Delay at Light Rail Transit Grade Crossings

BRUCE RYMER, THOMAS URBANIK II, AND
JAMES C. CLINE, JR.

The concept of light rail vehicles (LRVs) operating at grade and alternately sharing the right-of-way perpendicular to the flow of automobile traffic is an attractive transit idea because of the potential cost savings to transit agencies. This paper is a partial review of an evaluation of the potential delay impacts on automobile traffic imposed by LRVs operating at grade. This report can assist decision-makers in determining where grade separations are appropriate. Also presented is a methodology for summarizing the operational characteristics of a light rail transit grade crossing with a single parameter, the crossing-volume-to-capacity ratio. The analysis centered on computer simulations using FHWA's NETSIM model. Results indicated that for light rail transit crossings located in excess of 400 ft from any adjacent intersection, the delay imposed on the motoring public warranted a grade separation only at very high traffic volumes or very short LRV headways.

INCREASED CONCERN OVER GROWING urban automobile congestion has regenerated interest in light rail transit (LRT) as a viable mass commuting alternative. LRT's attractiveness lies in its potentially lower implementation costs versus the much higher costs of a heavy rail system. Because of power supply hazards and operational objectives, heavy rail systems are usually totally grade separated from surrounding automobile traffic, making the initial capital costs very high.

B. Rymer and T. Urbanik, Texas Transportation Institute, Texas A&M University, College Station, Tex. 77843. J. C. Cline, Jr., Kimley-Horn and Associates, Inc., 9330 LBJ Freeway, Suite 790, Dallas, Tex. 75243.

By comparison, the lower costs of an LRT system result from the less stringent design requirements. One of the key factors is the lack of an absolute requirement for the complete grade separation of an LRT line. LRT can be run in the traveled way, in roadway medians, or on semiexclusive rights-of-way. Although these arrangements use at-grade crossings, the possible impact of the light rail vehicle (LRV) on crossing automobile traffic has not been adequately evaluated.

One measure of this impact is the additional delay experienced by the vehicular traffic because of LRVs crossing the roadway. Delay can be used for a relative comparison of the impact with other crossings, or it can also be used in economic analyses by assigning a value to this delay time. The objective of this report is to study the vehicle delay impact to traffic of at-grade crossings on an LRT line operating on semiexclusive right-of-way. The calculation of this vehicle delay will be quantified for ease of application. Vehicle delay can then be used as one of the criteria for considering grade separation of these at-grade crossings.

LITERATURE REVIEW

Although much attention has been paid to the topic of LRT, limited research has been done on assessing the impact on traffic of at-grade crossings. The following paragraphs focus on the previous work that has been done in analyzing this impact and the appropriateness of using person delay as a method of evaluation.

The most recent work on this topic (*1*) established the criteria for the grade separation of LRT and busway crossings from the closure time and the resulting loss of capacity. The resulting warrants are a function of the average daily traffic crossing the tracks and the volume of transit units on the system per hour. Another report (2) noted the need to avoid severe disruption to the traffic flow as a result of a grade crossing. While capacity and level of service are important parameters in traffic analysis, they do not fully describe the magnitude of the impact on the roadway system. A more quantitative method should be used that can evaluate different operational and geometric conditions with respect to their total impact on the traffic flow.

Two reports (*3*, *4*) suggest the use of delay in analyzing grade crossings. The use of person delay provides a quantitative measure of the impact on the traffic stream. This methodology also provides a way to evaluate the user benefits and costs of LRT grade crossings. Different geometric and operating scenarios can also be compared on the same basis.

There are different alternatives for the control of traffic at the crossing. These can range from conventional traffic signals to railroad crossing gates.

The conventional traffic signals are more efficient in terms of delay to motorists, but the crossing gates provide a higher degree of safety (*3*).

The impact of an LRT grade crossing should be evaluated not only for the crossing itself, but also for the surrounding network. Any effect on nearby intersections and roadways should be included in the total assessment of impact. These effects may be limited, but they cannot be neglected in analyses of the problem (*3, 5*).

Recent work (*6*) has also shown that the crossing clearance time can be varied to reflect a broad spectrum of operating conditions. This crossing clearance time is defined as the time it takes for the LRV to negotiate the crossing and for the crossing gates to operate. The length of the train, the speed of the train, and the location of the station can all be reflected in the calculation of the total clearance time.

Several priority schemes can be implemented into the control plan for an at-grade crossing (*7*). These schemes can range from an unconditional priority at all times for the LRVs to a situation in which the LRVs must wait for an acceptable gap in the traffic stream. The worst case for the automobile traffic exists when the unconditional scheme is implemented.

It has been concluded from the literature and current practice that person delay as a measure of effectiveness will provide a method of associating a quantifiable user cost with the operation of an LRT system with at-grade crossings. These costs can then be used as part of the criteria for the grade separation of a crossing. It is clear from this review of the current literature that there has been limited study of this problem using person delay. The current trend toward LRT technology utilizing at-grade crossings further indicates the need to expand the depth of knowledge in this field.

STUDY PROCEDURE

The development of the procedure for this study was guided by several requirements. The chosen methodology must allow the evaluation of a large range of conditions in a roadway network. A fairly large data base was also required to provide a sound statistical analysis of the results. The absence of adequate study locations because of the inability to control the variables at the crossings indicated a need for a comprehensive network model. For these reasons, the NETSIM program, developed for FHWA, was chosen for this analysis.

A key assumption made in the design of this procedure should be noted at this point. In all scenarios, the worst-case condition will be analyzed. The investigation of a complete spectrum of operational improvements is beyond the scope of this study. Examining this worst case will fix the upper boundary. A crossing that does not warrant grade separation under these conditions can be discarded as a possible candidate for grade separation. Crossings that do have substantial delay under these conditions should be studied further to see if possible operational improvements could lower the user costs of the grade crossings to a point where a grade separation is no longer needed.

LRT Grade Crossing Simulation

The NETSIM model was chosen for this analysis for several reasons. It is a microscopic, stochastic simulation model. It was developed as an evaluation tool for use on urban street networks. Many different operational strategies can be implemented, but there is no optimization algorithm for the timing of the signals. Intersection control can range from a yield sign to a fully actuated controller. The model also provides an algorithm for the operation of buses in the network. Queue discharge rate and free flow speed are also specified for each link (*8*).

One other key input to the program is a random number seed. The stochastic nature of the program requires this number to be changed for each simulation run. Many of the characteristics of traffic flow are determined as a function of these random numbers. To preserve the validity of the results, each run was made with a different random number obtained from tabulated listings (*9*). The randomness built into this model also requires that each set of conditions be evaluated several times. In this study, each separate case was run three times. This number of simulations is within the practical limits of the computer facilities and is in accordance with previous work.

The output from a NETSIM simulation run includes a list of all input parameters and a tabulation of all operational statistics. These results include delay, number of trips, percent stop delay, travel time, vehicle miles of travel, and the number of cycle failures. This information is broken down on a link-by-link basis. The level of detail and flexibility in both the input and output allowed the model to be adapted to the study of this problem.

While NETSIM is not specifically designed for the simulation of LRT grade crossings, the networks can be coded to represent them. The LRT tracks are modeled as single-lane roadways. The grade crossing is represented as a fully actuated intersection of these "tracks" and the crossing roadway. The crossing roadway is given a short minimum green and is set on recall. The minimum green plus amber for the tracks is set as the crossing clearance time. This will account for the crossing gate operation time and the time for the train to negotiate the crossing. The LRV arrivals at the crossing are represented by buses operating on the "track." This bus algorithm allows the buses to be discharged at a specified headway. The difference in the operation of the bus and LRVs is accounted for in the crossing clearance time.

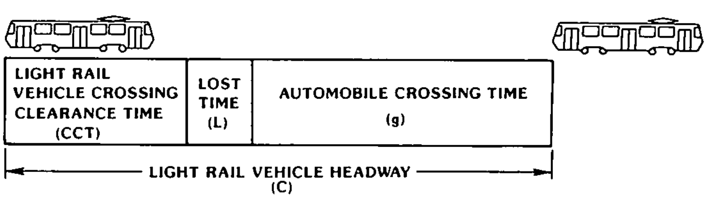
This model allows the roadway volume, roadway cross-section, LRV headway, and clearance time to be varied in the same network.

It should be noted that this model provides unconditional priority for the LRVs. This scenario is the worst case for automobile traffic. No allowance is made for nearby signals and possible progression. When this model of the interaction between the LRVs and the automobile traffic is used, the LRVs (buses) will be discharged onto the network from one direction only. The headway assigned to the model will refer to the mean time between roadway closures. The effect of two-way operation can be estimated by calculating the mean time between road closures. This model does not take into account the effect of a simultaneous arrival of two LRVs at a crossing during two-way operation. It is felt that the impact to traffic would be greater for two separate closures than for two overlapping arrivals. Further study involving different priority strategies will be needed to account for this.

Development of Crossing-Volume-to-Capacity Ratio

At an at-grade crossing, the LRT tracks and the automobile right-of-way occupy the same space. At some time, both modes of transportation will be vying for the same space simultaneously. The problem at an at-grade LRV crossing consists of the allotment of time between the LRVs and the automobiles.

Referring to Figure 1, headway is the time gap between the front of one LRV and the front of the following LRV. The crossing clearance time (*CCT*)



$$g = \frac{C - (CCT + L)}{C}$$

Light Rail Vehicle Headway = Cycle Length = C
Light Rail Vehicle Crossing Clearance Time = CCT
Lost Time = L
Automobile Crossing Time = g
All Units in Seconds

FIGURE 1 Light rail vehicle headway relationship.

has three components: the time involved in the lowering of the guard gates (or some other safety device or warning signal), the time the LRV actually occupies the roadway, and the time consumed in raising the guard gates. For purposes of this study, the crossing clearance time ranged from 30 to 50 sec. A longer LRV is accommodated by a greater crossing clearance time. Lost time is the fragment of time spent in starting the waiting automobiles once the guard gate is raised and the LRV has cleared the right-of-way. Lost time was assumed to be 4 sec.

Automobile crossing time (g) is just a ratio that represents the portion of time available for the motorists to cross the tracks. Obviously, this number will vary between 0 and 1. A larger ratio reflects more crossing time for the automobiles. Note that as the LRV headway (C) increases and approaches infinity, the automobile crossing time (g) approaches 1. This situation is very similar to a traffic signal; the fraction of time available for automobiles to cross the LRT tracks is analogous to the green time on a traffic signal head.

$$g = \frac{C - (CCT + L)}{C}$$

where

C = LRV headway = cycle length,
CCT = LRV crossing clearance time,
L = lost time, and
g = automobile crossing time.

(All units are in seconds.)

The automobile green time is then used in the calculation of the crossing-volume-to-capacity ratio (Xcr). But first another parameter must be introduced. Within the Xcr ratio is a second ratio, the demand/saturation ratio (v/s). This demand/saturation ratio is essentially a percentage that reflects the demand-to-supply relationship of the roadway that serves the automobiles.

$$v/s = \frac{\text{(Actual Number of Automobiles per Lane per Hour)}}{\text{(Saturation Level of Automobiles per Lane per Hour)}}$$

So, Xcr consists of two ratios—one ratio that indicates the portion of time that is available to the automobiles to traverse the tracks (g), and the other ratio that shows the operational capacity of the roadway segment (v/s).

Crossing-Volume-to-Capacity Ratio = $Xcr = (1/g)(v/s)$

Xcr is inversely proportional to the time available for the automobile crossing time (g) and directly proportional to the demand/saturation ratio. The automobile crossing time (g) decreases as lost time and LRV crossing clearance time increase, which in turn penalizes the operational capacity of the roadway segment.

Isolated Crossing

An isolated crossing is defined to be unaffected by any adjacent intersections or conflicting flows. Only vehicles crossing the LRT tracks will be affected by the crossing LRVs. The objective in this case is to determine the relationship, if any, between the delay per vehicle and the crossing-volume-to-capacity ratio. Figure 2 illustrates the network to be used in this study. Four key variables were analyzed for their effect or combined effect: roadway cross-section, roadway crossing volume, LRV headway, and total clearance time. Cross-section was varied from two to six lanes. Volume ranged from 250 vehicles to 1,000 vehicles per hour per lane. LRV headway varied from 2.5 to 12.5 min. Crossing clearance times of 30, 40, and 50 sec were evaluated.

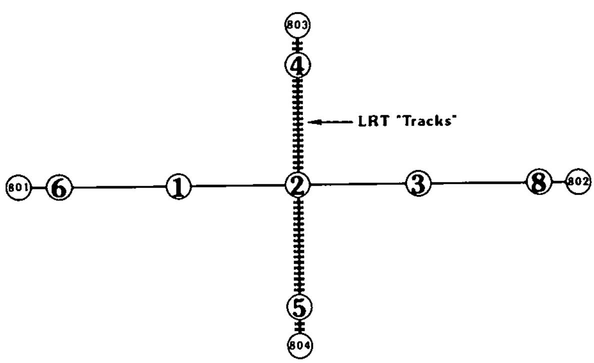


FIGURE 2 Isolated crossing—link/node diagram.

STUDY RESULTS

The purpose of the isolated crossing analysis was to find a mathematical model that would represent the relationship between the crossing-volume-to-capacity ratio (Xcr) and average automobile delay. Delay calculation methodology used by Webster (*10*) and the Highway Capacity Manual (*11*) indicates that volume/capacity ratio is a key parameter for computing delay per vehicle. Each variable—roadway volume, roadway cross-section, LRV headway, and clearance time—was varied through a complete range of values. A total of 384 simulation runs were completed for this case. The Statistical Analysis System (SAS) was used to analyze the resulting data (*12*).

The NETSIM model does not contain any options that simulate LRV operation. It was necessary to select inputs to NETSIM such that the bus traffic simulation option approximated LRV operation. The bus delay statistics were subtracted from the overall system delay statistics. The average delay per vehicle was then calculated from these adjusted values for each simulation run. The resulting data points were then plotted for comparison and analysis.

The effect of LRV headway on delay per vehicle is illustrated in Figure 3. Crossing clearance time and the roadway cross-section are held constant as the traffic volume is varied for different headways. The resulting curves show that decreasing the LRV headway increases the delay per vehicle on the crossing roadway. It also shows the nonlinear relationship between delay per vehicle and traffic volume.

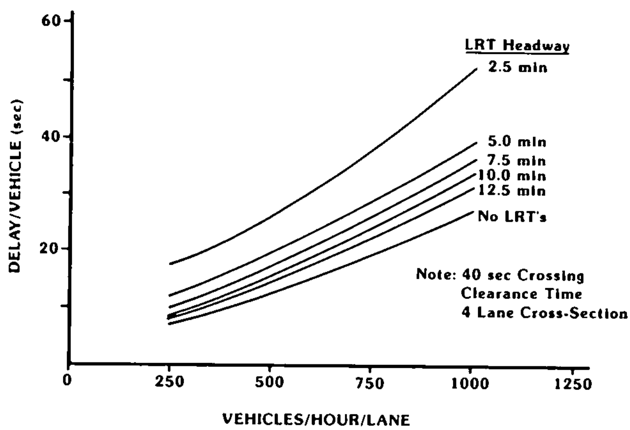


FIGURE 3 Effect of LRT headway on delay.

The effect of crossing clearance time is shown in Figure 4. The roadway cross-section and LRV headway are held constant as the traffic volume is varied for different crossing clearance times. An increase in crossing clearance time results in an increase in delay per vehicle.

The effect of roadway cross-section on delay per vehicle is illustrated by Figure 5. LRV headway and crossing clearance time were held constant while

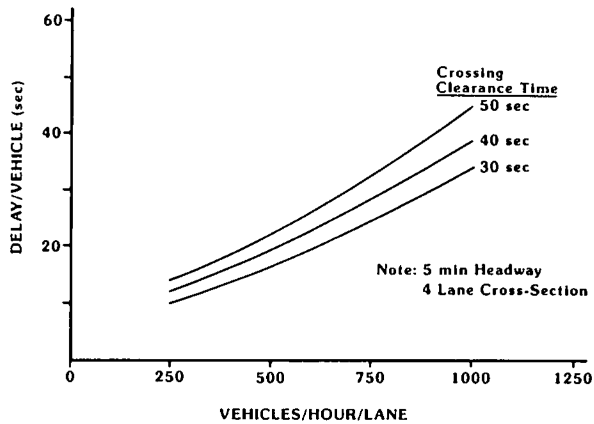


FIGURE 4 Effect of crossing clearance time on delay.

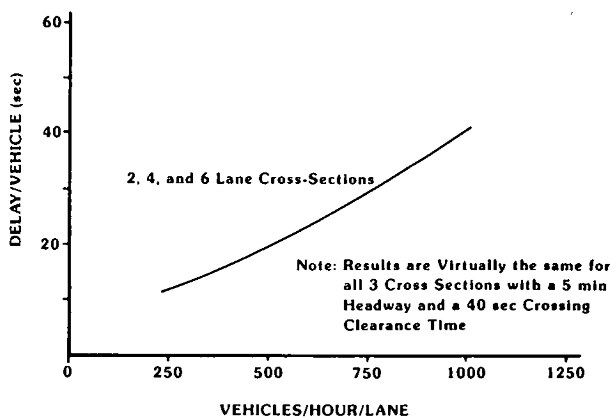


FIGURE 5 Effect of roadway cross-section on delay.

traffic volume and cross-section were varied. Traffic was uniformly distributed over the number of lanes and the delay remained constant. Larger cross-sections will accommodate more traffic, but if the demand/saturation ratio per lane is constant, the average delay per vehicle will remain constant.

The relationship between delay per vehicle and the crossing-volume-to-capacity ratio is shown in Figure 6, which shows a definite relationship between these two variables. This function appears to be nonlinear. Regression analysis was performed on the data sets to determine the best relationship between these two values for this data set.

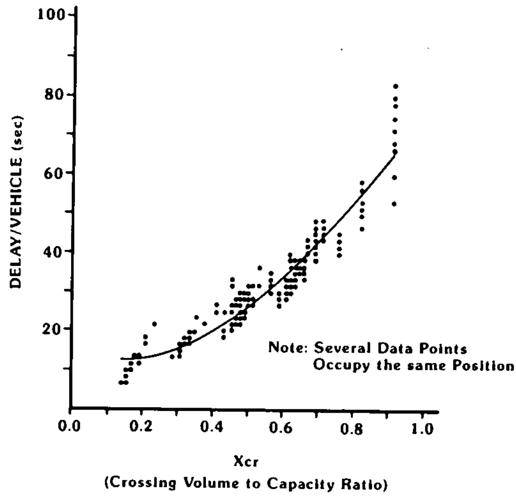


FIGURE 6 Scatter plot with prediction curve.

The following equation was found:

Delay/vehicle (sec/veh) = 9.56 + 67.26 (crossing volume/capacity)^2

The R-squared for this model is 0.92.

It should be noted that the equation includes an intercept term. There is no reason to expect a nonzero intercept term, as a single vehicle proceeding through the system should incur no delay. However, the model suggests that when the crossing-volume-to-capacity ratio is very low, an inherent delay of 9.56 sec per vehicle is unavoidable. If there are no LRV crossings, zero delay should be experienced by the motoring public. In actual application, the effect of the intercept term creates unrealistic delays at low volumes. Therefore, it was felt that the equation developed for the isolated crossing should be modified. The original data from the NETSIM runs were retained and the resulting relationship was determined:

Delay (sec/veh) = $91.16\, Xcr^2$

The modified equation is more appropriate because there is no intercept term. From a planning viewpoint, the modified equation and the original equation yield similar results.

Refer to Figure 7 for a comparison of the original delay equation and the modified delay equation. The modified equation produces conservative delay estimates for *Xcr* below 0.6. For values of *Xcr* greater than 0.6, the modified equation yields a somewhat higher delay than the original equation. It should be noted that the delay equations follow an x^2 relationship that is consistent with the delay function used in the Highway Capacity Manual.

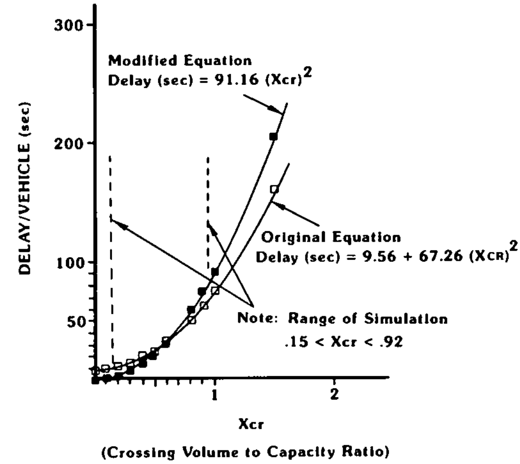


FIGURE 7 Original delay equation versus modified delay equation.

This equation represents an estimate of the systemwide delay that includes both the inherent automobile base delay and the incremental delay induced by the LRVs. To obtain the incremental delay of the LRVs, the base delay is subtracted from the total delay. Once the incremental delay is determined, a benefit/cost evaluation can be made. Summarized in equation form:

$$\text{Automobile delay due to LRT (sec/veh)} = 91.16\, Xcr^2 \text{ (with LRVs)} - 91.16\, Xcr^2 \text{ (without LRVs)}$$

ECONOMIC ANALYSIS FOR GRADE SEPARATION

The objective of this analysis is to translate the results of this study into economic terms. In other words, will the savings in delay time to the motoring public offset the construction costs of a grade separation? This analysis is intended to be used as a planning tool for evaluating isolated crossings.

The study developed a relationship that quantified the delay time experienced by the motorist because his right-of-way is obstructed by LRVs. The economic analysis places a monetary value on this delay time and then projects, over the course of 20 years, whether or not the expense to the motoring public because of the delay would justify building a grade separation for the LRVs.

A grade separation costs somewhere between \$3 million and \$5 million (or more), depending on site-specific conditions. If the public's delay time (the time spent waiting for the LRVs to cross) is equal to or exceeds the construction cost of a grade separation, then the grade separation is warranted.

The economic evaluation assumed a Texas urban traffic distribution developed by Urbanik (*13*). Once the average daily traffic count at a point is determined, the urban distribution is used to assign an estimated amount of traffic to each hour of the day. By assuming an hourly volume and varying the crossing times for the LRVs, an economic assessment of the delay can be evaluated. For purposes of this study, occupancy of each automobile was set at 1.25 persons. A value of \$7.80 per vehicle-person-hour was allotted for the delay time. This \$7.80 reflects the value of time to the motor vehicle occupants and associated vehicle operation costs (*14*).

The 24-hour day was divided into two demand periods, peak and off-peak. During the off-peak periods the LRV crossings were held at a constant crossing frequency of once every 15 min (900 sec). In the peak periods, when the traffic demand is heaviest, the LRV crossings were varied in frequency and duration. The delay was accrued only between the hours of 6 a.m. and 9 p.m. with 6 a.m. to 9 a.m. and 4 p.m. to 7 p.m. representing the peak traffic demand periods. Given that the LRVs were operating on some timetable, the delay they prompted at an isolated crossing was then calculated. Yearly delay was based on 250 working days. A net present worth approach with a 5 percent interest rate and a 20-year project life was used to assess the current economic value of the delay. No traffic growth for the average daily traffic was assumed during the 20-year project life.

Tables 1 through 3 were generated with the isolated delay relationship. The crossing-volume-to-capacity ratio (*Xcr*) varied from a low of 0.05 to a high of 1.24. The NETSIM simulations applied only to *Xcr* ratios below 0.92. The region above 0.92 is extrapolated (refer to Figure 7). The tables indicate that at low average daily traffic volumes and low LRV crossing frequencies, the delay imposed on the motoring public does not offset the cost of building a grade separation. However, at high average daily traffic volumes and frequent LRV crossings, the grade separation may be warranted.

TABLE 1 ISOLATED CROSSING NET PRESENT WORTH EVALUATION: TOTAL DELAY COSTS TO AUTOMOBILE USERS (30 sec)

LRV Crossings per Peak Hour	Cost to Users ($) by Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48[a]	10,200	81,400	272,600	651,000	1,271,400	2,197,000
24	3,100	24,600	82,900	196,600	384,000	663,600
12	1,400	11,100	37,100	88,000	171,900	297,000
8	950	7,500	25,400	60,400	117,900	203,800
6	750	6,000	20,200	47,800	93,300	161,300
4	550	4,500	15,200	35,900	70,200	121,300

NOTE: LRV crossing clearance time = 30 sec.
[a]LRV crossings per hour is beyond the range of simulation. Actual delay costs may be more than indicated.

TABLE 2 ISOLATED CROSSING NET PRESENT WORTH EVALUATION: TOTAL DELAY COSTS TO AUTOMOBILE USERS (40 sec)

LRV Crossings per Peak Hour	Cost to Users ($) by Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48[a]	20,900	167,400	563,900	1,335,900	2,609,000	4,509,000
24	4,500	36,300	122,700	290,800	567,900	981,400
12	1,900	15,100	50,600	120,000	234,400	405,100
8	1,300	10,100	34,000	80,700	157,700	272,400
6	1,000	7,900	26,700	63,400	123,800	213,900
4	750	5,900	20,000	47,300	92,400	159,700

NOTE: LRV crossing clearance time = 40 sec.
[a]LRV crossings per hour is beyond the range of simulation. Actual delay costs may be more than indicated.

TABLE 3 ISOLATED CROSSING NET PRESENT WORTH EVALUATION: TOTAL DELAY COSTS TO AUTOMOBILE USERS (50 sec)

LRV Crossings per Peak Hour	Cost to Users ($) by Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48[a]	50,200	401,700	1,355,800	3,213,700	6,276,800[b]	10,846,300[b]
24	6,500	51,800	174,900	414,600	809,700	1,399,200
12	2,400	19,500	65,600	155,600	303,900	525,200
8	1,600	12,800	43,200	102,400	200,100	525,200
6	1,200	10,000	33,600	79,700	155,700	269,000
4	900	7,400	24,900	59,100	115,500	199,600

NOTE: LRV crossing clearance time = 50 sec.
[a]LRV crossings per hour is beyond the range of simulation. Actual delay costs may be more than indicated.
[b]X_{cr} ratios greater than 0.92.

Tables 1 through 3 apply only to isolated LRV crossings, or crossings located in excess of 400 ft from any adjacent signal. For grade separations with project lives of 50 years, multiply the table figures by 1.5 to obtain the net present worth.

CONCLUSIONS

The operational characteristics of an isolated LRT grade crossing can be described by a single parameter. This parameter is the crossing-volume-to-capacity ratio. This one parameter is composed of the LRV headway, the crossing volume per lane, lane saturation, lost time, and the crossing clearance time. It should be noted that the crossing-volume-to-capacity ratio does not account for the degree of progression on the roadway system. Heavily platooned arrivals are not accurately analyzed on the basis of this value.

Although only general conclusions could be drawn, the location of an isolated LRT crossing operating with unconditional preemption does not affect the traffic greatly for the crossing conditions studied. The economic analysis suggests that most isolated crossings (more than 400 ft from a traffic signal) will not justify grade separations on the basis of delay imposed on the crossing automobile drivers and their passengers.

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