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16. Abstract

This report represents the results of computer simulation work using Federal Highway Administration's NETSIM model to evaluate the delays incurred by automobile traffic when light rail transit (LRT) vehicles cross arterial streets at-grade. The operation simulated indicates the upper-bounds of delay that would occur when light rail transit vehicles operating in street medians, and special signal phasing are not considered.

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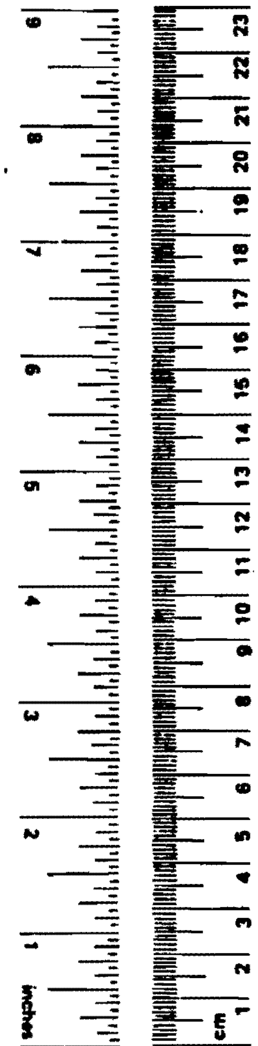
METRIC CONVERSION FACTORS

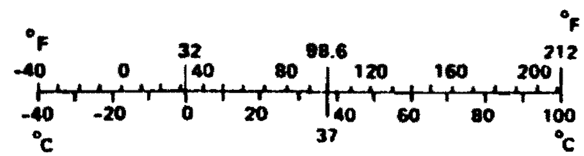
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

DELAY AT LIGHT RAIL TRANSIT GRADE CROSSINGS

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Research Report 339-10

Improving Urban Mobility Through Application of High Occupancy
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Federal Highway Administration

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

March 1986

ABSTRACT

This report represents the results of computer simulation work using Federal Highway Administration's NETSIM model to evaluate the delays incurred by automobile traffic when light rail transit (LRT) vehicles cross arterial streets at-grade. The operation simulated indicates the upperbounds of delay that would occur when light rail transit vehicles operate independently of the traffic signal system. Signal pre-emption, light rail vehicles operating in street medians, and special signal phasing are not considered.

DISCLAIMER

IMPLEMENTATION STATEMENT

The study findings indicate the range of conditions under which additional delay will accrue to the motoring public due to the at-grade operation of light rail transit. The potential impacts vary widely depending on conditions. Given the increasing application of light rail transit, additional research is required to determine what mitigation techniques, if any, can reduce delay under those conditions indicated as having a large impact on delay.

analysis suggests that intersections can not be examined as single entities, but must be examined as a network.

Further research is clearly needed to determine if a simple planning relationship can be developed for intersections in close proximity to traffic signals. Furthermore, the ability to analyze intersections in which light rail vehicles operate on either compatible or exclusive phases merits additional research. Desirably, the NETSIM model should be modified to accommodate a variety of light rail vehicle operating strategies. However, the modification of NETSIM would be a major undertaking and other alternatives may warrant evaluation.

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INTRODUCTION

Background

Light rail transit (LRT) has received much attention as a viable mass transit alternative in recent years. Part of its attractiveness lies in the potentially lower implementation costs in comparison to a heavy rail system. These lower costs are a result of the lesser design requirements of the light rail transit systems. One of the key factors is the lack of an absolute requirement for the complete grade separation of a light rail transit line. Heavy rail lines are generally powered by a third rail located at ground level. Light rail transit lines are usually powered by overhead catenary wires. The possibility of a pedestrian coming in contact with this third rail precludes the use of any grade crossings for heavy rail systems. The use of an overhead power supply eliminates this problem, and opens many possibilities for implementing a light rail transit system. Lines can be run in the travelled way, in roadway medians, or on semi-exclusive right-of-way with grade crossings. While these arrangements provide the opportunity for the use of grade crossings, they do not address the possible impact to the crossing vehicular traffic.

One measure of this impact is the additional delay experienced by the vehicular traffic due to light rail transit vehicles 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 analysis by assigning a value to this delay time.

Objective

The objective of this report is to study the impact to traffic of at-grade crossings on a light rail transit line operating on semi-exclusive right-of-way in terms of vehicle-delay. The calculation of this vehicle delay will be quantified for ease of application. Vehicle delay can then be used as part of the criteria for considering grade separation of these at-grade crossings.

Literature Review

While much attention has been paid to the topic of light rail transit, limited research has been done on assessing the impact to traffic of at-grade crossings. The following discussion will 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 (1) on this topic established the criteria for the grade separation of light rail transit and busway crossings based on 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 to the roadway system. A more quantitative method should be used that can evaluate different operational and geometric conditions with respect to their total impact to 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 to the traffic stream. This methodology also provides a way to evaluate the user benefits/costs of light rail transit 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, but the crossing gates provide a higher degree of safety (3).

The impact of a light rail transit grade crossing should be evaluated at not only the crossing itself, but also on 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 analysis 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 for the light rail transit vehicle 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 a light rail transit at-grade crossing (7). These schemes can range from an unconditional priority at all times for the light rail transit vehicles to a situation where the light rail transit vehicles 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 a light rail transit system with at-grade crossings. These costs can then be used as part of the criteria for the grade separation of a light rail transit 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 light rail transit technology utilizing at-grade crossings further indicates the need to expand the depth of knowledge in this field.

STUDY PROCEDURE

Light Rail Transit Grade Crossing Simulation

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 and the ability to evaluate the roadway network near the grade crossings indicated a need for a comprehensive network model. There is also an inability to control the variables at an actual crossing. For these reasons, the "NETSIM" program, developed for the Federal Highway Administration (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.

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. In order to preserve the validity of the results, each run was made with a different random number. These random numbers were 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 listing 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 allow the model to be adapted to the study of this problem.

While NETSIM is not specifically tailored for the simulation of light rail transit grade crossings, the networks can be manipulated to represent them. The light rail transit tracks are modelled as single lane roadways. The grade crossing is represented as a fully actuated intersection of the "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 light rail transit 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 light rail transit vehicles is accounted for in the crossing clearance time. This model allows the roadway volume, roadway cross-section, light rail transit headway, and clearance time to be varied in the same network.

It should be noted that this model provides unconditional priority for the light rail transit vehicles. This scenario is the worst case for the automobile traffic. No allowance is made for nearby signals and possible progression. When using this model of the interaction between the light rail transit vehicles and the automobile traffic, the light rail vehicles (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 light rail transit vehicles 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.

Isolated Crossing

The first phase of the analysis investigated the isolated at-grade crossing. An isolated crossing is defined to be unaffected by any intersections or conflicting flows. Only vehicles crossing the light rail transit tracks will be affected by the crossing light rail transit vehicles. The objective in this case is to determine the relationship, if any, between the delay per vehicle and the crossing volume-to-capacity ratio. This phase will also seek to determine if there is a significant difference between results obtained on a per vehicle basis for varying cross-sections. This portion of the study will form the cornerstone for the rest of the study.

Figure 1 illustrates the network to be used in this portion of the study. Four key variables were analyzed for their effect or combined effect. These were roadway cross-section, roadway crossing volume, light rail transit headway, and total clearance time. Cross-section was varied from two to six lanes. Volume ranged from 250 vehicles to 1000 vehicles per hour per lane. Light rail transit headway varied from 2.5 to 12.5 minutes. Crossing clearance times of 30, 40 and 50 seconds were evaluated.

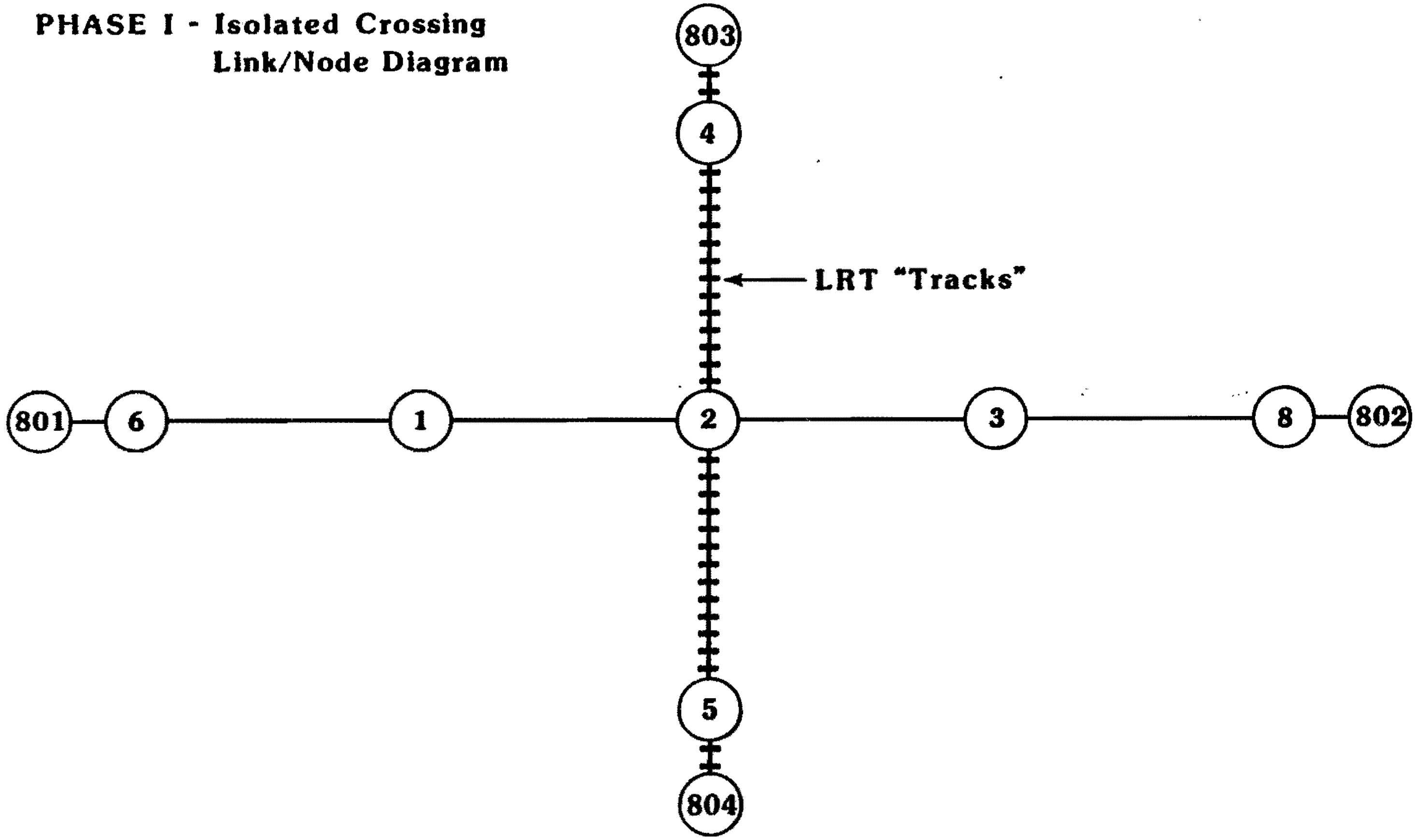

Figure 1. Isolated Crossing - Link/Node Diagram

Adjacent Intersection

The second phase of this report studied the effect of a light rail transit crossing on a nearby intersection. The objective of this portion of the study is twofold. The first objective is to determine the distance from an intersection at which a light rail transit crossing has no effect on the nearby intersection and is acting in isolation. This assumption of an isolated crossing greatly simplifies the analysis of a crossing. The second objective is to quantify the effect on an intersection of a light rail transit crossing that cannot be assumed to be isolated. Many possible locations for a light rail transit line exist in close proximity to existing roadways and intersections in Texas cities.

The network to be used in this analysis is shown in Figure 2. The distance between the intersection and the light rail transit crossing will be varied from 50 feet to the point where the assumption of an isolated crossing holds. This will be determined from the results of Phase 1.

Three sets of volumes were analyzed for the intersection of the two roadways. These scenarios were balanced flow crossing the tracks and parallel to the tracks, heavier flow crossing the tracks, and heavier flow parallel to the tracks. Unbalanced flow was split 60/40. Turning volumes were assumed to be ten percent left and ten percent right from all approaches. To maintain consistency in the volumes between cases, the traffic volumes were calculated so that there was a critical lane volume of 1400 vehicles per hour in all cases. This critical lane volume was chosen from the planning analysis methodology in the 1985 Highway Capacity Manual (10). Signal timings were optimized for delay using the SOAP84 computer program. The signal phasing in all cases was dual leading lefts (11).

The light rail transit headways to be used in each case will be varied to study a high and low crossing volume/capacity ratio for each set of volumes. The chosen range for the crossing volume/capacity ratio and the volume crossing the tracks were used to determine the appropriate light rail transit headway. The crossing clearance time was fixed at forty seconds.

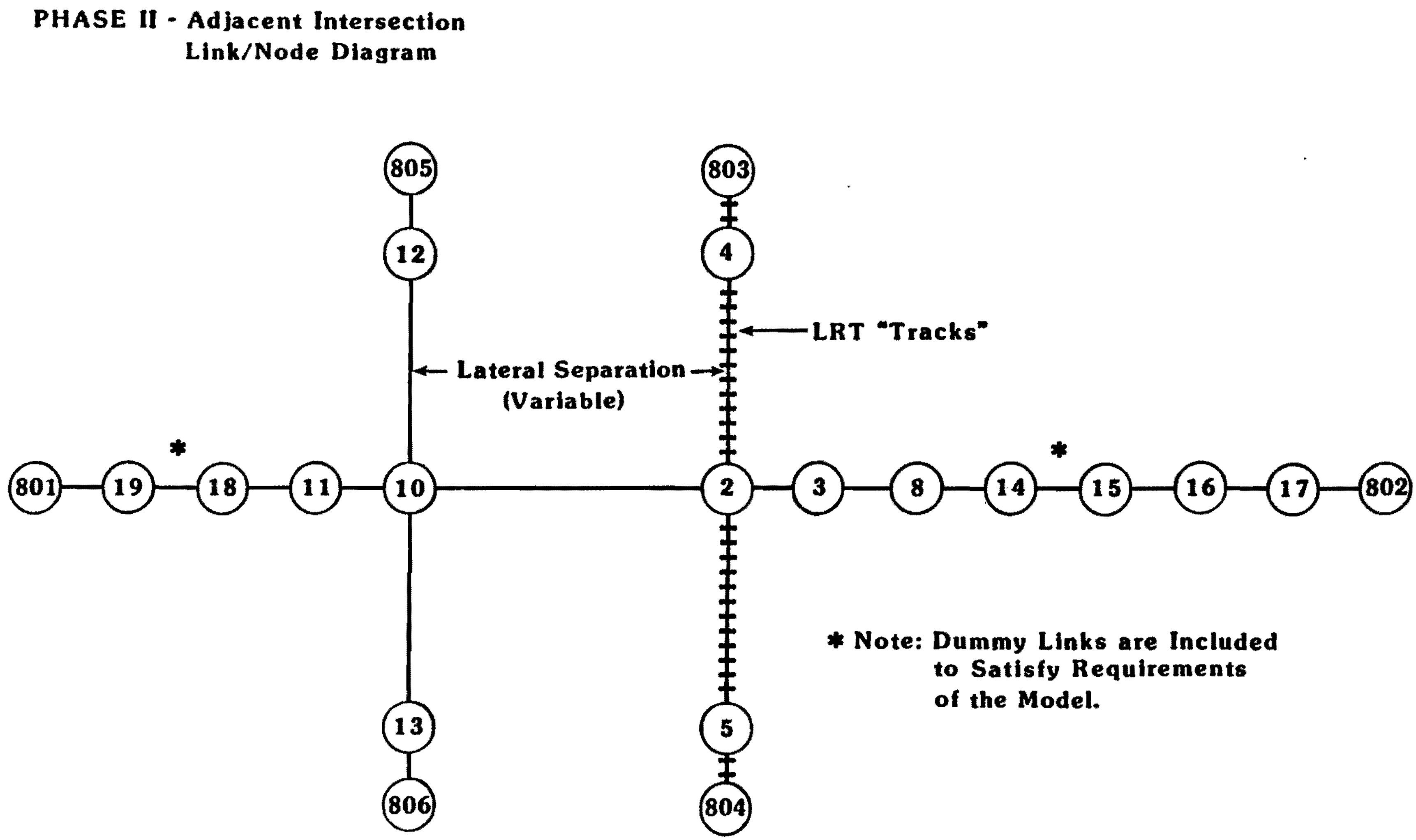

Figure 2. Adjacent Intersection - Link/Node Diagram

Progression Interruption

The third phase of this study was developed to determine the effect of a light rail transit grade crossing located in a series of coordinated intersections. The objectives of this phase are to determine any additional impact to the traffic beyond that of an isolated crossing, and also to determine if the location of the light rail transit tracks between the intersections has any effect on the traffic flow.

Figure 3 shows the network used in this analysis. As in Phase 2 of this study, each of the intersections in this system operates with a critical lane volume of 1400 vehicles per hour. Sixty percent of the traffic was placed on the main street, and forty percent on the cross streets. The turning movements on the main street are ten percent left and ten percent right. The turning movements on the cross streets are fifteen percent left and fifteen percent right in order to maintain similar volumes at all intersections in the system.

The geometry of the system to be analyzed was developed from a time-space diagram used for this phase of the study. A seventy second cycle length was chosen, and the optimal intersection spacing was determined from the following formula:

$$\text{Optimal Spacing (ft)} = \frac{\text{Cycle Length (sec)} * \text{Vehicle Speed (ft/sec)}}{2}$$

The signal timings and offsets were determined from analysis with the PASSER II program (12). The signal phasing used was dual leading lefts without overlap. The timing plan (See Figure 4) resulted in a system that was optimized for the given conditions with a fifty percent band width split for each direction on the main street.

Two locations for the light rail transit crossing were determined from the final time space diagram. The first light rail transit track location was selected because it was in the progression band for both directions at

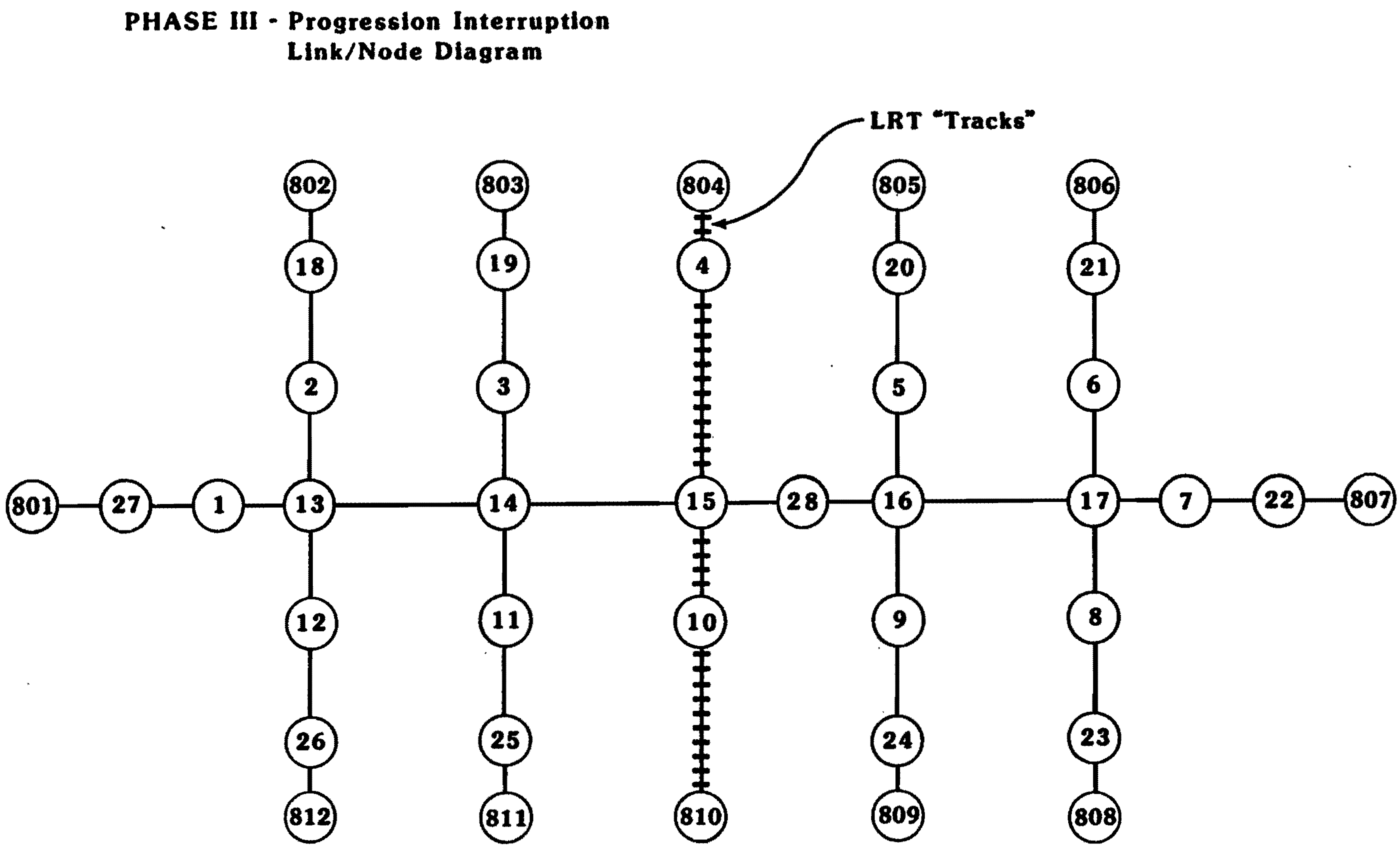

Figure 3. Progression Interruption - Link/Node Diagram

the same time. The second location, a worst case scenario, was located such that the platoons would arrive from each direction at different times. Both of these locations (See Figure 4) were selected so they were not close enough to either of the intersections to violate the isolated crossing assumption. A range of headways from two to seven and one-half minutes were chosen for use in all scenarios that include light rail transit vehicles operating in the system.

To satisfy the objectives of this phase, simulation runs were made with light rail transit vehicles crossing at optimal and non-optimal locations. Simulation runs without any light rail transit vehicles were also run to determine a base delay value for the system. The comparison of these results will determine the effects of unconditional preemption on delay in coordinated signal systems.

Case Study

The fourth phase of this study was a case study to determine the degree to which the previously determined relationships would predict the delay in a large, real world transportation network, once the network was coded into NETSIM. The objective of this phase was to determine if there had been something of significance deleted from the analysis.

The Westpark Corridor, chosen as a possible route for a light rail transit line in Houston, Texas, was the setting for this phase of the analysis. The study area runs east from Howell Sugarland and Alief-Clodine to US 59 and Shepherd. Size limitations with the NETSIM model require that this area be broken into five sections. Figure 5 illustrates the study area and the borders of the different sections. Figures 6 and 7 show the link/node diagrams to be used in this final phase of the project.

The traffic volumes, turning movements, and geometrics used in this phase are based on extensive data collected on this site during July 1985. Signal timings were based on existing conditions and on information obtained from the City of Houston. At locations with incomplete information, the

PHASE III - Progression Interruption
Time/Space Diagram

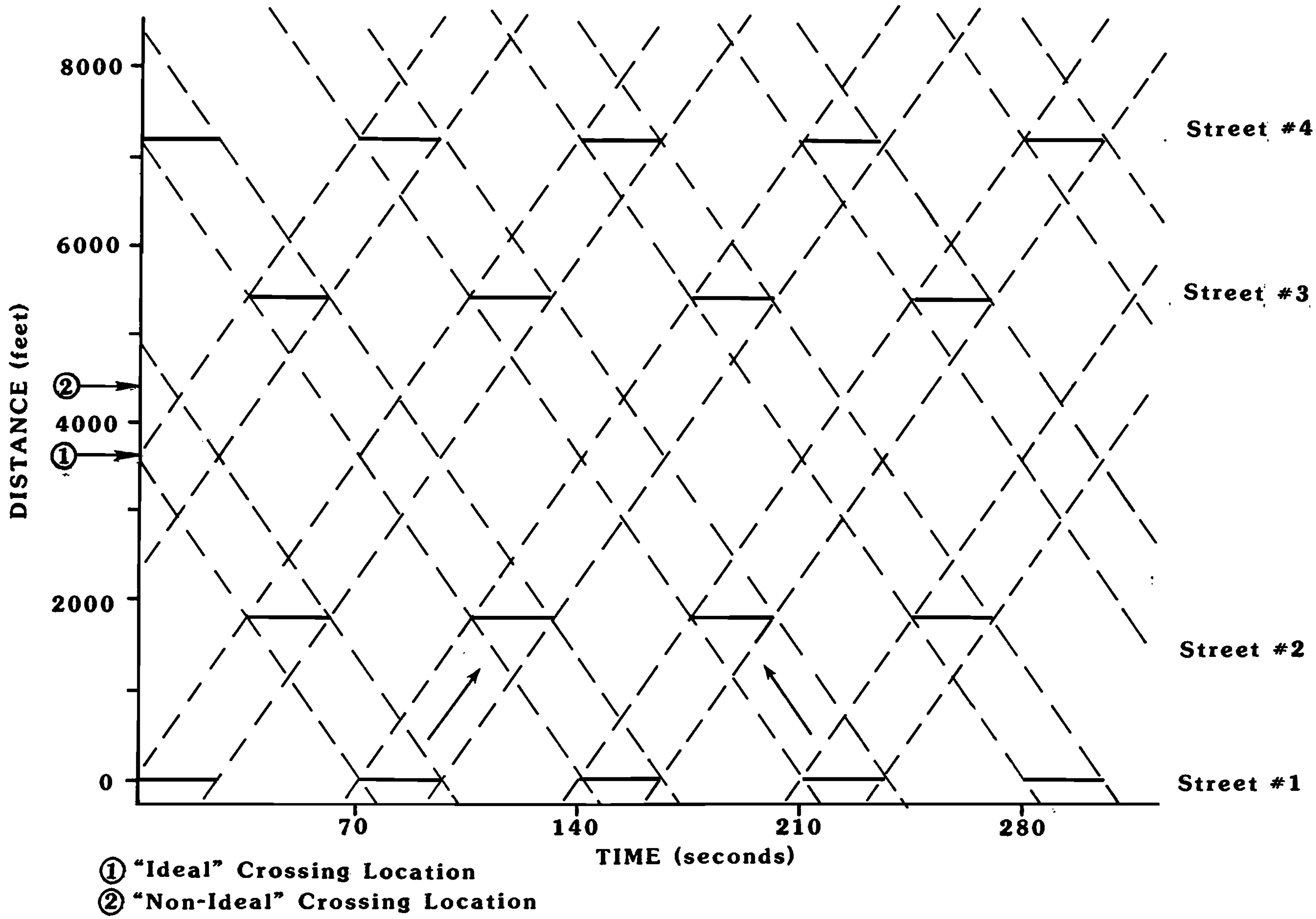

Figure 4. Progressin Interruption - Time/Space Diagram

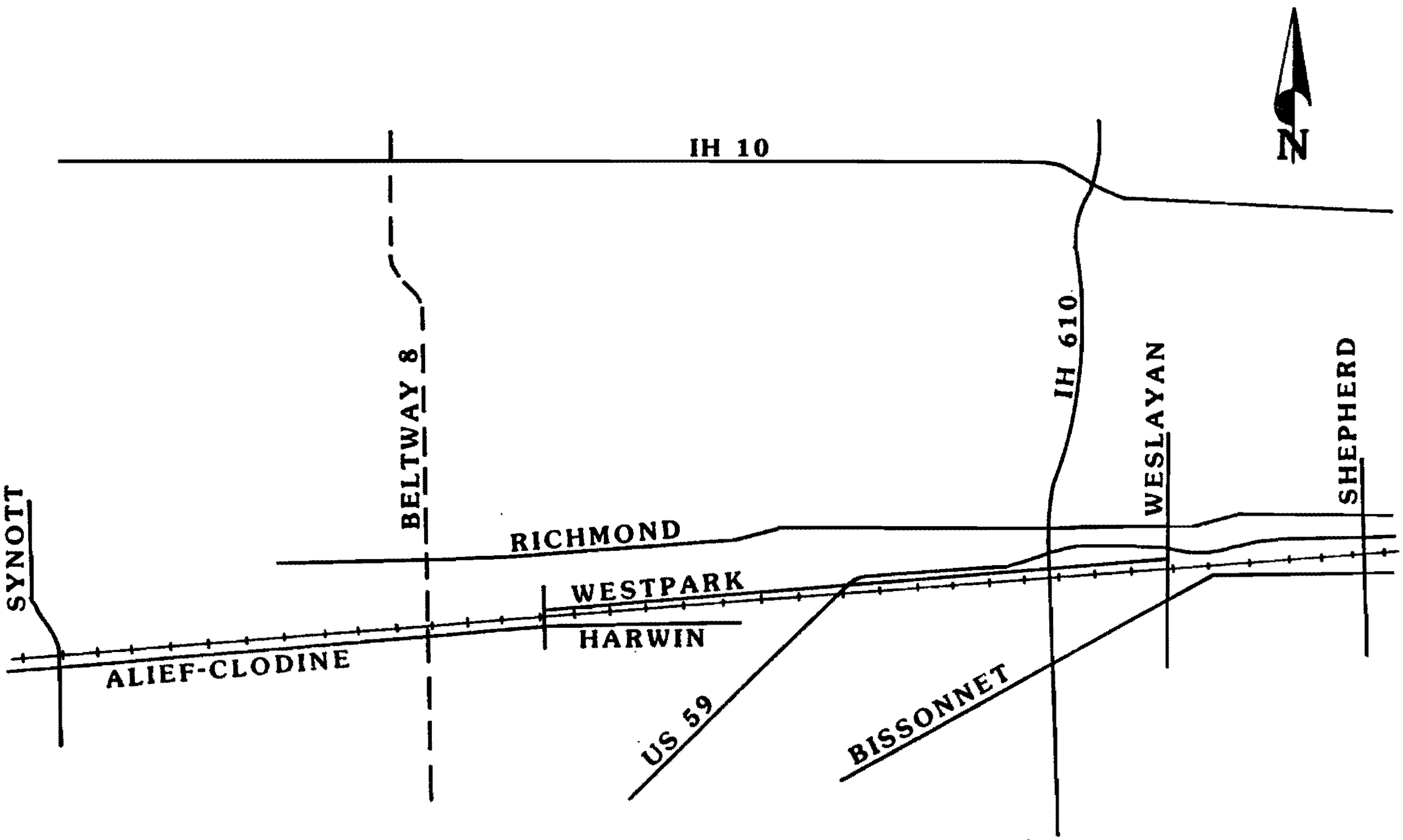

Figure 5. Case Study - Study Area, Houston, Texas

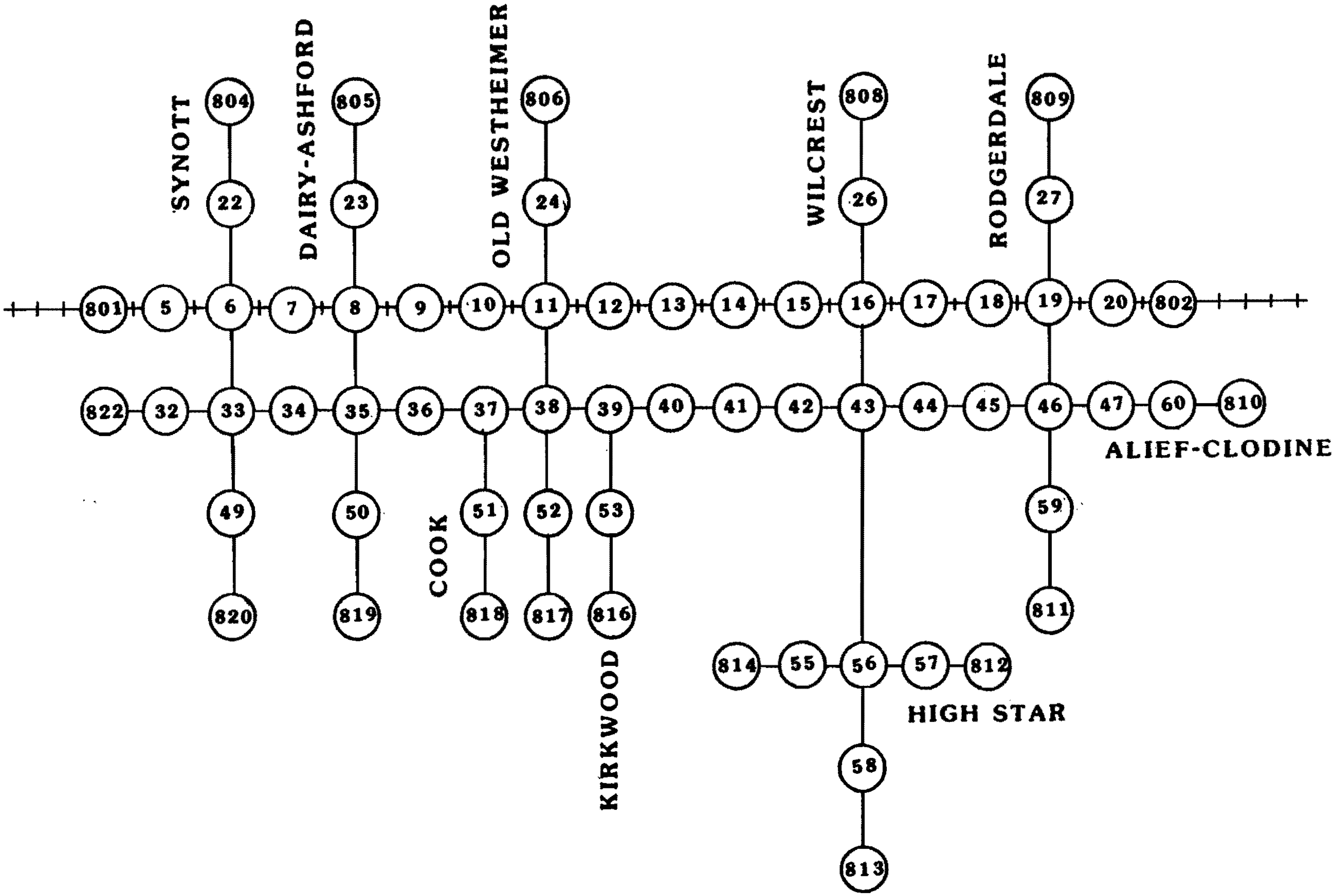

Figure 6. Case Study - Section A Link/Node Diagram

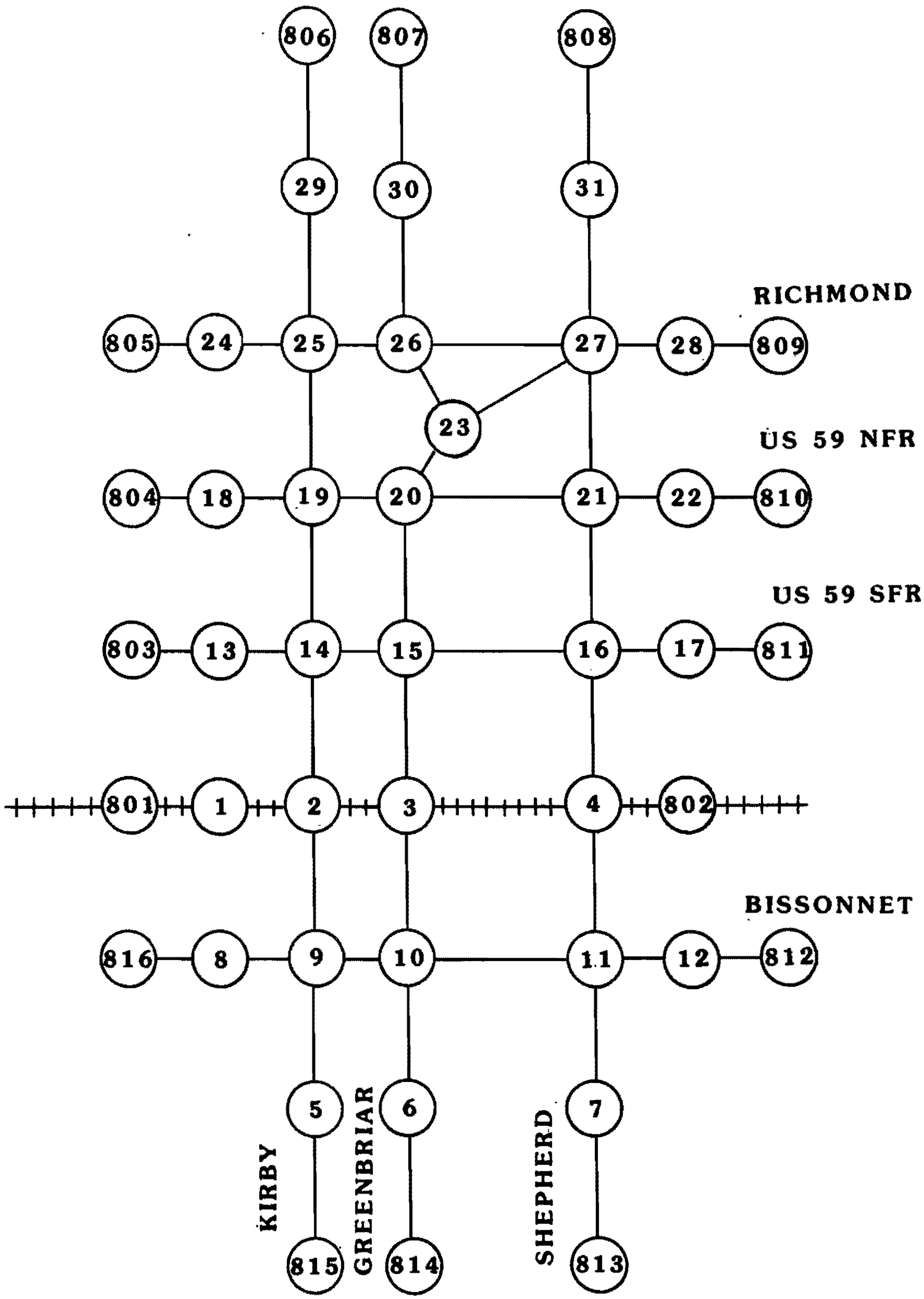

Figure 7. Case Study - Section B Link/Node Diagram

timing plans were developed using the SOAP84 analysis package (11). Consistent cycle lengths and offsets were used when available.

To achieve the objective of this phase of the study, a comparison was made between the existing traffic conditions and these same conditions with the addition of light rail transit at-grade crossings. These runs were made with the light rail transit vehicles operating at five minute headways.

STUDY RESULTS

Isolated Crossing

As outlined in the procedure section, the purpose of the first study was to investigate the isolated crossing case. This section is the cornerstone for the remainder of the report. Each variable - roadway volume, roadway cross-section, light rail transit 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 (14).

The NETSIM model does not contain any options which simulate light rail vehicle operation. It was necessary to manipulate the model into mimicking light rail operation by utilizing the bus traffic simulation option. 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 light rail transit headway on delay per vehicle is illustrated in Figure 8A. 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 light rail transit headway increases the delay per vehicle on the crossing roadway. It also shows the non-linear relationship between delay per vehicle and traffic volume.

The effect of crossing clearance time is shown in Figure 8B. The roadway cross section and light rail transit 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.

Figure 9 shows the lack of an effect as a result of the varying cross-section. Crossing clearance time and light rail transit headway are held constant as the traffic volume is held constant for different cross-sections.

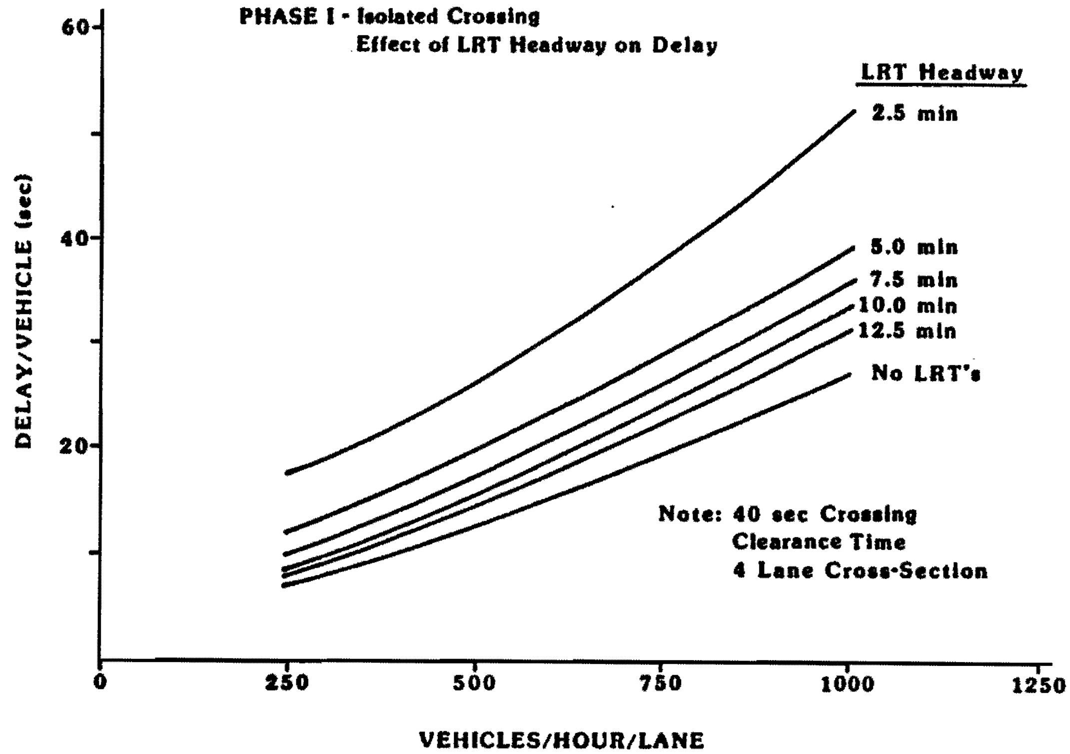

Figure 8A. Isolated Crossing - Effect of LRT Headway on Delay

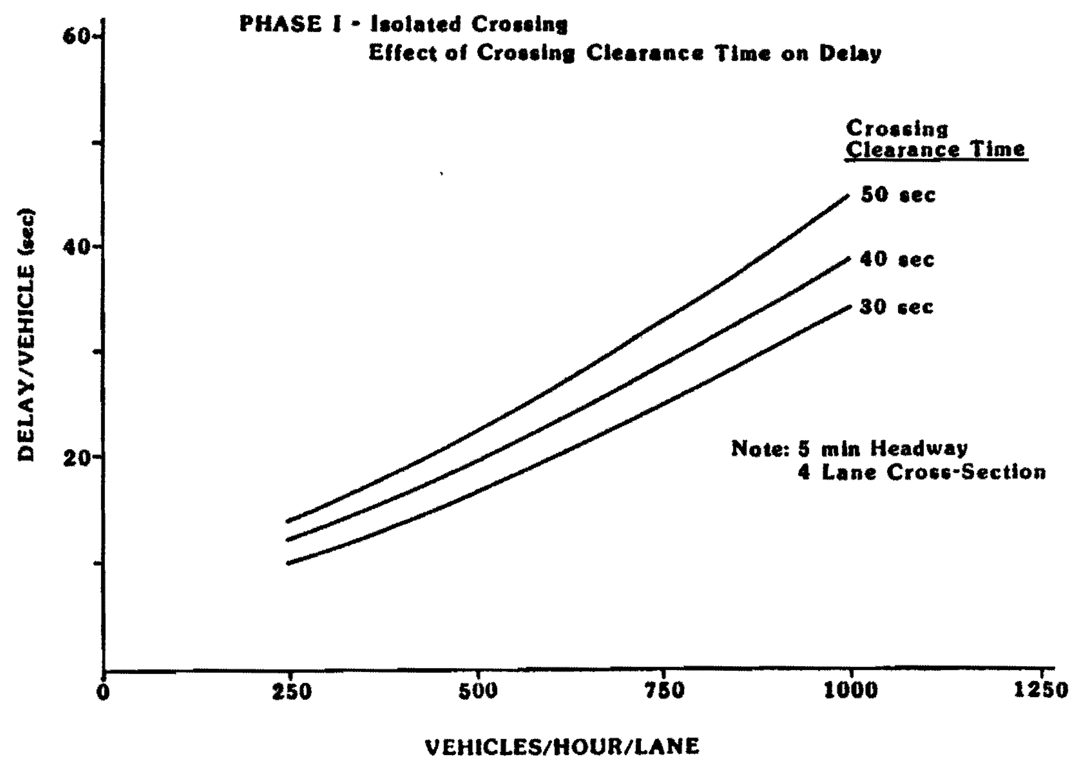

Figure 8B. Isolated Crossing - Effect of Crossing Clearance Time on Delay

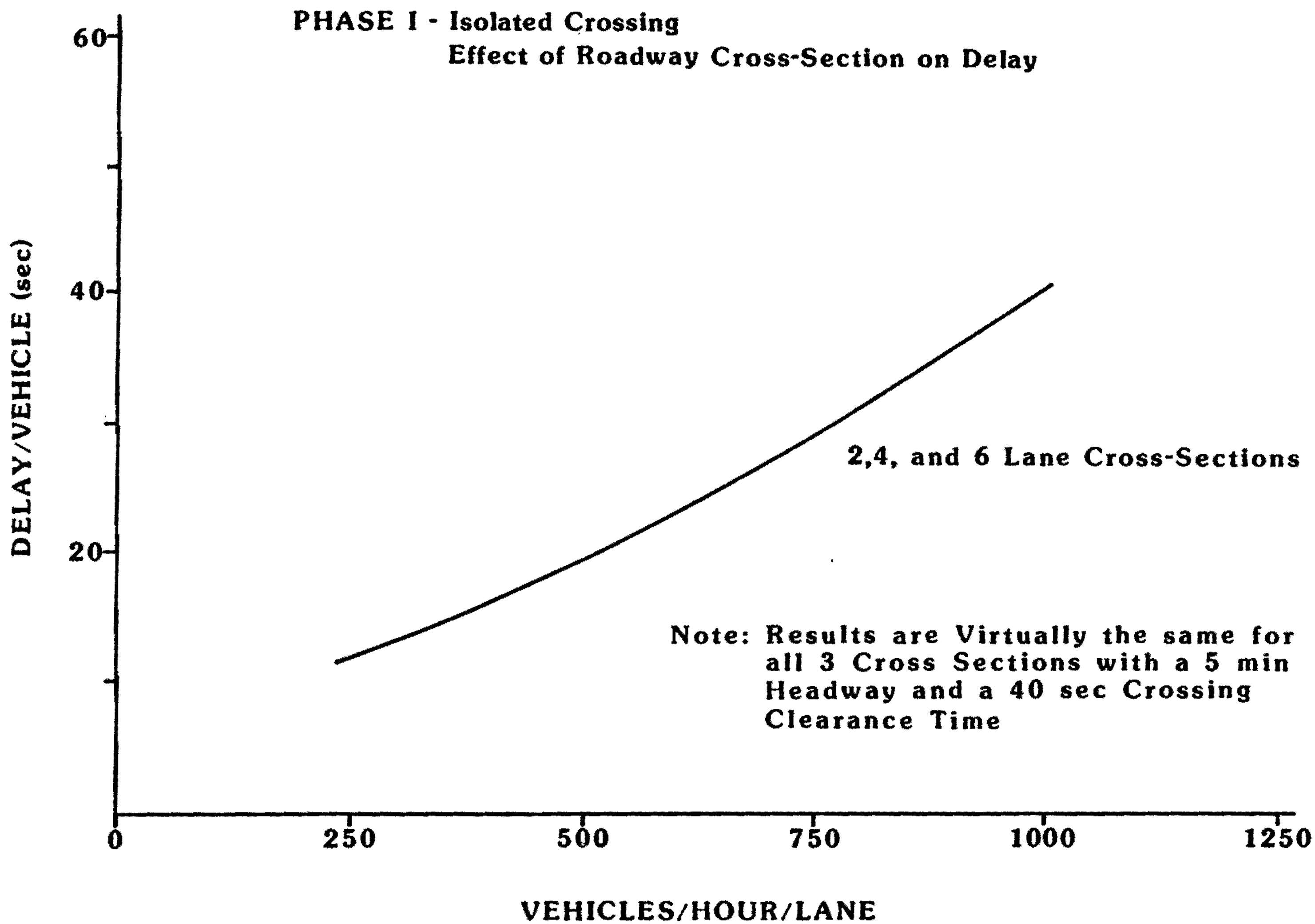

Figure 9. Isolated Crossing - Effect of Roadway Cross-Section On Delay

This figure shows that the results for all three cases are virtually the same for an isolated crossing with a 5-minute light rail vehicle roadway and a 40 second crossing clearance time.

One of the purposes of the isolated intersection analysis was to simplify the calculation of delay for the isolated crossing. Delay calculation methodology used by Webster (15) and the 1985 Highway Capacity Manual (10) indicate that volume/capacity ratio is a key parameter for computing delay per vehicle. Also included in these calculations was the ratio of green time to cycle length and the saturation flow on the roadway. The development of the crossing volume to capacity ratio (Xcr) that will be used in this study is shown in the Appendix. This ratio was developed by dividing each light rail transit arrival headway into its components. This ratio accounts for all variables explored in this study except for roadway cross-section.

The relationship between delay per vehicle and the crossing volume to capacity ratio is shown in Figure 10A. This graph shows a definite relationship between these two variables. This relationship appears to be non-linear.

Regression analysis was performed on the data sets to determine the best relationship between these two values for this data set. Analysis of models including and not including roadway cross-section as a variable show the effect to be insignificant.

The following equation was shown to be the most appropriate model:

$$\text{delay/vehicle} = 9.56 + 67.26\ (\text{crossing volume/capacity})^2$$
$$(\text{sec/veh})$$

The R-square for this model is 0.92. Figure 10B shows the scatter plot of the data and the prediction curve fit to these points.

It should be noted that the equation includes an intercept term. There is no reason to expect a non-zero intercept term, as a single vehicle pro-

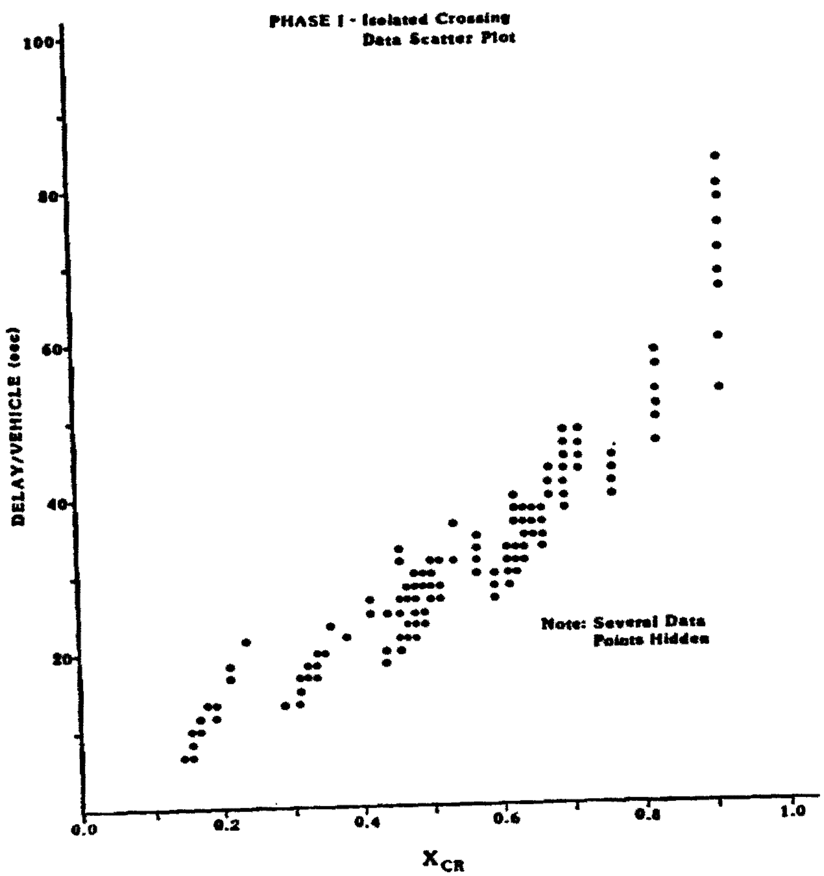

Figure 10A. Isolated Crossing - Data Scatter Plot

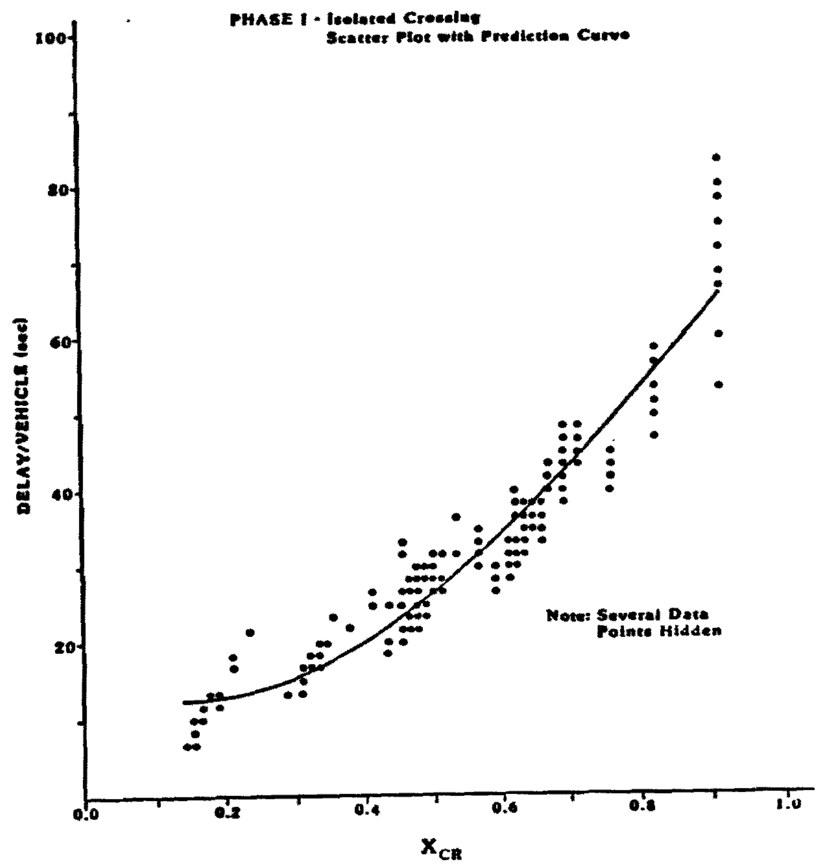

Figure 10B. Isolated Crossing - Scatter Plot with Prediction Curve ceeding through the system should incur no delay. However, the model suggests that when the crossing volume to capacity ratio is very low, an inherent delay of 9.56 seconds per vehicle is unavoidable. If there are no light rail vehicle crossings, there should be zero delay 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 was retained, but the intercept term was forced from 9.56 to 0.0. The resulting relationship was determined:

$$\text{Delay (sec/veh)} = 91.16\ (\text{crossing volume/capacity})^2$$

This equation represents an estimate of the system wide delay which includes both the inherent automobile base delay and the incremental delay induced by the light rail vehicles. In order to obtain the incremental delay of the light rail vehicles, the base delay is subtracted from the total delay. The base delay is calculated by substituting the volume/saturation ratio for the roadway in place of the Xcr ratio in the above equation (see Part II of the Appendix for a full example). Once the incremental delay is determined, a benefit/cost evaluation can be made.

Summarized in equation form:

$$\text{Vehicular delay due to LRT (in sec/veh)} = 91.16\ (Xcr)^2 - 91.16\ \left(\frac{v}{s}\right)^2$$

Where:

Xcr = crossing volume/capacity ratio

v = automobile approach volume (vphpl)

s = saturation (vphpl)

Refer to Figure 11 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.

	Delay (sec)	
Xcr	Modified	Original
0	0	9.56
.1	.91	10.23
.2	3.65	12.25
.3	8.20	15.61
.4	14.59	20.31
.5	22.79	26.36
.6	32.82	33.75
.7	44.67	42.49
.8	58.34	52.57
.9	73.84	63.99
1.0	91.16	76.76
1.5	205.11	160.76

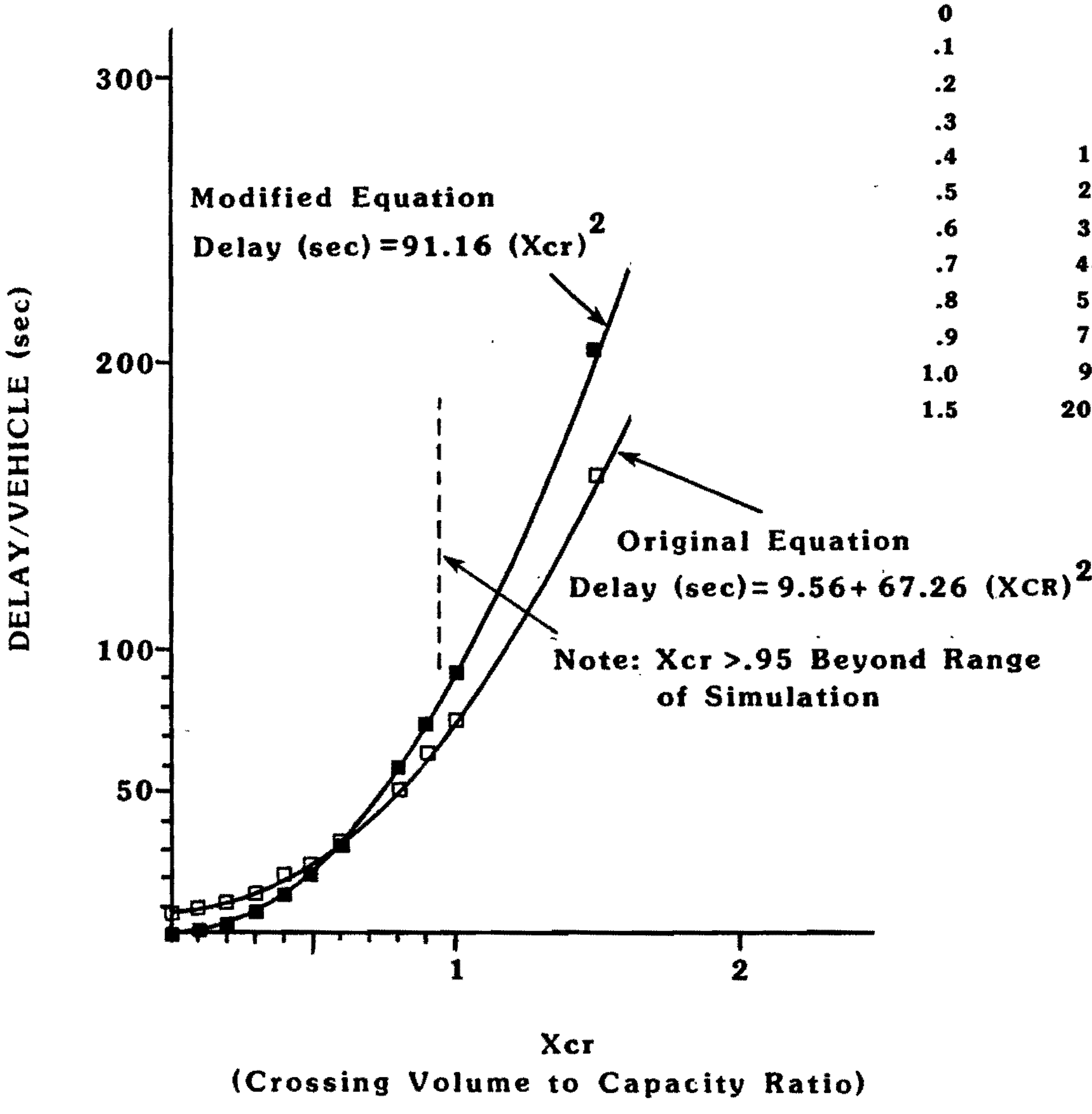

Figure 11. Original Delay Equation vs. Modified Delay Equation

It should be noted that the delay equations follow an x^2 relationship which is consistent with the delay function used in the Highway Capacity Manual.

Adjacent Intersection

The analysis of the results from this portion of the study focused on determining the limit for assumption of isolation for a light rail transit grade crossing and on quantifying the impact of locating a light rail transit grade crossing near a roadway intersection for the scenario analyzed. Both portions of this analysis were completed using graphical and statistical analysis techniques.

The analysis began by first plotting the total system delay versus the lateral separation between the intersection and the grade crossing. Each set of traffic volume scenarios was plotted separately, and a curve was roughly fit to the resulting points. Figures 12 through 15 show these curves. Cases one, two, and three are the balanced flow case. Cases four and five have heavier volumes crossing the tracks. Cases six and seven have the heavier volume parallel to the tracks. The different cases within each volume scenario have different light rail transit headways. With each curve, the total delay became constant at some point for greater lateral separations. As the lateral separation decreased from the point of constant delay, the total delay began to increase. This increase continues as lateral separation gets smaller. The point at which this increase occurs was determined to be the limiting distance for the isolated crossing assumption. In each scenario, a base delay was determined from simulation runs without light rail transit vehicles on the system and is shown as a dashed line in Figures 12 through 15. The difference between this base value and the constant delay values at lateral separations greater than the isolation distance were comparable with the expected additional delay from the results of the isolated crossing analysis.

Figure 16 shows the relationship between the limiting distance for the assumption of an isolated crossing and the crossing volume to capacity ratio. This linear relationship has an R-square of 0.85. In order to more closely examine the simulation results, two statistics were tabulated. The first set

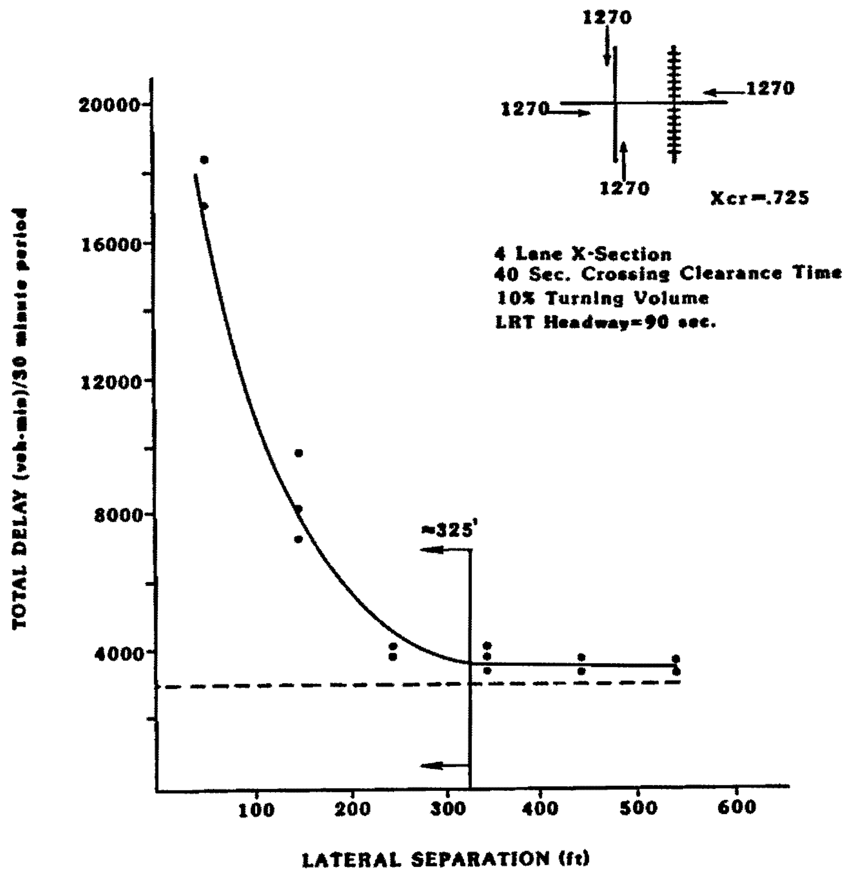

Figure 12 A. Adjacent Intersection - Effect of Lateral Separation on Delay - Case 1

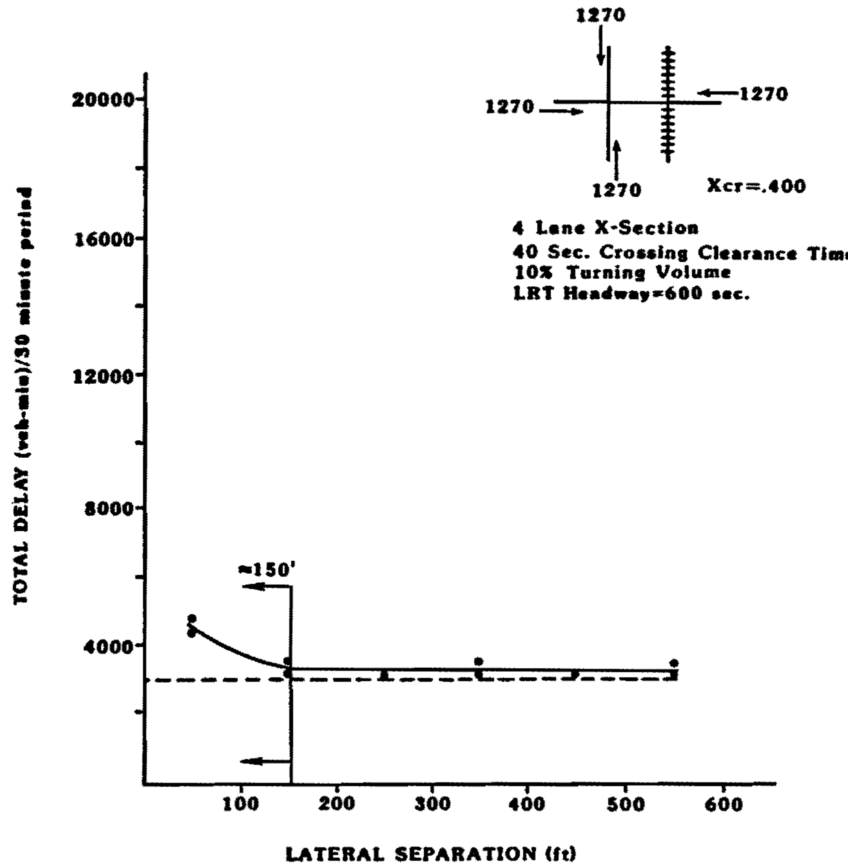

Figure 12B. Adjacent Intersection - Effect of Lateral Separation on Delay - Case 2

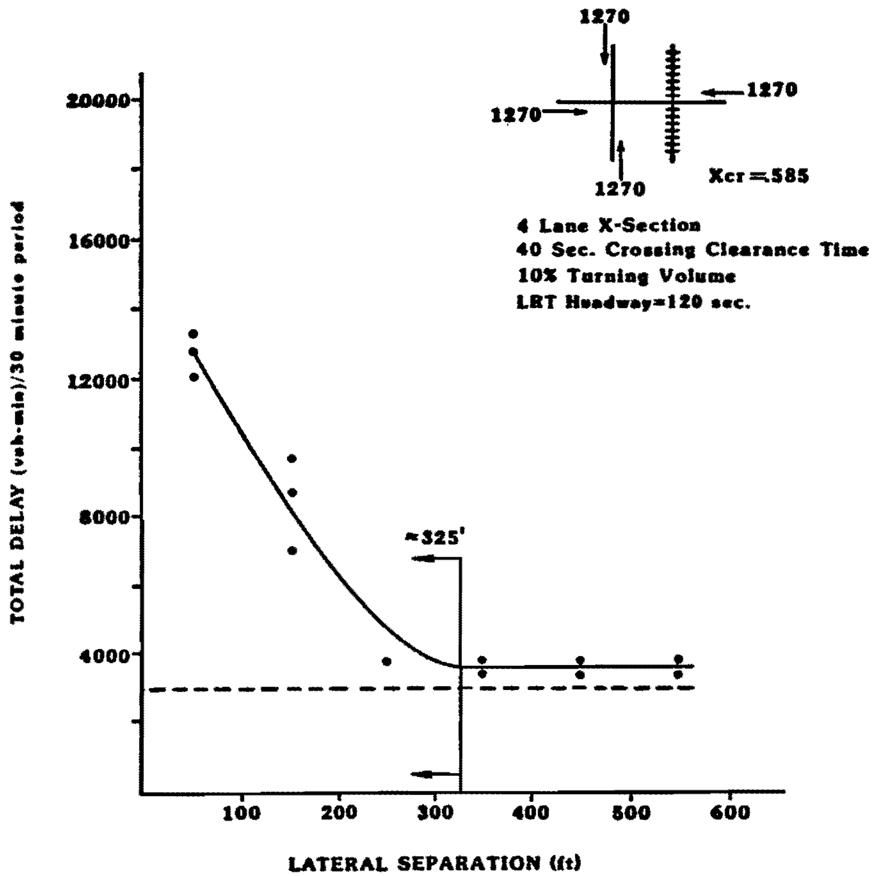

Figure 13A. Adjacent Intersection - Effect of Lateral Separation On Delay - Case 3

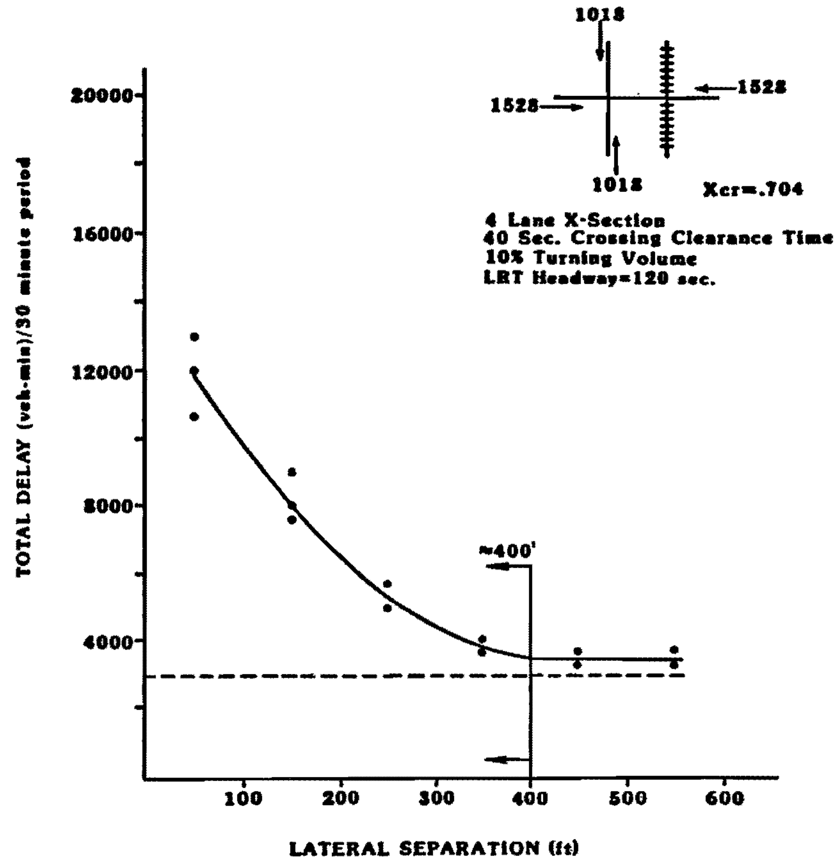

Figure 13B. Adjacent Intersection - Effect of Lateral Separation On Delay - Case 4

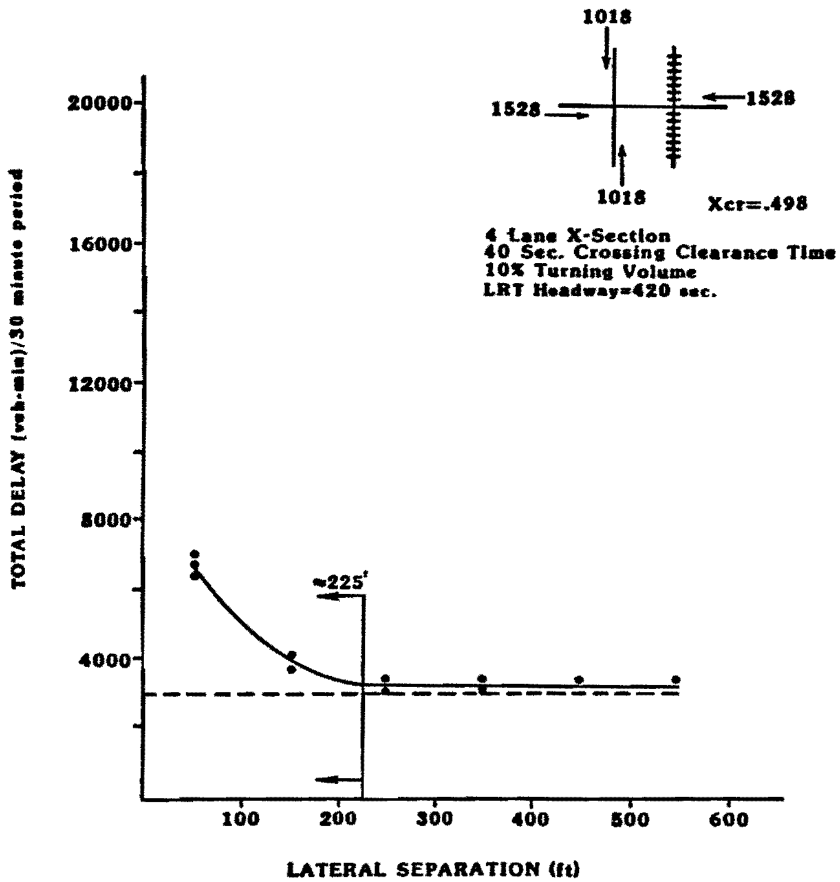

Figure 14A. Adjacent Intersection - Effect of Lateral Separation On Delay - Case 5

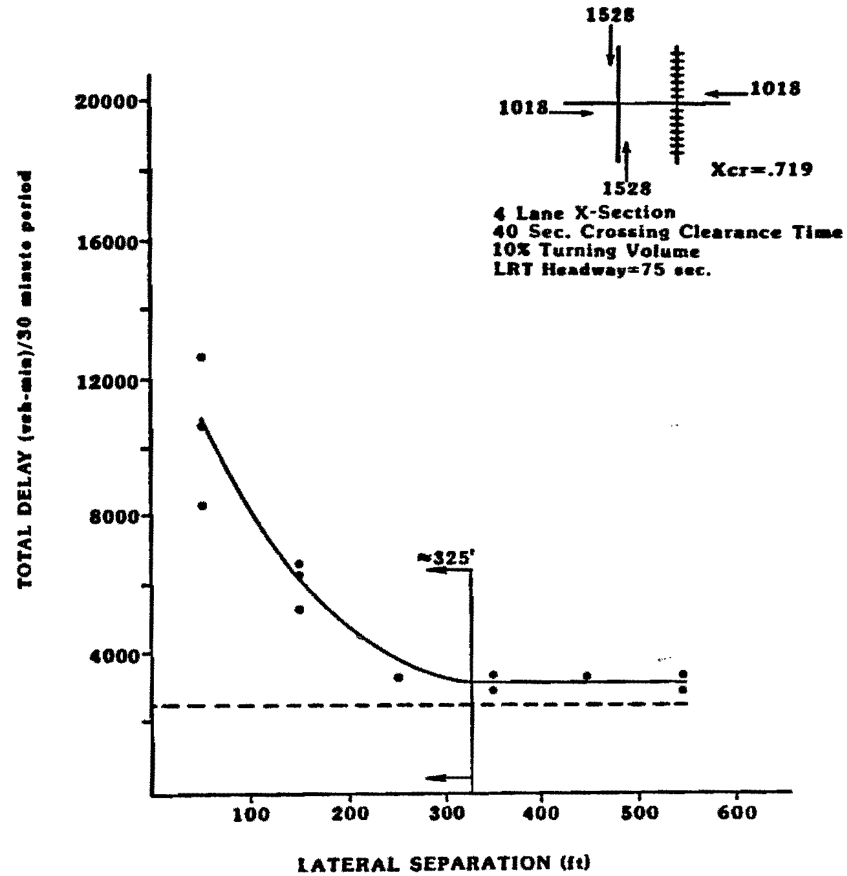

Figure 14B. Adjacent Intersection - Effect of Lateral Separation On Delay - Case 6

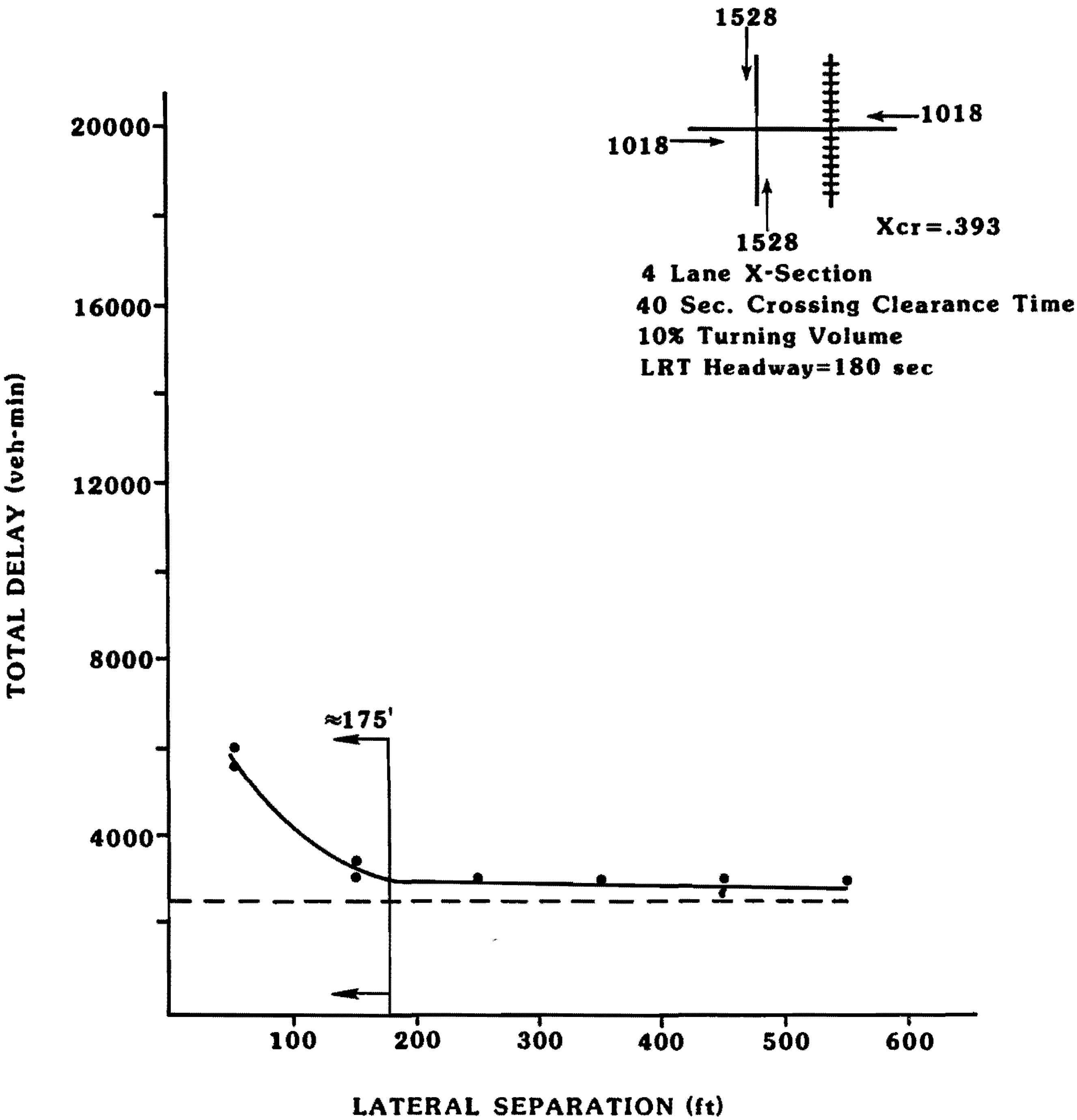

Figure 15. Adjacent Intersection - Effect of Lateral Separation on Delay - Case 7

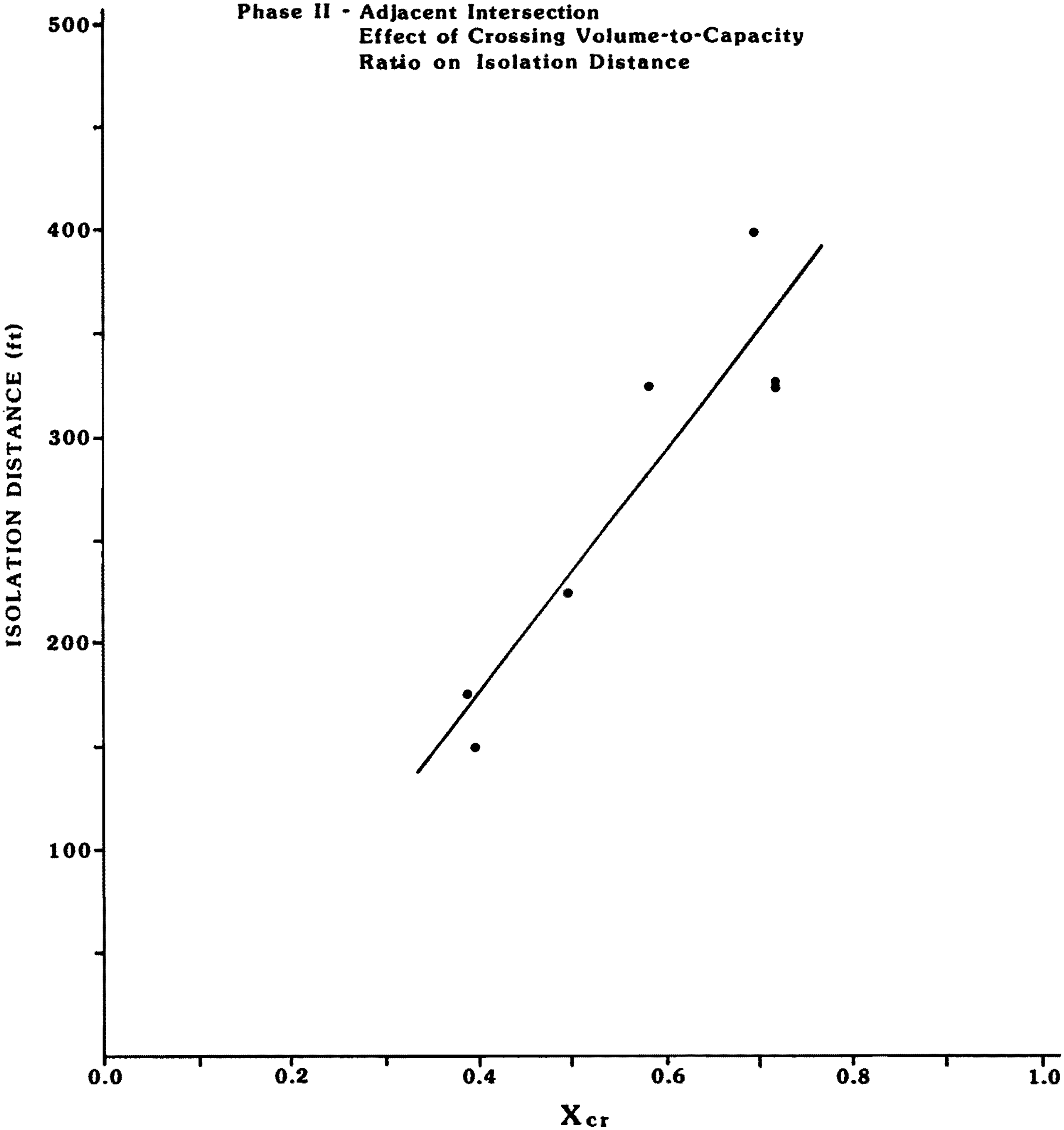

Figure 16. Adjacent Intersection - Effect of Crossing Volume-to-Capacity Ratio on LRT Isolation Distance

of statistics tabulated was the amount of time that traffic approaching the crossing from the intersection backed up into the intersection. This value is defined as the spillback time. The second set of information compiled was the additional delay per vehicle on the approaches. These results were grouped into two sets: the additional delay per vehicle crossing the tracks from both directions and parallel to the tracks from both directions. This value was tabulated from the difference between the base simulation runs and the simulation runs made with light rail transit vehicles on the system.

Figures 17 and 18 show the relationship between spillback time and lateral separation for the three previous traffic volume scenarios. In all cases, the spillback time is very low for the greater lateral separations. At a certain point, the spillback time increases for the lesser lateral separations. These results are similar to the results obtained through analysis of the total delay versus lateral separation curves using the point of zero spillback time as an indication of the lateral separation at which the isolated crossing assumption will hold. While these results are similar in magnitude, they do not correspond well to one another. The comparison of these results does not fully substantiate the earlier relationship between isolation distance and the crossing volume to capacity ratio. This comparison does however, show that beyond 400 feet of lateral separation, there is very little impact to the traffic on the system. It should be noted, however, that the relationship between isolation distance and crossing volume to capacity ratio does account for the magnitude of the impact from the light rail transit vehicles. Examination of the spillback data reveals that often a small amount of spillback may occur at some of the larger lateral separations. The relationship between spillback and lateral separation also shows that the queuing of vehicles from the crossing back to the cross street seems to drive the effect of the light rail transit grade crossing.

Analysis of the additional delay per vehicle for the traffic parallel to the tracks showed there to be little impact to this traffic due to the different lateral separations. It should be noted that turn bays for both left and right turning vehicles were provided. The lack of these turning

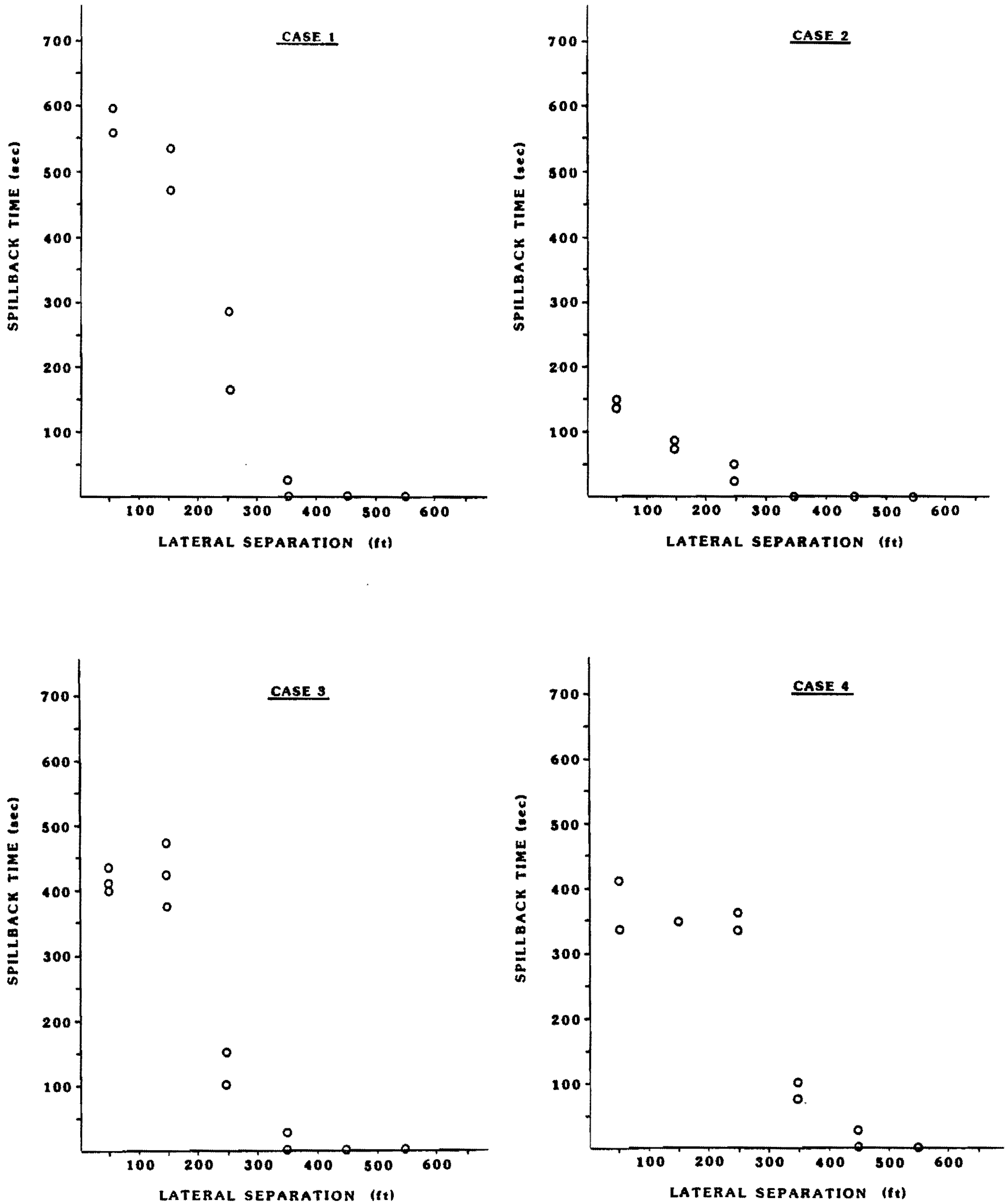

Figure 17. Adjacent Intersection Analysis - Effect of Lateral Separation on Spillback Time

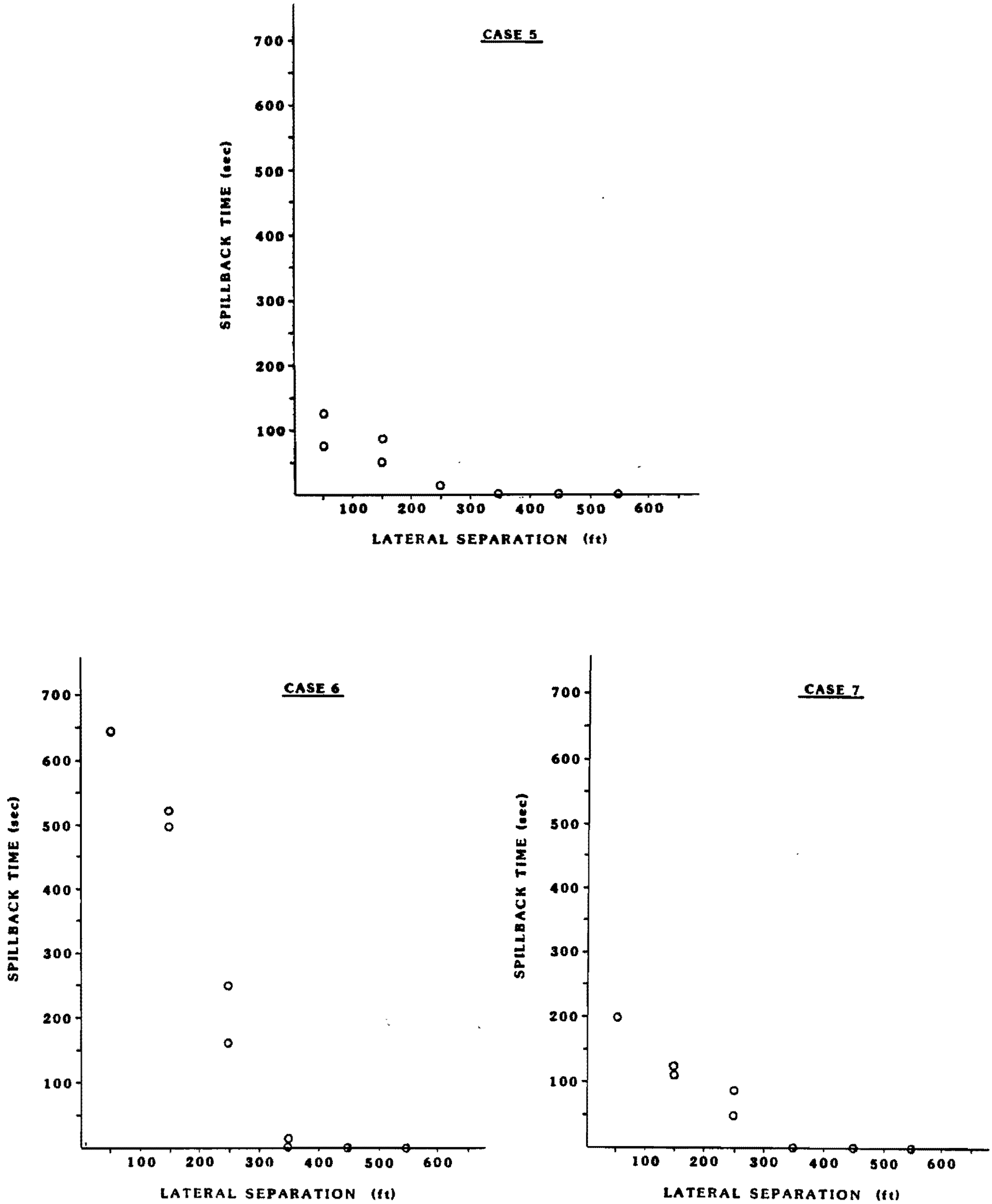

Figure 18. Adjacent Intersection Analysis - Effect of Lateral Separation on Spillback Time

bays could cause a back-up of vehicles making turns in order to cross the light rail transit tracks.

Figure 19 shows the relationship between the additional delay per vehicle crossing the light rail transit tracks and the lateral separation. This plot showed a possible relationship between the delay per vehicle and the reciprocal of the lateral separation. Analysis of the combined data set from all scenarios shows the best model to include the crossing volume to capacity ratio and the reciprocal of the lateral separation. This model was found to be:

$$\underset{\text{(seconds)}}{\text{Additional Delay per Crossing Vehicle}} = -398 + \frac{30871}{\underset{\text{(feet)}}{\text{Lateral Separation}}} + (Xcr * 597)$$

The R-square for this model was 0.66

Progression Interruption

The results from this portion of the study were very similar in all the cases considered. The magnitude of the total system delay was such that the variability of delay due to the stochastic nature of the model overshadowed the impact of a single crossing on the system. Computer simulations (with and without light rail transit vehicles on the system) were in the same range, with no apparent effect due to the crossing closures.

In light of the nature of these results, it was only appropriate to draw general conclusions from this information. The key objective of this phase of this study was to determine if the location of a light rail transit at-grade crossing (ideal or non-ideal) had an impact on the traffic stream. It was concluded that no great effect was seen by varying the location of the crossing. This does have a logical foundation. Roughly, the same delay would result if each progression band was blocked for the same length of time. The difference in the two cases would be in the timing of the interruption. The blockage would occur simultaneously at the ideal location or at different times at the non-ideal location. It can also be generally

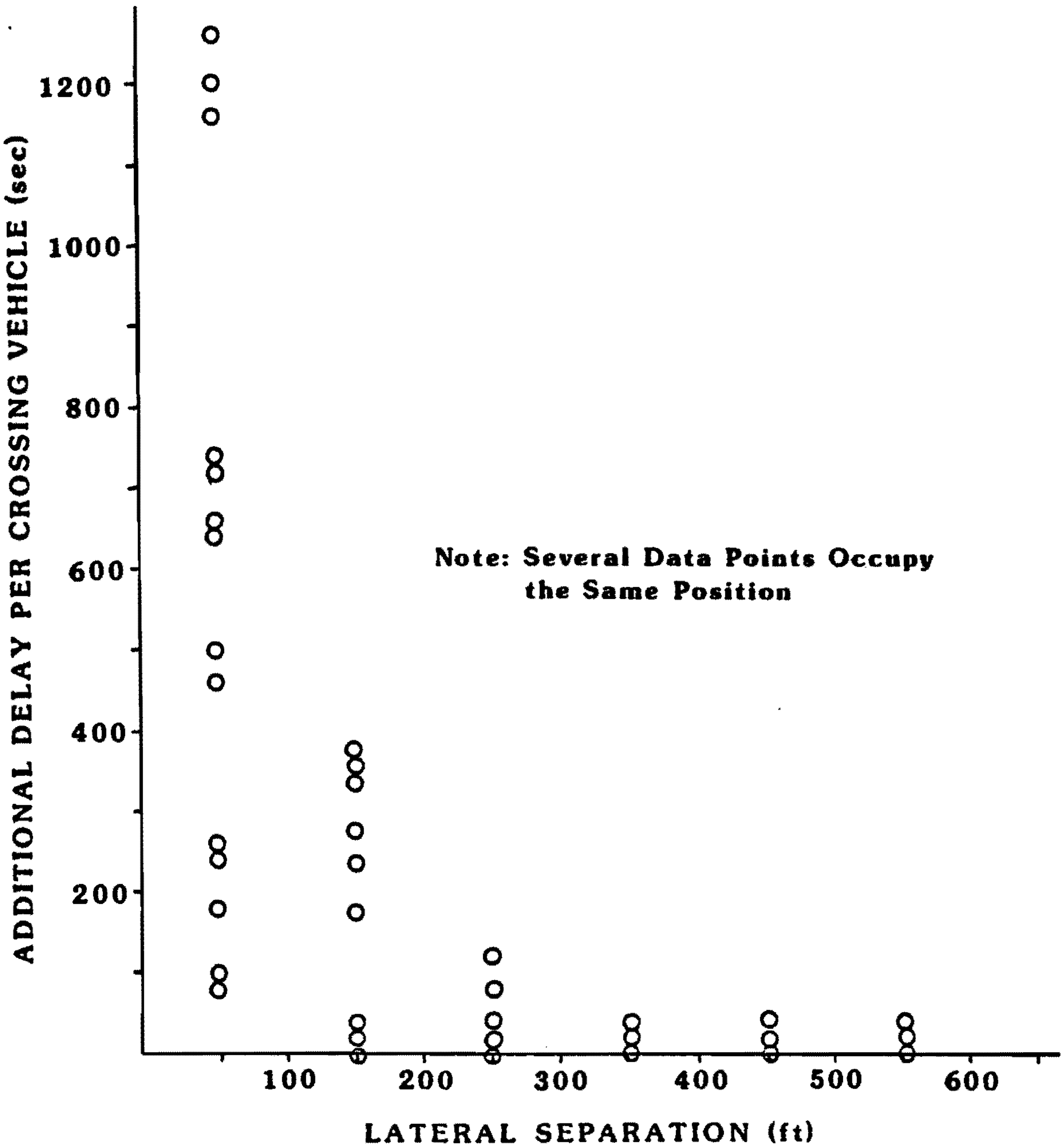

Figure 19. Adjacent Intersection - Effect of Lateral Separation On Additional Delay Per Crossing Vehicle

concluded that there is no great additional impact to traffic as a result of the location of light rail transit crossing between coordinated intersections. That is to say, all locations greater than 400′ from a signalized intersection produce the same delay. This conclusion is valid for a crossing that is operational under unconditional preemption that can be assumed to be acting in isolation. It should be noted that the coordination of the crossing and the signals in the system and different preemption policies could greatly affect these results.

Case Study

The results of this case study were compared with estimates of the expected delay on each of the networks. The isolated crossing effects and the effects of the adjacent intersections were taken into account where applicable. The objective was to determine if the previously determined results accounted for the entirety of the delay impacts to the traffic on the network. The comparison of the results showed that the effects were not completely described. The following paragraphs detail the differences in the results.

In Section A, the average total system delay with the light rail transit vehicles operating on the system was 14,916 vehicle-minutes per 30 minute period. The value without the presence of light rail transit vehicles on the network was 13,547 vehicle-minutes per 30 minute period. The difference was 1,370 vehicle-minutes per 30 minute period. The estimate of the additional delay from the previous equations in this study was found to be 376 vehicle-minutes. Further examination of the simulation results identified the links on which there was a significant increase (or decrease) in delay as a result of the light rail transit operation. Figure 20 illustrates these affected areas. The techniques developed in the study resulted in underestimates of delay on the links indicated. The arrows indicate the direction of traffic on the links with underestimates of delay.

In Section B, similar results were obtained. The average total system delay with the light rail transit vehicles operating on the system was 6,611 vehicle-minutes per 30 minute period. The total delay without light rail

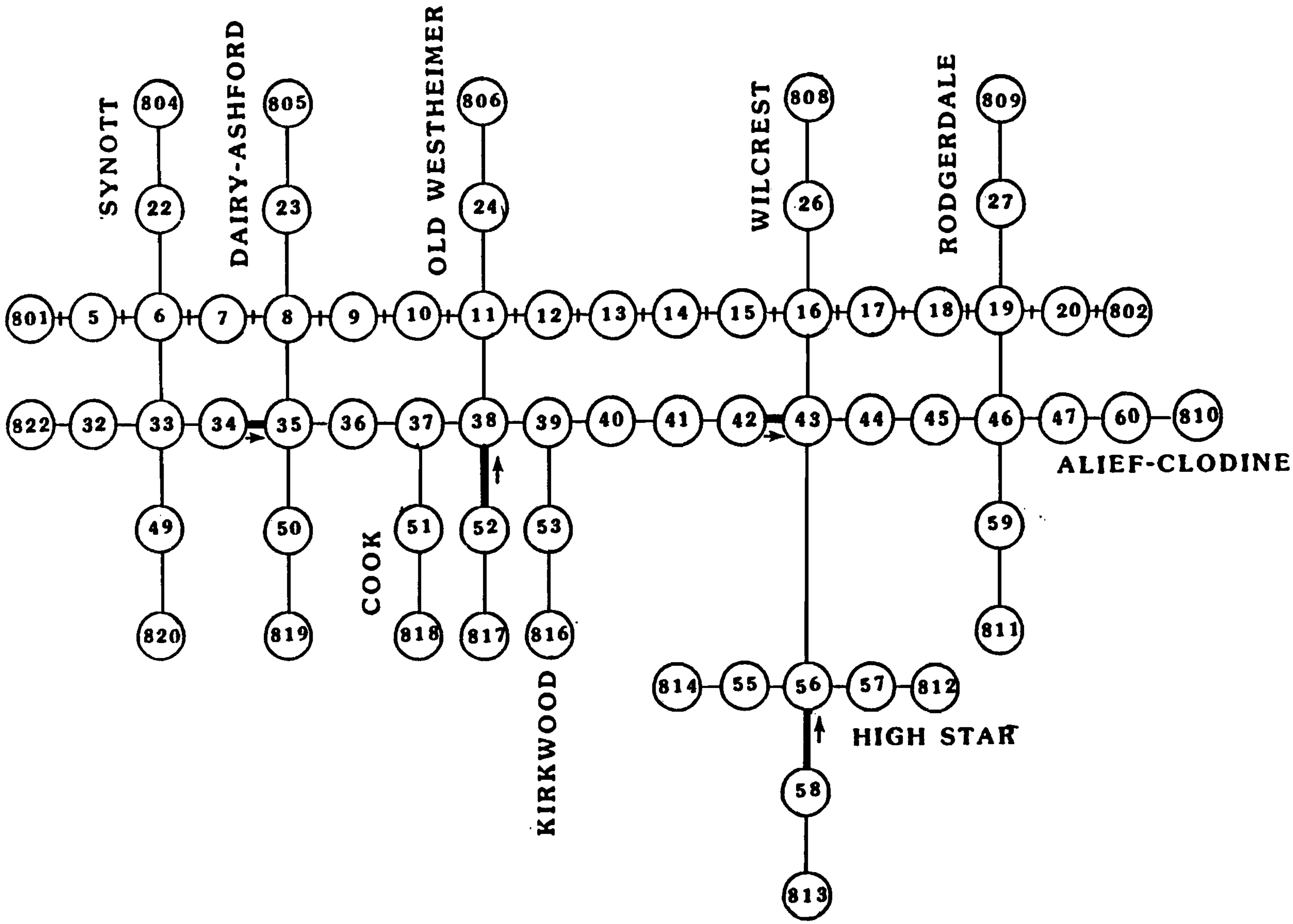

Figure 20. Location of Underestimates of Delay on Section A

transit vehicles was 6,349 vehicle-minutes per 30 minute period. The difference was 262 vehicle-minutes. Calculating the additional delay to the traffic on the network yielded a value of 17.5 vehicle-minutes. Again, further analysis identified these links affected by the light rail transit operation. Figure 21 shows the links with underestimates of delay.

Recognizing that the results from the previous portions of the study greatly underestimate the delay encountered on the network, the deficiencies in the analysis technique were sought in order to direct future efforts. Section A was found to have most of its significant delay impacts at the intersections adjacent to the light rail transit tracks. It is important to note that large increases in delay did occur on the links parallel to the light rail transit tracks. This contradicts the results that previously found the parallel streets to be unaffected by the light rail transit operation. A node further from the tracks (node 56) was also affected. The results of simulation runs on Section B were very similar to those in Section A.

Further consideration was given to the adjacent intersection analysis. Figure 22 combines the 7 cases previously shown separately in Figures 12 to 15. There is no reason to expect the curves to cross based on the formulation of the sensitivity analysis. Something is affecting the delay that has not been accounted for or controlled in the analysis. However, we are unable to explain the cause of the relationships. Clearly, the adjacent intersection case is more complicated than anticipated. The "system" effects appear to be more significant than anticipated. That is to say, the various intersections begin to have an affect upon each other. The delay equations developed appear to be conservative in their estimate of delay in complicated networks.

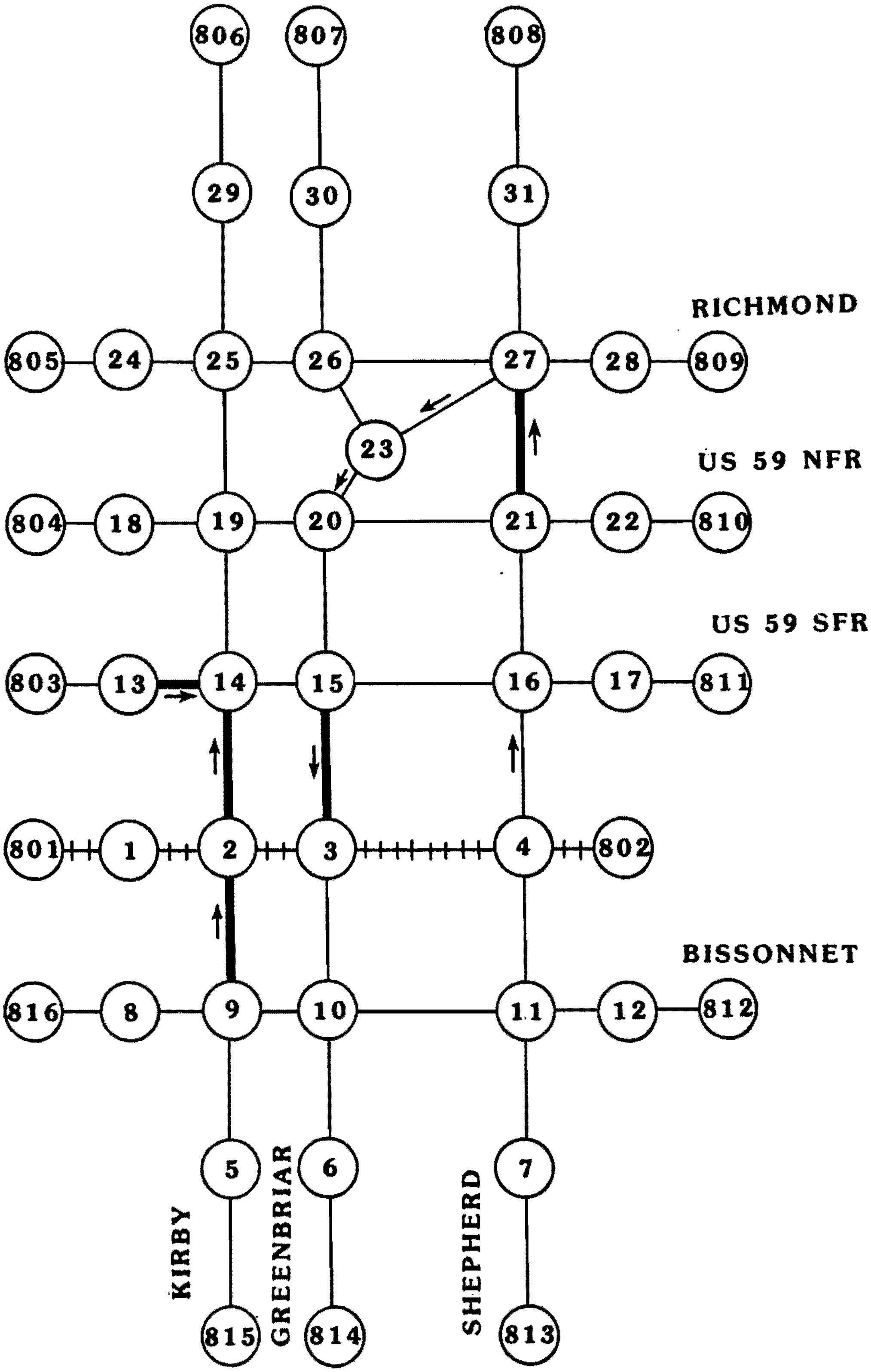

Figure 21. Location of Underestimates of Delay on Section B

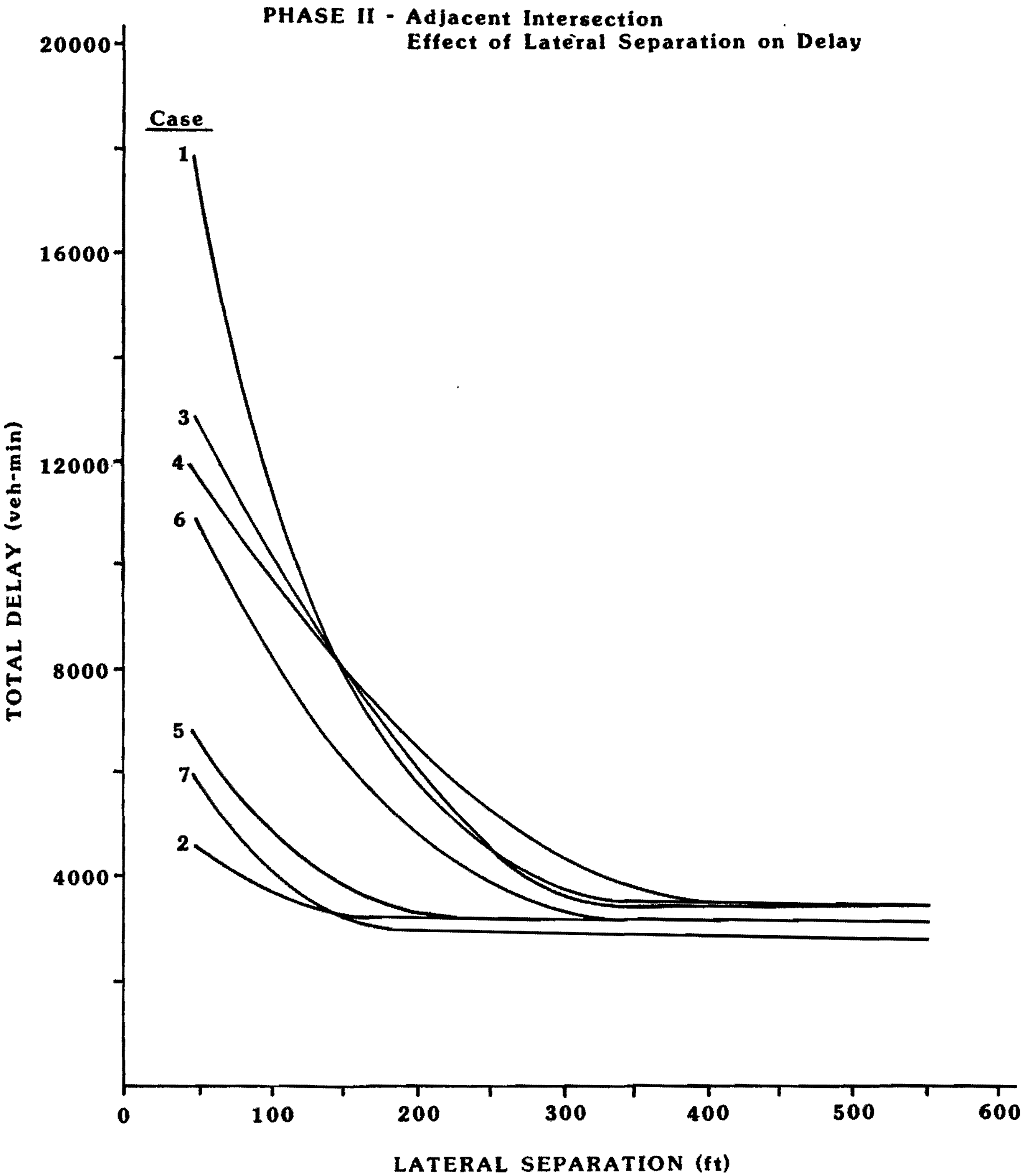

Figure 22. Adjacent Intersection - Effect of Lateral Separation on Delay - All Cases

ECONOMIC ANALYSIS FOR GRADE SEPARATION

Isolated Crossing Economic Analysis

The objective of this section of the report 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 report developed two relationships which quantify the delay time experienced by the motorist due to the light rail vehicles (LRV) closing the motorist's right-of-way, and forcing him/her to wait until the light rail vehicle has crossed the automobile's traveled way. 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 due to the delay would justify building a grade separation (over pass) for the light rail vehicles.

A grade separation costs somewhere between 3 to 5+ million dollars, depending on site specific conditions. If the public's delay time (the time spent waiting for the light rail vehicles 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 (16). 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 light rail vehicles, an economic assessment of the delay can be evaluated. For purposes of this study, occupancy of each automobile was set at 1.25 people. 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 (17).

The 24 hour day was divided into two demand periods, peak and off peak. During the off-peak periods the light rail vehicle crossings were held at a constant crossing frequency of once every 15 minutes (900 seconds). In the peak periods, when the traffic demand is heaviest, the light rail vehicle crossings were varied in frequency and duration. The delay was accrued only between the hours of 6 AM and 9PM with 6AM to 9AM and 4 PM to 7PM representing the peak traffic demand periods. Given that the light rail vehicles were operating on some given time table, the delay prompted by the light rail vehicles on an isolated crossing was then calculated. Yearly delay was based on 250 working days. A net present worth approach with a 5% 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.

The following tables were generated with the isolated delay relationship.

Table 1. Isolated Crossing Net Present Worth Evaluation for Light Rail Vehicles

LRV Crossing Clearance Time = 30 Seconds

LRV Crossings Per Peak Hour	Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48	$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

Table 2. Isolated Crossing Net Present Worth Evaluation for Light Rail Vehicles

LRV Crossing Clearance Time = 40 Seconds

LRV Crossings Per Peak Hour	Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48	$20,900	$167,100	$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	15,000	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

Table 3. Isolated Crossing Net Present Worth Evaluation for Light Rail Vehicles

LRV Crossing Clearance Time = 50 Seconds

LRV Crossings Per Peak Hour	Average Daily Traffic					
	5,000	10,000	15,000	20,000	25,000	30,000
48	$50,200	$401,700	$1,355,800	$3,213,700	$6,276,800	$10,846,300
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: Region above and to the right of solid line has peak hour crossing volume to capacity ratios greater than .95. Actual delay costs may be more than indicated.

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 0.95. The region above 0.95 is extrapolated (refer to Figure 11). The tables indicate that at low average daily traffic volumes and low light rail vehicles 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 light rail vehicle crossings, the grade separation may be warranted.

Tables 1 through 3 apply only to isolated light rail vehicle crossings, or crossings located in excess of 400 feet 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.

Adjacent Intersection Economic Analysis

A second model in the report attempted to define the delay light rail vehicles imposed on nonisolated intersections; intersections located less than 400 feet from the tracks. The model was:

$$\underset{\text{(sec)}}{\underset{\text{vehicle}}{\underset{\text{per}}{\text{Addition delay}}}} = -398 + \frac{30871}{\underset{\text{(feet)}}{\text{Lateral Separation}}} + (Xcr * 597)$$

The correlation coefficient of 0.66 is not particularly high for the adjacent intersection delay, but the model does give an indication of the magnitude of the delay costs.

The delay at the adjacent intersections accumulates quickly due to the proximity of the light rail transit tracks. Holding all other variables constant and maintaining a 10 minute peak period light rail vehicle crossing rate and a 30 second crossing clearance time, the following results were obtained:

Table 4. Adjacent Intersection Net Present Worth Delay Costs

Average Daily Traffic	Lateral Displacement between Intersections & LRV tracks				Isolated Delay Costs
	75 feet	100 feet	200 feet	300 feet	400 feet
5,000	$ 1,216,000	$ 750	$ 750	$ 750	$ 750
10,000	$ 4,893,000	$ 252,000	$ 6,000	$ 6,000	$ 6,000
15,000	$11,079,000	$ 1,975,000	$ 20,200	$ 20,200	$ 20,200
20,000	$19,819,000	$ 6,662,000	$ 47,800	$ 47,800	$ 47,800
25,000	$31,161,000	$14,714,000	$1,727,000	$ 93,300	$ 93,300
30,000	$45,150,000	$25,414,000	$4,105,000	$2,698,000	$ 161,300

The case study indicated that the delay calculations on the adjacent intersection were conservative. Actual delay costs could be 3 to 15 times greater that the values in Table 4. This suggests that a large percentage of the adjacent intersections may warrant grade separated light rail transit crossings.

The delay costs for the isolated and adjacent intersections have essentially been bounded. Very low average daily traffic, low light rail vehicle crossing frequency, and isolated operation, generally would not warrant a grade separation. An adjacent intersection could easily justify a grade separated crossing; however, each situation should be independently evaluated.

CONCLUSIONS/RECOMMENDATIONS

Conclusions

The operational characteristics of an isolated light rail transit grade crossing can be described by a single parameter. This parameter is the crossing volume to capacity ratio. This factor accounts for the light rail transit headway, the crossing volume per lane, and the crossing clearance time. The different roadway cross-sections were found not to impact the delay per vehicle. 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.

The assumption of isolation for a light rail transit grade crossing was found to be valid at lateral separations greater than 400 feet. The regression analysis of the delay values for the crossing vehicles showed the delay to be a function of the volume to capacity ratio and the reciprocal of the lateral separation when the adjacent intersection is operating at capacity levels.

While only general conclusions could be drawn, the location of an isolated light rail transit crossing operating with unconditional preemption between coordinated signals does not seem to impact the traffic greatly for the crossing conditions studied. The case study, while limited in nature, showed that the previously determined relationship appeared to underestimate the delay impact of a light rail transit grade crossing operating within a signalized roadway network. The deficiencies in the estimate of the additional delay due to the crossing appear to be with the adjacent intersection.

The economic analysis suggests that most isolated crossings (greater than 400 feet from a traffic signal) will not justify grade separations. However, many grade crossings in close proximity to a traffic signal may warrant grade separation.

Recommendations

Further study of the adjacent intersection case is needed. Future methodology for the calculation of delay due to a crossing located near an intersection should include the degree of saturation at the intersection as a variable. The critical lane volume, as used in this report, described capacity conditions, but did not fully describe the operating conditions at the intersection.

Additional work is also needed to expand the NETSIM model to include light rail transit vehicle operating characteristics and to include pre-emption of traffic signals. Special signalization would most certainly be employed in the actual application of a light rail transit line in an urban environment.

APPENDIX

Development of Crossing Volume to Capacity Ratio

At an at-grade crossing, the light rail vehicle tracks and the automobile right-of-way occupy the same space. At some point, both modes of transportation will be vying for occupancy of the same space at the same time. The problem, at an at-grade light rail vehicle crossing, consists of the allotment of time between the light rail vehicles and the automobiles. The following relationships are basic to the discussion in this report.

Light Rail Vehicle Crossing Clearance Time (CCT)	Lost Time (L)	Automobile Crossing Time (g)

← Light Rail Vehicle Headway →

Headway is the time gap between the front of one vehicle and the front of the following vehicle. The light rail vehicle crossing clearance time is composed of three components; the time involved in the lowering of the guard gates (or some other safety device or warning signal), the time the light rail vehicle 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 seconds. A longer light rail vehicle 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 light rail vehicle has cleared the right-of-way. Lost time was assumed to be four seconds.

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

Light Rail Vehicle Headway = cycle length = C

Light Rail Vehicle Crossing Clearance Time = CCT

Lost time = L

Automobile Crossing Time = g

all units are in seconds

Automobile crossing time (g) is just a ratio which represents the proportion of time available for the motorists to cross the light rail transit tracks. Obviously, this number will vary between 0 and 1. A larger number reflects more crossing time for the automobiles. This situation is very similar to a traffic signal; the fraction of time available for automobiles to cross the light rail vehicle tracks is analogous to the green time on a traffic signal head.

$$\text{Demand to Saturation Ratio} = \frac{\text{Actual Number of Automobiles per Lane per Hour}}{\text{Saturation Level of Automobiles per lane per Hour}} = \frac{v}{s}$$

This is a demand/saturation ratio of the roadway servicing the automobiles.

$$\text{Crossing Volume to Capacity Ratio} = X_{cr} = \frac{1}{g} * \frac{v}{s}$$

X_{cr} 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 light rail vehicle crossing clearance time increases.

Once the crossing volume to capacity ratio (X_{cr}) is determined, the delay may be calculated.

For light rail vehicle crossings located more than 400 feet from any adjacent intersection:

$$\underset{\text{(seconds)}}{\text{Delay/Vehicle}} = 91.16\,(X_{cr})^2$$

For light rail vehicle crossings located closer than 400 feet from any adjacent intersection:

$$\underset{\text{(seconds)}}{\text{Additional Delay per crossing vehicle}} = -398 + \frac{30871}{\underset{\text{(feet)}}{\text{Lateral Separation}}} + (X_{cr} * 597)$$

Part II

Isolated Crossing Delay Calculation Example

The relationship developed by the NETSIM model in the isolated crossing scenario is the total light rail vehicle system delay. In order to evaluate just the delay induced only by the light rail vehicles, the inherent base delay must first be deducted from the total system delay. The modified delay equation is based on a crossing volume/capacity ratio (Xcr) for the light rail crossing intersection. The volume/saturation ratio of the roadway is subtracted from Xcr in order to obtain the incremental delay prompted by light rail vehicle crossings. The following example will help clarify the issue.

Given: An isolated light rail vehicle crossing with no traffic signal within 400 feet

- Saturation level of roadway = s = 1700 vphpl
- number of lanes in roadway = 4
- peak hour traffic = 4000 vehicles (Passenger Car Equivalents)
- light rail vehicle headway = 5 minutes = 300 seconds
- crossing clearance time for light rail vehicle = 50 seconds
- assume 50/50 directional split
- lost time = 4 seconds

Find: The average delay experienced by each vehicle due to the modified isolated light rail equation:

$$\text{Delay} = 91.16\ (X_{cr})^2$$
(sec/veh)

First, calculated the demand/saturation ratio for the roadway.

With a 50/50 split;
.50 * 4000 vehicles per hour = 2000 vehicles per hour each direction
2000 vehicles per hour/2 lanes each direction = 1000 vphpl

$$\frac{\text{volume (vph)}}{\text{saturation (vph)}} = v/s = \frac{1000 \text{ vph}}{1700 \text{ vph}} = .59$$

Substitute this value into the modified equation:

$$91.16\ (.59)^2 = 31.5 \text{ sec/veh}$$

31.5 sec/veh represents the average delay NETSIM assigns to the motorists as they move through a congested (4000 Passenger Car Equivalent) System which contains no light rail vehicle operations.

The next step is to determine the Xcr ratio; (see Part I of Appendix):

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

$$g = \frac{300 - (50 + 4)}{300} = .82$$

$$Xcr = \frac{1}{g} * \frac{v}{s}$$

$$X_{cr} = \frac{1}{.82} * \frac{1000 \text{ vphpl}}{1700 \text{ vphpl}} = .72$$

It is appropriate to consider the increase of .59 to .72, the "cost" of operating light rail vehicles in competition with the right of way for the motoring public. The light rail vehicles are essentially acting as a special case traffic signal which robs the automobiles of precious green time. This Xcr relationship is inversely proportional to the automobile crossing time and in no case should it exceed 1.2

Substitute this into the modified delay equation.

$$91.16\ (.72)^2 = 46.9 \text{ sec/veh}$$

To obtain the delay induced by the light rail vehicles, subtract the vehicular delay from the total system delay.

Solution: 46.9 sec/veh - 31.5 sec/veh = 15.4 sec/veh

An average delay of 15.4 seconds is experienced by each vehicle during the course of one hour, when the given conditions prevail.

Summarized in equation form, the discussion above translates into:

$$\text{Avg. delay} = 91.16\ (Xcr)^2 - 91.16\ (v/s)^2$$
(sec/veh)

REFERENCES

1. "Criteria for Grade Separation", Barton-Aschman and Associates, Inc., June 1985.

2. Dallam, L.N., Diag, N., and Ruben, D., "Feasibility Criteria for Light Rail Transit", Transportation Research Board, TRB Special Report 195, 1982.

3. Stone, T.J. and Wild, W.A., "Design Criteria for LRT in Existing Medians: Developing Warrants for Priority Treatments", Transportation Research Board, TRB Special Report 195, 1982.

4. Railroad-Highway Grade Crossing Handbook, USDOT-FHWA, August 1978.

5. Gibson, P.A., Lin, B.B., and Roben Symer R., "Traffic Impacts of Light Rail Transit", Transportation Research Board, TRB Special Report 195, 1982.

6. Grote, W., and Yu, J.C., "Analysis of Light Rail Vehicle Clearance Time at Intersections", Transportation Research Board, TRR 1005, 1985.

7. Lombart, A., "Evolution of Light Rail in Europe Since 1977: Trends, Future Perspectives, and New Approaches", Transportation Research Board, TRB Special Report 195, 1982.

8. "Traffic Network Analysis with NETSIM: A User's Guide", FHWA, January 1980.

9. Standard Mathematical Tables, Fourteenth Edition, The Chemical Rubber Company, Cleveland, Ohio, 1965.

10. Highway Capacity Manual, Transportation Research Board, Transportation Research Board Special Report 209, 1985.

11. "SOAP84 User's Manual", FHWA, January, 1985.

12. Chang E.C.P., Messer, C.J., and Marsden, B.G., "Analysis of Reduced-Delay Optimization and Other Enhancements to Passer II-80-Passer II-84 Final Report", Texas Transportation Institute, April, 1984.

13. Pignataro, L.G., Principles of Traffic Engineering-Theory and Practice, Prentice-Hall, New York, 1973.

14. "SAS User's Guide: Basics and Statistics", SAS Institute, Inc., Cary, North Carolina, 1985.

15. Webster, F.V., "Traffic Signal Settings", Road Research Technical Paper No. 39, Road Research Laboratory, London, England, 1958.

16. Urbanik II, Thomas, "Speed/Volume Relationships on Texas Highways," Texas Transportation Institute, April, 1984.

17. Chui, Margaret K., McFarland, William F., " The Value of Travel Time: New Estimates Developed Using a Speed-Choice Model," Texas Transportation Institute, May, 1986.