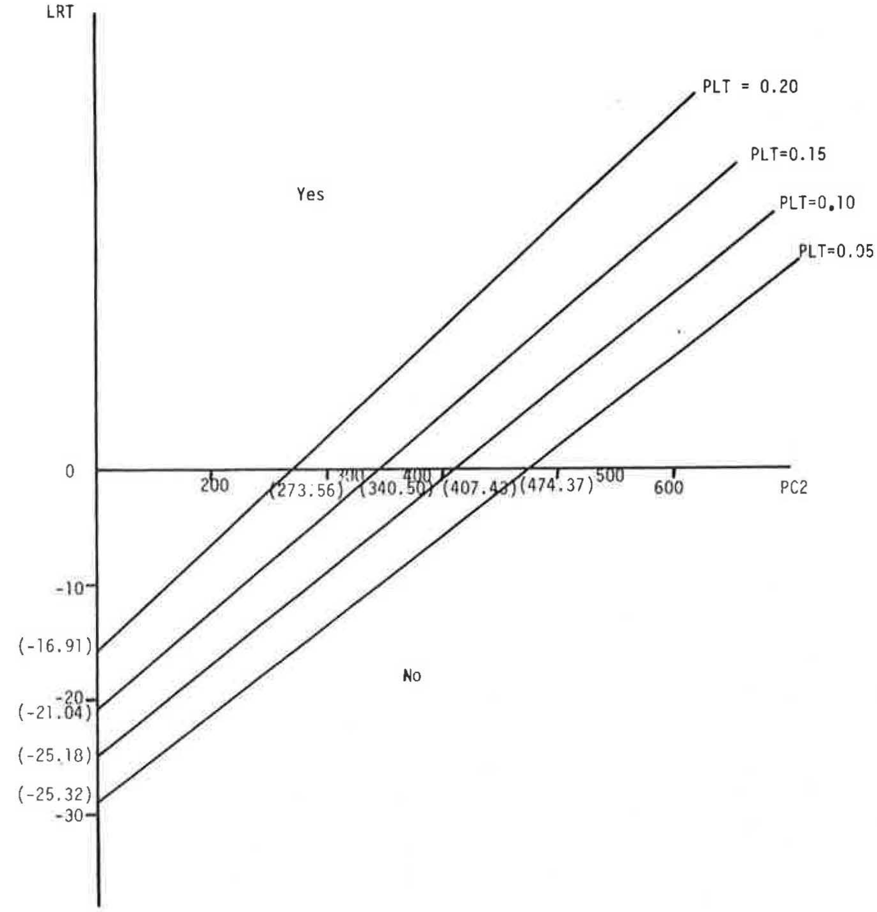


**FIGURE 9** Preferential control warrants for Option 2.

and the probability expressions for a selected option were documented. Webster's delay model was adopted to estimate the average delay per vehicle per approach.

The model was tested by using a set of hypothetical demand parameters to validate the model. The results of the model testing proved that the model parameters consistently produce reasonable results, and that the model is sensitive to variations in the 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 proportioned to LRT volume, and that there was no impact of advance detection duration on the intersection gain. It was also found that 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. As 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 in a chart format.

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